ENGINEERING DATA COMPENDIUM

Human Perception and Performance

VOLUME II

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Integrated Perceptual Information for Designers Program

NASA

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"Engineers have been aware of the desirability of designing equipment to meet the requirements of the human operator, but in most cases have lacked the scientific data necessary for accomplishing this aim."

In honored memory of

PAUL M. FITTS

We dedicate this work to the past and future achievements
of the organization he founded

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Contents for Volume II

Foreword

As a result of his experience in the United States Army Air Force during World War II, Dr. Paul M. Fitts fully comprehended the need for the translation of human engineering design criteria and data into a form readily accessible to the design team. He appreciated the complexity of the typical crew interface design problem, in terms of the multiple technologies involved, the interdisciplinary skills required of the design team, and the many compromises necessary to achieve a practical solution to a complex design issue. This belief in the value of concise, reliable human performance data for practical application by designers was reflected in his approach to applied problems throughout his professional career. This concern for enhancing the value of basic technology to aid the solution of practical problems has continued to influence the organization responsible for the development of this *Engineering Data Compendium* and thus it represents an extension of Paul Fitts' conviction that a well-designed crew interface significantly contributes to the safety and effectiveness of the system in which it is incorporated.

This *Engineering Data Compendium* is the second in a series of tools aimed at providing the data necessary for the human engineering design of crew systems. The first was the two-volume *Handbook of Perception and Human Performance,* edited by K. Boff, L. Kaufman, and J. Thomas and published by John Wiley and Sons, New York, in 1986. The Handbook contains an extensive treatment of the basic data on perception and performance designed for use by the human engineering specialist. It can be considered the primary reference for the Compendium.

Although necessarily limited in scope, e.g., physical anthropology is not treated, the Compendium provides in-depth treatment of human perception and performance in terms of the variables that influence the human operator's ability to acquire and process information, and make effective decisions. Both subject matter experts and potential users were consulted on an unprecedented scale in the course of preparation and review of these volumes and every effort was made to ensure the practical value of the data presented. To meet this objective, the guidance and support of a variety of US federal agencies concerned with fielding complex systems were obtained throughout the development and testing of the Compendium. Potential users were consulted on all aspects of Compendium development, including content, readability and packaging. These consultations and extensive field testing are responsible for the usability of the volumes in typical design settings. For instance, the presentation anticipates a user who, while reasonably sophisticated in the application of technical and quantitative data, may have little prior training or experience with a specific technical area of immediate interest. For this reason, details regarding statistical and methodological reliability are included. In all entries, data are presented in an easy-to-use, standardized format and re-scaled to Système International (SI) units wherever appropriate. The packaging of the individual volumes, including the binders, volume size, internal organization, composition and type design, is based on field test results and agency guidance. Careful attention was paid to data accessibility in the design of the Compendium. Data may be accessed through a detailed table of contents, as well as key word indices, glossaries, checklists keyed to specific design topics, and knowledge maps logically organized to reflect the hierarchy of topics treated.

The *Engineering Data Compendium* is packaged in four volumes—three loose-leaf volumes containing design data and a bound *User's Guide*. It is anticipated that within a given organizational element, the three data volumes can be centrally maintained, with the *User's Guide* more generally available. The three data volumes in the loose-leaf format can thus be dynamic in the sense that multiple users can share the common data base they represent.

It was the intention of the editors and the Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory to produce a practical compendium of human engineering guidance in the tradition of Dr. Paul M. Fitts. These volumes are offered to the design community at large for their evaluation of our success in meeting this objective.

CHARLES BATES, JR.
Director, Human Engineering Division

Preface and Acknowledgments

Attempting to use the research literature in perception and human performance as a means for guiding tradeoffs between equipment characteristics and human performance capabilities or limitations can be a formidable task. This is due, in part, to difficulties in retrieving and interpreting specialized data from the multitude of information sources distributed widely over a variety of report media. The intent of the *Engineering Data Compendium* is to provide an alternative basis for efficient access to the research literature. It is designed as a professional desk reference for the practitioner in search of pertinent and reliable information on human perception and performance.

The worth of any secondary reference is inextricably tied to the user's trust in the author's objectivity and expertise in selecting and interpreting the subject matter. In the design and development of the Compendium, we have made a deliberate commitment to honor this trust.

The *Engineering Data Compendium* owes its existence to the efforts, committment and faith of an extraordinary group of individuals—extraordinary in terms of their skills, dedication, professionalism, endurance, and sheer numbers. Below, we provide an outline of the development of the Compendium so that acknowledgments to contributors may be placed within the relevant context.

Development of the Compendium

The development of the *Engineering Data Compendium* involved many iterative stages, procedures, and processes requiring control and communications on an international scale among many participants and organizations in government, industry, and academia. In addition to the formidable challenges in accessing and dealing with technical data, many hundreds of hours were spent in planning the logistics of the contracting, management and production of the Compendium. The principal stages in the development of the *Engineering Data Compendium* are briefly outlined below.

Data Consolidation

The first step in the development of the *Engineering Data Compendium* was to identify, collect, and consolidate human perception and performance data relevant to design requirements into a primary reference—the *Handbook of Perception and Human Performance*. To accomplish this task, the domains of sensation, perception, human information processing, and human performance were reviewed. Forty-five technical subareas were selected for detailed treatment on the basis of their potential value to control and information display design. A team of more than sixty recognized experts in these technical subareas was assembled to achieve this data consolidation. The Handbook was completed in December 1984 and published in two volumes by John Wiley and Sons in Spring 1986. It has served as the principle data resource in the development of this Compendium and is frequently cross-referenced as a source of useful background information and more detailed treatment of selected empirical and theoretical topics.

Data Selection and Evaluation

The selection and evaluation of data appropriate for the Engineering Data Compendium were accomplished through a series of structured reviews of selected data sources and the candidate items extracted from them. Specialists familiar with a given topic area first reviewed information on that topic contained in the primary data source (the Handbook or applied literature) and selected candidate data items for the Compendium. A brief proposal was prepared for each data item that specified the anticipated treatment in the final entry, including data functions, illustrations, and citations of original reference sources (journal articles, technical reports, etc.). This proposal was then evaluated by at least three reviewers with expert knowledge in the subject area. Candidate data items were assessed for applicability (generalizability and usefulness for system design), representativeness (soundness and currency of the data), and overall appropriateness for the Compendium. Reviewers were free to suggest alternative or supplementary data on the specific topic, recommend different organization or treatment, or reject the proposed data item altogether as inappropriate for the *Engineering Data Compendium*.

Entry Development

Candidate data items that passed this review were assigned to selected contributors who completed the necessary research and prepared draft entries in the required format. These drafts underwent an intensive editorial and technical audit that included recursive evaluations of each entry against the original candidate entry proposals as well as the data sources on which the entries were based. Special attention was given to ensuring that details of the methodology, data analysis, and experimental results were represented accurately in the entry (and that the errors occasionally found in the original reference sources were not reproduced in the Compendium). Many entries were rewritten, combined, or eliminated during this editing stage.

Edited entries were then sent for review to subject matter experts and, wherever possible, to system designers. The entries were evaluated along three dimensions:

(1) Relevance: Will the information be useful to the target groups, or is it of purely academic interest?

(2) Content: Is the basic information thoroughly represented? Is it accurate and usable as presented?

(3) Form and style: Does the entry adhere to the prescribed format? Is it written in clear and concise language?

During the course of the successive outside reviews that occurred as each data item progressed from entry proposal to final written entry, the qualifications and background of the reviewers selected shifted from expertise in the specific subject matter under review to experience with the conditions under which the information could be applied. This procedure assured that the information in the Compendium would not only be accurate and up to date but also relevant to system design needs and comprehensible to non-specialists in the field.

Prototype

In 1984, a prototype version of the Compendium was produced, both to provide suitable materials for on-going field evaluations and to serve as an interim product in sustaining the enthusiasm of the project's patient sponsors at DoD and NASA.

The prototype Compendium was comprised of two technical sections dealing with stereoscopic vision and vibration and display perception. These topic areas were developed in full to demonstrate the flexibility of the format in covering various topics as well as different categories of information (e.g., data, models, tutorials). So that the prototype would fully embody the image and feel of the final product, we designed and incorporated front matter, keyword indices, glossaries, and other organizational and packaging elements. Compilation of the prototype served as a trial by fire for IPID project team members that allowed the refinement of managerial and editorial procedures to make production of the final volumes flow more smoothly.

Final Preparation

Final preparation of the entries for publication involved interactive audits, edits, reviews and much retyping across multiple drafts. Quality control concerns were central to our processing of the entry manuscripts. Quantitative formulations, authors' names, and reference citations were checked and rechecked. Several thousand figures, tables, and illustrations were drafted, converted to SI (Système International) units, reviewed, proofed and corrected. Permissions for the use of copyrighted materials were sought and paid for, and the multitude of individual credit lines specified by copyright holders were inserted.

Production

To maintain control over Compendium design, product quality, and costs to the final consumer, we assumed the traditional role of publisher in managing the production, manufacturing and distribution of the Compendium. This included the complete design of the document (artwork design, type style and layout of text, binder design), type composition, proofreading of galleys and page proofs, printing and photographic work, binder manufacture and packaging. In addition, we took primary responsibility for defining the logistics for the shipping, handling, warehousing and distribution of the Compendium.

Acknowledgment of the Cast

It is difficult, given a project of this scope, to acknowledge appropriately the contributions and dedication of the many individuals indispensable to its success. This task is further complicated by the many different roles assumed by contributors, including fiscal support, management, and administrative and secretarial support. All of these individuals deserve considerably greater recognition for their contributions than can possibly be achieved by this acknowledgment. Without doubt, we have inadvertently omitted some individuals who made contributions; for this, we sincerely apologize.

The program was accomplished under USAF project 7184, task 26, work units 02, 03 and 06. Crucial support was provided by Colonel Donald Carter in his role as Program Manager of the program element under which this Compendium was funded. It was managed through the offices of the Visual Display Systems Branch of the Fitts Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH. Thomas A. Furness III, Branch Chief, and Charles Bates, Jr., Division Chief, provided encouragement and moral support during the many periods of frustration inevitable in a project of this size. Most importantly, they created an environment in which novel ideas, such as the one that inspired this project, could be nurtured and sustained through final delivery of products. As the Compendium took form, Charlie orchestrated the support and marshalled the resources needed for its production and widespread distribution throughout the international human engineering community.

In the branch and the Fitts Human Engineering Division, we are indebted to many individuals for support and constructive criticism that helped define the project's conceptual basis and immeasurably improved the quality of the product. Gloria Calhoun aided much of the early planning that enabled the project to flourish. Herschel Self contributed long hours and enormous intellectual effort in the review, editing and critiquing of Compendium entries. Herschel single-handedly drafted the thousands of design-related questions that comprise the design checklists in the *User's Guide* (Vol. IV). Robert Eggleston contributed many thoughtful suggestions and much personal energy in aiding major aspects of the project. David Post, our resident color perception expert, gave generously of his time and expertise to ensure the technical accuracy of the treatment of color vision in the Compendium. Professional contributions and peer reviews were also provided by Mark Cannon, Bill Crawford, Thomas Furness, Fran Green, Michael Haas, Steve Heckart, Gilbert Kuperman, Grant McMillan, Wayne Martin, Gary Reid, Donald Topmiller, Sharon Ward, Richard Warren, and Melvin Warrick. Al Chapin, Division Custodian, made heroic efforts to ensure that the special binder requirements for the Compendium would be met. Last, but by no means least, Barbara Osman, Executive Secretary for the Fitts Human Engineering Division, carefully proofread volumes of project correspondence. Sandy Stevenson expedited contractual matters and expertly proofread all IPID product reports. Within the Visual Display Systems Branch, Tanya Ellifritt personally gave wide-ranging administrative assistance and attention to the project.

We are also very grateful for the advocacy and support provided by Henning Von Gierke (Division Chief) and members of the technical staff of the Biodynamics and Bioengineering Division of the Armstrong Aerospace Medical Research Laboratory. These include the invaluable contributions by Tim Anderson, Jim Brinkley, Urena Erasmo, Charles Harris, Richard McKinley, Thomas Moore, Charles Nixon, Daniel Repperger, Richard Shoenberger, Mark Stephenson, Bill Welde, and Robert Van Patten.

Ken Zimmerman and Patricia Lewandowski, of the AAMRL Scientific and Technical Information Office, worked with the appropriate agency officials to clear many limited-distribution government documents for public release so that useful data from these reports could be included in the Compendium.

The idea for the project evolved from a former Air Force effort for which much inspiration is owed our colleagues Patricia Knoop, Lawrence Reed, Rick Gill, Bert Cream, Don Gum, and Gordon Eckstrand. Belief in the idea of an

Engineering Data Compendium and its potential value to the design engineering community spurred Art Doty, former Chief Engineer for the Air Force Deputy for Simulators, to agree to provide major sponsorship of this project. There is little doubt that this initial support opened the doors to subsequent multi-agency funding that supported the project and, in fact, enabled its survival. We are also grateful for the steadfast support and trust throughout the project provided by the Office of the Air Force Deputy for Training Systems (formally the Deputy for Simulators), presently under the leadership of Colonel Wayne Lobbestael. Many useful suggestions and valuable support were rendered by the technical and administrative staffs of the Training Systems SPO. In particular, we wish to acknowledge Jim Basinger, George Dickison, Jim O'Connell (current Chief Engineer), Bob Swab, Chris Hanson, and Nancy Droz.

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Introduction

In science, by a fiction as remarkable as any to be found in law, what has once been published, even though it be in the Russian language, is spoken of as known, and it is too often forgotten that the rediscovery in the library may be a more difficult and uncertain process than the first discovery in the laboratory.

Lord Rayleigh (1884)

Despite spectacular advances in display systems and data handling technologies, modern crew systems confront their operators with a staggering volume of codified information that competes for scarce attentional and control resources. Unabated, these increasing psychological and physiological demands have the potential to undermine critical technology gains in system performance. While it is generally accepted that the ability of the human operator to acquire and process task-critical information is a key contributor to system effectiveness, significant difficulties arise in translating this realization into meaningful action in system design and acquisition. Recognition of the problem has spurred concerted efforts across the Department of Defense to influence early design tradeoffs in favor of an improved match between system specifications and operator characteristics.

Whether or not an optimal fit will be achieved between system capabilities and the perceptual and performance capabilities of the operator depends, among other things, on the nature of the design process, the inclinations and biases of designers, and the availability of usable data resources. In particular, human performance data are needed in a form and at a level of precision that will allow operator characteristics to be traded off against other design variables (Ref. 1).

While a good deal of potentially useful human performance data exist, these data have had very little direct impact on the design of system interfaces. In large measure, this failure to translate relevant research findings into practice is due to the perceived high costs and risks associated with their *accessibility, interpretability,* and *applicability* for system design problems.

Accessibility. Much of the research data of potential value to system designers is embedded in the huge volume of psychological and technical literature distributed among countless journals, periodicals, and government and industrial reports. Furthermore, the contextual and theoretical framework within which researchers typically generate and disseminate technical information does not necessarily coincide with the logical framework or needs of the practitioner. Designers may not readily locate the information they need in the places they expect to find it (Ref. 2).

Interpretability. The difficulty of the nonspecialist in understanding and evaluating the technical data found in traditional sources of ergonomics information is also a major problem. Researchers typically feel little responsibility to the applied world beyond reporting their findings in the scientific literature. Hence, interpreting scientific communications generally adds considerable overhead and in fact may be a barrier for the practitioner who lacks the ability to evaluate the relevance of ergonomics information to the problem at hand (Ref. 3). The human factors profession is particularly guilty of failing to tailor the presentation of human perception and performance data to the needs of practitioners (Ref. 4).

Applicability. A major problem influencing the use of ergonomics data is the obvious difficulty and continuing controversy regarding the relevance and translatability of research data to practice (Refs. 5, 6). Not only are data collected under highly controlled circumstances, but the experimental conditions set by researchers are often so synthetic that a major stretch of the imagination is required to find analogous circumstances in the real world to which these conditions might relate. The concern is that data collected under such highly limiting conditions cannot be reasonably extrapolated to multivariate environments where it is difficult to take account of the many interacting factors that may contribute to performance variability. Unfortunately, this criticism is also true of most applied multivariate studies in which the problems of comparing and extrapolating between experimental and dynamic "real world" contributors to variance are severely compounded. Therefore, if the utility of ergonomics is gauged solely in terms of the extent to which it can supply "cookbook" answers to designers, then the ergonomics discipline itself will be judged a failure. Neither the time nor the resources are ever likely to exist, particularly in the midst of design problem solving, to evaluate parametrically all the conditions pertaining in an interactive real-world system problem. Ergonomics data are useful not because they are directly translatable to multifactor conditions (though some "cookbook" answers exist for some "cookbook" questions), but rather because they offer cues, clues, and confirmations to support the designer's reasoning processes (Refs. 3, 7).

The *Engineering Data Compendium: Human Perception and Performance* produced under the Integrated Perceptual Information for Designers (IPID) project is intended to provide ergonomics data as a technical resource for system design. To help ensure that the *Engineering Data Compendium* finds its way to the designer's workbench, rather than simply to the designer's bookshelf, the presentation of information has been tailored to the needs of the user. In particular, during development of the Compendium, systematic attention has been given to: (a) defining and validating approaches to effectively communicating ergonomics data to system designers in terms of presentation format, style, terminology, and level of technical content; and (b) enhancing the accessibility of specific technical information relevant to design problems by providing the user with reliable means of locating specific data.

In the development of the *Engineering Data Compendium,* we have learned from previous efforts in this area (Refs. 8-12) and have freely borrowed and integrated their successful elements into our approach. Nevertheless, the Compendium does have several unique features: one is the range and depth of the perception and performance data treated; another is the approach devised for communicating this information so that it is both comprehensible and accessible to the intended user.

What the Compendium Contains

The available body of psychological research contains a staggering volume of human perceptual and performance data and principles that are of potential value to system design. This includes data regarding basic sensory capacities and limitations (contrast sensitivity, spatial/temporal eye movement dynamics, aural and vestibular thresholds, etc.), as well as perception and human information processing (visual, aural, and proprioceptive pattern recognition, information portrayal, etc.). In the *Engineering Data Compendium,* basic data and principles from these areas are treated in depth and combined with applied human factors data into a single comprehensive reference source.

Eight classes of information are included in the *Engineering Data Compendium:*

1. ***Basic and parametric data*** (e.g., dynamic range of the visual system, spatial and temporal contrast sensitivity functions, physical response constants of the vestibular system, receiver operating characteristic curves).

2. ***Models and quantitative laws*** (e.g., CIE spaces, probability summation, operator control models). A model or law had to meet two criteria in order to be included: (a) it had to provide a way of interpolating or extrapolating existing data and relating them to a specific application, either to answer a design question directly or to specify the research needed to answer the question; and (b) it had to have a well defined and documented domain of reliable application.

3. ***Principles and nonquantitative or nonprecise formulations*** that express important characteristics of or trends in perception and performance (e.g., Gestalt grouping principles, interrelationship between size and distance judgments, depth and distance cues).

4. ***Phenomena*** that are inherently qualitative or that are general and pervasive, although quantitatively described in specific instances (e.g., simultaneous brightness contrast, visual illusions, motion aftereffects).

5. ***Summary tables*** consolidating data derived from a body of studies related to a certain aspect of sensation, perception, or performance (e.g., table showing different acuity limits as measured with Landolt rings, grating patterns, etc.; table summarizing the effects of various factors known to affect stereoacuity).

6. ***Background information*** necessary for understanding and interpreting data entries and models (such as rudimentary anatomy and physiology of sensory systems, specialized units of measurement or measurement techniques; specific examples are anatomy of the ear, geometry of retinal image disparity, colorimetry techniques).

7. ***Section introductions*** to topical areas that describe the topic and set out its scope, explain general methods used in the given area of study, note general constraints regarding the application of data in the area, and provide references for further general information.

8. ***Tutorials*** containing expository material on general topics such as psychophysical methods, linear systems analysis, signal detection theory, etc., included both to help the user fully understand and evaluate the material in the Compendium, and to support research and evaluation studies in engineering development.

To make pertinent information more accessible to the user, graphic modes of presentation are used wherever possible. The Compendium contains over 2000 figures and tables, including data graphs, models, schematics, demonstrations of perceptual phenomena, and descriptions of methods and techniques. Other features of the Compendium include indicators of data reliability, caveats to data application, and the use of standardized units of measurement (Système International).

Data Presentation

To help the user locate and interpret pertinent information, a standardized presentation format has been developed for entries in the *Engineering Data Compendium* that is tailored to the needs of the design engineer. This format has evolved over several years through an iterative process of review and discussion with the user community, sponsors, and consultants. In its present form, it represents our best attempt at "human factoring" the presentation of relevant perceptual and performance data.

The basic unit of information in the Compendium is the individual *entry* addressing a narrow, well-defined topic. Each entry is centered around a graphic presentation such as a data function, model, schematic, etc. Supporting text is compartmentalized into a set of text modules or elements. Each of these elements provides a concise subunit of information designed in content and style to support understanding and application of the data. The entry format is described in detail in the *User's Guide* (Vol. IV).

The prescribed entry format has the advantages of both formal structure and adaptive modularity. The appearance of entries is generally uniform. In most cases, entries are presented on two facing pages. The type of information contained in each entry subsection is consistent across entries. Hence, the user can confidently access those elements needed to interpret or apply the data without being distracted by information irrelevant to the problem at hand. The format is also adaptable; only those elements appropriate to a given class or type of entry are presented.

Data Access

The *Engineering Data Compendium* provides system designers with a wealth of relevant human performance and perceptual data heretofore unavailable to them in a useful form. However, access to the data in the Compendium is complicated by the fact that the perceptual concepts that underlie the data typically fall outside the scope of the training or experience of most practitioners. If these concepts are to be recognized as relevant to specific design problems, they must be linked to information or issues familiar to the designer.

Several different means of accessing material are provided so that users with different interests and technical background can readily locate the information pertinent to their needs.

1. ***Tables of contents.*** Two levels of contents listings are provided: A brief, global table of contents enabling the user to quickly determine the overall scope and organization of the Compendium may be found at the front of each volume. An expanded table of contents listing all subsections and entries by title is provided in the *User's Guide* (Vol. IV). An expanded contents for each major section of the Compendium is also located at the beginning of the corresponding section.

*2. **Sectional dividers.*** Each major section listed in the table of contents can be located rapidly by means of marginal tab dividers imprinted with the corresponding subject area title. Three of the topical sections (Sections 1.0, 5.0 and 7.0) are further subdivided by marginal tabs using size and color codings appropriate to the hierarchical scheme.

*3. **Glossary of technical terms.*** A brief glossary of definitions is provided at the beginning of each major topical section. A consolidated glossary is contained in the *User's Guide*.

*4. **Indices.*** A sectional keyword index is provided at the beginning of each major topical section. This index is designed to help both naive and experienced users formulate their search questions in terms of relevant perceptual issues that may then be directly accessed within the Compendium.

*5. **Logic diagrams.*** At the beginning of each major topical section is a diagram showing the taxonomic hierarchy of subtopics and supporting entries for that section.

*6. **Cross references.*** Each Compendium entry includes extensive cross references to other Compendium entries and to sections of the *Handbook of Perception and Human Performance* (Refs. 11, 12) that provide more detailed treatment of a topic or subtopic, discussion of related topics, or explanatory material to aid in understanding or interpreting the data.

*7. **Design checklists.*** Found in the *User's Guide* are checklists of design-oriented questions suggesting human performance variables that should be considered in the specification of equipment.

In addition, the *User's Guide* comprising Volume IV of the Compendium provides instructions for accessing data and a description of the format and organization of information in the Compendium.

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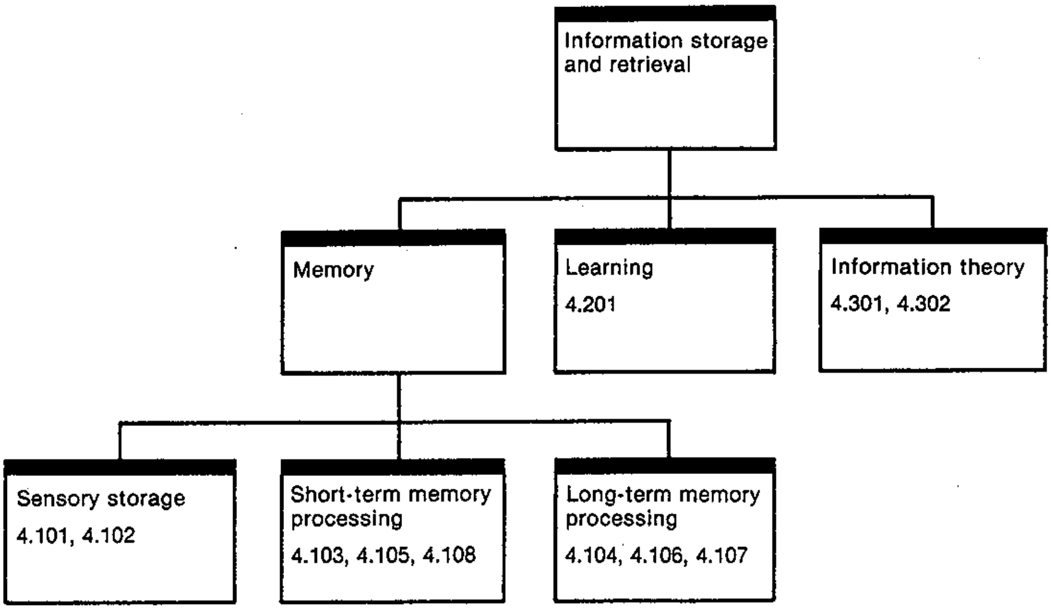
Contents for Volume II

Organization of Entries



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Section 4.2 Learning

Section 4.3 Information Theory

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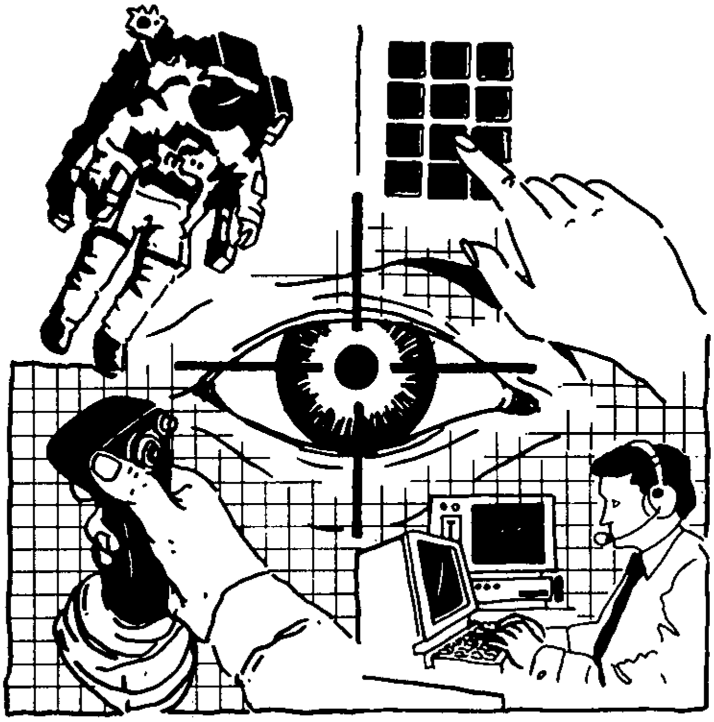
Section 4.0 Information Storage and Retrieval



4.101 Factors Affecting Acoustic Memory

Factor	Methodology	Effect on Recall	References
Presentation rate	Dichotic listening	With slow presentation (one pair per sec) items reported in temporal order; with fast presentation (two pairs per sec) material to one ear reported first, then material to other	Ref. 1
Acoustic similarity of list items	Serial recall	The greater the acoustic similarity, the poorer the recall for the most recently presented items	Ref. 5
Duration of masking stimulus	Backward masking	No effect	Ref. 7
Interval between target and mask	Backward masking	Intervals <250 msec result in interference, which increases as the target and mask become closer; intervals >250 msec result in no interference	Ref. 7 CRef. 7.206
Laterality of mask	Backward masking	A masking stimulus has equal effect regardless of whether it is presented to the same ear or the opposite ear as the target item	CRef. 8.307
Presence of suffix at varying interval after last memory item	Serial recall with suffix	A suffix presented simultaneously with the last test item has little, if any, effect; a suffix presented after an intermediate delay of 300-1000 msec yields a maximal decrease in recall of the last test item; a suffix presented >2 sec after the last test item has little, if any, effect. The delay yielding maximal decrease in recall is independent of item presentation rate. If the suffix is relatively loud (when compared to the memory items), the function becomes monotonically decreasing rather than inverted-U shaped	Ref. 3 CRef. 4.102
Acoustic similarity of suffix and list items	Serial recall	The greater the acoustic similarity (pitch, voice, intensity, spectral characteristics), the smaller the memory advantage for the last item presented	Refs. 5, 8
Semantic similarity of suffix and list items	Serial recall	No effect	Ref. 8
Suffix in different ear from list	Serial recall	Better recall for most recent items than if in same ear. Binaural (both ears) suffix produces fewer errors than ipsilateral (same side) suffix if list is presented to only one ear	Ref. 8 CRef. 4.102
Multiple suffixes	Serial recall	Better recall for most recent items than with only one suffix	Ref. 4 CRef. 4.102

Key Terms

Backward masking; dichotic listening; echoic memory; precategorical acoustic store; recency effect; serial recall

General Description

Short-term recall and backward masking experiments indicate the existence of an auditory sensory memory (termed *echoic memory*), which briefly retains a relatively unprocessed auditory image of acoustic input. The accompanying table lists several factors that affect echoic memory and summarizes their effects on the retention of acoustic information. In a dichotic listening (split-span) task, pairs of items (such as words or numbers) are presented simultaneously, one to each ear, and the subject then recalls the items presented. In a serial recall task, lists of items (such as numbers, words, or nonsense syllables) are presented to subjects, who then must recall the items in the order in which they were heard. Subjects typically show better recall for items at the beginning (primacy effect) and end (recency effect) of the list than for items in the middle of the list. The memory list may be followed by a suffix — an additional item presented at the end of the list which does not need to be recalled by subjects. The presence of a suffix may eliminate the memory advantage for the most recently presented list items (recency effect). In a backward-masking task, a test item (such as a tone or vowel sound) is presented briefly and is followed after a short interval by a masking stimulus (which may be similar to or different from the test item). The subject must detect the test item or identify which of two or more alternative test items is presented on a given trial.

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Constraints

- The effect of any one factor on auditory memory depends heavily on the methodology used.

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Cross References

4.102 Acoustic memory: effect of serial position, suffix and response prefix on probed recall;

7.206 Divided versus selective attention: effect on auditory recognition accuracy;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

4.102 Acoustic Memory: Effect of Serial Position, Suffix, and Response Prefix on Probed Recall

Key Terms

Echoic memory; interference; primacy effect; recency effect; serial recall; suffix effect

General Description

Items at the beginning or end of an auditorially presented list are recalled more accurately than are items in the middle of the list. The memory advantage for items early in the list is called the primacy effect, and for those late in the list, the recency effect. Auditory presentation of a suffix (an additional item such as "zero" or "uh..." presented after the list to be recalled) diminishes recall and particularly diminishes the recency effect. Semantic differences between the suffix and list items do not change the effect. Physical differences between suffix and items partially restore the recency advantage. Having subjects say an item (e.g., "zero" or "uh...") after list presentation and prior to the beginning of recall (i.e., as a response prefix) has the same effect as a suffix, except that the last item on the list is remembered as well as when there is no prefix or suffix.

Methods

Test Conditions

- Probed recall task required subjects to listen to orally presented series of digits and then fill in one or more missing digits on a written card containing the same series of digits
- Randomized lists of eight or nine digits, six animal or utensil names, or eight words selected from one of two frequency-of-occurrence classes and one of three rated emotionality classes; presented **monaurally** or **binaurally** over headphones at the rate of two items per sec
- Lists presented alone or followed by a suffix or a response prefix ("zero" or "uh"); suffix could be semantically similar or dissimilar to prelist items or semantically empty ("uh..."), or physically similar or dissimilar to list items; suffixes presented to both ears or to the same ear or the opposite ear as was a set of list items; subjective loudness and pitch for suffixes were either the same or twice that of the list item; subject either said or wrote response prefix
- 10-54 subjects per condition; 36-200 trials per condition

Experimental Procedure

- Independent variables: serial position of item in list, suffix (presence or absence), response prefix (presence or absence), semantic similarity of suffix to list items, meaningfulness of suffix and response prefix, acoustic similarity (loudness, pitch, voice, ear of presentation) of suffix to list items, semantic similarity of list items, frequency of occurrence and emotionality of list items
- Dependent variable: recall accuracy at each list position
- Subject's task: recall (in writing), immediately following presentation, the list items in order of presentation; for the response prefix and suffix conditions recall (from the series of digits just heard) only the absent digits (probed recall)
- Subjects were college students or homemakers
- Conditions were appropriately counterbalanced

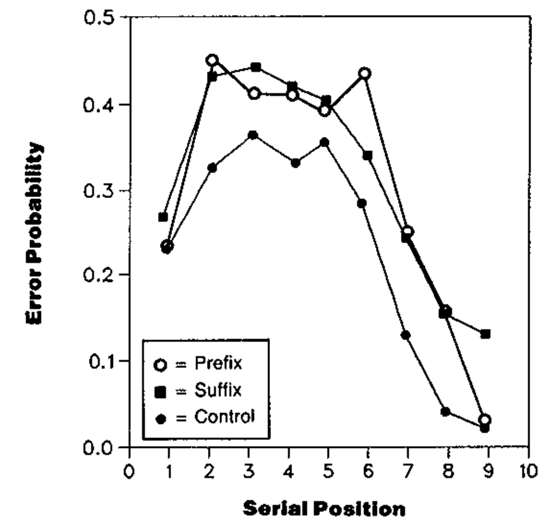

Figure 1. Probability of an error in serial recall of a digit as a function of its position in a nine-digit list. Memory list was presented alone (control condition), followed by an additional nonmemory item (suffix condition), or subject spoke the word "zero" prior to beginning list recall (response-prefix condition). Relative loudness and pitch of the prefix and suffix are assumed to be the same. No information was given on prefix-suffix semantic and physical similarities/dissimilarities. Both prefix and suffix were presented to both ears. (From Ref. 3)

Experimental Results

- Initial and final items in a list presented auditorily are recalled with less error than middle list items.
- An auditory suffix reduces recall at all list positions, but most markedly at the last list position ($p<0.002$).
- An auditory response prefix reduces recall at all list positions except for the last item in the list.
- Semantic variables, such as frequency of occurrence, meaningfulness, emotionality, or meaning relationship between suffix and list items, do not affect the suffix effects (data not shown).
- Physical differences between the suffix and list items, such as ear of presentation, loudness, pitch, or voice, diminish the effect of the suffix (data not shown).

Variability

Significance of differences ($p<0.05$) was usually determined by one- or two-tailed Wilcoxon tests or sign tests. Results replicated across many subjects and experiments.

Constraints

- Results apply only to auditory presentation and short term recall.
- Multiple suffixes diminish the suffix effect.
- List items were individual words. The same result cannot be generalized to an eight-word sentence, for example.

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Cross References

Handbook of perception and human performance, Ch. 26, Sect. 3.2

4.103 Memory Search Rates

Key Terms

Memory search; recognition memory; serial exhaustive scanning; short-term memory

General Description

The time to search a list of items in memory for a specified item (probe) increases linearly as the number of items in the memory list increases. The search rate is the same whether the probe is in the list (a target) or is not in the list (a nontarget). Visually degrading the probe stimulus increases the time to encode the probe (i.e., to represent the probe in memory), but does not affect the memory search rate.

Methods

Test Conditions

- Random series of one to six digits (a memory set) displayed singly for 1.2 sec each, followed by a 2-sec blank interval, warning signal, and then probe digit
- Probability of occurrence of target digit (probe contained in memory set) or nontarget digit (probe not in memory set) depended on memory set size (s): target probability $= (2s)^{-1}$, nontarget probability $= [2(10-s)]^{-1}$

Experimental Procedure

- Two-choice **reaction time** (RT) procedure; repeated-measures design
- Independent variables: memory set size (list length), target or nontarget probe item (appeared or did not appear in list)
- Dependent variables: memory search rate, defined by the slope of the RT function; combined time to encode stimuli and respond, defined by the y-intercept of the RT function
- Observer's task: decide whether probe item was in memorized list of digits and give manual response; feedback provided
- Payoffs encouraged observer to respond as quickly as possible while maintaining low error rate
- 8 observers with some practice

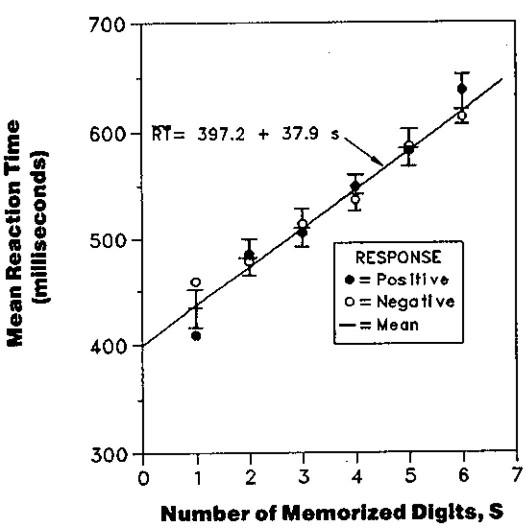

Figure 1. Linear relationship between memory search time and number of items to be searched in memory. Reaction time is the total time required to compare a visually presented probe digit with a previously memorized list of digits and to indicate whether the probe was (positive or "yes" response) or was not (negative or "no" response) contained in the memorized list. The y-intercept represents the time required to encode the probe stimulus and respond; the slope of the function represents the time required to compare the probe digit with each item in memory. (From Ref. 2)

Experimental Results

- Time to search through a previously memorized list for a specified item increases linearly with the number of items in the list. The linear reaction time (RT) function (fit by the least squares method) accounts for 99.4% of variance of mean overall RTs. This implies that observers scan memory serially, item by item, instead of scanning all items in parallel.
- The 38-msec slope for the RT function represents the time it takes to make each memory comparison; the slope is the same for both target and nontarget probes. This implies an exhaustive scan of the list in memory; if the search terminated as soon as the target item matched the probe item, the target slope would be half as great as the nontarget slope.
- In a related study (Ref. 3), different variables were found to influence various aspects of the RT function. For example, degrading the probe stimulus by superimposition of a checkerboard grid increases the y-intercept (which represents encoding time plus responding time) but does not affect the slope of the function (which represents memory comparison time). This implies that the memory search task is actually composed of several stages, and that each stage can be examined independently of the others.

Variability

Error bars represent standard error of ±3.8 msec for the slope of the response time function. Standard error of the y-intercept is ± 19.3 msec.

Repeatability/Comparison with Other Studies

Numerous other studies have found that reaction time increases linearly with memory set size. However, the implication that it is more efficient to scan an entire memory list before checking for a match (exhaustive scan) than to check for a match after each comparison has not always been supported (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Computed values for the slope and y-intercept given here hold only for the viewing conditions described and should not be applied, except qualitatively, to different conditions.
- Stimuli used here were very familiar to observers and memory set lists were small (7 items or fewer); results may differ for less familiar stimuli and larger lists.
- A number of factors (e.g., repetition of probe digits, probe digits near memory-set boundaries) may cause response times to deviate from the serial exhaustive scanning model proposed to explain the results shown in Fig. 1 (Ref. 1; CRef. 4.105).

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Cross References

4.105 Memory search time: effect of memory probe characteristics;

Handbook of perception and human performance, Ch. 28, Sect. 2.1

4.104 Skilled Memory Effect

Key Terms

Expert knowledge; imagery; pattern recognition; problem solving; training

General Description

For a wide variety of problem-solving domains (e.g., from games to circuit analysis and architecture), individuals with expertise in the domain show better memory for information in the domain than do novices. This effect may result from (1) the accumulation of a vast store of solutions to particular problems, and (2) a well-organized conceptual knowledge base that provides for organizing and storing new information.

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Cross References

4.102 Acoustic memory: effect of serial position, suffix, and response prefix on probed recall;

4.103 Memory search rates;

4.106 Memory for visual patterns: effect of perceptual organization

Table 1. Summary of studies on the skilled memory effect.

Task Domain	Test Conditions	Results	References
Memory for computer programming code	Recall FORTRAN code, after brief study (3 min or 15 min) of either a short program or a similar number of randomly mixed lines of code Amount of FORTRAN experience (none, one course, one course plus experience, and much experience in one study; none of graduate level in second study) varied across groups	Recall of *program* was a direct function of amount of programming experience, but recall of random code was essentially the same for all groups	Ref. 14
Baseball knowledge	Brief description of baseball game situations, presented to undergraduates with high ("experts") or low ("novices") knowledge of baseball Recognition test or free recall test	"Experts" could better classify information as "new" when it had not been seen before "Experts" required fewer prompts to recognize old information "Experts" had better recall for baseball, but not for nonbaseball sequences "Experts'" recall was improved by adding baseball context, but "novices'" was impaired	Ref. 7

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Task Domain	Test Conditions	Results	References
The game of Go	Two sets of patterns of playing pieces on a Go board, with 10 actual game patterns and four random placements in each set Pattern reproduction task, from memory (after 5 sec of study) or while looking at pattern One master Go player, one novice; videotaped observation	Memory for *random* patterns was similar for master and novice (30% versus 25% correct), but master had far superior memory for game patterns (66% versus 39%) Inter-response time (IRT) analysis of chunking found patterns similar to those seen in chess, but chunks could not be reliably indentified from a single IRT criterion	Ref. 14
	A pair of patterns, one a rotation and reflection of the other, viewed as either a board position from game of Go or from game of Gomuku Subjects were shown each pattern and attempted to reconstruct the board from memory	Memory for placement of pieces critical in one game but not in the other was better when board was viewed as an example of that game	Ref. 10
The game of bridge	Recall of 10 tournament simulation hands Reconstruction of 10 structured and 10 nonstructured bridge hands, either from memory after 20 sec of study or while looking at hands Expert, life master, casual player, novice	Expert and life master were far superior to others in tournament recall Expert and life master remembered structured hands much better than casual and novice players, but all players were equally poor on nonstructured hands Expert appeared to chunk by suit and position	Ref. 11
	State line of play for four bridge problems, followed by unexpected recall of hands Give an opening bid as fast as possible to each of 20 hands. Recall ordered or random bridge hands after 5-sec exposure 20 bridge players, novices (0 master points) to life masters (300 + points)	Players with increasing levels of skill (a) gave better solutions to bridge problems, (b) had higher recall of hands, (c) gave faster and more accurate opening bids, and (d) recalled more cards with ordered but not random hands Older players were less accurate on memory tests than younger players at every skill level	Ref. 3
Memory for symbolic circuit drawings	18-36 drawings of standard circuits or drawings with randomly placed circuit elements Reconstruct circuit after 10 sec of study Electronics technicians or undergraduate novices	Technicians were more accurate in remembering real circuits than were novices, but the two groups did not differ for random arrangements Technicians appear to have slightly larger chunks than novices Recall improved for both groups as study time increased from 5-15 sec	Ref. 9
Chess	Master level and weak chess players (5 subjects at each level) were either shown a chess position for 5 sec and asked to reconstruct it or asked to guess the position of pieces without seeing the board ("blind guessing")	Masters were far superior to weak players (90% to 40%) in reconstruction after one look Masters were not much better than weak players in blind guessing	Ref. 8
	Reconstruct chess positions (from middle game, end game, or random) either with the position constantly visible (perception task) or from memory after 5-sec viewings (memory task) Master, Class A, and beginner level chess players (one each)	Reproduction accuracy was directly related to playing strength for actual positions but not for random positions Response organization was similar in perception and memory tasks Master had information stored in more and larger chunks	Refs. 5, 6

4.105 Memory Search Time: Effect of Memory Probe Characteristics

Key Terms

Memory search; recognition memory; self-terminating search; serial exhaustive scanning; short-term memory

General Description

The time taken to search through a list of items in memory (memory set) for the presence of a specified item (probe) depends upon the nature of the probe item and of the items in the memory set. Increasing probe stimulus probability and recency of serial position of the probed item within the memory set decreases reaction time for a given probe item. These results run contrary to those expected if a serial exhaustive scan is used to search the items in memory without processing information about the nature of the items (CRef. 4.103).

Applications

Tasks in which an operator must search through limited sets of memorized information; systems in which a scan through stored information results in recording the nature of the scanned items.

Methods

Test Conditions

Study 1 (Ref. 4)

- Memory set of 4 digits presented at beginning of session, shown for 2 sec; memory set constant for entire experiment
- Probe items (digits 1-8) presented individually at fixated location; 4 of the probe digits belonged to the memory set (target probes) and 4 did not (nontarget probes)
- Each probe digit presented on 50, 25, or 12.5 percent of target or nontarget trials
- All characters 0.48 cm wide by 0.71 cm high
- CRT display; viewing distance 0.61-0.76 m
- Room light provided by one 25-W lamp

Study 2 (Ref. 3)

- Single digits photographed onto frames of 16-mm film strips and rear-projected onto screen 0.61 m (2 ft) in front of observer; each digit ~2.54 cm high
- 1-7 digits in memory set serially presented, one digit every 1500 msec; new memory set every trial; presented 800, 2800, or 4800 msec after last digit of memory set
- 50% of trials contained a target probe, 50% of trials contained a nontarget probe

Experimental Procedure

Study 1

- Choice reaction time; repeated measures design
- Independent variables: presence of probe item in memory set (target or nontarget probe), frequency of presentation of each probe digit
- Dependent variables: reaction time, error rate
- Observer's task: indicate whether probe item was present in memory set; feedback provided
- 16 subjects, university students with unknown amount of practice

Study 2

- Choice reaction time; repeated measures design
- Independent variables: memory set size, presence of probe item in memory set (target or nontarget), delay of probe item presentation, serial position of probe item in memory set
- Dependent variables: reaction time, error rate
- 12 female observers (ages 13-15) with some practice; selected on basis of <10% error rate

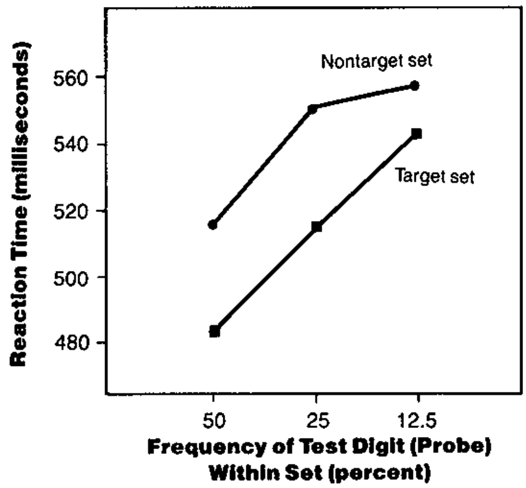

Figure 1. Memory search with probes of different frequencies (Study 1). The reaction time to indicate whether a probe digit is contained (target) or is not contained (nontarget) in a previously memorized list of digits is shown as a function of the frequency of occurrence of the probe within the set of all target or nontarget probes. (From Ref. 4)

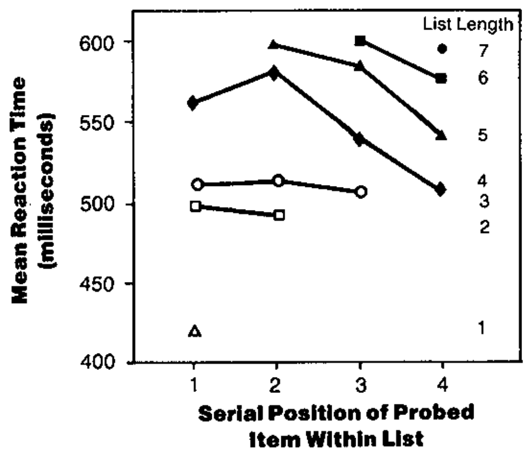

Figure 2. Memory search as a function of memory set length and position of probed item (Study 2). The figure shows the relation between the reaction time to indicate that a probe digit is contained in a previously memorized list of digits and the serial position in the memory set of the item matching the target probe, for memory sets of differing lengths. The probe digit was always presented 800 msec after the last digit of the memory set. (From Ref. 3)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- For both target and nontarget probes (i.e., those in the memory set and those not, respectively), reaction time decreases as probe frequency increases ($p < 0.001$). This is a linear function for target but not for nontarget probes (Fig. 1).
- When the probe is presented 800 msec after the end of the memory list, response time is faster for probe memory set items near the end of the memory list (a recency effect; $p < 0.01$) (Fig. 2).
- Observers use different scanning strategies in Study 2. The slope of the reaction time function for nontarget probes is significantly greater than the slope for target probes ($p < 0.05$). This is because the mean slope of the negative-response function for 3 of the 12 observers is twice the slope of the positive-response function, implying that these 3 observers performed a serial self-terminating scan of the memory set (i.e., stopped comparing memory items with the probe item once a match was found).
- The nature of the individual probe item has an effect on reaction time; this runs counter to the predictions of the serial-exhaustive scanning model (Ref. 7; CRef. 4.103). This latter model proposes that a memorized list is scanned exhaustively; that is, each item in the memory set is compared with the probe in turn, even if a match is found before the end of the memory set is reached. The exhaustive scan is very efficient only if the occurrence of a match is registered and information about the individual stimulus items is lost.

Variability

An analysis of variance was conducted for each study. In Study 1, the linear component of the sum of squares on the functions depicted in Fig. 1 accounted for 99.9% of the variance for the target set, 85.6% of the variance for the nontarget set, and 96.4% of the variance for both sets analyzed together.

In Study 2, the linear component of the functions accounted for 96% of the variance for positive responses, and 99% of the variance for negative responses.

Repeatability/Comparison with Other Studies

The general finding that the predictions of the serial exhaustive scanning model fail depending upon test conditions has been obtained in a number of different studies (Refs. 1, 2, 6, 8). The precise aspects of the model that are called into question vary from study to study.

In a related study, when the memory set consisted of consecutive items (e.g., 1, 2, 3, 4), reaction time to nontarget probes depended upon remoteness from the memory set boundary. The regression lines for reaction time as a function of boundary remoteness for memory set sizes of 2 and 4 items both had slopes that differed significantly from zero (Ref. 5).

Constraints

- The serial position effects obtained in Study 2 require a very short delay (800 msec) between end of list and probe presentation.

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Cross References

4.103 Memory search rates

4.106 Memory for Visual Patterns: Effect of Perceptual Organization

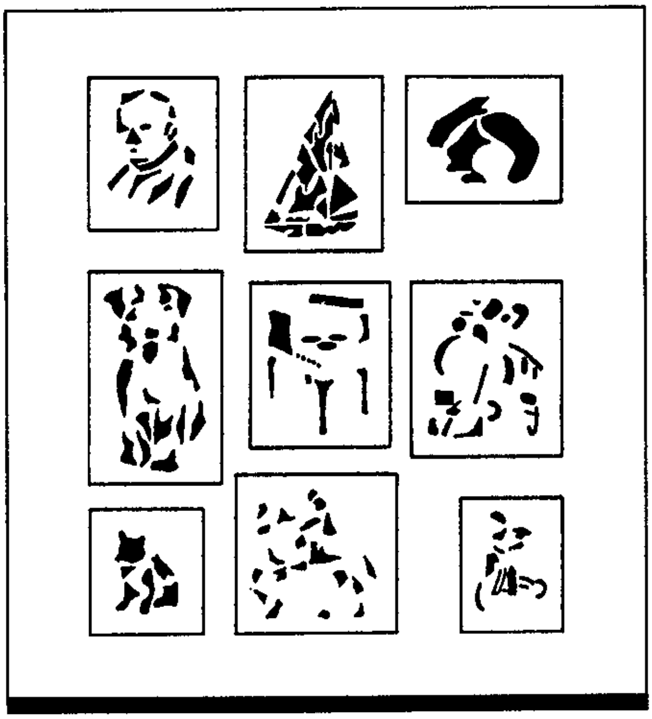

Figure 1. Fragmented figures of the kind devised by Street. (From Ref. 2)

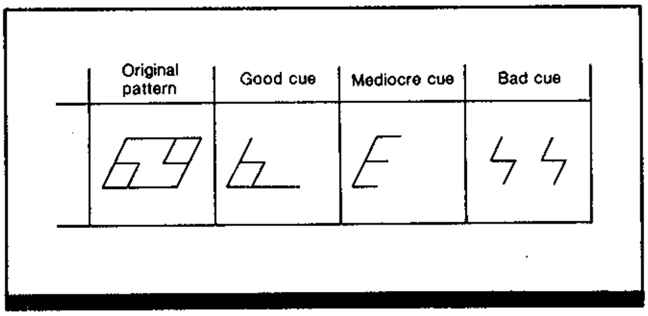

Figure 2. Illustrations of three levels of pattern cue. (From Ref. 1)

Key Terms

Multistability; object perception; pattern memory

General Description

Perceptual organization affects subsequent memory for a pattern. An ambiguous target (i.e., figure with multistable organization) (CRef. 6.306) will be recognized later only if it is perceived as organized in the same way it was during initial exposure (Ref. 4). Certain figures, such as Street figures (Fig. 1) (Ref. 5), are very difficult to identify initially. Upon subsequent presentation, however, identification is much faster. When a retrieval cuing method is used to study the structural units of visual pattern memory, it is found that pattern fragments may permit the entire pattern to be regenerated completely from memory. The fragments which promote the greatest recall (the best retrieval cues) are those which follow the Gestalt principles of common direction, proximity, and closure (CRef. 6.301).

Applications

Machine pattern recognition requires storage of figural descriptions that must be activated during recognition.

Methods

Test Conditions

- For each of 27 figures similar to Fig. 1, good, mediocre, and bad cues were constructed and roughly equated for total line length
- Cues were pattern fragments ranked as good, mediocre, or bad (Fig. 2) in accordance with Gestalt principles of proximity, closure, and common direction
- All patterns drawn with felt tip pen on white cardboard 2.3 × 3.0 cm
- Subject presented with 27 test patterns and 6 filler patterns; subject drew as many patterns as could be recalled (free recall); subject then presented with 81 recall cues (27 patterns x 3 levels of cue) and attempted to draw the entire pattern represented by the cue

Experimental Procedure

- Free and cued recall
- Independent variable: cue type (none, good, mediocre, bad)
- Dependent variable: proportion of patterns correctly recalled
- Subject's task: draw as many patterns as remembered
- 24 subjects, either high school or undergraduate college students

Experimental Results

- 46% of patterns are recalled during free recall (no recall cues).
- Bad cues reduce the recall of patterns; only good cues function as effective retrieval cues.
- A pattern is more likely to be recalled, the more often it has been recalled previously (under free recall or cued conditions) (Fig. 3).

Variability

Sign test indicated that good cues were significantly better than mediocre cues, which were significantly better than bad cues.

Repeatability/Comparison with Other Studies

Similar results have been obtained by other investigators (Ref. 3).

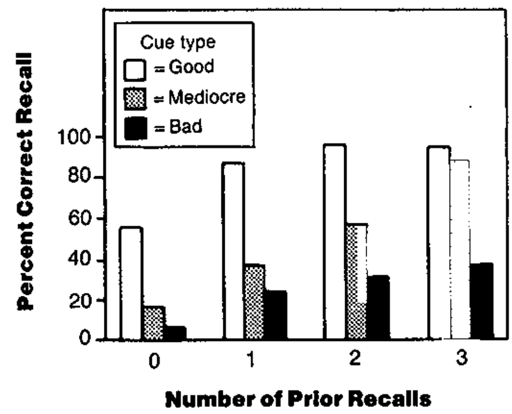

Figure 3. Percentage of correct pattern recall on current trial as a function of number of prior recalls and type of cue. (Based on Ref. 1)

Constraints

- Definition of cues as good, mediocre, or bad was determined partly by algorithm and partly by intuition. Application of the results to problems in machine vision would require rules for generating and determining structural descriptions of objects (Ref. 2).

Key References

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Cross References

6.301 Principles of Gestalt grouping and figure-ground organization

6.306 Reversible or multistable figures;

Handbook of perception and human performance, Ch. 33, Sects. 1.7, 2.4

4.107 Cognitive Mapping of the Environment

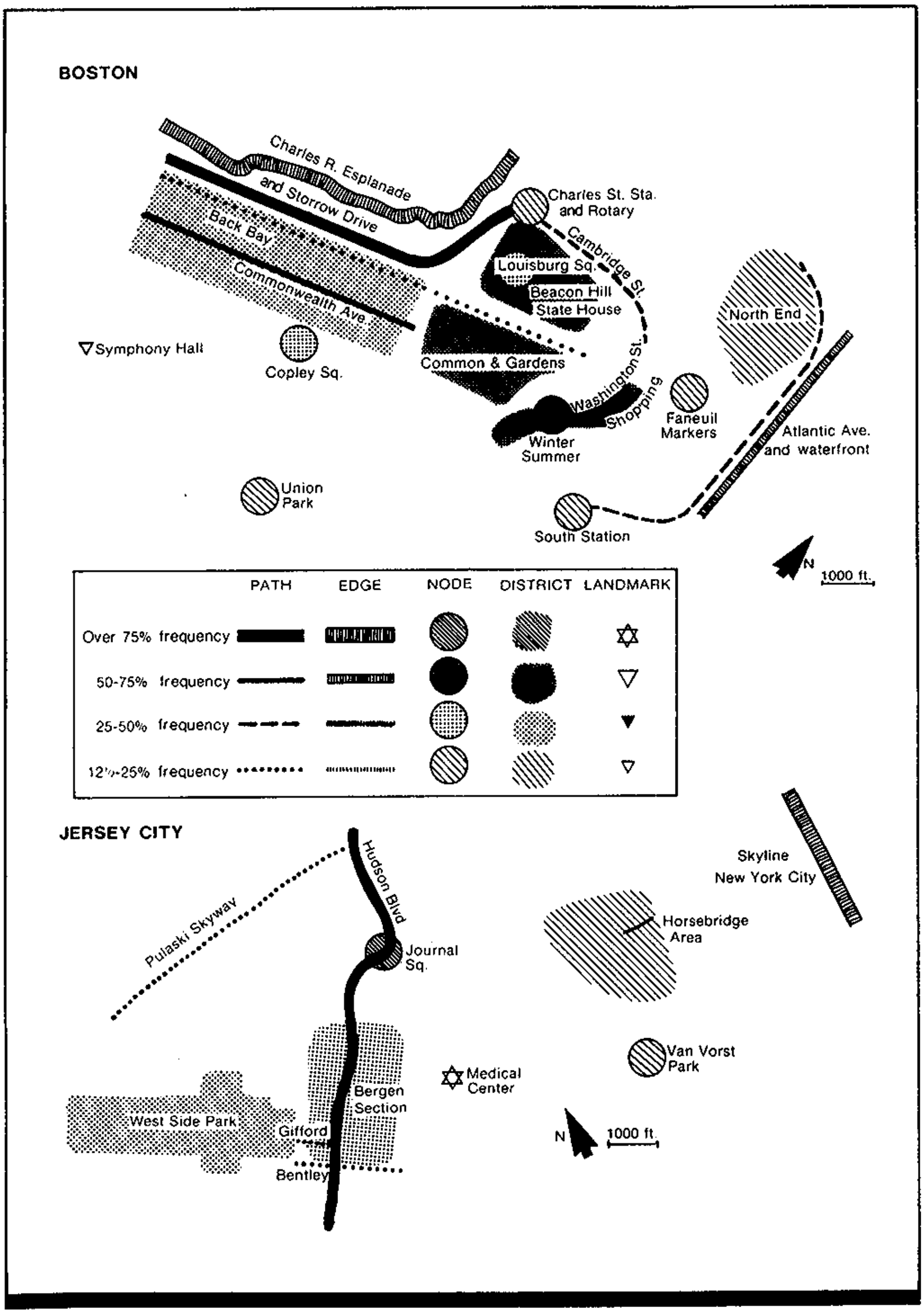

Figure 1. Abstract maps of Boston and Jersey City showing the important psychological elements of each environment. The five basic elements listed in the legend are coded in terms of the frequency with which they were mentioned in each sample of subjects (N = 30 for Boston and N = 25 for Jersey City). (From Ref. 3)

Key Terms

Cognitive maps; geographical orientation; maps; spatial knowledge

General Description

Relatively large environments, such as cities and countries, are represented in memory as a hierarchically organized set of abstracted features. According to an influential analysis of cities by Kevin Lynch (Ref. 3), we abstract five principal kinds of features from the environment:

A *path* is a channel along which the subject moves, such as a walkway, street, or subway line. Paths are the predominant elements in the representation of a large-scale environment and form a skeleton on which the rest of the representation is constructed (Refs. 1, 5).

An *edge* is a visible boundary, such as a river, wall, or street that marks the limit of a district, or any other environmental feature that provides a psychological edge. Edges often serve as organizing features but they also often disrupt organization by introducing artificial discontinuities.

A *district* is simply an area that is relatively homogeneous and distinct from adjoining areas in some way.

A *node* is a strategic spot involving a junction or a break in paths or a thematic concentration. Nodes are focal points, the places to and from which people travel.

A *landmark* is a conspicuous and/or well-known feature of the environment.

Using information from field analyses, verbal protocols, and interviews with residents of and visitors to Boston, Jersey City, and Los Angeles, Lynch defined paths, edges, nodes, districts, and landmarks, and then constructed abstract psychological maps for each city (Fig. 1 does not include Los Angeles). The more sparse representation of Jersey City compared to that of Boston reveals that different environments can generate psychological representations of varying complexity. More important, the psychological maps for all three cities show that interrelationships among many elements lack strong representation, giving rise to faulty knowledge of the environment.

Lynch attributes weak representation partly to poor environmental design. He argues that strong images require paths that are identifiable, continuous, uniform in overall directionality, and joined in simple intersections of a pair of paths meeting approximately at right angles.

Empirical studies have repeatedly confirmed several key points which are consistent with Lynch's theoretical analysis:

1. Pathways tend to be represented as intersecting at right angles, independent of amount of individual experience in traversing the environment (Refs. 1, 2, 7).
2. Spatial knowledge is hierarchically organized in terms of relatively global regions within which there are more richly detailed structures (Refs. 1, 6, 7).
3. Spatial relations tend to be distorted toward alignment on a north-south or an east-west axis (Refs. 6, 7).
4. The spatial relations between two points in different regions tend to be based on the relation between the regions, particularly when there is no path specifically connecting the two points. This can lead to major orientation errors, such as believing the Atlantic entrance to the Panama Canal is east of its Pacific entrance or that Philadelphia is north of Rome (Refs. 6, 7).
5. Travel plans are generated first from the superordinate level of the spatial knowledge hierarchy, by finding a path that connects regions. Use of the lower level of spatial knowledge depends on goals and experience (Refs. 2, 3, 5).

Applications

The design of maps can be improved by identifying the paths, edges, nodes, districts, and landmarks that are major elements of the psychological representation of the environment. Complex environments can be structured for most effective use if built around careful design in terms of psychological map elements.

Constraints

- There is no quantitative analysis of the relative benefits and costs among alternative structural arrangements of design elements.
- There is only a weak data base on which to base general conclusions or applications.

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Cross References

4.104 Skilled memory effect;

6.315 Mental rotation of objects;

11.222 Map learning;

11.223 Design of "you-are-here" maps;

Handbook of perception and human performance, Ch. 28, Sect. 3.4

4.108 Tactile Short-Term Memory

Key Terms

Short-term memory; tactile persistence

General Description

Immediate memory (recall) for the location of brief tactile stimuli applied to interjoint regions of the fingers of both hands ranges from 3.5 to 7.5 locations (after correction for guessing). The storage capacity of tactile short-term memory is slightly greater (by about one stimulus location) than indicated by immediate recall (i.e., the information in short-term memory decays before it can be fully reported). The duration of tactile short-term memory is <0.8 sec. The data suggest that tactile short-term memory has much less storage capacity than analogous visual short-term memory.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

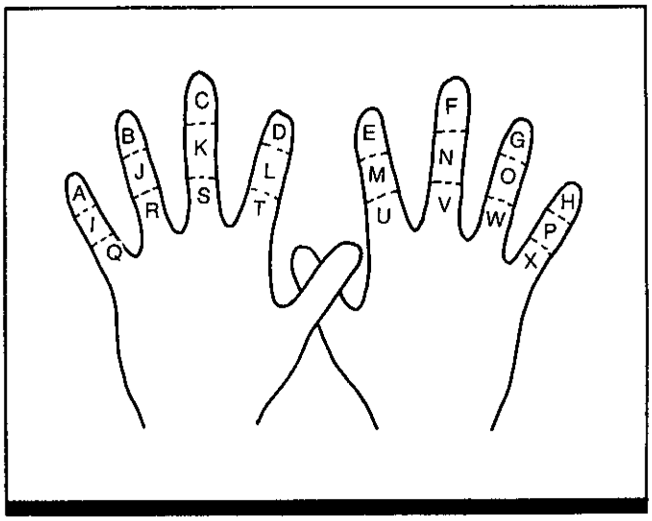

Figure 1. Finger labelling used for the two hands. (From Ref. 1)

Methods

Test Conditions

- 24 airjet tactile stimulators; one airjet for each interjoint region of each finger (thumb excluded); 20,700-N/m² (3-psi) pulse with rise and decay time of ~1 msec and pulse width of ~2.5 msec; 200-Hz pulse repetition rate during 100-msec presentation; palmar side of fingers suspended 0.32 cm (1/8 in.) above airjet outlet
- 2-12 interjoint regions stimulated simultaneously on each trial with number of regions constant and known by subject for each session; interjoint segments labelled in alphabetical order as represented on a visual display continuously in front of the subject (Fig. 1)

Experimental Procedure

- Independent variables: number of locations stimulated, interjoint region stimulated
- Dependent variable: number of correctly reported locations of stimulation
- Subject's task: orally report in alphabetical order the interjoint regions stimulated on each trial; on whole report trials, the same number of response positions had to be reported as positions contained in the stimulus; on partial report trials, only a specified portion (one of the three rows of interjoint regions) of the stimulus had to be reported as indicated by a marker presented at varying times after the stimulus; feedback was given by repeating the tactile stimulus and also presenting the points of tactile stimulation visually on a display box (verbal feedback was given for trials with 1, 2, or 4 stimulated locations for blind subject)
- 4 naive male subjects (one totally blind)

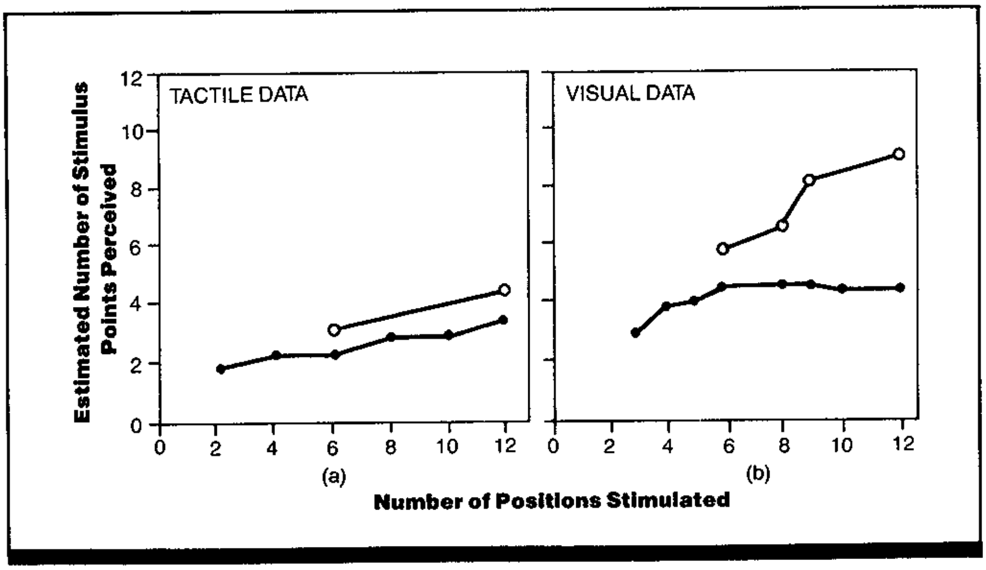

Figure 2. Average number of stimulus locations perceived (after correction for guessing) as a function of the number of locations stimulated; (a) tactile data; (b) data from a comparable visual experiment (Ref. 3, Fig. 3). The lower curves (solid circles) are for whole-report performance (subject named as many locations as remembered). The upper curves (open circles) represent the estimated number of stimulus locations available in memory immediately after termination of the stimulus (partial report, i.e., subject named only locations in subset indicated by marker presented with 0-sec delay after stimulus offset). (From Ref. 1)

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Experimental Results

- Subjects can correctly report the location of up to 3.5-7.5 different tactile stimuli (corrected for guessing) immediately after a brief presentation in which multiple tactile sites are stimulated (see Constraints section). This limit is referred to as the span of immediate memory.
- The span of immediate memory is measured in a whole-report condition (i.e., the subject names as many stimulus locations as can be remembered). When subjects are asked to report on only a specified portion of the tactile stimulus (partial report condition), they are found to have more information available at the time of reporting than is indicated by immediate-memory span. That is, the total number of tactile locations available in short-term memory, as estimated from the number of locations reported for a subset of the total stimulus, is slightly greater than the number reported when subjects must name all locations stimulated (up to one tactile location greater for 12 stimulated interjoint positions).
- The duration of short-term tactile memory is <0.8 sec (i.e., there is no advantage of partial reporting over whole reporting when the marker specifying the subset of stimulus locations to be reported follows stimulus presentation by >0.8 sec).
- The span of immediate memory is about the same for tactile and visual stimuli. However, tactile short-term memory has less storage capacity than that found for short-term visual memory (Fig. 2).
- The amount of information transmitted per stimulus presentation can be calculated by the following formulas:

$$H(S) = \log \binom{24}{n}$$

$$I(S;R) \geq p \log \binom{24}{n} + p \log p + (1-p) \log (1-p)$$

where

$H(S)$ = stimulus entropy

$I(S;R)$ = information the response gives about the stimulus

p = estimated proportion of stimulus positions perceived.

- The amount of transmitted information is ~6 bits per presentation for a whole report and ~7.5 bits per presentation for a partial report. Transmitted information is relatively independent of the number of locations stimulated (Fig. 3). Therefore, information per presentation apparently cannot be increased by constructing codes with large numbers of stimulated sites, at least at the level of training used in these experiments.

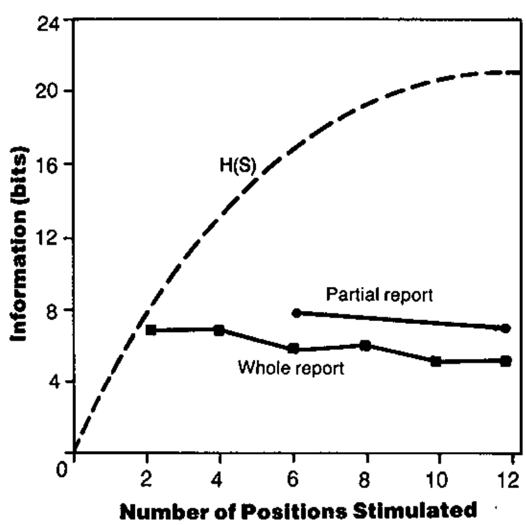

Figure 3. Lower bound on transmitted information as a function of the number of tactile locations stimulated. H(S) is stimulus entropy. The partial report curve is for 0-sec marker delay; the dotted curve is the information in the stimulus as calculated by the formulas given in the results section. (From Ref. 1)

Variability

While there is considerable between-subject variability, the patterns of results for the subjects are similar.

Repeatability/Comparison with Other Studies

Results are analogous to those reported for vision (Refs. 2, 3) but visual short-term memory has a larger capacity.

Constraints

- The low value (3.5) of the range is the whole-report mean for the four naive subjects in the reported experiment (Fig. 2). The high value (7.5) is for a well-trained subject who participated in an earlier experiment with minor procedural differences. It is unclear whether the better performance is a result of subject or procedural differences.
- Extent of training influences performance.
- Performance is limited by spatial interaction of stimuli in this experiment.

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Cross References

4.301 Information theory

4.201 Power Law of Practice

Key Terms

Cognitive skills; motor skills; practice; reaction time; response organization; skill acquisition; training

General Description

For many perceptual-motor and cognitive processing skills (e.g., reading, problem-solving, etc.), performance time (T) is an approximate power function of trial number (N), as given by Eq. (1):

$$T = BN^{-\alpha} \tag{1}$$

where B is the performance time on Trial 1 and α is a learning rate parameter. Taking logarithms of both sides of Eq. (1) yields the useful re-expression:

$$\log(T) = \log(B) - \alpha \log(N), \tag{2}$$

which shows that performance time on a log-log plot is a decreasing linear function of practice, with a slope equal to $-\alpha$. Application of the power law to practice effects is illustrated in Figs. 1a and 1b, which depict data for choice reaction time (RT) for one subject (Ref. 9). The subject faced an array of 10 lights with fingers and thumbs positioned on 10 response keys, one assigned to each light. The task on each trial was to depress keys to match the pattern in which lights were illuminated. All combinations of lights were equally possible; each of the 1,023 patterns was presented in each trial block.

Figure 1a shows the effects of practice on RT. The data are typical of many practice effects, showing an initial rapid decline in RT followed by progressively slower degrees of improvement with additional trials. Figure 1b shows the linearity of the same data when plotted on log-log coordinates, as predicted by Eq. (2).

Comparison to Exponential Law of Learning

An exponential law of learning takes the form

$$T = Be^{-\alpha N} \tag{3}$$

where B and α are free parameters. The exponent law predicts a more rapid rate of reaching asymptote than a comparable power law. This is seen most easily by comparing the rate of change in T as a function of trials, i.e., the derivative of T with respect to N, dT/dN. For the exponential law,

$$dT/dN = -\alpha T, \tag{4}$$

whereas for the power law,

$$dT/dN = -(\alpha/N)\,T. \tag{5}$$

Hence, the power law predicts that the instantaneous rate of learning slows with practice (i.e., as N increases).

Generalized Power Law

Two common deviations from the power law function (Eq. 2) seen in Fig. 1b are the departures from linearity at each end of the curve. The departure on the left side reflects the problem of estimating the degree of transfer from prior learning, and the departure on the right side reflects the presence of a performance asymptote >0. These problems are corrected in the generalized power law (Ref. 8):

$$T = A + B(N + E)^{-\alpha}, \tag{6}$$

where A is the asymptote and E is the effective number of trials prior to observation. By moving A to the left side of the equation and taking logarithms, this law can be re-expressed as

$$\log(T-A) = \log(B) - \alpha \log(N+E). \tag{7}$$

Unlike Eq. (2), Eq. (7) requires a computer search to find estimates of A and E to use in fitting a line.

Figure 1c fits the generalized power law of Eq. (6) to the data of Fig. 1a. Reference. 8 has shown that the generalized power law provides a good fit to a number of data sets, including all those in Fig. 2.

A Theory of Skill Acquisition

Theories of skill acquisition should explain power law learning functions. Reference. 8 has shown that power law functions are produced if skill acquisition involves the development of special-purpose knowledge units in the method for performing a task. Such improvements speed performance when they can be used, but are less frequently applicable than more general methods.

The theory of cognitive skill learning set forth in Ref. 1 incorporates a mechanism of this type. In this theory, skill learning involves the acquisition of procedural knowledge, stored as a set of production rules. (A production rule states a condition-action sequence, such that if a condition obtains, the corresponding action is implemented.) Complex production rules are formed by composition; that is, two production rules repeatedly applied in sequence will be collapsed into a single procedure. This complex production rule will be activated by a more specific condition than either of its component production rules; hence the complex rule will be applied less often. However, the time needed to apply a production rule is assumed to be a linear function of the strength of the production rule, and every correct application of the production rule increases its strength by a constant amount. Hence, repeatedly activated productions will be applied more quickly. Thus, skill acquisition is seen as a result of learning new, more specialized production rules and a faster application of old rules.

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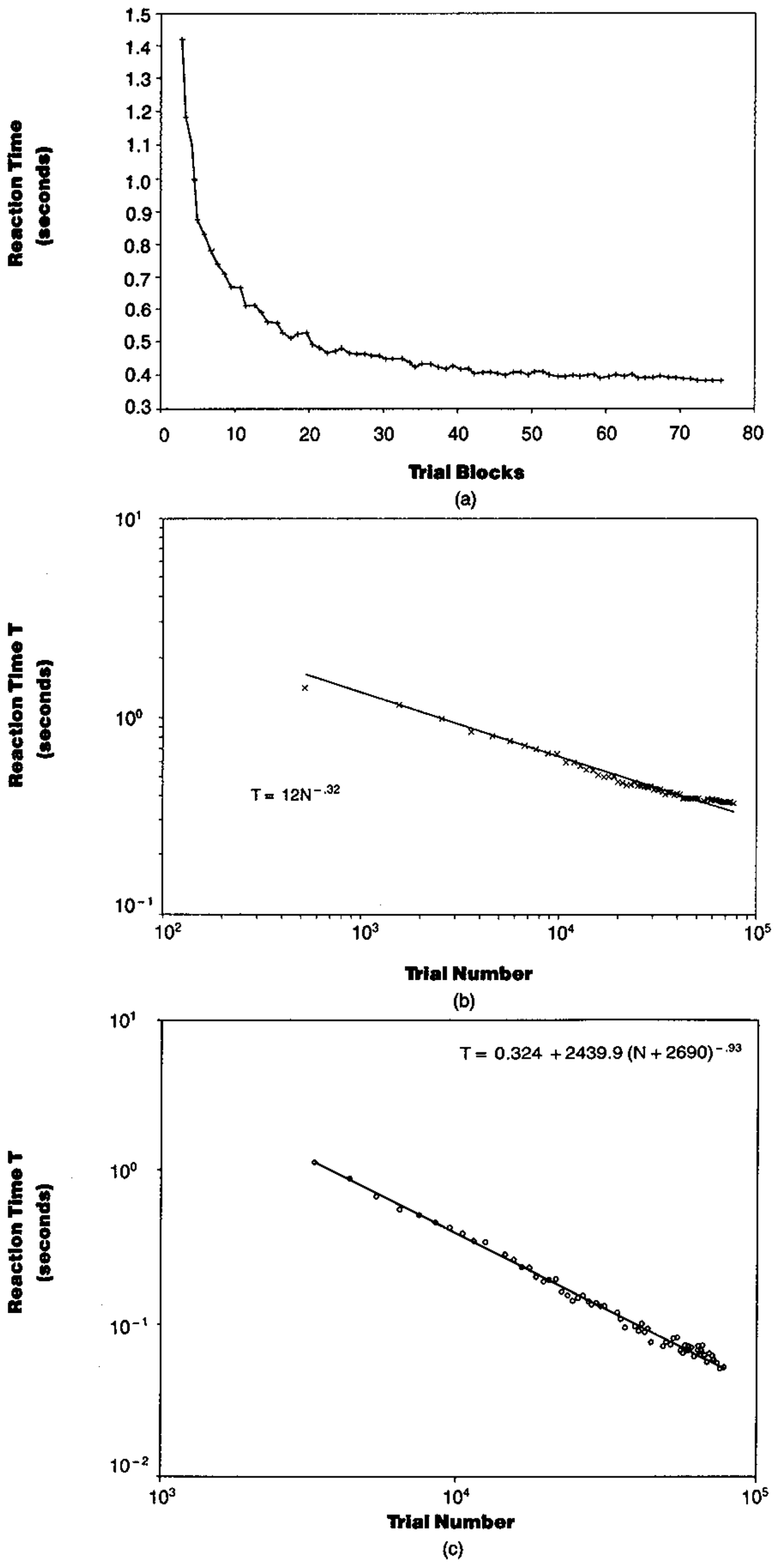

Figure 1. (a) Practice curve for a 1,023-choice reaction time task based on data for the single subject (of three) with the best performance (Based on Ref. 9). Each trial block contained one presentation each of 1,023 patterns (i.e., 1023 trials) and was spread over two 20-30-min sessions. (b) Data from Fig. 1a plotted on log-log coordinates and fitted with a simple power law function (Eq. 2). (From Ref. 8) (c) Data from Fig. 1a (without the first 2690 trials and with an assigned asymptote of 0.324 rather than zero) plotted on log-log coordinates and fitted with generalized power law (Eq. 4). (From Ref. 8)

Applications

Estimates of training time necessary to achieve designated performance goals can be obtained by extrapolation from a fit of the power law to practice data in a log-log plot.

Constraints

- Not all practice effects follow the power law, but the theoretical basis for these deviations is not known at present.
- Fits of the generalized power law (Eqs. 6, 7) do not always yield sensible values for B.
- The power law does not account for changes in accuracy.

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Cross References

9.403 Response chunking in the training of complex motor skills;

Handbook of perception and human performance, Ch. 28, Sect. 4.4

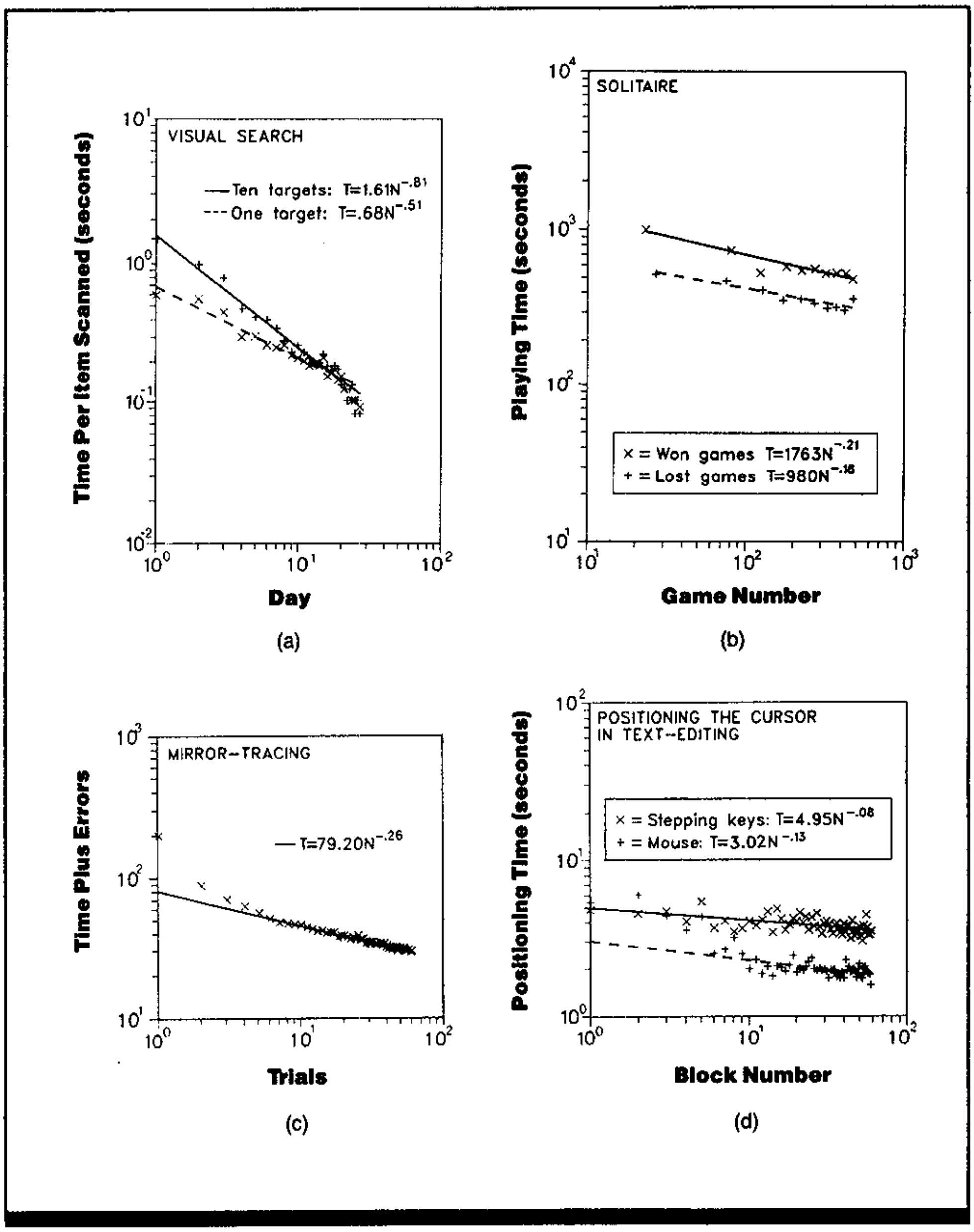

Figure 2. Log-log plots of practice curves for a variety of skills, fitted according to a simple power law (Eq. 2). The data come from (a) scanning for visual targets (Ref. 6); (b) playing a game of solitaire called Stair (Ref. 8); (c) mirror tracing (Ref. 10); (d) positioning the cursor in a text-editing system using either a set of keys or an analog device ("mouse") (Ref. 2); (e) performing the same text-editing procedure on the same sentence repeatedly, broken into total time to do task and execution time due to particular method used (Ref. 6); (f) recognizing a learned sentence; (g) operating a cigar-making machine (Ref. 3); and (h) reading inverted text (Ref. 4). (From Ref. 8)

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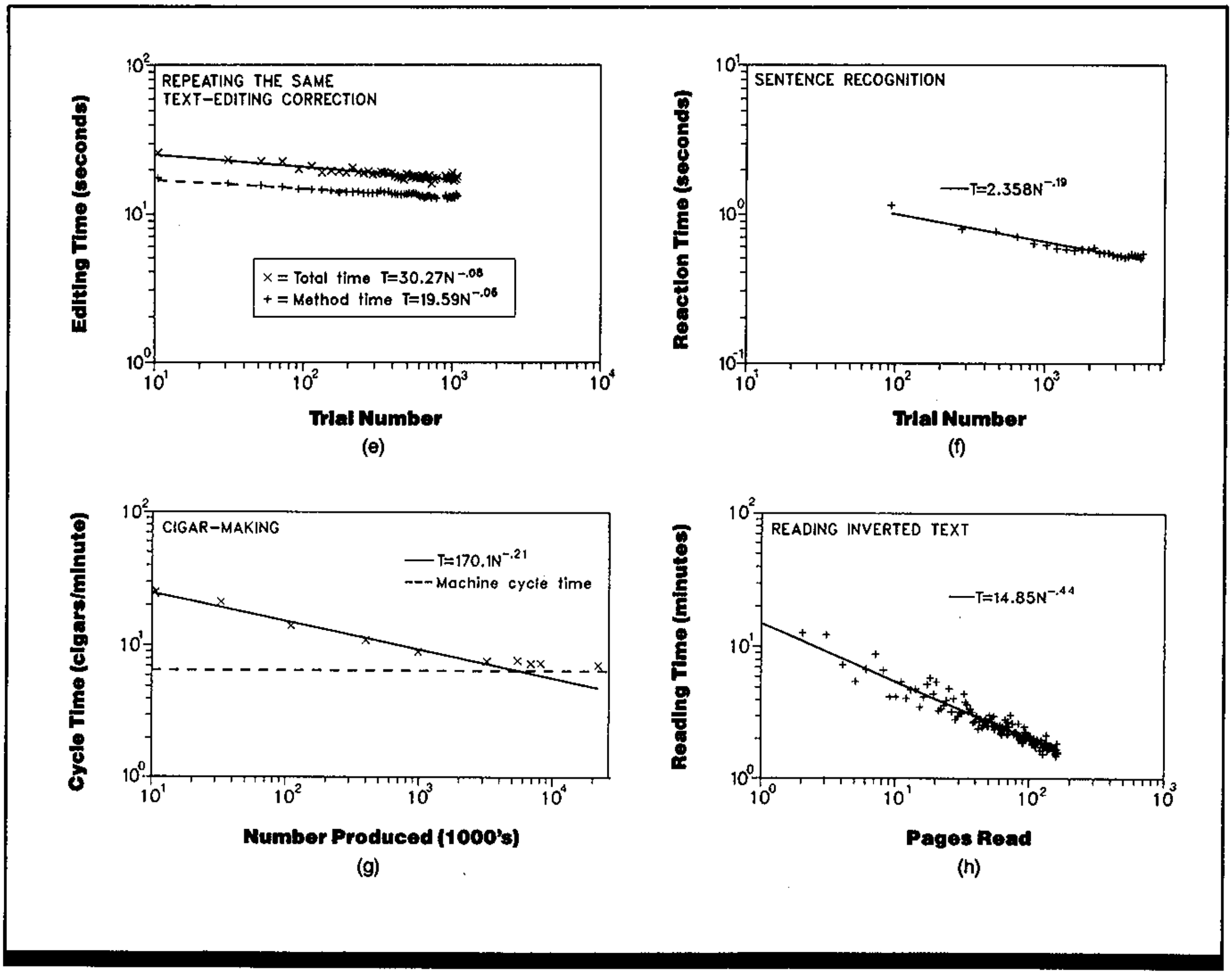
REPEATING THE SAME TEXT-EDITING CORRECTION
× = Total time T=30.27N^-.08
+ = Method time T=19.59N^-.06
Editing Time (seconds)
Trial Number
(e)
SENTENCE RECOGNITION
T=2.358N^-.19
Reaction Time (seconds)
Trial Number
(f)
CIGAR-MAKING
T=170.1N^-.21
Machine cycle time
Cycle Time (cigars/minute)
Number Produced (1000's)
(g)
READING INVERTED TEXT
T=14.85N^-.44
Reading Time (minutes)
Pages Read
(h)

4.301 Information Theory

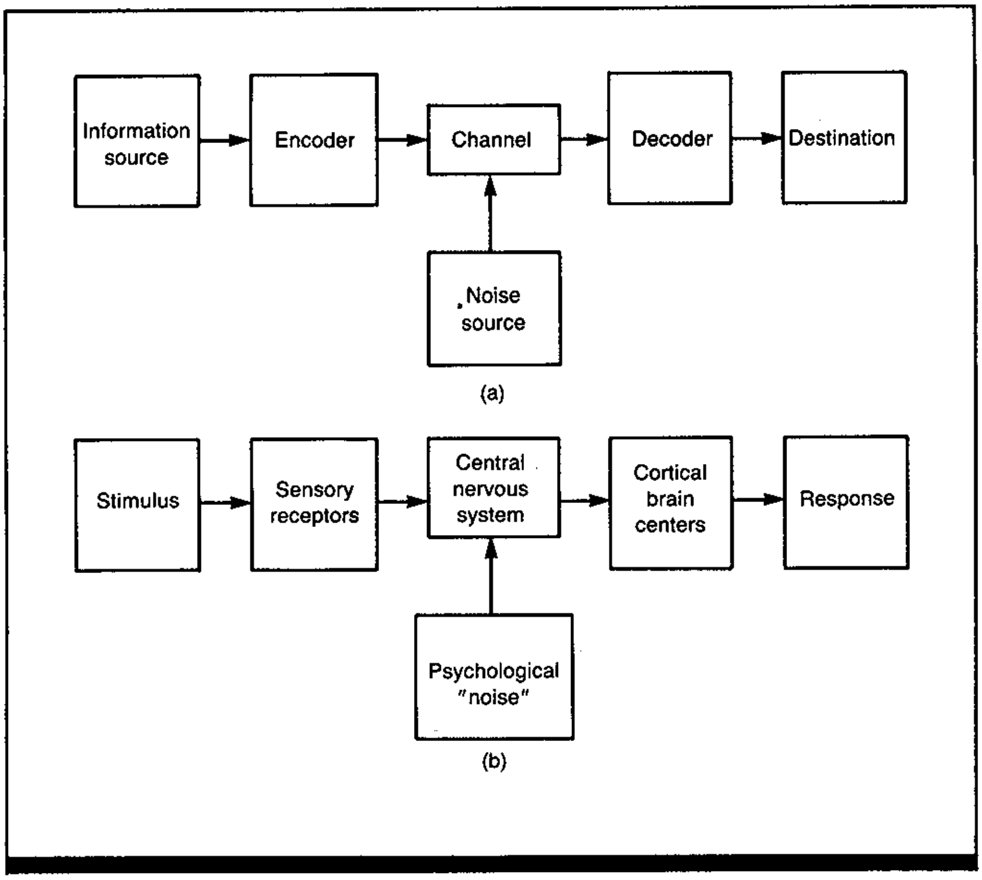

Figure 1. (a) Information flow in a general communications system. (From C. E. Shannon & W. Weaver, *The mathematical theory of communication.* Copyright 1949 by the University of Illinois Press. Reprinted with permission.) (b) Information flow for a human perceiver. (From Ref. 3)

Key Terms

Channel capacity; communication theory; uncertainty

General Description

A system may be defined as an interacting or interdependent set of components forming a network for the purpose of fulfilling some objective. A system whose purpose is to transmit information between locations is called a communication system (Fig. 1a). The source and destination of information must be separated in space and/or time and must be linked by means of a channel. Since the physical form of the information from the source may be incompatible with the physical nature of the channel or the destination, or both, the signal to be transmitted must be encoded for use by the channel or destination. For example, a telephone system transmits sound from a source (speaker) to a destination (listener), but does so by converting the energy of mechanical pressure variation that is physical sound into an electrical signal, and then reconverting or decoding the electrical signal back into mechanical pressure.

The concept of a communication system has been applied to human observers as well as to inanimate communication networks. Figure 1 illustrates similarities between the components required for the flow of information within inanimate (Fig. 1a) and human (Fig. 1b) systems. In the human system, the physical form of information transmitted by the stimulus (source) is incompatible with signal transmission within the observer, and so must be encoded or transduced by the sensory system. For example, the information from a visual stimulus is not transmitted to the brain in the form of light, but instead is encoded as an electrochemical signal that the brain can understand. The brain decodes this signal, decides what action to take, and then sends the information to the motor system to make a response.

Performance of any communication system will be affected by the amount of information to be transmitted. There may be limits on the maximum amount of information that can be transmitted (channel capacity). In addition, the rate of transmission will determine how much information can be handled within specified time limits (transmission rate). Finally, noise may intrude upon information transmission and affect performance. All of these concerns require that information be quantified, so that system performance under varying information loads can be evaluated. Information theory provides the means for the quantification of information.

By popular definition, information is linked to the idea of knowledge. While not incompatible with the more technical definition afforded by information theory, this definition is less precise and more difficult to quantify. According to the definition of information within information theory, information is transmitted whenever there is a reduction of uncertainty regarding the content of the transmitted message. For example, in Morse code, one of two symbols may be sent at a time: a long pulse (dash) and a short pulse (dot). Thus, before a pulse is sent, there is some uncertainty as to whether the pulse will be a dot or dash. That uncertainty is reduced once the pulse is sent and received; in other words, the identity of the pulse is known after it is sent and received. In such a situation, information has been transmitted because uncertainty has been reduced; technically, when there is no reduction in uncertainty, there is no transmission of information. The popular and technical definitions are related because an event will not be informative in the popular sense if the receiver already possesses knowledge concerning what is transmitted. Ignorance can be considered as a state of uncertainty.

Information may be quantified in terms of the number of alternative messages that may be sent; thus, the amount of information gained equals the reduction in uncertainty. The unity of measurement is called a bit, for "*bi*nary digi*t*," because the minimum condition for information transmission occurs when a choice must be made between two possible outcomes (as in the Morse code example). Each time the number of alternatives is doubled, uncertainty is increased by 1 bit. Consequently, the amount of information transmitted is increased by 1 bit each time the number of possible messages doubles. An analogous way of thinking around this is in terms of the game "Twenty Questions," in which the goal is to discover what one of the players is thinking about by asking not more than twenty questions. The questioning strategy that on the average will produce the answer with the fewest number of questions is to ask binary (i.e., yes-no) questions that reduce the number of alternatives by half with each question.

By convention, certainty is symbolized by H. The number of possible alternatives is given by Eq. (1).

$$n = 2^H \tag{1}$$

The uncertainty (in bits) associated with the number of alternatives can be written as shown in Eq. (2).

$$H = \log_2 n \tag{2}$$

where H is equivalent to the amount of information in bits that is transmitted when one alternative is sent from the set of possible alternatives. Table 1 lists the values of uncertainty/information associated with alternatives of various sizes. It should be noted that these values and the formulas given previously refer to alternatives with equal probability of occurrence. The more general case, however, does not require equal probability of all alternatives, and the amount of information transmitted can be calculated with Eq. (3),

$$H = -\Sigma P_i \log_2 P_i \tag{3}$$

where P_i is the probability of each alternative.

Table 1. Uncertainty (*H*) as a function of stimulus set size (all stimuli equally likely). (From Ref. 1)

Size of Stimulus Set		Uncertainty	
Number of Elements (n)	Number of Elements (2^H)	Number of Binary Questions (H)	Units of Information (bits)
1	2^0	0	0
2	2^1	1	1
4	2^2	2	2
8	2^3	3	3
16	2^4	4	4
32	2^5	5	5
64	2^6	6	6

To see what effect this has on the amount of uncertainty in a given set, consider the following example (Ref. 6). In November 1975, there were 16 leading candidates for Democratic nomination for President. Assuming equal probability of nomination for each candidate, there are 4 bits of uncertainty associated with this set of alternatives. However, it was estimated that the probabilities of nomination were unequal, as given in Table 2. This reduced the uncertainty to 3.5363 bits, somewhat less than the estimate assuming equal probabilities.

Applications to the Human Operator

As stated earlier, there are similarities between inanimate communication systems and a human operator, particularly when the human operator is construed as an information processor. Thus, the concepts of channel capacity and transmission rate can also be applied to the human observer. Information theory has also been used to understand and interpret experiments involving human subjects. Information measurement has been helpful in studying reaction time, perceptual recognition, and verbal learning and memory.

Table 2. Amount of uncertainty (*H*) for the set of Democratic candidates for President as of November 1975. (From Ref. 7)

Candidate	Probability of Nomination (p)	$-p \log_2 p$
Humphrey	0.25	0.5000
Jackson	0.15	0.4105
Carter	0.10	0.3322
Kennedy	0.07	0.2686
Bayh	0.05	0.2161
Bensten	0.05	0.2161
Church	0.04	0.1858
Sanford	0.04	0.1858
Shapp	0.04	0.1858
Udall	0.04	0.1858
Wallace	0.04	0.1858
Glenn	0.04	0.1858
Muskie	0.04	0.1858
Harris	0.02	0.1129
Shriver	0.02	0.1129
McGovern	0.01	0.0664
	H = 3.5363 bits	

Channel Capacity

Investigations of channel capacity have often employed absolute judgments, in which subjects must identify a signal (stimulus) as belonging to a particular category. Table 3 shows empirically determined channel capacities for several stimulus dimensions. It is clear that humans' abilities to make absolute judgments are limited and are rather small. The table also shows that the greater the range of stimulus values, the greater the amount of information transmitted in bits per stimulus. Furthermore, when multidimensional stimuli are used (i.e., varying along several dimensions simultaneously), there is an increase in information transmission over a single dimension, but not so large an increase as to indicate summation of channel capacities for each dimension judged separately (Ref. 4).

Transmission Rate

If signals or events are presented to subjects at a known and constant rate, it is possible to calculate the average information transmitted per second. Information rated is given by Eq. (4).

$$R_{IT} = nH(S) \tag{4}$$

where R_{IT} is rate of information transmission, n is the number of stimuli per unit time, and $H(S)$ is the uncertainty associated with each stimulus presented. However, calculation of transmission rate depends on type of response required and stimulus modality, as well as on information variables. For example, verbal naming of one of ten digits yields transmission-rate estimates of 6 bits/sec, whereas the estimate for a manual response is only ~ 3 bits/sec (Ref. 1). For the auditory modality, transmission rate of the ear is estimated at 8000 bits per sec for random sound and 10,000 bits/sec for loud sounds. In contrast, maximum estimated transmission rate for spoken English is ~ 50 bits/sec. Similarly, the transmission rate for visual nerve fibers is estimated at 1000 bits/sec, which is much higher than the amount of information that could be absorbed and interpreted by the brain in that time. Therefore, the information transmission rates of peripheral sensory systems are much higher than central processing rates.

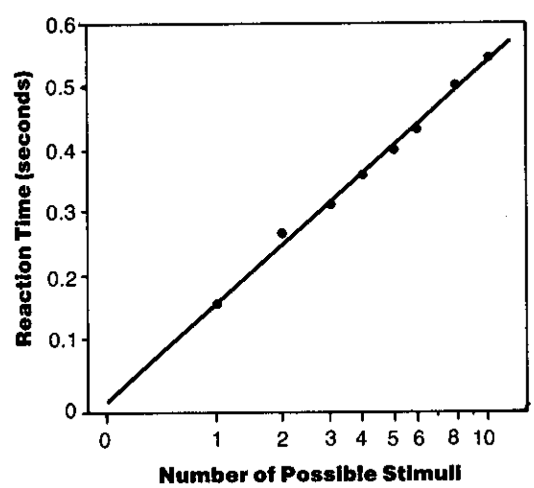

Figure 2. Choice reaction time as a function of the number of equally probable stimuli. (From Ref. 5)

Table 3. Channel capacity for various stimulus modalities. (From Ref. 3)

Stimulus Dimension	Channel Capacity (bits)	Approximate Number of Stimuli Discriminated
Brightness	1.7	3
Duration	2.8	7
Hue	3.6	12
Loudness	2.3	5
Odor intensity	1.5	3
Pitch	2.5	6
Position on a line	3.2	9
Saltiness	1.9	4
Shock intensity	1.7	3
Vibration intensity	1.6	3

Reaction Time

Choice reaction time is a logarithmic function of the number of stimulus alternatives. This is known as Hick's Law (Ref. 5), and has been validated in many studies (Ref. 1; CRef. 9.111). Figure 2 illustrates the results from a study in which observers had to give a manual response indicating which of up to ten lights had been presented. Furthermore, unequal stimulus probabilities decrease reaction time (Ref. 6). This is consistent with the idea that reaction time is a function of stimulus uncertainty, since, as stated above, unequal stimulus probabilities decrease the amount of information in a stimulus set. This concept was given formal definition in the Hick-Hyman Law, which states that reaction time is a linear function of the amount of information in a stimulus.

Perceptual Recognition

Perceptual recognition performed against a background of noise is affected by stimulus uncertainty, and the size of this effect increases with the amount of noise present. Figure 3 shows the results of an experiment in which subjects had to indicate recognition of nonsense di-syllables by writing them; the di-syllables were presented in stimulus sets of different sizes and presented at different signal-to-noise ratios (Ref. 7).

The critical factor affecting recognition performance is not stimulus uncertainty, however, but response uncertainty. When the number of possible responses equals the number of stimuli, (i.e., the size of the stimulus set), recognition performance decreases with increasing uncertainty. However, when the number of responses remains constant at 2 (a 1-bit decision), the size of the stimulus set has no effect on recognition performance (Ref. 9).

Verbal Learning and Memory

Difficulty in learning verbal material depends upon the number of items that must be learned. Learning difficulty increases with the size of the stimulus set, particularly if the probability distribution of items is uniform (Ref. 1). Fur-

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thermore, if forgetting is considered as information loss, then the amount of information loss is a linear function of the average amount of information input (Ref. 1). Memory performance is generally measured by means of recognition or recall paradigms, and recognition performance is generally better than recall performance. However, this is not due to the amount of information transmitted in the two methods, but to the fact that recognition usually involves selection from fewer possible alternatives (Ref. 2).

Constraints

- Calculation of measures in bits should be applied only in situations in which statistical parameters do not change over time; this would tend to exclude experimental or operational situations in which learning or practice effects are likely to occur.
- The use of transmitted information as an index of channel capacity does not consider either the direction or magnitude of subject errors, even though it is inversely related to the number of errors made.

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Cross References

4.302 Channel capacity for human information processing;

9.111 Choice reaction time: effect of number of alternatives

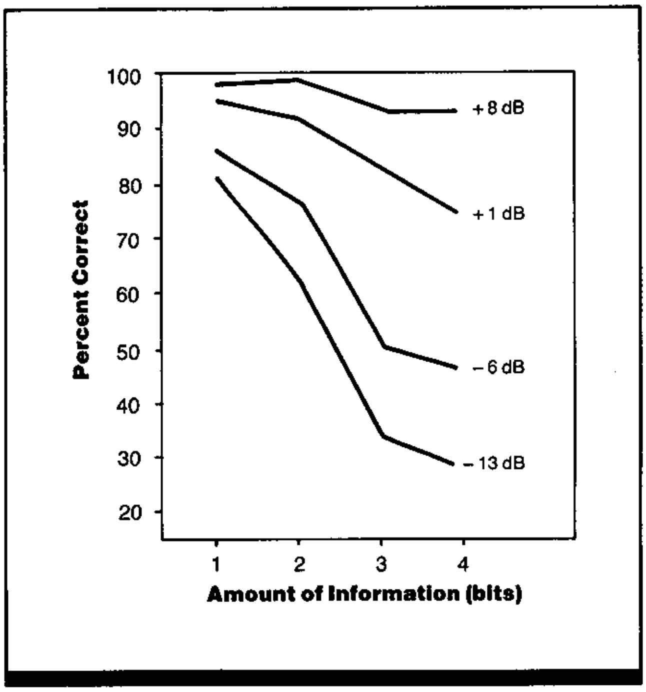

Figure 3. Perceptual recognition of nonsense di-syllables as a function of information in bits at different signal-to-noise ratios (in decibels). (From Ref. 8)

4.302 Channel Capacity for Human Information Processing

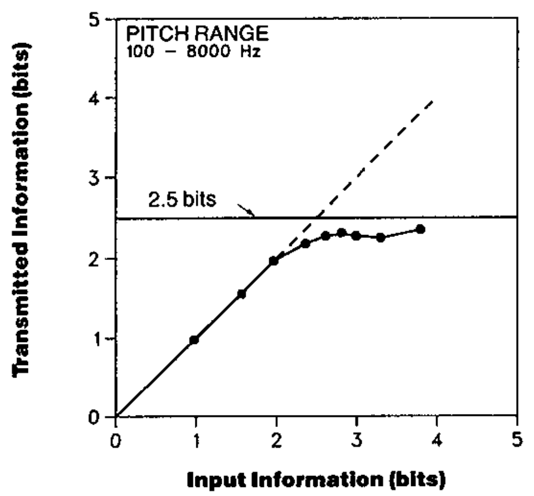

Figure 1. Relation between input information and transmitted information (both measured in bits) in an absolute judgment of pitch task. Dotted diagonal represents perfect transmission. (From Ref. 6)

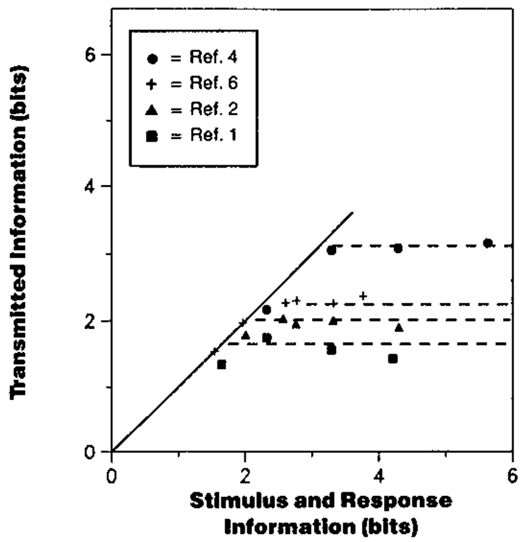

Figure 2. Information transmitted as a function of information input for perceptual tasks in different modalities. Subjects had to identify the stimulus presented on each trial from among a set of alternatives varying along a given dimension. Results are shown for discriminations of spatial position, pitch, loudness, and saltiness. All data suggest a channel capacity of at most 3 bits (i.e., eight different stimuli). Diagonal represents perfect transmission. (From *Handbook of perception and human performance*)

Key Terms

Channel capacity; discrimination; workload

General Description

When the frequency of a single tone is varied in equal logarithmic steps in the range between 100 Hz and 8000 Hz, subjects perform perfect identification among only five tones. The amount of information transferred is thus approximately 2.3 bits (i.e., $\log_2 5$). Related studies on vision, audition, and taste all support the conclusion of a limit on channel capacity of approximately 2-2.5 bits of information (i.e., four to six perfect discriminations), and imply that the workload associated with a task increases as the number of items to be processed increases.

Applications

Situations in which operators must identify stimuli along a single dimension (e.g., pitch) from among a number of possibilities, especially when the number of possibilities exceeds five different stimuli.

Methods

Test Conditions

- Tones from 100-8000 Hz equidistantly spaced on a logarithmic scale, presented via headphones
- Sound pressure level (SPL) of tones was ~85 dB, varied randomly over a range of 15 dB to reduce differential loudness cues
- Tone duration was ~2.5 sec; interval between successive presentations was ~25 sec

Experimental Procedure

- Absolute judgments; repeated-measures design; randomized order of presentation (each tone presented equal number of times)
- Independent variables: input information, defined as the size of the set of tones from which a specific tone must be identified, measured in bits of information; tone frequency
- Dependent variable: transmitted information, defined as the number of correctly identified tones, measured in bits of information
- Subject's task: identify which one of a series of tones was presented by responding with a number assigned to that tone; feedback provided
- 6 subjects with extensive practice

Experimental Results

• Average information transmitted matches input information up to ~2.3 bits, the equivalent of perfect identification among only five tones. Subjects can identify tones, but not if the number is too large. This implies that as the number of items to be processed increases, the workload associated with the task increases.
• Other studies on vision, audition, and taste (Fig. 2) find the limit on channel capacity to be about 2-2.5 bits of information, i.e., 4-6 perfect discriminations (Refs. 1, 2, 4).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The finding of a channel capacity of 2-2.5 bits is consistently replicated in other studies. However, when multidimensional stimuli are employed (e.g., pitch *and* loudness are systematically varied), higher estimates of channel capacity are obtained. These estimates are higher than for a single dimension (channel) alone, but lower than channel capacity predicted by additivity of channels, implying interaction between channels (CRef. 4.301; Ref. 3).

Constraints

• Results should not be considered as ultimate informational capacities, but simply in terms of information received per stimulus presentation.
• Effects of long practice, presentation rate, and individual differences were not examined.

Key References

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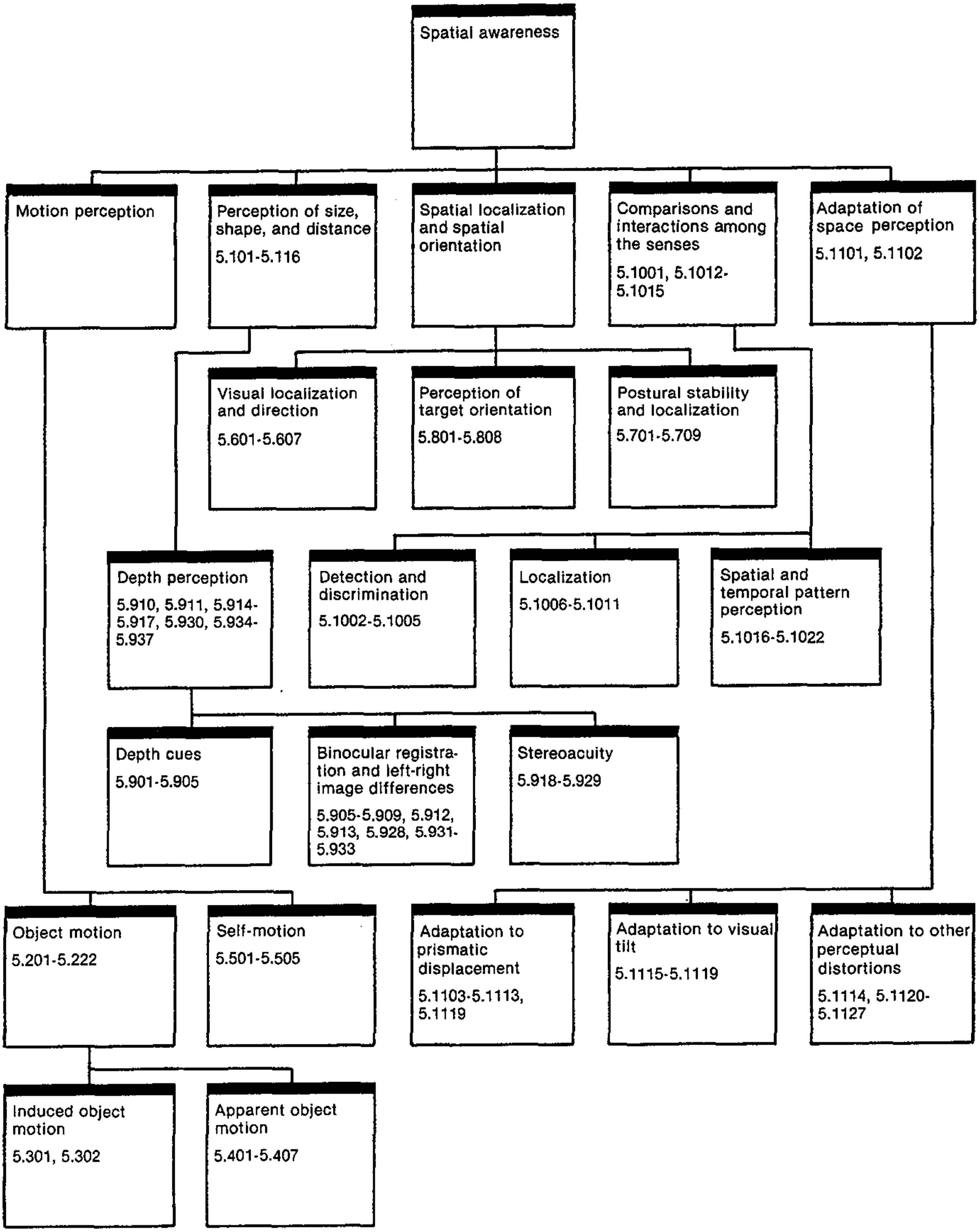
Cross References

4.301 Information theory;

Handbook of perception and human performance, Ch. 41, Sect. 2.2

Notes

Organization of Entries



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Section 5.11 Adaptation of Space Perception

Key Terms

Glossary

Absolute threshold. The amount of stimulus energy necessary to just detect the stimulus. Usually taken as the value associated with some specified probability of stimulus detection (typically 0.50 or 0.75).

Accommodation. A change in the thickness of the lens of the eye (which changes the eye's focal length) to bring the image of an object into proper focus on the retina. (CRef. 1.222)

Active movement. Movement of a limb or body part by the individual under his or her own volition.

Adaptation. (1) A change in the sensitivity of a sensory organ to adjust to the intensity or quality of stimulation prevailing at a given time (also called **sensory adaptation**); adaptation may occur as an increase in sensitivity (as in dark adaptation of the retina) or as a decrease in sensitivity with continued exposure to a constant stimulus. (2) A semipermanent change in perception or perceptual-motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors induced by this discrepancy (also called **perceptual adaptation**). (CRef. 5.1101)

Asymmetric convergence. Fixation on a target to one side rather than directly ahead of the observer. (CRef. 1.808)

Bimodal. Pertaining to, affecting, or impinging simultaneously upon two sensory modalities (such as vision and touch).

Binocular. (1) Pertaining to, affecting, or impinging upon both eyes; sometimes used to imply the identity of both eyes' views (*see also* **dichoptic**). (2) Employing both eyes at once, with each eye's view contributing to the final percept.

Binocular suppression. Decrease or loss or visibility of a portion or all of one eye's view due to stimulation of the same portion of the other eye. Binocular suppression is most clearly demonstrated when the two eyes are presented with conflicting information (such as different colors or different orientation of contours) in corresponding parts of the retinas. (CRef. 1.804)

Choice reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus in conditions where there is more than one stimulus alternative and more than one response alternative. (CRef. 9.101)

Chromatic aberration. Image degradation in an optical system, resulting from unequal refraction of light of different wavelengths; commonly manifested in simple optical systems as colored fringes on the border of an image. (CRef. 1.212)

Conditioning (classical) Learning in which a neutral stimulus comes to elicit a given response after being paired repeatedly with a second stimulus that previously elicited the response.

Cone. A cone-shaped photoreceptor in the retina of the eye; cones are distributed primarily in the fovea and function only at photopic (daylight) levels of illumination; they are responsible for color vision and fine visual resolution. (CRefs. 1.201, 1.301)

Contrast. The difference in luminance between two areas. Contrast can be expressed mathematically in several different ways. (CRef. 1.601) (*See also* **Michelson contrast.**)

Contrast threshold. The contrast associated with the minimum perceptible difference in luminance between two areas, often measured in terms of the luminance difference detectable on some specified proportion of trials (generally 0.50).

Convergence. An inward rotation of the eyes to fixate on a point nearer the observer.

Convergence angle. The angle formed between the lines of sight of the two eyes when the eyes are fixated on a point in space. (CRef. 1.808)

Convergent disparity. Lateral retinal image disparity associated with a point in the visual field that is closer than the fixation point; also known as **crossed disparity**. By convention, convergent disparity is given a negative value when expressed in terms of visual angle.

Convergent lateral retinal disparity. *See* **convergent disparity.**

Critical flicker frequency. The modulation frequency of an intermittently illuminated target at which the target ceases to appear flickering and appears steady.

Cross-modality matching. A procedure in which the subject adjusts the magnitude of a stimulus in one sensory modality to match the apparent magnitude of a stimulus in a different modality. For example, the loudness of a tone might be adjusted until it appears equal in magnitude to the brightness of a light.

Cyclofusional eye movements. Disjunctive rotational eye movements around a horizontal axis through the pupil; such movements are generally made to bring differentially rotated left and right images into alignment on the two retinas.

Dark adaptation. Adjustment of the eye to low levels of illumination which results in increased sensitivity to light.

Dependent variable. The response to a stimulus presentation measured by the investigator to assess the effect of an experimental treatment or independent variable in an experiment; for example, the investigator might measure the absolute visual threshold (dependent variable) for light targets of different diameters to assess the effects of target size (independent variable). (*Compare* **independent variable.**)

Difference threshold. The least amount by which two stimuli must differ along some dimension to be judged as nonidentical. Usually taken as the difference value associated with some specified probability of detecting a difference (typically 0.50 or 0.75).

Diopter. (1) A measurement unit expressing the refractive power of a lens and equal to the reciprocal of the focal length in meters. (2) A measurement unit expressing the vergence of a bundle of light rays equal to the reciprocal of the distance to the point of intersection of the rays in meters (taking a positive value for diverging rays and a negative value for the converging rays); the unit is often used to express the distance to an object being viewed, since it indicates the amount of eye accommodation necessary to bring the object into proper focus on the retina. (3) A measurement unit expressing the strength of a prism and equal to 100 times the tangent of the angle through which light rays are bent (generally called **prism diopter**).

Diplopia. *See* **double vision.**

Divergence. An outward rotation of the eyes to focus on a point further from the observer.

Divergent disparity. Lateral retinal image disparity associated with a point in the visual field that is further than the fixation point; also known as **uncrossed disparity**. By convention, divergent disparity is given a positive value when expressed in terms of visual angle.

Divergent lateral retinal disparity. *See* **divergent disparity.**

Double vision. A condition in which a single object appears as double because the images of the object in the left and right eyes do not fall on corresponding portions of the retinas; also called **diplopia**.

Dove prism. A prism such as that invented by J. W. Dove with two slanted faces and a mirrored base. A ray entering parallel to the base is refracted, then internally reflected, and then refracted again, emerging parallel to its incident direction. When the prism is rotated about its longitudinal axis, the image formed rotates through twice the angle of the prism rotation. (CRef. 5.1102)

Extorsion. Cyclorotational eye movements away from the midline; from the observer's viewpoint, the right eye rotates clockwise and the left eye counterclockwise. Extorsion usually occurs in response to orientation disparity between the right and left eyes' views.

Factorial design. An experimental design in which every level or state of each independent variable is presented in combination with every level or state of every other independent variable.

Fixation disparity. Convergence of the eyes to a plane in front of or behind the intended plane of fixation.

Fixation distance. The distance to which the eyes are converged.

Fovea. A pit in the center of the retina (approximately 2 deg of visual angle in diameter) where the density of photoreceptors is highest and visual acuity is greatest.

Frontal plane. The plane passing vertically through the body from side to side, perpendicular to the medial plane and dividing the body into front and back, or any plane parallel to this plane.

Functional stretch reflex. A reflexive contraction of the leg muscles in response to passive longitudinal stretching that aids in maintaining postural stability.

Half-field. The view of one eye only; most commonly used to refer to one of the two parts of a stereogram.

Haploscope. A stereoscope in which the arms holding the displays for the left and right eyes can be rotated to produce a wide range of symmetric and asymmetric convergence angles.

Haptic. Pertaining to or arising from tactual perception based on both cutaneous and kinesthetic information.

Heteromodal. Pertaining to or affecting more than one sensory modality.

Horizontal disparity. *See* **lateral retinal image disparity.**

Independent variable. The aspect of a stimulus or experimental environment that is varied systematically by the investigator in order to determine its effect on some other variable (i.e., the subject's response). For example, the investigator might systematically alter the diameter of a target light in order to assess the effect of target size (independent variable) on the observer's absolute visual threshold (dependent variable). (*Compare* **dependent variable.**)

Induced effect. In stereoscopic vision, apparent tilting of the visual field about the vertical axis caused by vertical magnification differences between the left and right eyes' views. The magnitude and direction of perceived tilt depend on which eye's image has greater magnification, as well as on the amount of magnification difference between right and left eyes, viewing distance, and interpupillary separation. (CRef. 5.909)

Intermanual transfer. Transfer of the change in performance due to practice or exposure from one hand or limb to the other.

Intorsion. Cyclorotational eye movements toward the midline; from the point of view of the observer, the right eye rotates counterclockwise and the left, clockwise. It usually occurs in response to orientation disparity between the right and left eyes' views.

Intra-modal matching. A procedure in which the subject matches the magnitude of a stimulus along some dimension with the magnitude of another stimulus in the same sensory modality that is presented as a standard. (*Compare* **cross-modal matching.**)

Kinesthesia. The sense of movement and position of the limbs or other body parts, arising from stimulation of receptors in joints, muscles, and tendons.

Lateral disparity. *See* **lateral retinal image disparity.**

Lateral retinal image disparity. The difference in the relative horizontal position of the visual images of an object on the left and right retinas due to the lateral separation of the eyes. (CRef. 5.905)

Light adaptation. The adjustment of the visual system to an increase in illumination in which sensitivity to light is reduced (threshold for light is increased) as illumination is increased.

Massed practice. Extended practice without interspersed rest or recuperation periods.

Medial plane. The vertical plane passing through the middle of the body from front to back and dividing the body into left and right. Sometimes called **sagittal plane.**

Method of adjustment. A psychophysical method of determining a threshold in which the subject (or the experimenter) adjusts the value of the stimulus until it just meets some preset criterion (e.g., just appears detectable or just appears flickering) or until it is apparently equal to a standard stimulus.

Method of constant stimuli. A psychophysical method of determining a threshold in which the subject is presented with several fixed, discrete values of the stimulus and makes a judgment about the presence or absence of the stimulus or indicates its relation to a standard stimulus (e.g., brighter, dimmer).

Method of limits. A psychophysical method of determining a threshold in which the experimenter varies a stimulus in an ascending or descending series of small steps and the observer reports whether the stimulus is detectable or not or indicates its relation to a standard stimulus.

Michelson contrast. A mathematical expression for specifying contrast of periodic patterns; defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} are the maximum and minimum luminances in the pattern. Michelson contrast ranges between 0 and 1. (CRef. 1.601)

Monaural. Pertaining to, affecting, or impinging upon only one ear.

Monocular. Pertaining to, affecting, or impinging upon only one eye.

Myotatic stretch reflex. A reflexive contraction of a muscle in response to passive longitudinal stretching.

Negative aftereffect. The occurrence of a perceptual effect in response to a stimulus that is opposite to the original effect elicited by a stimulus that preceded it. For example, after a heavy weight is lifted, a second weight appears lighter than if the first had not been lifted.

Neutral density. *See* **neutral density filter.**

Neutral density filter. A light filter that decreases the intensity of the light without altering the relative spectral distribution of the energy; also known as a **gray filter.**

Nonius markers. A pair of lines or other contours presented, one to each eye, which are in vernier alignment in the combined (binocular) view when left and right stereoscopic half-fields are in proper registration on the retinas. Nonius markers are used in stereoscopic displays to facilitate proper fixation as well as to assess convergence (fixation distance), vertical eye rotation, and image size differences between the eyes.

Nystagmus. Involuntary rhythmic movements of the eyes, which generally take the form of a slow drift alternating with a quick movement in the opposite direction.

Optic node. The optical center of the compound lens system of the eye (center of curvature of the cornea in the simple lens equivalent).

Orientation disparity. Rotation of the image in one eye with respect to the image in the other eye. This causes corresponding image points to fall on noncorresponding (disparate) retinal locations for all points in the binocular field except a point at the center, provided optical axes are parallel. (CRef. 5.908)

Otolith organs. Two small sack-shaped organs (the utricle and the saccule) that are embedded in the temporal bones on each side of the head near the inner ear and are sensitive to gravity and linear acceleration of the head.

Panum's fusional area. A small area surrounding the fixation point (or any point on the horopter [CRef. 5.910]) in which objects are seen as single, even though corresponding image points may not fall on precisely corresponding locations of the two retinas. (CRef. 5.911)

Passive movement. Movement of a subject's limb or body by a device or by the experimenter while the subject keeps the moved part as relaxed as possible.

Perceptual adaptation. *See* **adaptation** (2).

Photopic. Pertaining to relatively high (daytime) levels of illumination at which the eye is light-adapted and vision is mediated by the cone receptors. (CRef. 1.103)

Plane of fixation. The plane parallel to the front of the observer's body that contains the point of convergence (or fixation) of the eyes.

Power spectral density. The average power of a time-varying quantity within a band 1-Hz wide, as a function of frequency.

Proactive inhibition. Interference of responses learned earlier with the performance of responses learned at a later time.

Probit analysis. A regression-like maximum-likelihood procedure for finding the best-fitting ogive function for a set of binomially distributed data. Originally developed in connection with pharmacological and toxicological assays to compute the lethal or effective dose (dosage affecting 50% of treated organisms); the procedure has also been applied in psychophysical studies in analyzing all-or-nothing (yes/no) responses to compute the 50% threshold (stimulus level eliciting a given response on 50% of trials) and its confidence limits.

Proprioception. The sensing of body movement and position.

Psychometric function. A mathematical or graphical function expressing the relation between a series of stimuli that vary quantitatively along a given dimension, and the relative frequency with which a subject answers with a certain category of response in judging a particular property of the stimulus (e.g., "yes" and "no" in judging whether a given stimulus is detected, or "less than, "equal to," and "greater than" in comparing the stimulus with a standard stimulus). (CRef. 1.657)

Pulfrich effect. Apparent motion in depth of a laterally moving target when the retinal illuminance of one eye is lower than that of the other eye. A pendulum target appears to move in an elliptical path in a plane perpendicular to the frontal plane and parallel to the floor. (CRef. 5.933)

Random-dot pattern. Matrix pattern of light and dark cells, usually computer-generated, in which the probability that any given cell will be light or dark is determined by a random function. Such patterns are used in the study of stereoscopic vision because they allow the construction of stereograms containing no depth cues except lateral retinal image disparity. Thus only those with intact stereopsis mediated by retinal disparity can perceive the patterns.

Randomized design. An experimental design in which the various levels of the independent variable are presented in random order within a given block of trials or experimental session.

Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).

Retina. The membranous structure lining the inside of the eyeball which contains the photoreceptors (rods and cones) that mediate vision.

Retinal disparity. *See* **lateral retinal image disparity**; **vertical retinal image disparity**.

Retinal eccentricity. Distance from the center of the fovea to an image on or to an area of the retina generally expressed in angular terms; corresponds to the distance in the visual field from the fixation point to a given object or point in the field.

Retinal image disparity. *See* **lateral retinal image disparity**; **vertical retinal image disparity**.

Risley prism. A prism assembly comprised of two thin wedge prisms (generally identical) arranged in series. Rotating the two prisms in opposite directions alters the magnitude of off-axis beam deviation but not azimuth, while rotating them in the same direction changes deviation azimuth but not deviation angle.

Rod. A rod-shaped photoreceptor in the retina of the eye; rods are distributed only outside the fovea and are responsive at low levels of illumination. (CRefs. 1.201, 1.301)

Sagittal plane. The vertical plane passing through the body from back to front, and dividing it into left and right (i.e., the medial plane), or any plane parallel to it.

Scotopic. Pertaining to relatively low (nighttime) levels of illumination at which the eye is dark-adapted and vision is mediated by the rod receptors. (CRef. 1.103)

Semi-circular canals. Three fluid-filled tubes oriented roughly at right angles to one another that are embedded in the temporal bones on each side of the head near the inner ear and that aid in maintaining body equilibrium. (CRef. 3.201)

Sensitivity. In a general sense, the ability to detect stimulation; in psychophysical studies, refers in particular to the ability to be affected by and respond to low-intensity stimuli or to slight stimulus differences; commonly expressed as the reciprocal of measured threshold.

Signal detection theory. A theory which holds that performance on a detection task is a function of both the detectability of the signal (or the sensitivity of the observer) and the observer's criterion or response bias in reporting the signal. (CRef. 7.420)

Sine-wave grating. A bar pattern in which some property (generally luminance) varies with spatial position according to a sine function in a direction perpendicular to the bars. (CRef. 1.601)

Single vision. The perception of a single object from the separate images of the object in each eye. (CRef. 5.911)

Spaced practice. Practice in which practice periods are interspersed with rest intervals.

Spatial frequency. For a periodic target, such as a pattern of equally spaced bars, the reciprocal of the spacing between bars (i.e., the width of one cycle, or one light bar plus one dark bar), generally expressed in cycles per millimeter or cycles per degree of visual angle.

Spherical aberration. Image degradation in an optical system that occurs when light rays passing through the central and outer zones of a lens are brought to a focus at different distances from the lens. (CRef. 1.211)

Stabilized vision. Vision in which, through optical or other means, the image of a target is made to move exactly with the eye so that the same portion of the retina is always stimulated, that is, the image does not move on the retina when the eye moves.

Staircase procedure. A variant of the method of limits for determining a psychophysical threshold in which the value of the stimulus on a given trial is increased or decreased depending on the observer's response on the previous trial or group of trials.

Standard deviation. Square root of the average squared deviation from the mean of the observations in a given sample. It is a measure of the dispersion of scores or observations in the sample.

Standard error of estimate. The standard deviation of the sampling distribution of a population statistic (such as the mean, median, or variance); it is a measure of the variability of the statistic over repeated sampling.

Standard error of the mean. The standard deviation of the sampling distribution of the mean; mathematically, the standard deviation of the given data sample divided by the square root of one less than the number of observations. It describes the variability of the mean over repeated sampling.

Stereoacuity. The ability to discriminate depth or distance solely on the basis of lateral retinal image disparity; usually expressed as the smallest detectable difference in depth of two targets (in seconds of arc of visual angle).

Stereogram. A pair of two-dimensional drawings, photographs, etc., presented separately to the right and left eyes by a stereoscope or other means; generally, each half of the stereogram represents the same scene from a slightly different viewpoint, so that their fusion by the visual system gives rise to a single impression characterized by relief, depth, or three-dimensionality.

Stereopsis. Visual perception of depth or three-dimensionality; commonly used to refer specifically to depth arising from lateral retinal image disparity.

Stereoscope. An instrument used to present a separate visual display to each eye. Typically utilizes a system of mirrors, prisms, or lenses to present two specially constructed flat pictures (one to each eye) that, when combined by the visual system, give the impression of solidity or three-dimensionality.

Stereoscopic. Of or pertaining to stereopsis.

Subjective vertical. The orientation the observer perceives (indicates) as being vertical, which may or may not be true (gravitational) vertical.

Telestereoscope. A device for producing an appearance of exaggerated depth in scenes by increasing effective interpupillary distance (and thus lateral retinal image disparity). It permits depth judgments for objects otherwise too distant to judge. (CRef. 5.1102)

Threshold. A statistically determined boundary value along a given stimulus dimension that separates the stimuli eliciting one response from the stimuli eliciting a different response or no response (e.g., the point associated with a transition from "not visible" to "visible" or from "greater than" to "equal to" or "less than"). (CRef. 1.657) (*See also* **absolute threshold, difference threshold**.)

T-test. A statistical test used to compare the mean of a given sample with the mean of the population from which the sample is drawn or with the mean of a second sample in order to determine the significance of an experimental effect (i.e., the probability that the results observed were due to the experimental treatment rather than to chance). Also known as **Student's t-test**.

Two-alternative forced-choice paradigm. An experimental procedure in which the subject is presented on each trial with one of two alternative stimuli and must indicate which stimulus occurred; a response must be made on each trial even if the subject must guess. Commonly referred to as a "criterion free" method of determining sensitivity.

Vernier acuity. The ability to discern the alignment (colinearity) or lack of alignment of two parallel lines placed one above the other, as in reading a vernier scale; frequently expressed in terms of the smallest detectable misalignment in seconds of arc of visual angle. (CRef. 1.602)

Vertical retinal image disparity. The difference in the relative vertical position of the visual images of an object on the left and right retinas.

Vestibular sense. The sense mediated by the otolith organs and semi-circular canals that is concerned with the perception of head position and motion and is stimulated by acceleration associated with head movements and changes in the pull of gravity relative to the head. (CRef. 3.201)

Visual acuity. The ability of an observer to resolve fine pattern detail. Acuity is usually specified in terms of **decimal acuity** defined as the reciprocal of the smallest resolvable pattern detail in minutes of arc of visual angle. "Normal" or average acuity is considered to be 1.0 (a resolution of 1 min arc), although many young adults have a decimal acuity slightly better than this. (CRef. 1.602)

Visual angle. The angle subtended at the eye by the linear extent of an object in the visual field. It determines linear retinal image size. (CRef. 1.240)

Visual capture. The tendency for visual information to dominate in determining perception when visual information and information from some other sensory modality (such as touch) are discrepant.

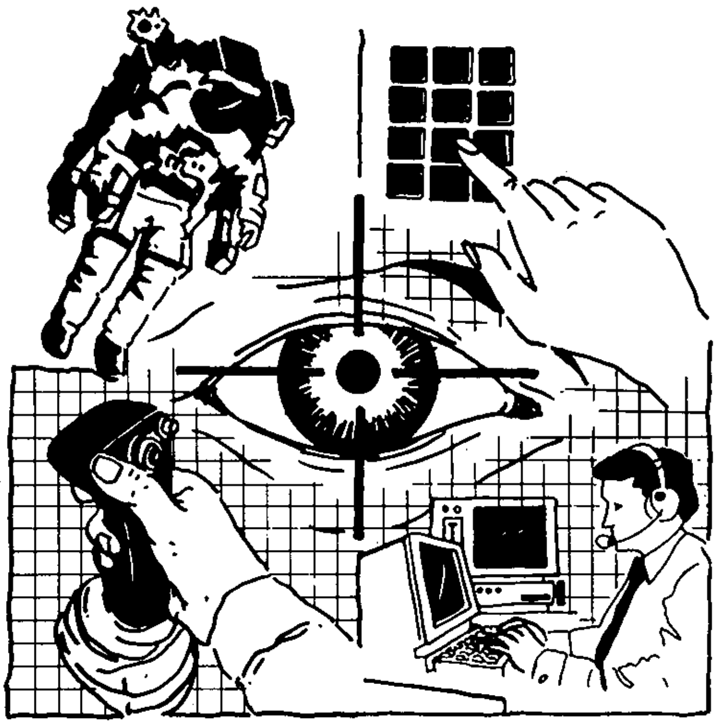
Visual direction. (1) The physical direction of the line of sight of the eye. (2) The relative direction in subjective visual space associated with a given point on the retina.

Visual position constancy. The tendency for the visual field to appear stable and motionless when the observer moves his or her eyes or head, despite the image motion on the retina caused by such movements.

Wheatstone mirror stereoscope. A stereoscope of the type invented by physicist Charles Wheatstone which utilizes a system of mirrors to present a different visual display to each eye; when the displays for the two eyes are appropriately constructed to represent the same object or visual scene from slightly different viewpoints (or positions in space), the result is the perception of a single image apparently having depth or three-dimensionality.

White noise. Random noise whose noise spectral level (noise-power density) is uniform over a wide frequency range; termed "white noise" by analogy with white light.

Section 5.1 Size, Shape, and Distance



5.101 Binocular Versus Monocular Aircraft Landing Performance

Key Terms

Aircraft landing; aircraft piloting; monocular viewing; motion in depth; range estimation

General Description

The ability of qualified pilots of both jet and light aircraft to land is not degraded by occluding one eye.

Applications

Relevant to certification of pilots who have lost an eye.

Methods

Test Conditions

Study 1 (Ref. 1)

- Good visibility conditions
- 18 **monocular** and 18 **binocular** touch-and-go landings were made
- Monetary reward for accurate monocular and bonocular landings used as performance incentive
- Dominant eye used on all monocular landings
- Pilots had no previous knowledge of monocular vs. binocular landing study results
- Landings performed in Beech Sport training aircraft (180 hp)

Study 2 (Ref. 2)

- Good visibility conditions
- 6 binocular and 12 monocular (6 left eye, 6 right eye) landings
- No monetary reward for good performance; instructions to guard against mental letdown when making binocular landings
- All pilots had prior knowledge of previous monocular vs. binocular landing study results
- Landings performed in Piper PA-28-180 Cherokee aircraft (180 hp)

Study 3 (Ref. 3)

- Good visibility conditions
- Number of binocular, left eye monocular and right eye monocular landings is not specified
- No monetary reward for good performance
- Pilots had no prior knowledge of binocular vs. monocular landing study results
- Landings performed in T-33A jet trainer

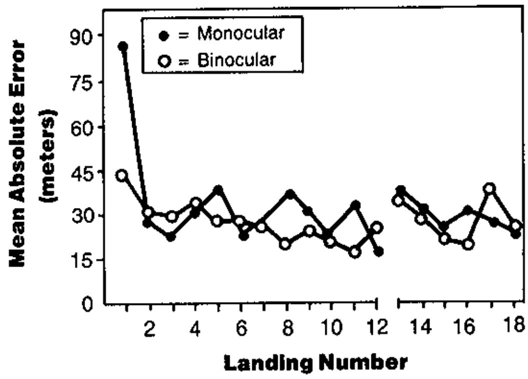


Figure 1. Mean distance errors made by 13 low-time private pilots landing binocularly and monocularly (Study 1). There was a rest pause between landings 12 and 13. (From Ref. 1)

Experimental Procedure (across studies)

- Independent variable: binocular versus monocular vision
- Dependent variable: distance from specified touchdown line, approach angle, sink rate, seismograph readings, physiological measures
- Subjects tasks: to land the aircraft as close as possible to a line extending across the runway
- 13 low-time private pilots (Study 1); 30 low-time general aviation pilots (Study 2); 13 NASA research pilots qualified for T-33A Jet Trainer (Study 3)

Experimental Results

- Ability to land an aircraft at a designated spot is not degraded by patching one eye of a qualified pilot.
- Monocular approaches are higher and steeper than binocular approaches.
- Pilot workload is increased during monocular landings.

Variability

The standard error of the average miss distance was 5.3 m for the binocular jet landings (Study 3) and 2.6 m for the monocular. For the general aviation pilots (Study 2), the standard errors of the average miss distances ranged for 0.78-2.09 m for the binocular landings and from 0.55-1.48 m for the monocular ones.

Constraints

- Experiments conducted only under conditions of clear visibility.
- The T-33A Jet Trainer used in Study 3 has relatively docile handling characteristics.

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Cross References

5.102 Perception of impact point for simulated aircraft carrier landings;

5.103 Pilot judgments of distance, height, and glideslope angle from computer-generated landing scenes;

5.104 Visual angle as a determiner of perceived size and distance;

5.901 Monocular distance cues;

5.907 Retinal image disparity due to image magnification in one eye

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.102 Perception of Impact Point for Simulated Aircraft Carrier Landings

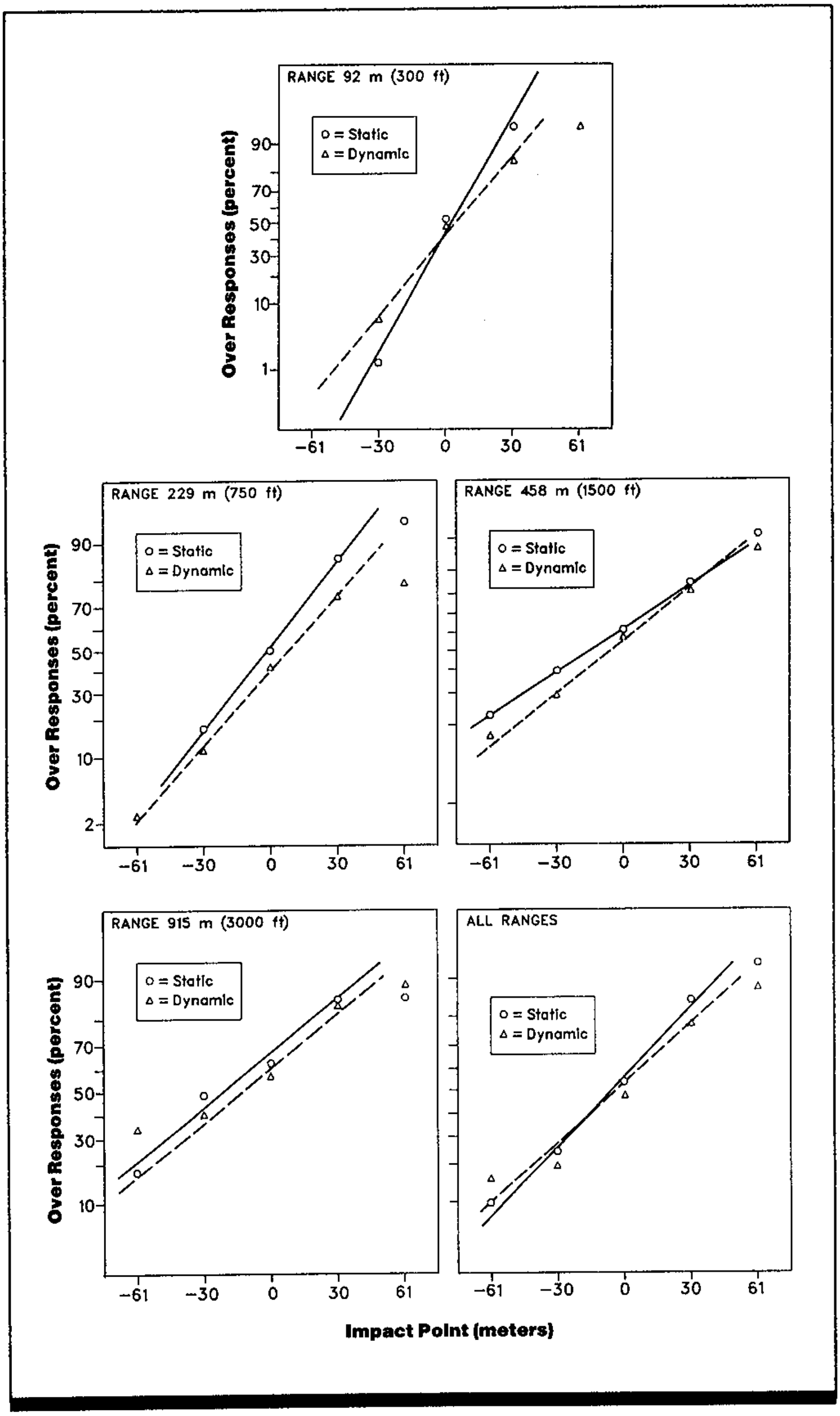

Figure 1. Percent of over responses (overshoots judged as "on" target) during simulated aircraft landings as a function of impact point. (From Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Aircraft carriers; aircraft landing; aircraft piloting; flight simulation; glideslope; motion cues; motion in depth; optic flow pattern; range estimation; training simulation

General Description

For simulated landings of an aircraft on an aircraft carrier (Ref. 2), the expansion pattern provided by optical flow (i.e., real motion) does not increase accuracy beyond that for the static scene: the aim point can be accurately determined on the basis of configural information provided by stern and deck combined. Also, neither horizon information nor ocean texture is necessary.

Applications

Training of aircraft pilots and design of equipment related to landing aircraft.

Methods

Test Conditions

- Carrier and ocean simulated by shadowgraph technique (casting shadows on an opal glass screen); approach to deck simulated by movement of model on track towards light source; manipulation of track and model produced different flight path angles
- Viewing distance ~254 cm (100 in.); monocular viewing through ~0.1 cm diameter artificial pupil
- Simulated approach was at 88 knots beginning at ~2 km on one of five glide paths at 5-deg angle
- Glide path impact point was reference zero (center of deck covered by arresting cables) or points 30 or 61 m (100 or 200 ft) fore or aft of reference zero
- Dynamic approaches varied in length, beginning at ~2 km (6500 ft) and ending at 915, 458, 229, or 92 m (3000, 1500, 750, or 300 ft)
- Static viewing at 915, 458, 229, or 92 m
- Observer viewed a full approach to reference zero before a block of trials, then viewed a set of randomized distance/glide path settings in a dynamic or static block

Experimental Procedure

- Independent variables: static versus dynamic viewing, impact point (glide path), length of approach
- Dependent variable: percent overshot responses
- Observer's task: judge whether the projected landing was "high," "on," or "low"
- 4 male high school seniors with normal vision

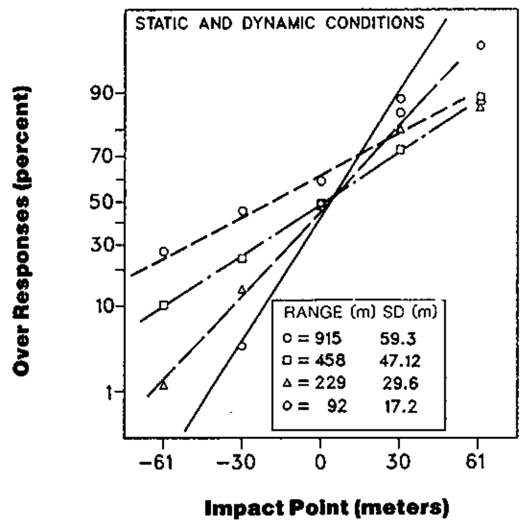

Figure 2. Data from Fig. 1 with dynamic and static results combined for each range value. (From Ref. 2)

Experimental Results

- Figure 1 shows results for static and dynamic conditions for each approach length. There are no differences between the conditions; therefore Fig. 2 shows the results collapsed across static and dynamic conditions.
- Longer approaches lead to more accurate judgments.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other studies have found good accuracy with experienced pilots under night-time conditions with only landing lights as guidance (Ref. 1).

Constraints

- Observers were not experienced pilots.

Key References

1. Gold, T., & Hyman, A. (1968). *Research in visual perception for carrier landing* (SGD-5265-0031) Great Neck, NY: Sperry Gyroscope Co. (DTIC No. AD682488)

*2. Kaufman, L. (1968). *Research in visual perception for carrier landing. Supplement 2. Studies on the perception of impact point based shadowgraph techniques* (SGD-5265-0031 [Suppl. 2]). Great Neck, NY: Sperry Gyroscope Co.

Cross References

5.101 Binocular versus monocular aircraft landing performance;

5.103 Pilot judgments of distance, height, and glideslope angle from computer-generated landing scenes;

5.104 Visual angle as a determiner of perceived size and distance;

5.502 Optical flow patterns and motion perspective;

Handbook of perception and human performance, Ch. 19, Sect. 3.3.

5.103 Pilot Judgments of Distance, Height, and Glideslope Angle from Computer-Generated Landing Scenes

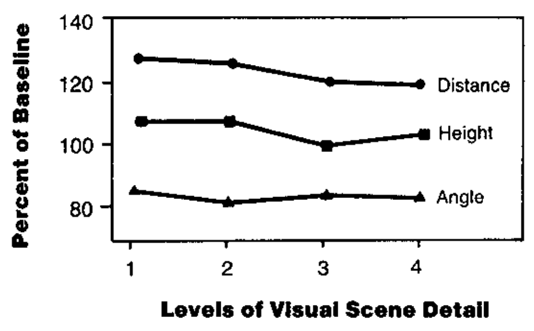

Figure 1. Distance, height, and glideslope angle judgments as a function of visual scene detail (dynamic imagery). Level 1 is most detailed; level 4 is least detailed. (From Ref. 1)

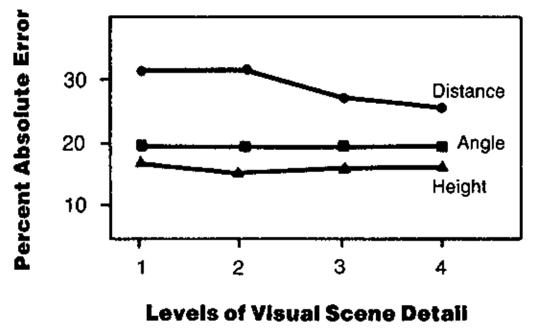

Figure 2. Distance, height, and glideslope angle judgments (dynamic imagery). (From Ref. 1)

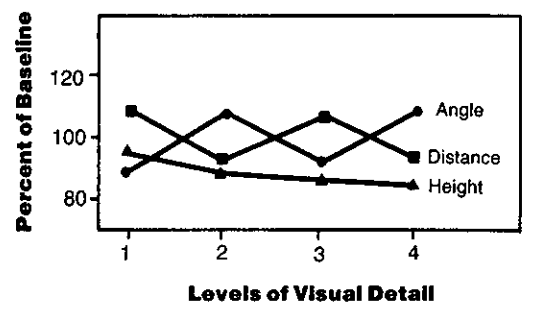

Figure 3. Distance, height, and glideslope angle judgments (static imagery). (From Ref. 1)

Key Terms

Aircraft landing; aircraft piloting; computer generated imagery; flight simulation; glideslope; pilot judgment; range estimation; scene content; training simulation; visual cues; visual simulation

General Description

Pilot judgments of distance, height, and glideslope angle were made from static and dynamic computer-generated landing approach scenes of four levels of detail from complex to austere. Visual scene detail significantly affects only absolute errors in distance judgments, with these errors being smaller for the less complex scene. Essentially, pilots obtain landing information as accurately from simplified visual scenes as from more complex ones.

Applications

The design of visual simulations for final aircraft approach.

Methods

Test Conditions

- Computer-generated imagery landing approach scenes electronically generated, stored on video tape, and presented on color television monitor of unspecified size; lens over display face to collimate this display; viewing distance not specified but display subtended 48 deg of visual angle horizontally and 36 deg vertically; display viewed in dimly illuminated room; illuminance not specified; viewing distance determined by collimating levels on display
- Four levels of scene detail; level 1 most complete (horizon, fields, streets, airfield with runway, parallel runway, taxiways, approach lights, runway threshold, centerline and touch down markings); level 4 least complete (horizon and airfield with single runway only); levels 2 and 3 intermediate to levels 1 and 4, with successively less complete content
- Scenes generated for five positions along glideslope, from 4,000-250 m from runway threshold
- Dynamic landing approaches: visual scene began +40% from nominal scene position and ended −40% from nominal scene position; simulated aircraft speed not reported
- Static-scene presentation: five positions used (+40% and +20% from nominal, nominal position, −20% and −40% from nominal); static-scene viewing time 3 sec
- Each observer received all experimental conditions; static scenes presented first to each observer; scenes with greatest nominal distance from runway threshold presented first, second greatest nominal distance second, etc; at each nominal distance, scenes of deviations from nominal as well as nominal presented in random sequence; nominal distance sequence same for dynamic trials; scene complexity always presented in following sequence: 1, 3, 2, 4; distance judgments made first, followed by height, and finally glideslope angle judgments

Experimental Procedure

- Independent variables: static versus dynamic imagery, nominal distances from runway threshold, and scene content
- Dependent variables: percentage of nominal, defined as judged value

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

divided by nominal value and multiplied by 100 (values >100% show underestimations; values <100% show overestimation); absolute error percentage, defined as the absolute difference value between the judged and nominal value, divided by the nominal value and multiplied by 100

• Observer's task: for static scenes, given a verbal description of nominal, verbally respond to each scene as nominal or not nominal; for dynamic imagery, when given a verbal description of nominal, depress a button when nominal scene value is observed; no feedback given

• 28 observers, military transport pilots, ages 23-44 years, 400-8,000 hrs flight experience, normal vision assumed

Experimental Results

• No statistically significant differences were found for any of the independent variables with static scene presentations.
• Level of scene detail produced significantly different performance only for distance judgment using absolute error percentages in the dynamic scene conditions. Higher error levels were obtained for the Level 2 scene than for Levels 3 and 4 (less complex levels).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results are in keeping with those for real-world landing approaches (Ref. 4) and for simulated night landing approaches (Ref. 3). Using computer-generated imagery and the task of judging adherence to a specified glide path, it also has been determined that the most important visual cue during landing is the motion of the leading edge of the runway, with the visual threshold corresponding to a total angular movement on the order of 0.1 deg (Ref. 2). This result is independent of the presence of a horizon and/or the changing geometric pattern formed by the runway.

Constraints

• Display field of view is believed to be relatively constrained.
• Whether the visual scenes simulated daylight or dusk was not specified.
• Results should not be generalized to tasks other than approach and landing without empirical verification.
• Generalizability of results to proper simulator manual control techniques requires verification.
• Performance differences due to observer experience were not reported.

Key References

*1. Dorfel, G. (1982). *Pilot judgments of distance, height, and glide-slope angle from computer-generated landing scenes.* International Conference on Flight Simulation, Avionic Systems, and Aero-Medical Aspects, London.

2. Edwards, G. D., & Harris, J.S., Sr. (1974). *Analysis of visual stimulus in aircraft approach to landing operations* (SIO reference 74-8). Claremont, CA: Scripps Institute of Oceanography.

3. Mertens, H. (1981). Perception of runway image shape and approach angle magnitude by pilots in simulated night landing approaches. *Aviation, Space, and Environmental Medicine, 52,* 373-386.

4. Mizumoto, K. (1975). *A study on altitude and distance judgments of pilots during final approach.* Aeromedical Laboratory, JASDF, Japan.

Cross References

5.101 Binocular versus monocular aircraft landing performance;

5.102 Perception of impact point for simulated aircraft carrier landings;

5.104 Visual angle as a determiner of perceived size and distance;

5.113 Perception of the objective shape of slanted surfaces;

7.514 Effect of irrelevant stimuli on search performance

5.104 Visual Angle as a Determiner of Perceived Size and Distance

Key Terms

Distance perception; monocular depth cues; moon illusion; range estimation; size constancy; size-distance invariance; target recognition; visual angle

General Description

Visual angle, A, refers to the angle measured from the nodal point of the eye of an observer, 0, to the endpoints of a linear extent, x, in the visual field (Fig. 1). The visual angle subtended by a given linear extent will depend on its magnitude, its distance from the observer, and its orientation with respect to the observer; however, when an object is perpendicular to the line of regard and the distance to the object is large relative to the linear extent of the object, the *visual angle relation applies*. This rule states that the *visual angle subtended by an object is directly proportional to its size and inversely proportional to its distance* from the observer. Thus, visual angle is relevant to assessing both size and distance information. Various studies indicate that people are aware of the differences in visual angle produced by an object at different distances, even under normal viewing, and especially if distances are large. Under reduced viewing conditions, size and distance judgments are both strongly influenced by visual angle.

Applications

Observers, such as nighttime operators of aircraft or naval craft, judging the size and distance of objects in the absence of good distance cues, are likely to make errors in both size and distance judgments.

Methods

Test Conditions

Study 1 (Ref. 1)

- Plane white isosceles triangles 1.1, 1.4, 1.7 or 2.0 m high, placed on level open field at distances of 30.5, 61, 122, 244, 488, or 1219 m from observer
- Variable triangle adjustable from 0-2.2 m, placed 30.5 m from observer
- Binocular viewing; unlimited viewing time

Study 2 (Ref. 3)

- Electroluminescent disc, 82-mm diameter, presented in darkness at distances of 59, 118, 235, or 470 cm to create visual angles of 1, 2, 4, or 8 deg
- Monocular viewing

Study 3 (Ref. 2)

- Electroluminescent discs; standard of 24-mm diameter placed 115 cm away and 17.5 deg to right of observer's median plane (1.2 deg visual angle); comparison placed 17.5 deg to left of observer's median plane at distances of 25, 45, 75, 115, 195, 295, or 395 cm (Conditions 1 and 2) or at fixed distance of 115 cm (Condition 3)
- Comparison stimulus either varied in size (Conditions 1 and 3) or was fixed 24 mm (Condition 2)
- Visual angle of comparison stimulus was fixed in Condition 1 and variable in Condition 2 (with fixed-size stimulus presented at different distances) and Condition 3 (with variable size stimulus presented at fixed distance)
- Monocular viewing; unlimited exposure time

Experimental Procedure

Study 1

- Method of adjustment
- Independent variables: distance of standard, size of standard, objective versus projective instructions, ascending versus descending adjustments, order of instructions
- Dependent variable: height of variable triangle
- Observer's task: adjust height of variable triangle to match either the objective height or the projective height of the standard triangle
- 32-36 high school student observers

Study 2

- Magnitude estimation
- Independent variables: visual angle of disc, order of size and distance judgments
- Dependent variables: size judgment, distance judgment
- Observer's task: estimate the size and distance from observer of illuminated disc
- 80 psychology students

Study 3

- Magnitude estimation
- Independent variables: viewing condition (visual angle of comparison)
- Dependent variable: magnitude estimation of comparison relative to standard
- Observer's task: estimate magnitude of comparison stimulus relative to the standard
- 96 psychology students (36 in Exp. 1 and 60 in Exp. 2)

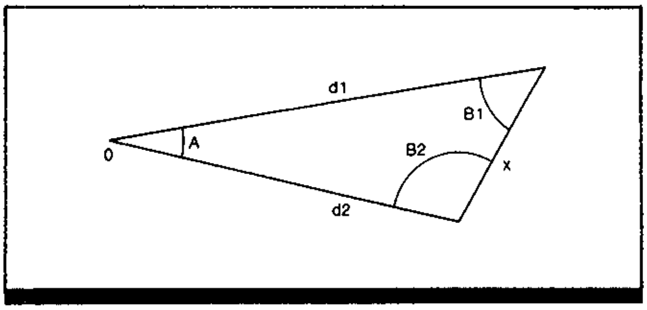

Figure 1. Illustration of the relation between visual angle, *A*, linear extent, *x*, and distance of an object from an observer, *0*. The endpoints of the linear extent are at distances *d1* and *d2* from the observer; angles *B1* and *B2* are taken with respect to the endpoints of the linear extent and the line of regard from *0*. The general geometric relation is $x/(\sin A) = d1/(\sin B2) = d2/(\sin B1)$. When *x* is small relative to *d1* and *d2*, and *B1* and *B2* are approximately 90 deg, this relation leads to the approximation $A = x/d$. (From *Handbook of perception and human performance*)

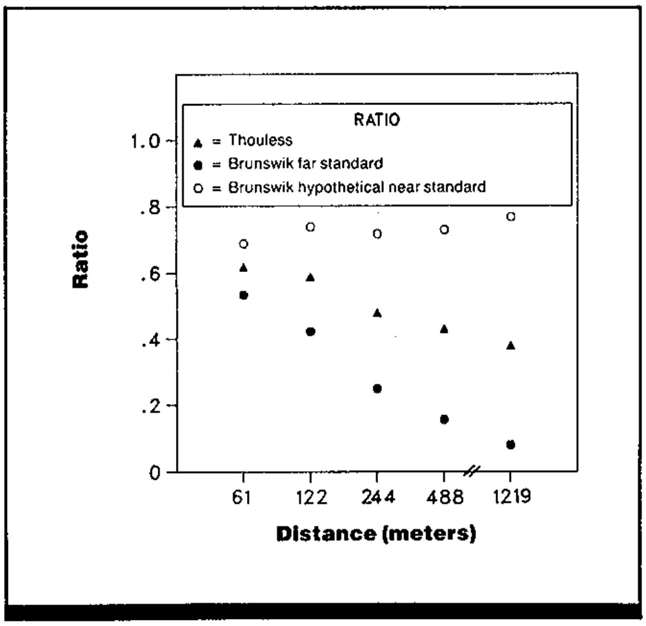

Figure 2. Perception of angular extent under naturalistic conditions (Study 1) with data plotted in Thouless ratios (filled triangles) and Brunswik ratios (filled circles), which measure relative closeness to objective (ratio = 1) and projective (ratio = 0) matches. Projective matches, requiring perception of angular extent, become more accurate with increasing distance. (Open circles show Brunswik ratios that would have been produced for the same data by reversing the designation of standard and comparison stimuli and illustrate the sensitivity of Brunswik ratios to the arbitrary designation of the standard.) (From *Handbook of perception and human performance*, based on data from Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

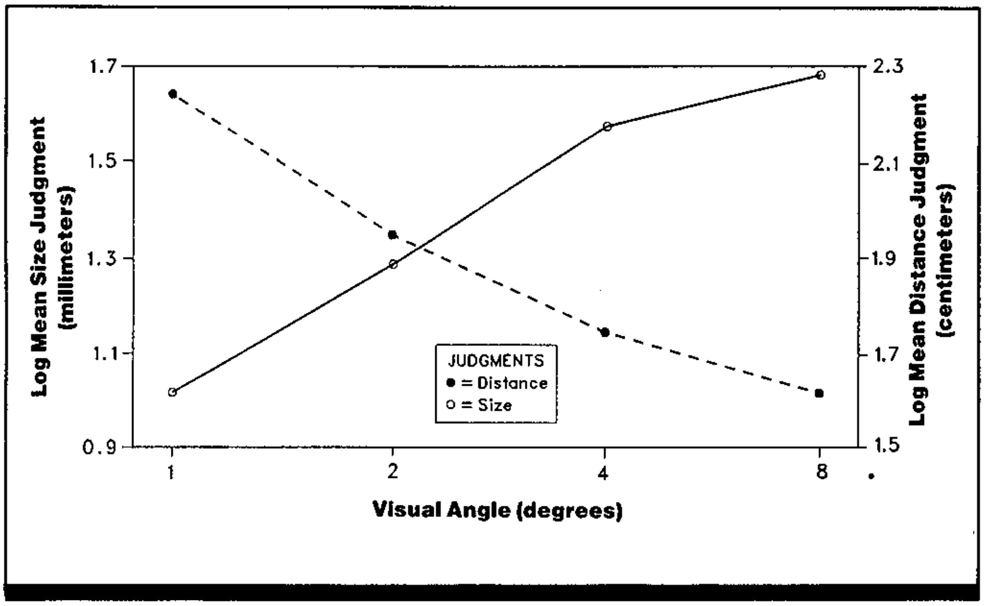

Figure 3. Perceived *absolute* size and distance as a function of the angular extent of an electroluminescent disk viewed with one eye in total darkness (Study 2). Estimated size increased and estimated distance decreased as the visual angle of the disc increased. (From Ref. 3)

Experimental Results

- In Study 1, observers slightly overestimate both objective and projective size.
- Projective matches become more accurate with increasing distance (Fig. 2).
- In Study 2, estimated size of disc increases with increasing visual angle; estimated distance of disc decreases with visual angle (Fig. 3).
- In Study 3, estimated size of disc compared to standard increases with increasing visual angle and estimated distance decreases with visual angle, independent of actual distance or size of comparison stimulus (Fig. 4).

Variability

Six observers unable to make objective matches for largest standard in Study 1; standard deviations of judgments ranged from 5-24% of mean for objective judgments and from 6-67% for projective judgments. Data from 3 observers were replaced in Study 2. No information on variability was given in Study 3.

Repeatability/Comparison with Other Studies

Most studies agree that when observers are provided good depth cues (a) objective judgments are fairly accurate and (b) projective judgments are difficult for comparisons over limited distances. Other studies have also reported that size and distance judgments vary with visual angle.

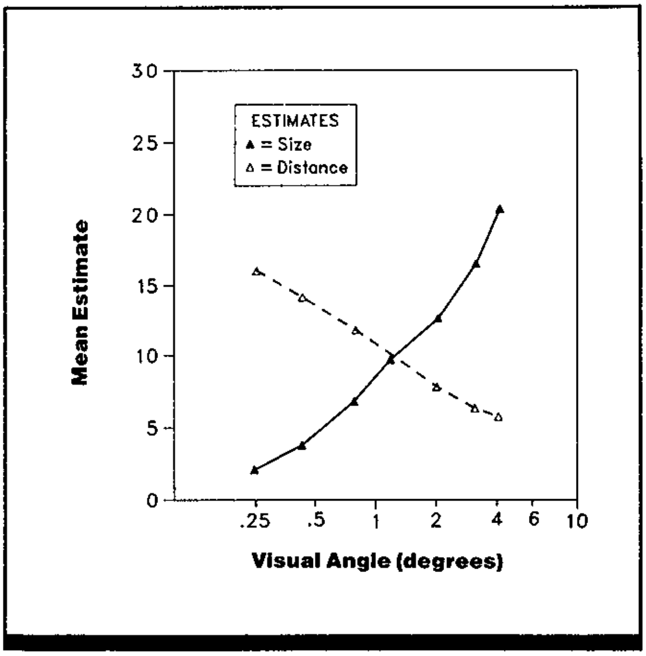

Figure 4. Perceived *relative* size and distance as a function of the angular extent of an electroluminescent disc viewed with one eye in dark field containing a standard disc of 1.2 deg (Study 3). Estimated relative size increased and estimated relative distance decreased as the visual angle of the comparison disc was increased, by presenting different sized discs at a fixed distance. (From Ref. 2)

Constraints

- Subjective matching tasks appear to be strongly influenced by the nature of instructions given to observer.
- Size and distance judgments are normally influenced by observer's familiarity with objects.

Key References

*1. Epstein, W., & Landauer, A. A. (1969). Size and distance judgments under reduced conditions of viewing. *Perception & Psychophysics*, *6*, 269-272.

*2. Gilinsky, A. S. (1955). The effect of attitude upon the perception of size. *American Journal of Psychology*, *68*, 460-482.

*3. Landauer, A. A., & Epstein, W. (1969). Does retinal size have a unique correlate in perceived size? *Perception & Psychophysics*, *6*, 273-275.

Cross References

1.240 Visual angle and retinal size;

1.615 Visual acuity: effect of viewing distance;

7.510 Search time: effect of target luminance, size, and contrast;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

Handbook of perception and human performance, Ch. 21, Sect. 2.2.

5.105 Visual Perspective and the Specification of Shape and Distance

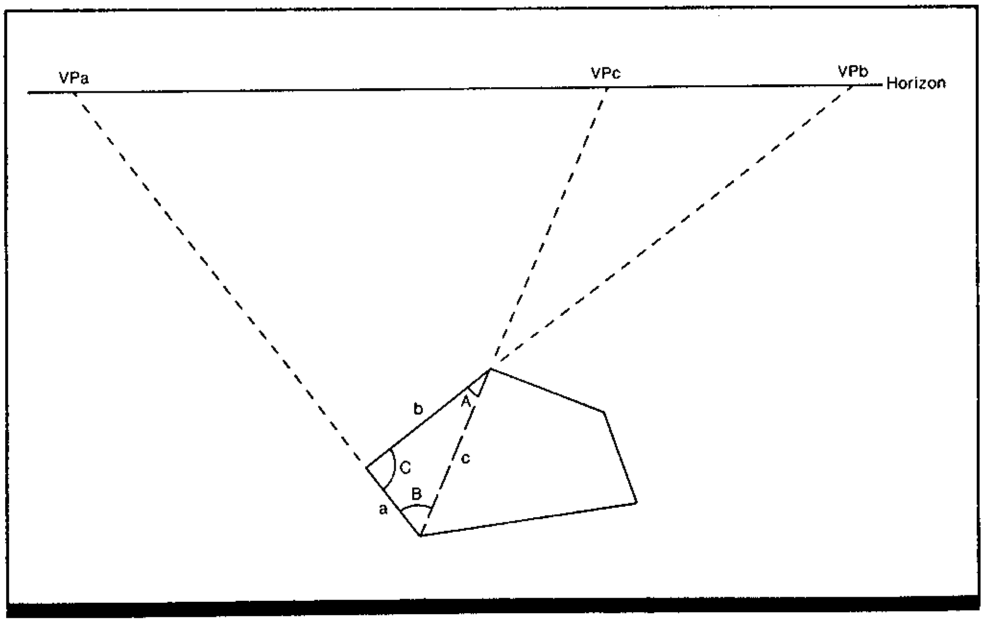

Figure 1. Specifying the shape of a polygon from vanishing points and horizons in the perspective structure. The shape of a polygon lying on a surface is specified by relations between the vanishing points of the sides and diagonals of the polygon. The angle *C* between any two adjacent sides, *a* and *b*, equals the angle from the point of observation to the vanishing points, *VPa* and *VPb*, of the sides on the horizon of the surface. The relative lengths of the sides can be specified by creating a triangle with the diagonal, c. Then, by law of sines, $a/b = \sin A/\sin B$. (From Ref. 2)

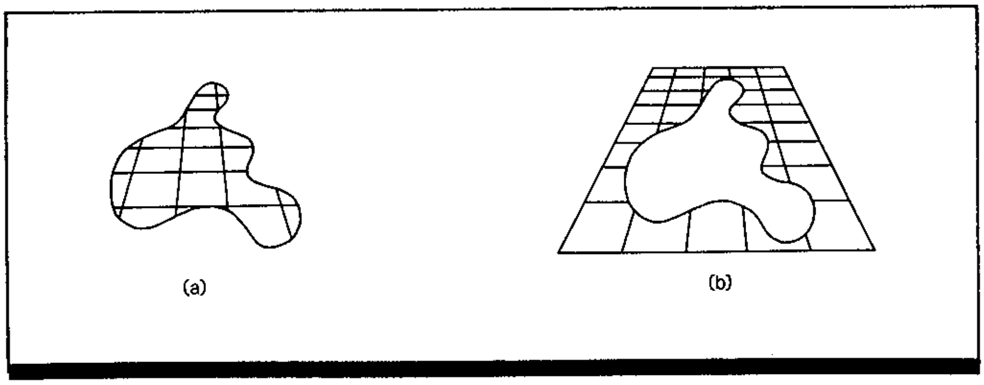

Figure 2. The shape of a surface or of an object resting on a surface can be determined by the surface's texture scale. Texture elements provide a unit of measurement to specify the distances between points on the boundary of the surface or of the object. Specification of enough distances determines the shape of the object. (From Ref. 2)

Key Terms

Egocentric distance; field of view; linear perspective; perceived distance; range estimation; target acquisition; texture gradient; training; vanishing point; visual simulation

General Description

The visual field available to an observer contains a set of linear perspective relations that impose a *perspective structure* on the field. This structure can be characterized in terms of *horizons* and *vanishing points*. The horizon of a surface can be defined as the limiting boundary of the two-dimensional projection of a surface extending indefinitely in depth, and a vanishing point can be defined as the intersection of the edge's two-dimensional projection with the horizon of the surface containing the edge (CRef. 5.115 for an

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

alternative definition). Horizons and vanishing points provide a means of specifying the shape, the size, and the distance from the observer of any object in the field of view.

Shape Specification

The shape of any polygon is determined if (1) the internal angles between every pair of adjacent sides are known and (2) the relative lengths of the polygon's sides are known. Both kinds of information are present in the perspective structure. The *internal angle* between any pair of adjacent sides equals the angle between the vanishing points of the sides from a point of observation (Fig. 1). The *relative lengths* of the polygon's sides are specified if the diagonals connecting each vertex are used to divide the polygon into triangles (see Line c in Fig. 1). Given the vanishing point of the diagonal, the internal angles of the Triangle abc are all specified. Hence, using the law of sines for triangular shapes, the relative length of sides a and b can be expressed in terms of the internal angles as

$$a/b = \sin A/\sin B,$$

where A and B are the internal angles opposite a and b, as shown in Fig. 1.

It is important to note that shape may also be specified by other features of a surface, such as the *texture scale*. A homogeneously textured surface contains an implicit scale in which the textural elements are the units of measurement both for the shape of the surface and for the shape of any object supported by the surface. These elements specify the relative distance between any two points on the boundary of the shape. The shape of any polygon is determined when distances are specified for all sides and enough diagonals are used to divide the polygon into triangles; the shape of any curved shape is closely approximated as more and more diagonals are specified (Fig. 2).

Distance Specification

The distance from an observer, or *egocentric distance*, of any point on a surface is specified by the following relations between the point of observation, the distant point, and the horizon of the surface. Egocentric distance, d_1, equals the height of the point of observation above the surface, h, times the cotangent of the angle, A_1, formed between a line of sight to the distant point and the horizon of the surface, that is,

$$d_1 = h(\cot A_1).$$

This relation is illustrated in Fig. 3.

In addition, the relative distance from an observer to each of two points on a surface, d_1/d_2, equals the ratio of the cotangents of the associated angles, $\cot A_1/\cot A_2$. When the distances are large relative to the height of the observer, relative distance is approximately equal to the relative angle between each point and the horizon of the surface, A_2/A_1.

Size Specification

The height of any object in contact with a surface (e.g., the height of any object in contact with the ground) is given by the *horizon-ratio relation*. This expresses the vertical height of an object, v, relative to the height of the observer above the surface, h, in terms of the angles between the horizon and the top of the object, E, and its bottom F (Fig. 4). The relation can be written as

$$v/h = 1 \pm (\tan E/\tan F),$$

where plus is used when the object extends above the horizon, and minus is used when the top of the object is below the horizon.

When the angles E and F are relatively small, as occurs when most objects are relatively distant from the observer, the height of the object is closely approximated by the simple ratio between the angle subtended by the object, V, and the angle between the horizon and the bottom of the object, F, so that

$$v/h = V/F.$$

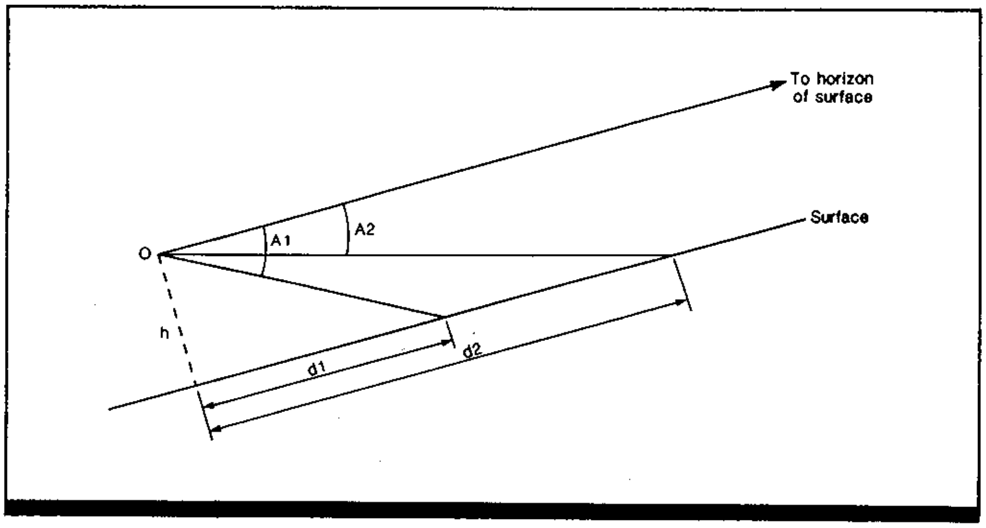

Figure 3. Specification of distance from an observer in terms of the horizon of a surface. The distance, d_1, from an observer to a point on a surface, such as the ground, is specified in terms of the height of the observer, h, and the angle, A_1, between the line of sight to the point and the horizon, such that $d_1 = h(\cot A_1)$. The relative distances from an observer of two points, d_1 and d_2, is specified in terms of the ratio $\cot A_1/\cot A_2$. When the distances are large in comparison to the observer's height, the relative distance is approximately A_2/A_1. (From Ref. 1)

Applications

To the degree that human observers use perspective structure to determine the shape, distance, and size of objects in the visual field, operators in field conditions with unusual elevations, such as on aircraft, naval craft, or mountainous terrain, will perform better if trained to compensate for changes in the height, h, of horizons.

Key References

*1. Sedgwick, H. A. (1973). *The visible horizon: A potential source of visual information for the perception of size and distance*. Unpublished doctoral dissertation, Cornell University, Ithaca, NY.

*2. Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

Cross References

1.240 Visual angle and retinal size;

1.603 Factors affecting visual acuity;

1.615 Visual acuity: effect of viewing distance;

5.103 Pilot judgments of distance, height, and glideslope angle from computer-generated landing scenes;

5.104 Visual angle as a determiner of perceived size and distance;

5.106 Classic geometric illusions of size and direction;

5.108 Illusions of perceived size and distance;

5.112 Relation between perceived and physical distance;

5.115 Representation of slant by linear perspective;

7.510 Search time: effect of target luminance, size, and contrast;

7.511 Search time and eye fixations: effects of symbol color, size, and shape

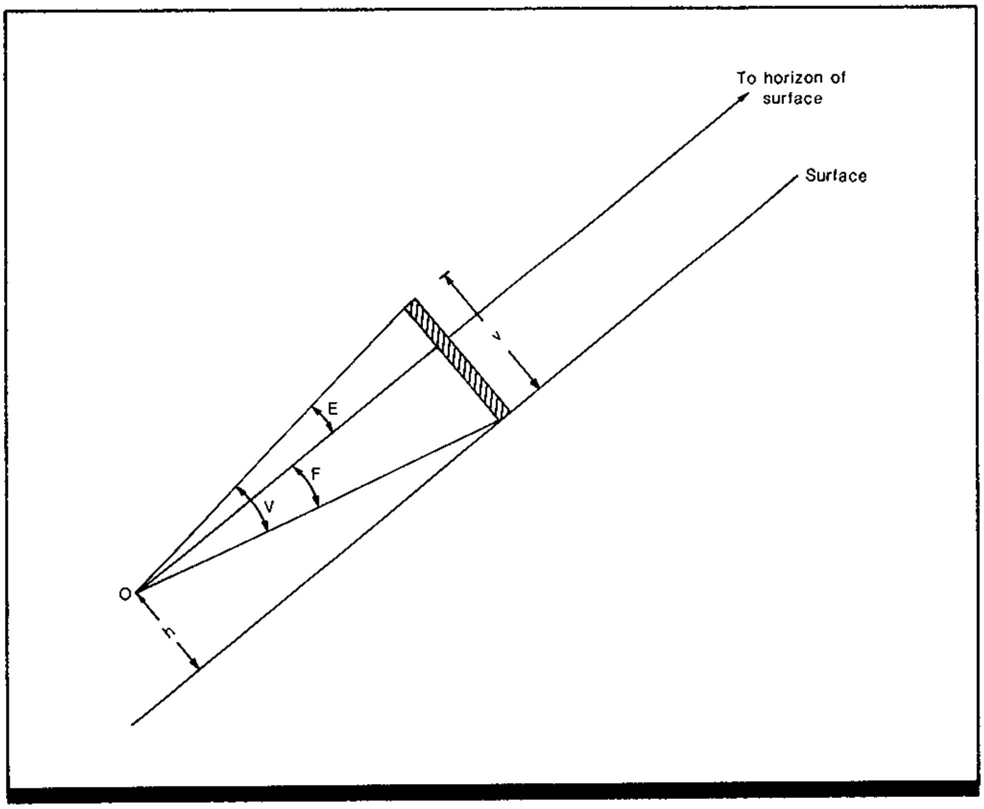

Figure 4. Specification of size in terms of the surface horizon. The height, v, of an object above a surface with which it is in contact, relative to the height, h, of an observer, is specified by the horizon-ratio relation in terms of the angle E, between the horizon and the top of the object, and the angle F, between the horizon and the bottom of the object. Formally, the relation is $v/h = 1 \pm (\tan E/\tan F)$, where the plus is used if the object extends above the horizon and the minus if the top of the object is below the horizon. If the object is relatively distant from the observer, so that the subtended angle is small, the relative height of the object is approximated by the simple ratio V/F, where V is the angle subtended by the object from the point of observation. (From Ref. 1)

Notes

5.106 Classic Geometric Illusions of Size and Direction

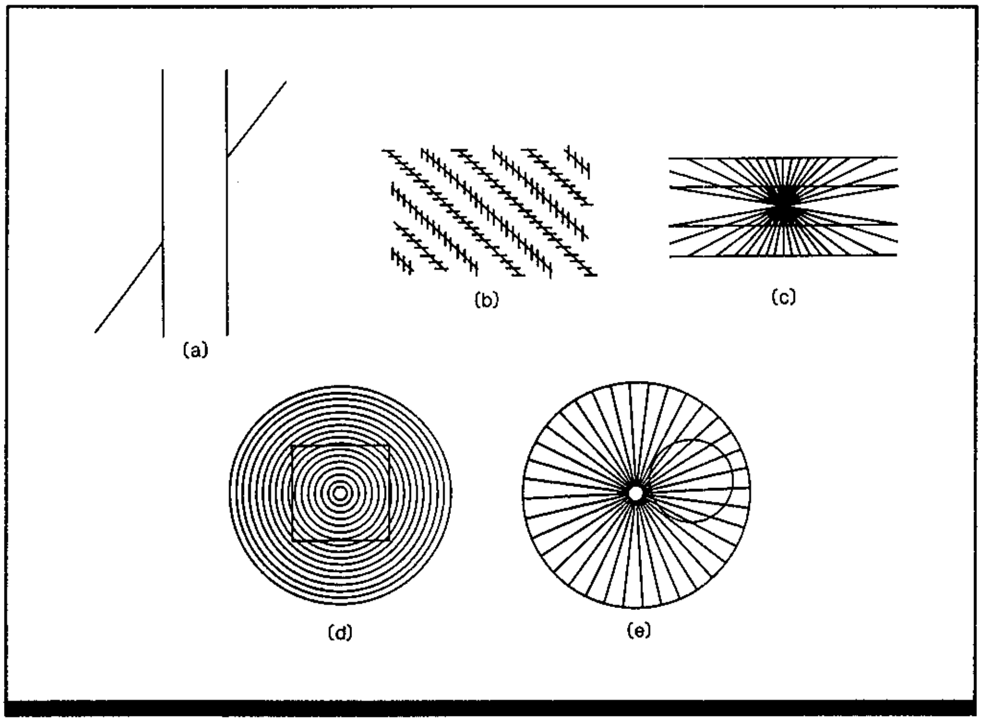

Figure 1. Illusions of direction. (From *Handbook of perception and human performance*)

Key Terms

Delboeuf illusion; Ebbinghaus illusion; Ehrenstein illusion; Hering illusion; illusions; Müller-Lyer illusion; Orbison illusion; perceived size; Poggendorff illusion; Ponzo illusion; target acquisition; vertical-horizontal illusion; visual search; visual stimulation; Zollner illusion

General Description

An illusion can be defined as a percept that is not in accord with what we know to be true. Of interest here are geometric illusions, which involve changes in apparent size or direction in certain lines in a figure (test lines) due to the presence of other lines in the figure (inducing lines). Some general findings:

- Illusions occur when eyes are prevented from scanning (Ref. 6)
- The illusions tend to be reduced by repeated viewing, but only if observers' eyes are allowed to move freely
- Illusions analogous with the sense of touch have been produced (Ref. 4).

The mechanisms responsible for these illusions remain controversial and are not likely to be the same for all illusions. The table provides representative examples of the most familiar geometric illusions of size and direction, briefly describes the illusions, and explains factors that affect the illusions.

Applications

Design of environments in which size or direction judgments are crucial.

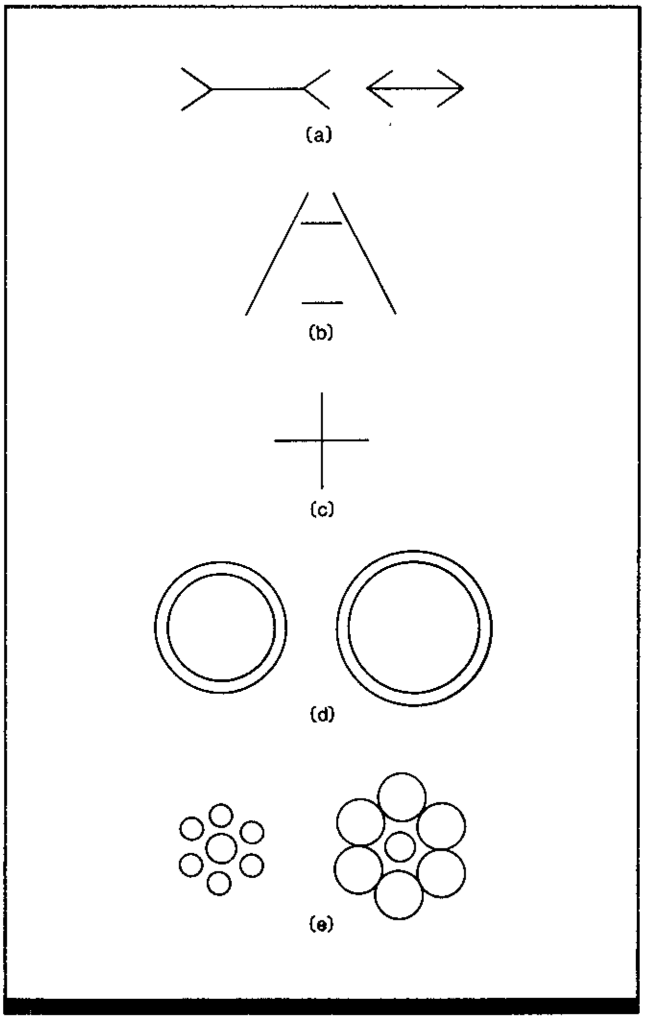

Figure 2. Illusions of size. (From *Handbook of perception and human performance*)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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2. Coren, S., & Girgus, J. S. (1980). Principles of perceptual organization and spatial distortion: The Gestalt illusions. *Journal of Experimental Psychology: Human Perception and Performance, 6*, 404-412.

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Cross References

1.909 Maladaptive eye movements: eliciting conditions;

5.104 Visual angle as a determiner of perceived size and distance;

5.108 Illusions of perceived size and distance;

5.110 Haptic perception of length: effect of orientation;

5.801 Factors affecting judgment of the visual vertical;

5.802 Illusory spatial displacements;

5.805 Illusions of perceived tilt;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.304 Role of reference frames in perception;

6.306 Reversible or multistable figures;

6.314 Subjective or illusory contours;

6.609 Haptic perception of curvature: effect of curve orientation and type of arm movement;

Handbook of perception and human performance, Ch. 33, Sect. 2.6

Illusion	Description	Factors	References
Illusions of Direction			
Poggendorff illusion (Fig. 1a)	An oblique line is interrupted by a vertical bar, and the visible segments of the line do not appear colinear	Illusion persists when only oblique angles remain in figure. Illusion opposite in direction when only acute angles remain. Can be produced when inducing contours are illusory contours	Ref. 3
Zollner illusion (Fig. 1b)	Long oblique lines interrupted by short horizontal and vertical lines no longer appear parallel	Magnitude of illusion affected by angle of intersection of inducing and test lines	Ref. 5
Hering illusion (Fig. 1c)	Horizontal parallel lines appear bowed due to oblique inducing lines	One can still produce illusion when intersection of contours is replaced by dots or empty spaces. Contradictory disparity cues do not affect illusion. Magnitude of illusion affected by angle of intersection of inducing and test lines	Ref. 5
Ehrenstein and Orbison illusions (Figs. 1d, 1e)	The square (Ehrenstein illusion) and circle (Orbison illusion) are distorted by inducing pattern		
Illusions of Size			
Müller-Lyer illusion (Fig. 2a)	Horizontal lines of equal length appear to be of different lengths	Contradictory disparity cues do not affect illusion. Factors which make it possible to differentiate shaft from inducing components are color change, gaps, etc. Scanning eye movements tend to reflect illusion magnitude	Refs. 2, 5
Ponzo illusion (Fig. 2b)	Two horizontal lines of equal length, enclosed by converging lines, appear to be of different lengths	Magnitude of illusion affected by angle of converging lines; intensified by use of large number of converging lines. Illusion persists when inducing lines are clearly separated from horizontal lines in depth	Ref. 5
Vertical-horizontal illusion (Fig. 2c)	Vertical line appears longer than horizontal one	Determined by retinal coordinates of lines	Ref. 1
Delboeuf and Ebbinghaus illusions (Figs. 2d, 2e)	Circles of equal size appear to be of different sizes		

5.107 Geometric Illusions: Contribution of Low-Spatial-Frequency Information

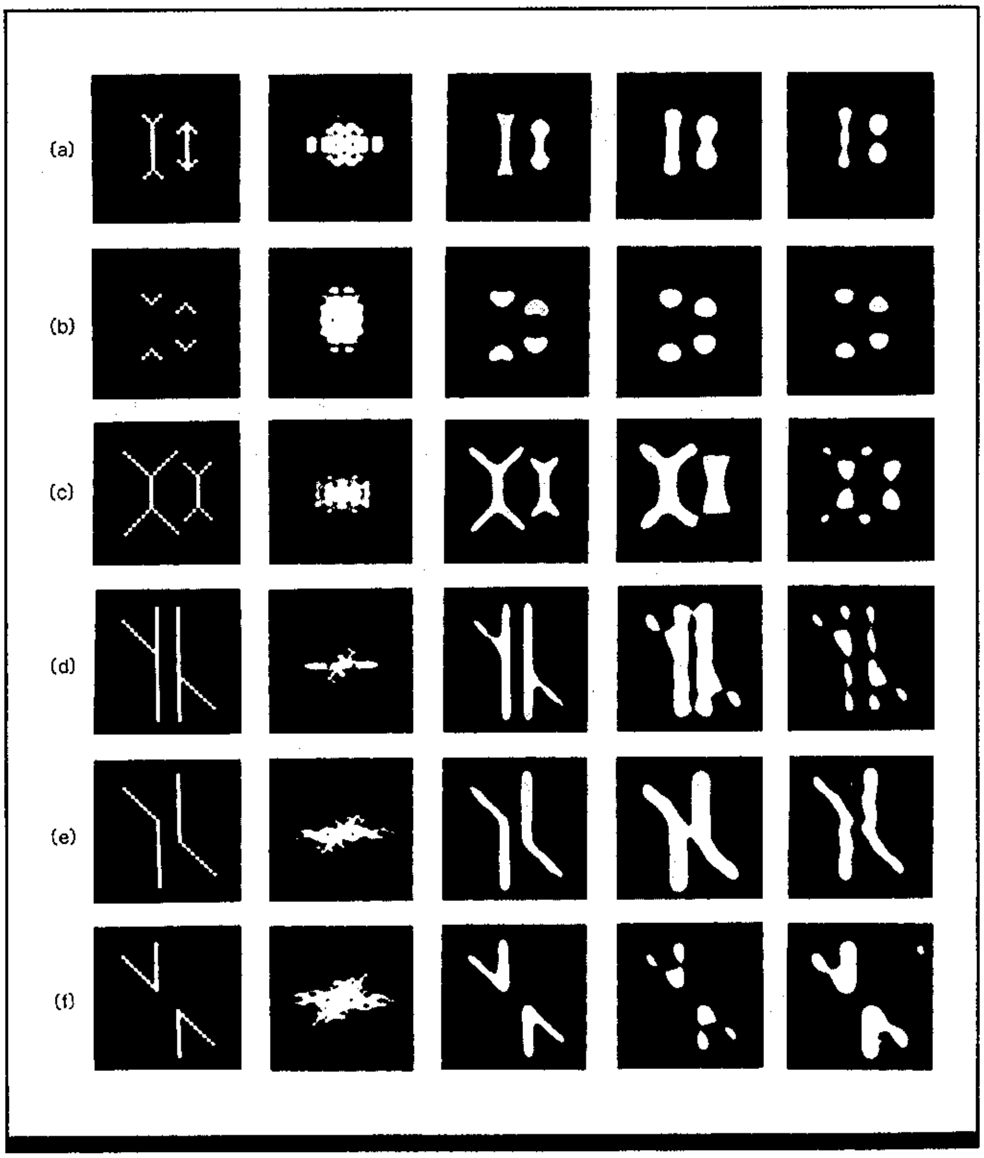

Figure 1. (a) Standard Müller-Lyer illusion; the shafts appear to be unequal, although their lengths are the same; (b) Müller-Lyer figure with fins only; (c) Müller-Lyer figure with fins of unequal size going in the same direction; (d) standard Poggendorff figure; although the two diagonal segments are co-linear, they appear to be displaced vertically; (e) Poggendorff variation with only obtuse angles; and (f) Poggendorff variation with only acute angles. The Fourier magnitude spectra of the original illusions in column 1 were filtered by a two-dimensional directional filter based on biological data (shown in column 2), producing the image shown in column 3; column 4 shows the filtered image created from just the lowest five spatial frequencies; column 5 shows the effect of using the overall biological filter before passing only the lowest five spatial frequencies. (From Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Form perception; Müller-Lyer illusion; Poggendorff illusion; spatial filtering; visual illusion

General Description

Images that have been filtered to remove all high **spatial frequencies** exhibit a number of interesting properties. These include preservation and accentuation of certain properties of the unfiltered image, such as Gestalt grouping properties (CRefs. 6.301, 6.312). Other properties that are merely illusory in the real image are revealed as actual properties of the filtered image. Figure 1 shows variants of two well-known geometrical illusions, the Müller-Lyer illusion and the Poggendorff illusion. Low-pass-filtered images of these illusions show physical distortions that resemble the perceptual distortions. This suggests that low spatial frequencies may play a role in these illusions.

Constraints

- Conclusions regarding the contribution of low spatial frequencies to visual illusions are based on limited observations.
- Other explanations for these illusions have been suggested, such as misapplied depth processing and contour displacement (Ref. 6).
- Many different factors, including experience and age, affect the perception of these illusions (Ref. 2).

Key References

1. Coren, S., & Girgus, J. S. (1978). *Seeing is deceiving: The psychology of visual illusions.* Hillsdale, NJ: Erlbaum.

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Cross References

5.106 Classic geometric illusions of size and direction;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.312 Form perception: contribution of different spatial-frequency bandwidths;

Handbook of perception and human performance, Ch. 34, Sect. 7.1

5.108 Illusions of Perceived Size and Distance

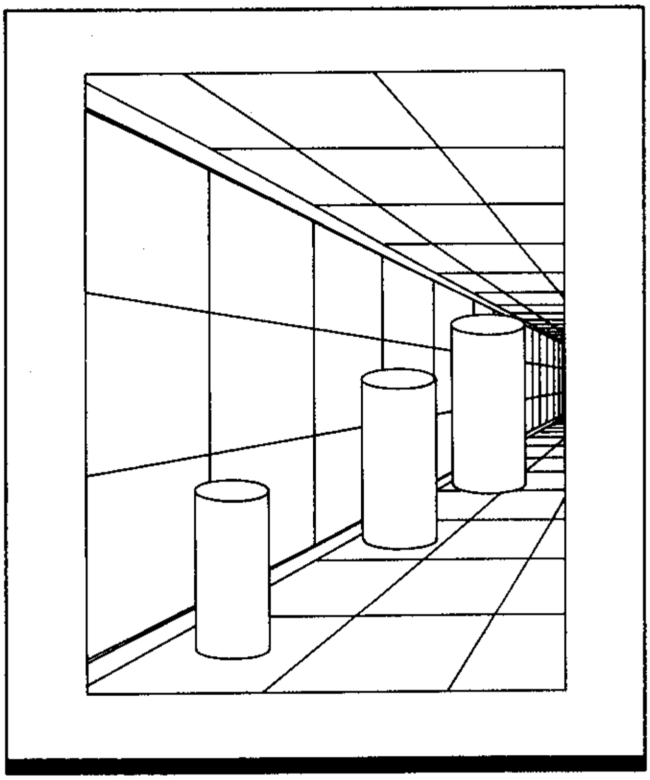

Figure 1. The corridor illusion. The three cylinders are equal in size on the surface of the page, but the leftmost cylinder appears to be the closest and smallest and the rightmost cylinder appears to be the most distant and largest. (From Ref. 1)

Key Terms

Corridor illusion; distance perception; horizon; linear perspective; Ponzo illusion; range estimation; size constancy; size perception; visual simulation

General Description

Linear perspective relations provide scales for judging the size of objects in an observer's visual field. One of the important scales is provided by the converging lines in a two-dimensional projection that represent parallel lines in three-dimensional space (CRef. 5.115). The degree of separation between a pair of converging lines serves to establish a scale factor for the size of any object placed within the convergence. For example, if the same-sized object is viewed from different distances on a runway, the size of the object relative to the convergence of the sides of the runway is constant. Even though, in a linear projection, the linear extent of the object is less at greater than at nearer distances, the linear extent of separation is also less at greater than at nearer distances.

The role of convergence in size perception is vividly illustrated in the *corridor illusion* shown in Fig. 1. Three cylinders are placed on a perspective drawing of a corridor, and the "nearer" cylinder appears much smaller than the "farther" cylinder. In fact, the three cylinders, as measured on the surface of the page, are identical in size.

The same phenomenon is seen in the *Ponzo illusion* illustrated in Fig. 2. The length of the upper horizontal line appears greater than the length of the lower horizontal line, even though the two lines are identical in length on the page.

Size is also indicated in linear perspective by relations involving the horizon of a surface. Illusions of size will be produced, however, if a visible terrestrial horizon is substituted for the actual horizon of a surface. As illustrated in Fig. 3, a line of sight from an observer to a true distant horizon runs parallel to the ground and therefore will transect an object in the same proportion at any distance along the line of sight. However, for most terrain, a line of sight to a terrestrial horizon does not lie parallel to the ground. This will produce an overestimation of size using the horizon ratio relation, with the overestimation increasing with increasing distance from the observer. If v is the true height and v' is the height specified by using the terrestrial horizon in the horizon-ratio relation, the ratio of v' to v will obey the relation

$$v'v = b/(b - d),$$

where b is the distance to the terrestrial horizon and d is the distance to the object.

There is evidence that size perception is directly influenced by changes in the height of a visible horizon.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

In visual simulation, the apparent size and/or distance of objects can be purposely or inadvertently modified through manipulation of linear perspective cues and visible horizons.

Key References

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Cross References

5.102 Perception of impact point for simulated aircraft carrier landings;

5.104 Visual angle as a determiner of perceived size and distance;

5.105 Visual perspective and the specification of shape and distance;

5.106 Classic geometric illusions of size and direction;

5.112 Relation between perceived and physical distance;

5.115 Representation of slant by linear perspective

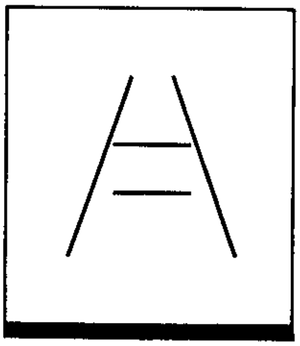

Figure 2. The Ponzo illusion. The two horizontal lines are equal in length, but the upper line appears to be longer than the lower one.

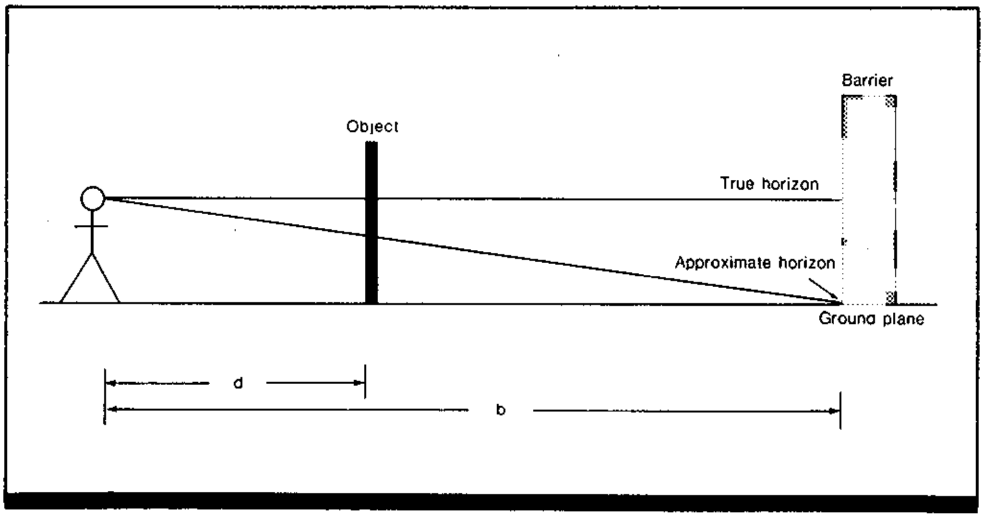

Figure 3. Size distortion produced by using a terrestrial horizon. The line of sight to a terrestrial horizon, unlike a line of sight to a true horizon, converges to the ground plane. Consequently, using the terrestrial horizon in the horizon-ratio relation will produce an overestimation of the size of an object, with the overestimation being greater the farther the object is from the observer. The amount of overestimation is equal to the ratio of the distance, *b*, from the observer to the terrestrial horizon over the distance, *b* − *d*, from the object to the terrestrial horizon. (From Ref. 2)

5.109 Judgment of Length Using Finger Span

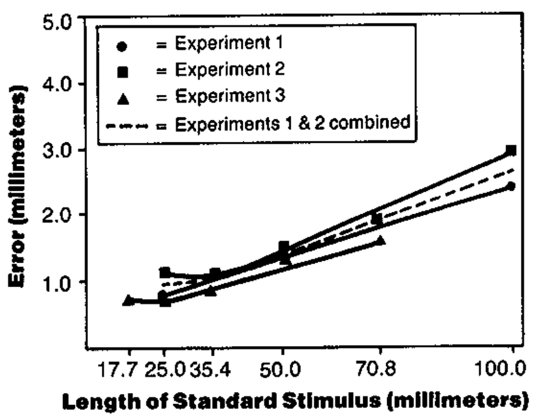

Figure 1. Error in judging length by finger-span as a function of the length of the judged object. (From Ref. 2)

Key Terms

Size estimation; size perception

General Description

A target cylinder held between the thumb and forefinger is judged to be longer than it actually is (overestimated) for lengths >25-35 mm. The magnitude of this error increases as the length of the target increases. For lengths <25-35 mm, error is a constant value.

Methods

Test Conditions

- Targets were standard 20-mm diameter aluminum cylinders with lengths varied across three experiments: 25, 50, and 100 mm for Exp. 1; previous lengths plus 35.4 and 70.8 mm for Exp. 2; 17.7, 25, 35.4, 50, and 70.8 mm for Exp. 3
- Adjustable cylinder simulated by two parallel 20-mm disks connected via rack-and-pinion mechanism
- Cylinder axes were horizontal and in subject's sagittal plane; proximal faces of cylinders 10 cm apart
- Cylinders hidden from view

Experimental Procedure

- Method of adjustment
- Independent variable: length of standard cylinder
- Dependent variable: estimation error (mm)
- Subject's task: estimate the length of a visually hidden cylinder spanned by thumb and forefinger by adjusting a similarly held, hidden, variable cylinder to a perceptually equal length
- 50 male undergraduates in Exp. 1, 50 in Exp. 2, and 20 in Exp. 3; 14 subjects in Exp. 3 had participated in either Exp. 1 or 2

Experimental Results

- Target length, as judged by spanning a target form between thumb and forefinger, is generally overestimated for lengths >25-35 mm. For shorter lengths, error is a constant value.
- The magnitude of error increases as the length of the target increases.

Variability

Error is shown in Fig. 1. Analysis of variance was used.

Repeatability/Comparison with Other Studies

Length judgments using other scanning methods are reported in Ref. 1.

Constraints

Performance in haptic (touch) perception of length varies with the scanning method used.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Appelle, S., Gravetter, F. J., & Davidson, P. W. (1980). Proportion judgments in haptic and visual form perception. *Canadian Journal of Psychology*, *34*, 161-174.

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Cross References

5.110 Haptic perception of length: effect of orientation;

5.111 Haptic perception of proportion

5.110 Haptic Perception of Length: Effect of Orientation

Key Terms

Haptic form perception; horizontal-vertical illusion; manual scanning; touch

General Description

When either a three-dimensional L or a three-dimensional inverted T is mounted in a horizontal plane and explored using touch and hand movements, the component part that evokes radial movement during exploration (movement along any radius intersecting the subject's body) is judged longer than the part of equal or slightly longer length evoking tangential movement (movement perpendicular to any radius). This illusion, sometimes called the horizontal-vertical illusion, is consistently larger for the inverted T than for the L. Rotating the forms into various orientations changes the radial and tangential components of movement and therefore the magnitude of the illusion (Fig. 1).

When the same stimuli are mounted in a vertical plane parallel to the front of the body, only the inverted T yields the illusion. The larger effect for the inverted T in the horizontal plane and the presence of an effect in the vertical plane are attributed to the vision of one line by another in the inverted T.

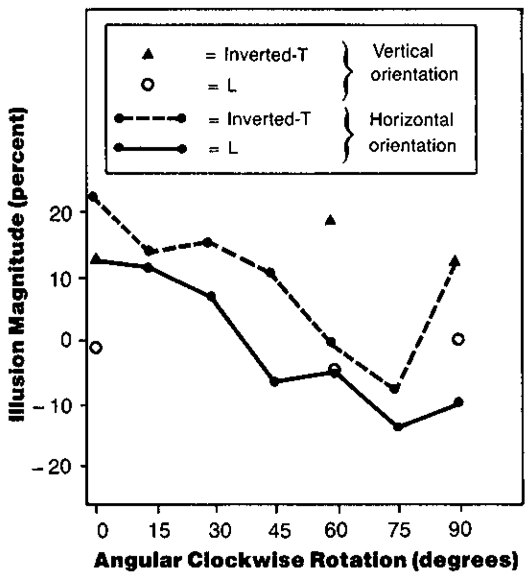

Figure 1. Magnitude of horizontal-vertical illusion for haptic forms as a function of the type and orientation of test figure. Illusion magnitude is measured as the percentage difference in length between the standard segment of an L-shaped or inverted-T test figure (base of L and cross-bar of T) and the length of the other segment when the two were judged equal in length. (Positive values indicate that the standard segment appeared longer.) (From Ref. 1)

Methods

Test Conditions

- L or inverted T form made of metal strips was mounted on a wood turntable lying flat on a table top in front of seated subject or standing up, facing the subject; board rotated from 0-90 deg; subject wore translucent goggles
- Stimulus (L or T) either lay flat in horizontal plane or was stood up in vertical plane facing or flush with the subject
- Metal strips protruded 6mm above the face of the wood turntable
- Lower link of L and dissected component of T were always 75 mm long; other link of each figure varied in length from 40-100 mm in 2.5 mm steps
- Subject was instructed to explore each target six times before reporting perception of the relative lengths of the two arms comprising each figure; exploration was restricted to use of the middle finger of the preferred hand

Experimental Procedure

- Method of limits (staircase procedure)
- Independent variables: form (L or inverted T), plane of rotation (horizontal or vertical), orientation (as measured by angular clockwise rotation from median plane of body)
- Dependent variable: illusion magnitude, as measured by percentage difference in length of component arms judged to be equal in length
- Subject's task: explore two arms of L or inverted T shape and indicate whether the comparison arm felt equal, longer, or shorter than the standard arm
- 12 male and 12 female subjects for the horizontal rotations; 4 male and 4 female subjects for the vertical rotations

Experimental Results

- For horizontally aligned forms, the component arm of an inverted T or an L form that evokes a greater component of radial movement during exploration feels longer than the component evoking tangential movement. Rotating an inverted T form into different orientations in the horizontal plane alters the radial and tangential components of movement, thereby changing the magnitude of the illusion.
- At all orientations, illusion magnitude is greater for an inverted T than for an L form.
- For vertically aligned forms, only the inverted T yields the illusion.

Variability

An analysis of variance was used to assess the effect of the independent variables and interactions.

Repeatability/Comparison with Other Studies

Similar results have been reported elsewhere (Ref. 2). With visual rather than haptic exploration, both figures yield the illusions in both planes.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.111 Haptic perception of proportion;

5.808 Haptic and visual perception of target orientation;

6.609 Haptic perception of curvature: effect of curve orientation and type of arm movement

5.111 Haptic Perception of Proportion

Key Terms

Haptic form perception; manual scanning; touch; visual form perception

General Description

When subjects use touch to judge the proportion (width-to-length ratio) of rectangles, they tend to adopt manual scanning strategies that involve use of the hand or fingers to directly measure the rectangles' sides. Interfering with subject's preferred method of exploration does not significantly affect judgment of proportion. In all cases, **haptic** judgment of proportion is considerably poorer than visual judgment, and judgment of 1:1 proportion is superior to all other proportions tested.

Applications

Designs or displays in which judgment of proportion in form is a consideration.

Methods

Test Conditions

- Stimuli were 4 mm-thick rectangles secured to a mounting board; four proportions of standard rectangles varied from 1:1-1:4; each standard rectangle was compared with nine other rectangles of different size and same or different proportions
- Subjects used their preferred hand to scan a standard rectangle for 30 sec and to scan a comparison rectangle for 30 sec; comparison pairs presented in random order
- Subjects blindfolded during three haptic scanning conditions: "no-measuring" condition prohibited any movements that used the hand or fingers as standard units of measure; "measuring" condition required subjects to use the hand or fingers as standard units of measure; "unrestricted" condition allowed subjects to use any scanning strategy they chose
- In the visual condition subjects sat at a table on which the stimuli were presented and viewed the standard and comparison successively

Experimental Procedure

- Independent variables: haptic or visual presentation, scanning method, proportions of standard rectangle
- Dependent variable: percentage correct same/different judgments
- Subject's task: explore a pair of rectangles in accordance with the scanning method instructions and judge whether pair appeared to have the same or different proportions (as defined by the rectangle's width-to-length ratio)
- Nine judgments per standard proportion
- 75 undergraduates, 15 in each haptic condition and 30 in the visual condition

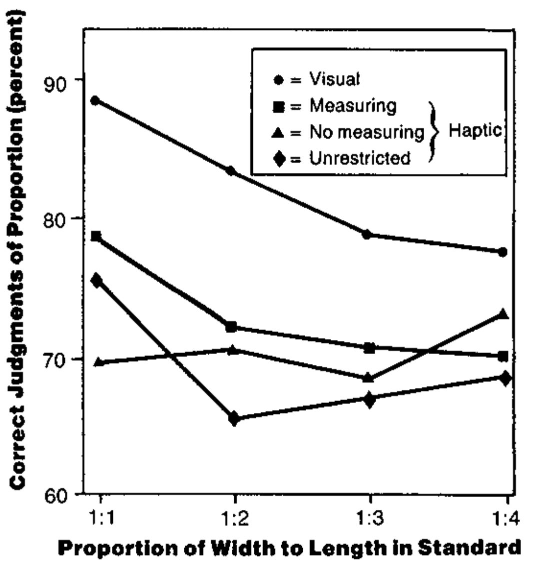

Figure 1. Accuracy in judging the proportions of rectangles by visual or manual (haptic) scanning. The percentage of trials on which the proportions (width-to-length ratio) of a test rectangle were correctly judged to be the same as or different from the proportions of a standard rectangle of different size is shown as a function of the proportions of the standard rectangle. (From Ref. 2)

Experimental Results

- There is no significant difference in the accuracy of haptic judgment of proportion when subjects use the fingers or hands as measurement units, when they are prohibited from using the fingers or hands in this way, or when manual scanning is unrestricted.
- When subjects are allowed to choose a haptic method of scanning for proportion judgments, the majority of subjects spontaneously adopt a scanning strategy that allows the use of fingers or hands as standard units of measure to judge the relative extent of the rectangle's component sides.
- Visual judgment of proportion is significantly better than haptic judgment, ($p < 0.01$) regardless of the type of manual scanning used.
- Discrimination accuracy for the 1:1 width-to-length proportion ratio was significantly better than the other three proportion ratios; this effect was significant for the visual condition, the measuring condition, and the unrestricted condition, but not for the no-measuring condition.
- Discrimination accuracy increases as the difference between standard and comparison proportions increases.
- Discrimination accuracy increases for all groups except the no-measuring condition as standard and comparison become more similar in size.

Variability

Analysis of variance was used to assess the effect of independent variables and interactions.

Repeatability/Comparison with Other Studies

The effects of other haptic scanning strategies on judgment of proportions are reported in Ref. 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Appelle, S., & Goodnow, J. L. (1970). Haptic and visual perception of proportion. *Journal of Experimental Psychology, 84*, 47-52.

*2. Appelle, S., Gravetter, F. J., & Davidson, P. W. (1980). Proportion judgments in haptic and visual form perception. *Canadian Journal of Psychology, 34*, 161-174.

Cross References

5.109 Judgment of length using finger span;

5.110 Haptic perception of length: effect of orientation;

5.808 Haptic and visual perception of target orientation

5.112 Relation Between Perceived and Physical Distance

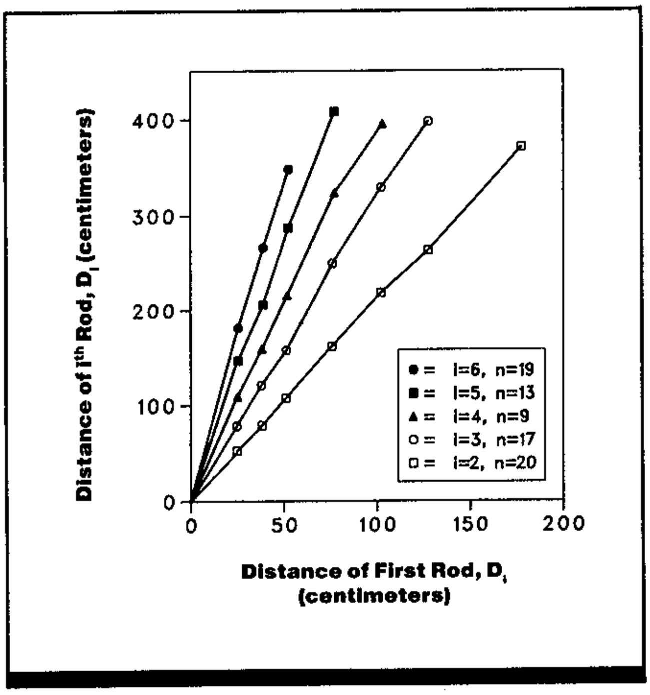

Figure 1. The five mean multiplication functions (i.e., the total distance to the further rod delimiting the *I*th interval for a given first standard interval on a six-interval scale) as a function of the length of the first interval. *I* indicates the interval (e.g., the second) and *n* indicates the number of subjects for a particular function. (From Ref. 2)

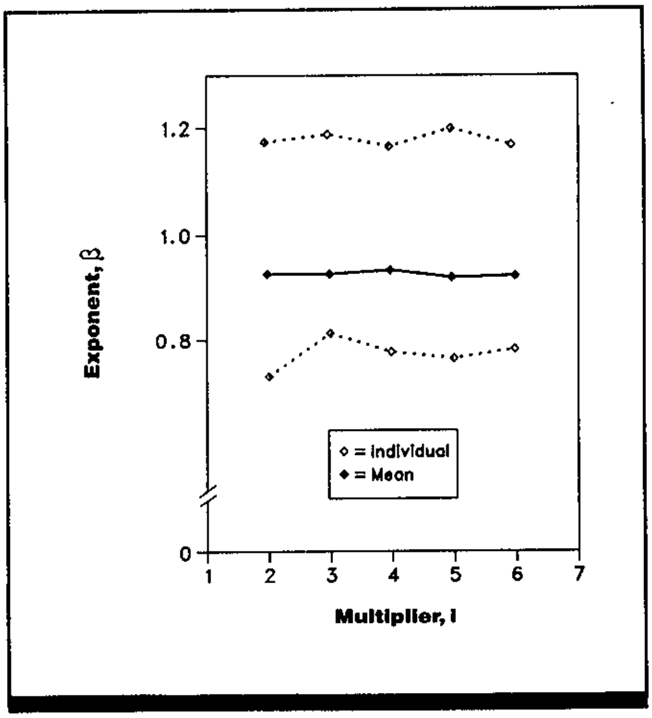

Figure 2. The value of the exponent for the power function relating perceived distance to actual distance (for the "average" observer and the two extreme observers) as a function of the *I*th interval for the multiplication functions in Fig. 1. The mean value is significantly less than 1.0. (From Ref. 2)

Key Terms

Distance cues; distance perception; perceptual constancy; range estimation; sighting accuracy; target acquisition; training; visual simulation

General Description

Under natural, unrestricted viewing conditions, the perception of distance is reliably accurate or, at least, consistent. The relation between perceived distance and physical distance, on the average, can be described by a power function with a constant exponent approximately 1.0, but there are significant differences across subjects and across studies.

Applications

Sighting aids can be designed to permit correction of characteristic over- or underestimation for individual observers. Adequate training can improve accuracy on relative (ratio) distance comparisons by observers.

Methods

Test Conditions

- Natural, unrestricted view of rectangular laboratory table top (horizontal plane) with maximum range of 540 cm, 150 cm wide; table top covered by grid with pattern visible in near half, but not in further half, from observer
- Target markers were 1-cm rods, varying randomly in length from 88-113 cm, placed laterally across viewing surface
- Two to six marker rods; first rod placed 25-175 cm from near table edge by experimenter to establish standard depth step; other rods successively positioned at apparently equal depth steps from first rod

Experimental Procedure

- Method of limits, two-alternative forced-choice procedure
- Independent variable: physical distance of first marker rod from table edge
- Dependent variable: distance at which last (*i*th) rod in a series had to be placed for all rods to appear at equal depth steps from near table edge
- Observer's task: instruct experimenter in adjusting successive marker rods to lie at equal depth intervals from the table edge by judging whether last interval was less than or greater than previous intervals
- 11 male and 9 female observers

Experimental Results

- The data points for the five mean multiplication functions shown in Fig. 1 are the total distances to the further rods delimiting the *i*th intervals (as set by the observer) for any given standard (first) interval (e.g., $i = 2$ indicates the second interval). All of the multiplication functions are linear.
- Median distance scales for the entire display plane can be constructed from the multiplication functions because the values of the exponent relating scale values (perceived distance) to actual distance are constant across the multiplication functions within subject (Fig. 2).
- There are large individual differences in the values of the exponents (Fig. 2).
- Consistency of observers' errors suggests that individual tendency toward over-constancy (overestimation of physical distances) or under-constancy (underestimation) may result from the effort to compensate for inner sense of error tendency.

Variability

Power exponent characterizing accuracy varies substantially among individual observers, ranging from .07-1.2 (Fig. 2; see also Refs. 4, 10).

Repeatability/Comparison with Other Studies

Reference 6 found similar results using a fractionation task.

Constraints

- With indoor observation, the exponent characterizing accuracy is generally >1.0 (Ref. 9); with outdoor observation, the exponent is generally <1.0 (Ref. 10).
- Exponents for airborne observation vary with angle of elevation. At vertical elevation, exponent is ~ 1.0; at low flight level ($\sim$ horizontal), exponent is ~ 1.27 (Ref 4).
- Mean errors are greater when distance judgments are made in artificial units (metrical rod length) than when they are made in natural units (arm length) (Ref. 8).
- Corrected practice, with numerous feedback trials, improves performance in naturalistic settings (Ref. 5). Practice effects are limited to short term for relative judgments with fractionation method (Ref. 11).

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Cross References

5.101 Binocular versus monocular aircraft landing performance;

5.102 Perception of impact point for simulated aircraft carrier landings;

5.103 Pilot judgments of distance, height, and glideslope angle from computer-generated landing scenes;

5.104 Visual angle as a determiner of perceived size and distance;

5.105 Visual perspective and the specification of shape and distance;

5.108 Illusions of perceived size and distance;

Handbook of perception and human performance, Ch. 21, Sect. 2.2

5.113 Perception of the Objective Shape of Slanted Surfaces

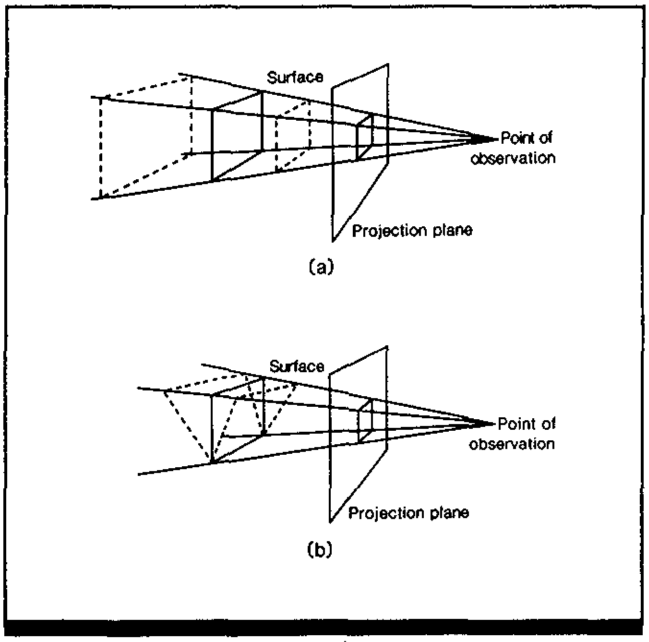

Figure 1. Illustration of the ambiguity in identifying a surface from its projection. (a) Surfaces of the same shape and orientation to the observer but of different sizes and placed at different distances all produce the same projection. (b) Surfaces of different shapes placed at a single distance from the observer but varied in size and orientation produce identical projections. (From *Handbook of perception and human performance*)

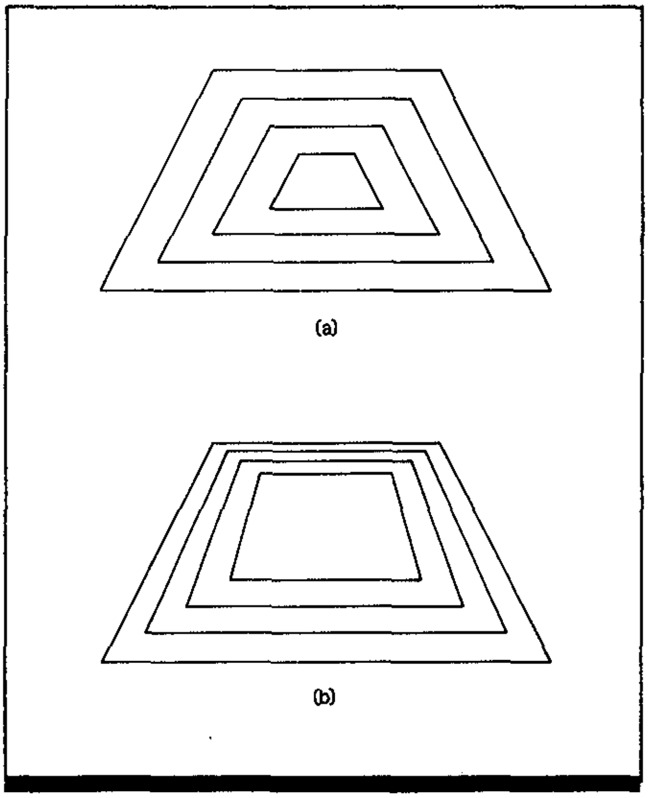

Figure 2. Illustration of the importance of size in the geometrical shape-slant relation. (a) Nested family of trapezoids having the same shape but different sizes. As projections of rectangles, these trapezoids specify rectangles at different slants. (b) Nested family of trapezoids having different shapes and different sizes. As projections of rectangles, these trapezoids specify a family having the same slant with respect to the observer. Unless both shape and size are specified, the slant of the object from which a projection is derived can vary. (From *Handbook of perception and human performance*)

Key Terms

Linear perspective; recognition; shape constancy; shape/slant relation; trapezoidal window illusion; visual simulation

General Description

The shape of any plane surface that is not perpendicular to the line of sight will be distorted, according to the rules of projective geometry, relative to when it is displayed on a plane perpendicular to the line of sight. The projection of any surface is not unique to that surface, however, and an important question is how to recover the objective shape of a surface from information in the projection.

For example, the same projection is produced by any one of an infinite family of surfaces having the same shape and orientation with respect to the line of regard but varying in size and distance (Fig. 1a). In addition, the same projection is produced by any one of an infinite family of surfaces having the same distance from the observer but varying in shape and orientation (Fig. 1b).

One way to recover shape from the information in a projection is to exploit the interdependencies among projective shape, size of the projection, and slant of the surface from which the projection is derived. Fixing any two of these terms uniquely specifies the third, an interdependency known as the *geometrical shape-slant relation*. Figures 2a illustrates the importance of specifying the size as well as the shape from which a projection is derived. Viewed as projections of rectangles, the nested trapezoids all having the same projective shape, define rectangles at different slants because of their difference in size. Conversely, the

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

size variation in the nested trapezoids (Fig. 2b) defines rectangles at the same slant, despite their difference in projective shape.

The perceived shape of an object's surface, seen under normal viewing conditions, is not substantially altered by the slant at which the surface is viewed. This is an example of *shape constancy*, which suggests that an observer interprets a visual display as representing a specified object oriented at a specified slant. This shape-slant linkage is supported by a moderate correlation between perceived slant and perceived shape.

That people interpret trapezoids as slanted rectangles is dramatically shown by the *trapezoidal window illusion*, in which a trapezoid that is physically rotating through 360 deg is perceived as a rectangle oscillating back and forth through an angle of ~100 deg. Under appropriate test conditions, human observers accurately match trapezoidal shapes with the slant implied by interpreting the trapezoids as rectangles, although there is a small constant error of underestimation.

Applications

Design of visual simulations. Also, shape constancy is theoretically important for the successful design of intelligent artificial vision systems.

Methods

Test Conditions

Study 1 (Ref. 4)

- Rectangular white boxes (125 × 125 × 250 mm or 125 × 125 × 500 mm) edged with 3-mm black lines, or photographic slides of the same boxes; each box (Fig. 3a) supported a cross, with one red arm and one green arm
- Boxes presented at slants of 40, 60, or 80 deg under uniform illumination against a black background that eliminated shading and texture cues
- Eleven vertical-to-horizontal length ratios for arms of cross: 4:1, 3:1, 2:1, 1.75:1, 1.5:1, 1.25:1, 1:1, 1:1.25, 1:1.5, 1:1.75, 1:2
- Binocular viewing; viewing distance 1.5 m; cross center 110 cm above floor; 15 x 10-cm viewing window
- Unlimited exposure time

Study 2 (Ref. 2)

- Shape response apparatus, slant response apparatus, and standard stimulus placed 30 deg apart along a 105-cm radius within an enclosed 81.2 × 130.8 × 76.2-cm box
- Three trapezoidal standards, designed to subtend equal visual angles when slanted at 15, 45, or 65 deg from frontal plane; height 5 deg, top 8 deg, base 10 deg
- Luminance of standard varied with slant: 15 deg stimulus—41 cd/m^2 (12 fL), 45 deg stimulus 30 cd/m^2 (8.5 fL), 60 deg stimulus—22 cd/m^2 (6.5 fL)
- Viewing distance 105 cm
- Unlimited exposure time; monocular or binocular viewing

Study 3 (Ref. 3)

- Two-channel viewing apparatus; monocular view of nonreflected field (Field 1), binocular view of reflected field (Field 2)
- 20 trapezoidal stimuli, varying in height/width ratio (9:15, 1:1, 15:9) and implied slant (50, 60, 70, or 80 deg), viewed in Field 1
- Adjustable response rod, 6.35.-mm diameter, indefinite extent to observer, rotated in horizontal plane at eye level about vertical axis, viewed in Field 2

Experimental Procedure

Study 1

- Method of constant stimuli
- Independent variables: age, box size, order of three- and two-dimensional views (between observers); box slant, cross-arm-length ratio, three- and two-dimensional views, color of cross arms (within observers)
- Dependent variable: frequency of report that vertical cross arm was longer
- Observer's task: report which cross arm appeared longer
- 16 psychology students; 16 five-yr-old children

Study 2

- Method of adjustment
- Independent variables: slant of standard, monocular or binocular view, order of viewing
- Dependent variables: slant response, height to base of shape, top to base of shape
- Observer's task: set both the slant and the shape apparatus to match the slant and shape of the standard
- 30 psychology students

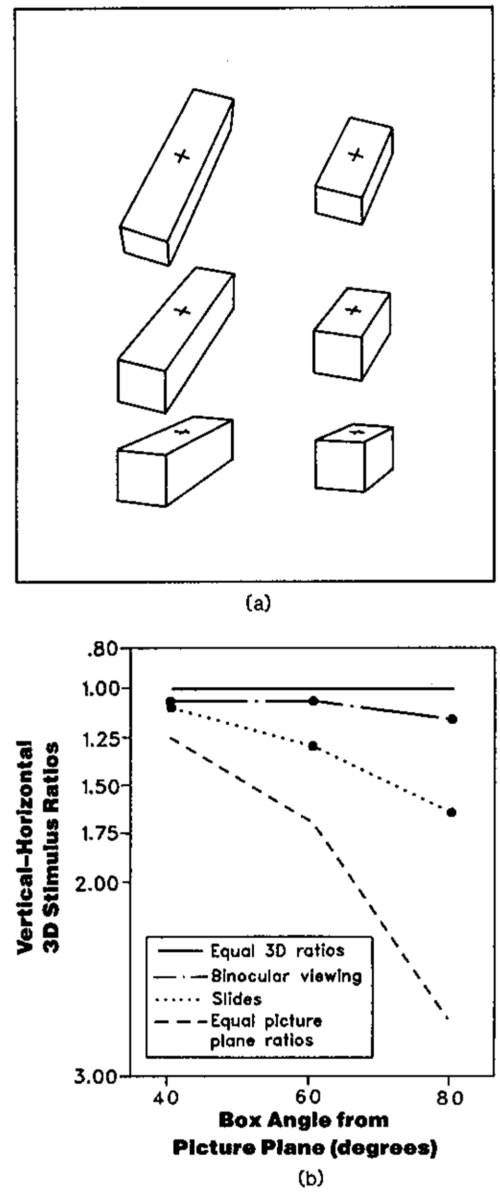

Figure 3. (a) Crosses placed on the top surface of the rectangular boxes have different projections as the boxes are observed at angles of 40, 60, or 80 degrees from the picture plane. (b) Observer's judgments of the ratio of the lengths of the two arms of the cross are close to 1.0 when the boxes are viewed binocularly (Study 1). When observers viewed photographic slides of the boxes, their judgments were intermediate between the objectively equal ratio and the projective (picture plane) ratios. (From Ref. 4)

Study 3

- Independent variables: linear perspective (implied slant), height/width ratio, static versus rotating stimuli, viewing eye, plane of apparent slant
- Dependent variable: slant setting of response rod
- Observer's task: set the slant of the response rod to match the slant of a rectangle implied by a static trapezoid or to match the apparent plane of reversal of an oscillating rectangle implied by a rotating trapezoid
- 8 naive observers

Experimental Results

Study 1

- Adults showed nearly vertical shape constancy under three-dimensional viewing conditions; under two-dimensional viewing, adult judgments deviated toward equal picture plane ratios (Fig. 3b), falling about midway between objective and projective equality.

Study 2

- Under monocular viewing, judged slant was positively correlated with judged shape, with correlations of 0.664 with top to base (t/b) and 0.616 with height to base (h/b).

Study 3

- Settings of perceived slant were closely tied to the slant implied by rules of projective geometry.
- Perceived depth varied with implied linear perspective, but not with angles of convergence of trapezoids.
- Perceived depth varied inversely with height-width ratio.

Variability

In Study 1, analysis of variance was used to check significance of results. In Study 2, judged slant with monocular viewing showed considerable variability between subjects, with ranges up to 64 deg in different groups; judged shape also showed a few extreme deviations from group means. In Study 3, one additional subject who was unable to see certain rotating trapezoids as oscillating was dropped from study. Pooled estimate of standard error of the mean was between 1 and 2 deg.

Repeatability/Comparison with Other Studies

Results are generally in agreement with other research, although present data are somewhat less "noisy." The accuracy of slant settings in Ref. 3 is higher than that found in other studies, which probably reflects both the greater range of implied slants used and the greater care taken to make the dependent measure a compatible response in this study.

Constraints

- Accuracy of monocular shape perception of unfamiliar slanted objects will generally be greater when objects are presented in a naturalistic setting than when they are presented in isolation.
- Judgments under monocular viewing are strongly influenced by instructions and subject's attitude.
- Relative importance of linear perspective, as compared to angle of convergence, may depend on retinal size of object.
- Accuracy of slant judgments can be strongly diminished if observers attempt to attend to retinal projection, rather than interpret stimuli as three-dimensional.

Key References

1. Gibson, J. J. (1950). *The perception of the visual world.* Boston: Houghton Mifflin.

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Cross References

5.105 Visual perspective and the specification of shape and distance;

5.115 Representation of slant by linear perspective;

5.116 Texture gradients and perceived slant;

5.222 Perception of rigid versus nonrigid motion;

6.309 Perceived shape: effect of target orientation;

6.311 Perception of shape distortion;

Handbook of perception and human performance, Ch. 21, Sect. 2.3

Notes

5.114 Optical and Geographical Slant

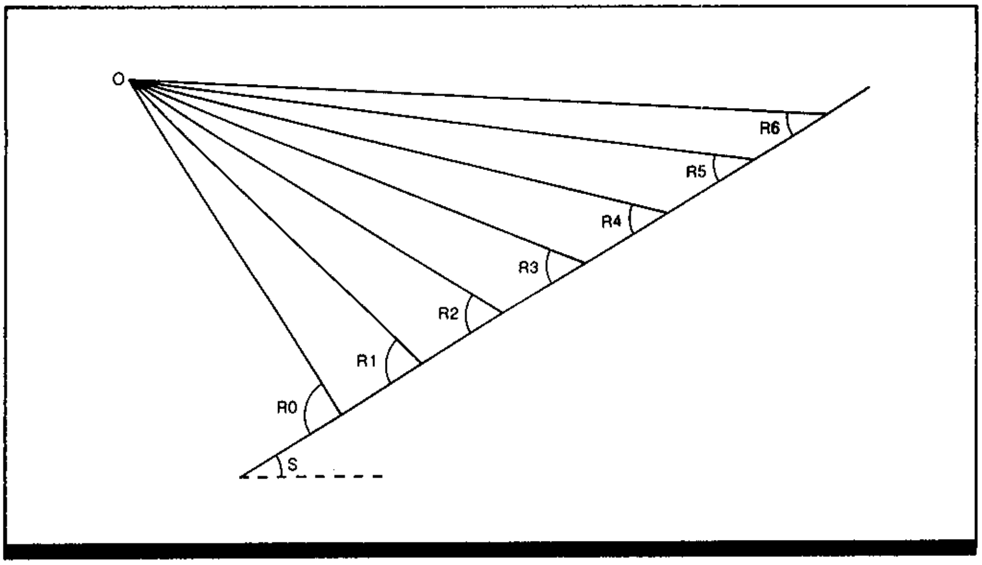

Figure 1. Illustration of the way optical slant changes as the line of sight is swept along a plane surface. An observer at O scans a surface placed at an angle *S* from the ground; as the line of sight moves along the surface, the optical slant shows continuous variation from *R*0 to *R*6. (From Ref. 4)

Key Terms

Geographical slant; optical slant; range estimation; shape constancy; shape-slant relation; target acquisition

General Description

The *geographical slant* of a surface is defined as the slant of the surface relative to some reference orientation. For example, in a rectangular room, the geographical slant of a wall is 90 deg, relative to the ground. Geographical slant for plane surfaces, such as a wall, is constant for the entire extent of the surface.

The *optical slant* of a location on a surface is defined as the slant of the surface at that location relative to the line of sight. For an observer scanning a stationary plane surface from a fixed vantage point, optical slant will vary continuously along the surface. This point is illustrated in Fig. 1, which shows the changing angle between the line of sight and a surface as the line of sight is swept along the surface.

There is a simple relationship between the optical slant of a location on a surface and the geographical slant of the surface for cases in which the observer can use a reference orientation such as horizontal. The relation is

$$S = R - U,$$

where S is the angle between the surface and the reference orientation, R is the optical slant of a location on the surface, and U is the angle between that location and the reference orientation. This relation is illustrated in Fig. 2, which shows that S is equal to the visual angle between the horizon of the surface and the horizon of the reference orientation, and R is equal to the angle between a line of sight to a location on the surface and the horizon of the surface.

Note that this relation implies that the optical slant of a location equals geographical slant only when that location lies on the horizon of the reference plane ($U = 0°$). If the ground plane is the reference plane, this condition occurs when the location is at eye level.

Applications

Field personnel may become better able to judge the optical and geographical slants of surfaces if they are aware of the distinction and are trained to use the relation between optical and geographical slant.

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Constraints

- Most experimental situations have confounded optical and geographical slant, although this is not necessary. Thus, little information is available comparing performance on these two types of judgments.

Key References

1. Gibson, J., & Cornsweet, J. (1952). The perceived slant of visual surfaces: Optical and geographical. *Journal of Experimental Psychology, 44*, 11-15.

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Cross References

5.113 Perception of the objective shape of slanted surfaces;

5.115 Representation of slant by linear perspective;

5.116 Texture gradients and perceived slant

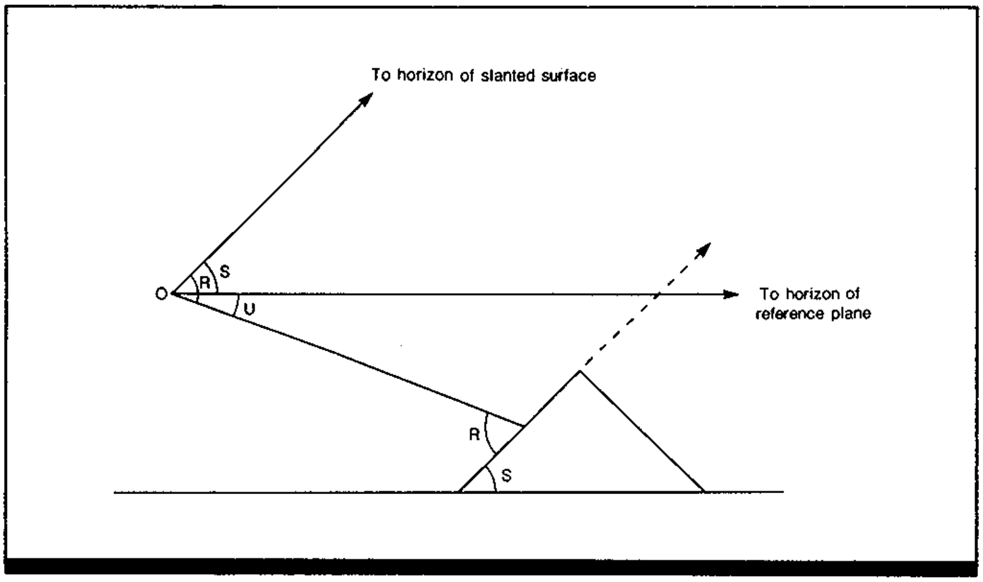

Figure 2. Relation between optical slant and geographical slant. An observer at 0 looks at a surface placed with a geographical slant *S* on a reference plane. The optical slant of one location on the surface is *R*, which is also the angle between the line of sight to the surface and the horizon of the surface. The geographical slant *S* is therefore equal to the optical slant *R* minus the angle *U* between the location on the surface and the horizon for the reference ground plane. (From Ref. 3)

5.115 Representation of Slant by Linear Perspective

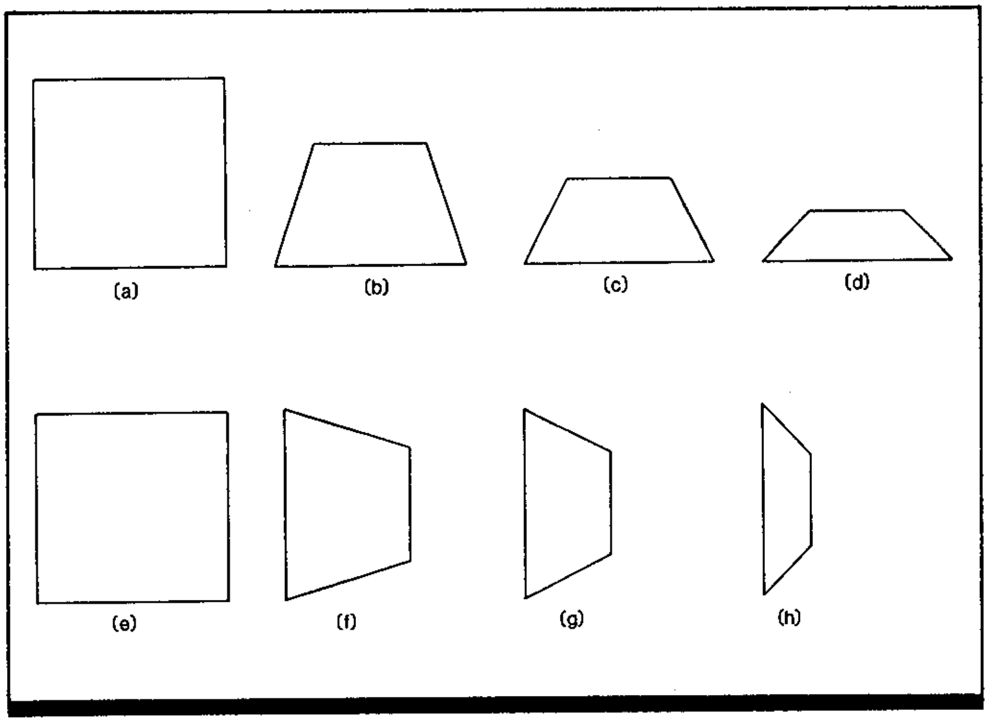

Figure 1. Linear perspective relations illustrated for an outline square as it is slanted away from the observer along a horizontal axis (top row, *a* to *d*) and along a vertical axis (bottom row, e to *h*). (From *Handbook of perception and human performance*)

Key Terms

Convergence; depth perception; linear perspective; shape constancy; texture gradient; vanishing point; visual simulation

General Description

In the study of space perception, *linear perspective* refers to the relations within the visual field that are associated with the representation of three-dimensional space on a two-dimensional projection. Many of these relations are explicitly identified in the complex set of rules developed by artists to create representational drawings and paintings.

Convergence. One of the most important relations of linear perspective is the *convergence of parallel lines*. With the single exception of parallel lines in a plane perpendicular to the line of regard, the two-dimensional projection of lines that are parallel in three dimensions (e. g., the sides of a road or the edges of a slanted rectangle) will converge, rather than appear parallel. Figure 1 illustrates this convergence for the sides of a square as it is tilted away from an observer along a horizontal axis (top row) or along a vertical axis (bottom row). Increasing degrees of convergence are associated with increasing amounts of slant, and human observers can judge fairly accurately the amount of slant implied by the trapezoidal shapes in Fig. 1.

The relation between degree of convergence and amount of slant is illustrated in Fig. 2 for sets of parallel lines which eliminate other cues for depth present in rectangular outlines (angular change and compression, which are discussed in the following section). The set of lines on the left (Fig. 2a) shows less convergence than the set of lines on the right (Fig. 2b). Correspondingly, the implied slant is less in the left lines than in the right lines.

Angular change and compression. The projections in Fig. 1 contain two additional relations associated with depth perception, namely *angular configuration* and compression or foreshortening.

Angular configuration refers to the fact that right angles on a surface slanted away from an observer are projected as acute angles.

Compression or foreshortening refers to the fact that the projection of a surface slanted away from an observer is compressed in the direction of the slant. Figure 3 illustrates the effect of compression alone (with convergence effects removed) on the projection of a square slanted around a horizontal axis (top row) and around a vertical axis (bottom row). Figure 4 illustrates how compression applies to lines lying parallel on a surface as the surface is tilted away from an observer along a horizontal (top row) or vertical (bottom row) axis.

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Vanishing points and horizons. Linear perspective relations define an implicit structure of the visual field that is useful for analyzing the information about space available in the visual field. Two key concepts of this structure are *vanishing points* and *horizons*, which specify the orientation of edges and surfaces, respectively. A *vanishing point* is the point of convergence for the projections of parallel lines. That is, the vanishing point for the lines in Fig. 2 is the point at which the lines, if extended indefinitely, would converge. A *horizon* is the line defined by the vanishing points of all the sets of parallel lines on a surface.

Vanishing points specify the orientation of edges, because all edges with the same orientation on a three-dimensional surface have the same vanishing point.

Moreover, the specification of an edge's orientation by its vanishing point is simple: *the orientation of an edge is equal to the orientation of the line of regard to the vanishing point of the edge*. The observers' line of regard is a member of the family of parallel lines that converge on the vanishing point.

Horizons specify the orientations of surfaces because all surfaces with the orientation in a three-dimensional space have the same horizon. The specification of a surface's orientation by its horizon is similar to that for edges: *the orientation of a surface is equal to the orientation of the plane containing the line of regard of the observer and the horizon of the surface*. The plane containing the observer's line of regard is a member of the family of planes that share the same horizon.

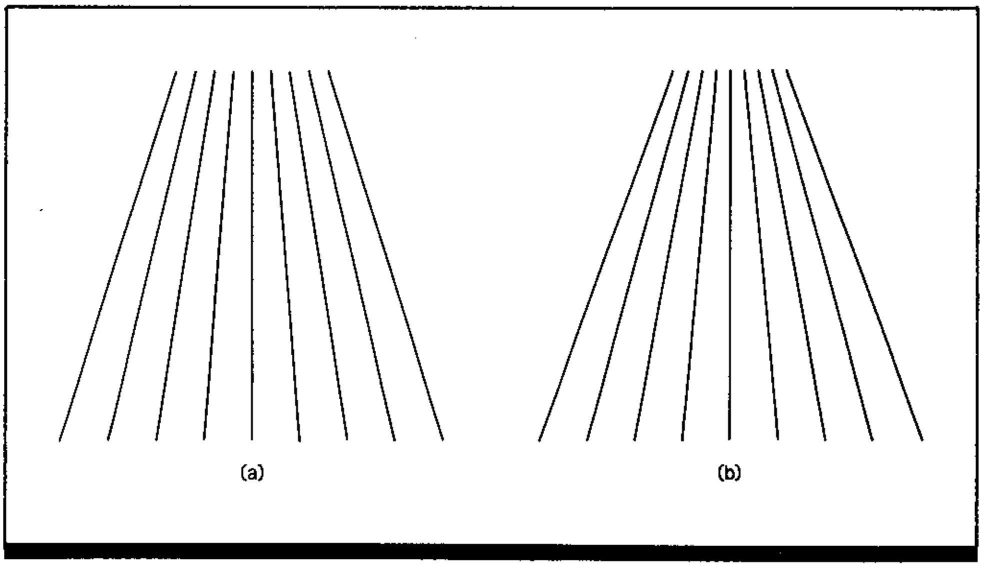

Figure 2. The projection of parallel lines on a plane is a set of converging lines, with the degree of convergence directly related to the degree of slant. The lines of the left show less convergence and therefore less slant away from the observer than the lines on the right. (From *Handbook of perception and human performance*)

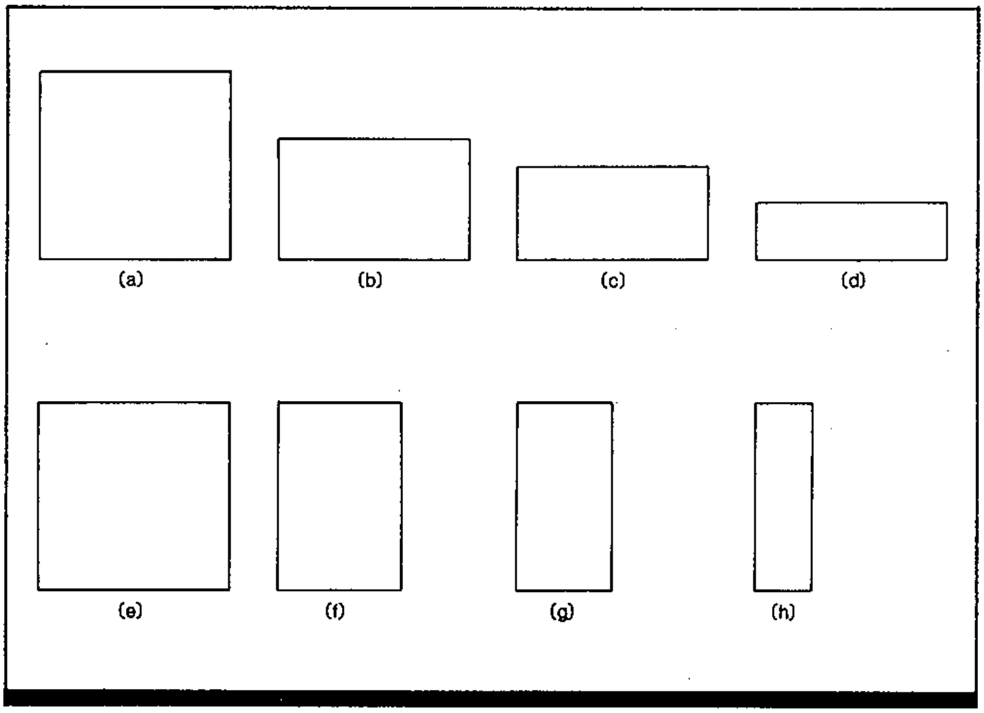

Figure 3. Compression in the projection of an outline square as it is slanted away from an observer along a horizontal axis (top row, *a* to *d*) and along a vertical axis (bottom row, *e* to *h*). The square is shown in parallel projection (i.e., as seen from a very great distance) to eliminate the convergence produced by linear perspection. (From *Handbook of perception and human performance*)

Applications

Two-dimensional representations such as in visual real-world simulations of three-dimensional spaces must use rules that embody the relations of linear perspective. Also, it is possible that observers may use, or may be trained to use, these relations in judging the three-dimensional orientations of surfaces and edges.

Key References

*1. Sedgwick, H. A. (1980). The geometry of spatial layout in pictorial representations. In M. A. Hagen (Ed.), *The perception of pictures* (Vol. 1.). New York: Academic Press.

Cross References

5.105 Visual perspective and the specification of shape and distance;

5.113 Perception of the objective shape of slanted surfaces;

5.114 Optical and geographical slant;

5.116 Texture gradients and perceived slant;

5.901 Monocular distance cues;

Handbook of perception and human performance, Ch. 21, Sect. 3.2

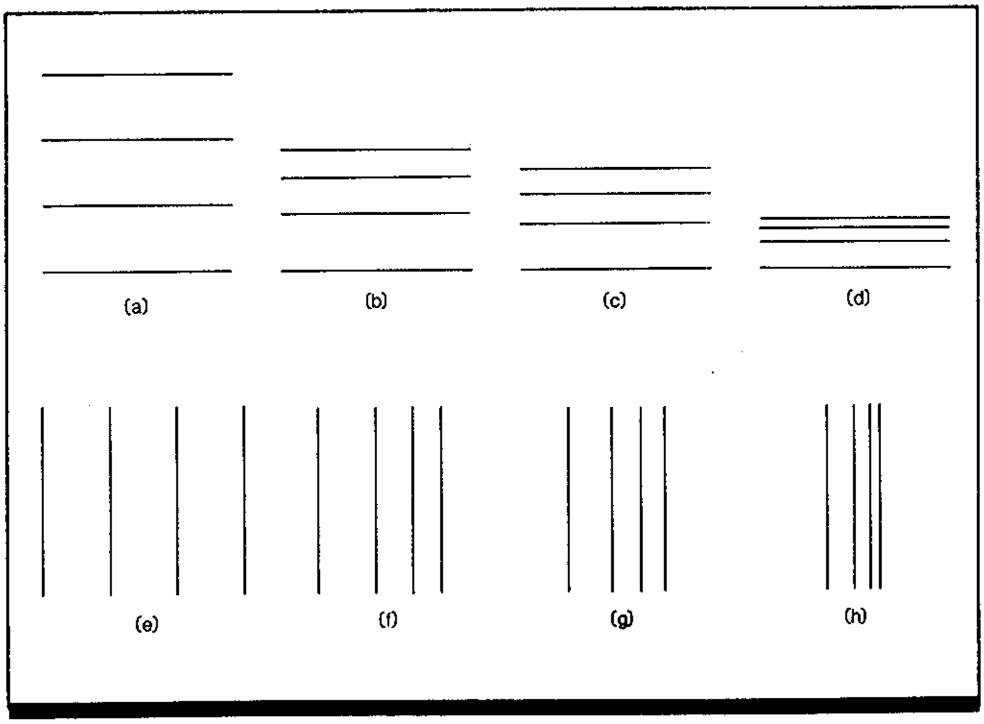

Figure 4. Compression is a set of evenly spaced parallel lines on a surface as the surface is slanted away from an observer along a horizontal axis (top row, *a* to *d*) and along a vertical axis (bottom row, *e* to *h*). The lines are shown in parallel projection (as if seen from a very great distance) to eliminate the convergence produced by linear perspective. (From *Handbook of perception and human performance*)

Notes

5.116 Texture Gradients and Perceived Slant

Key Terms

Depth perception; linear perspective; monocular depth cues; range estimation; texture gradient; visual simulation

General Description

The two-dimensional projection of a homogeneously textured surface is a *texture gradient*, in which the projected density and size of the texture elements of the surface change in a continuous, graded manner. Elements in the foreground will be relatively large and widely spaced; elements in the background will be smaller and more densely packed. Human observers perceive texture gradients as being slanted in depth (Fig. 1), although perceived slant underestimates objective slant. Size and spacing of the texture elements is an important determinant of the angle of perceived slant. With a constant spacing of elements, perceived slant increases as element size increases up to the point at which elements are nearly touching; at this point perceived slant decreases (Fig. 2).

Applications

Visual simulations in which texture gradients may be used alone to establish a two-dimensional representation of depth.

Methods

Test Conditions

Study 1 (Ref. 2)

- Projection screen viewed through circular aperture of 24 deg; slant board adjustable without visual guidance
- Slides of a regular and an irregular texture presented at angles of 10, 22, 30, or 45 deg away from observer
- **Monocular** viewing
- Unlimited viewing time

Study 2 (Ref. 1)

- Two surfaces, 80 cm from observer, visible through circular apertures; texture gradient of ellipses visible through lefthand aperture; 10 x 10 cm chessboard pattern visible through righthand aperture
- Retinal area of target gradient varied from 6.4-12.4 deg; area of chessboard aperture fixed at 10.4 deg
- Element density varied from 6-34 mm; element size varied from 0.6-5.0 mm
- Target placed at inclination of 43 deg away from observer for data trials; inclinations of 13, 23, 33, or 53 deg included as fillers
- Monocular view of gradient and binocular view of chessboard; darkened room; unlimited viewing
- Slant of each surface independently adjustable

Experimental Procedure

Study 1

- Method of adjustment for slant board setting; within-subject design with alternation of regular and irregular textures and upward or downward direction of slant
- Independent variables: regularity of texture, angle of gradient, direction of slant
- Dependent variable: setting of slant board
- Observer's task: adjust slant board to reproduce the slant perceived in the texture gradient
- 10 observers

Study 2

- Method of adjustment for slant setting; within-subjects design; random order of slants
- Independent variables: retinal area, texture element density, texture element size, target slant
- Dependent variable: slant setting of chessboard to match a 43-deg slant of texture gradient
- Observer's task: adjust the slant of the chessboard to match the apparent slant of the texture gradient
- 8-12 psychology students in each of three experiments

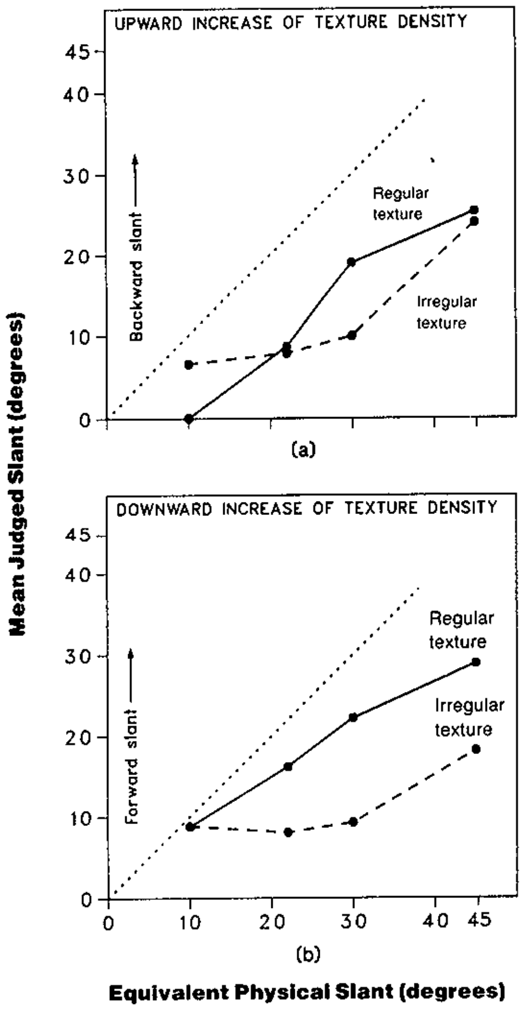

Figure 1. Mean slant judgments for texture densities as a function of the actual physical slant of the surface for regular (solid lines) and irregular (dashed lines) textures (Study 1). Dotted line indicates accurate judgment of slant. (a) a "ground" gradient, with foreground at the bottom of the gradient; (b) a "sky" gradient, with foreground at top of gradient. (From Ref. 2)

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Experimental Results

- Judged slant was less than actual slant, but regular texture was judged closer to actual slant than was irregular texture (Fig. 1).
- Perceived slant of texture gradient interacts with variations in retinal area, element size, and element density.
- Perceived slant increases with increasing element size until elements are close together, than perceived slant decreased. (Fig. 2).
- Perceived slant increases with increasing retinal size for spaced elements, but decreases for closely packed elements.

Variability

Study 1 found substantial individual differences in accuracy of slant judgments. No information on variability was given for Study 2.

Repeatability/Comparison with Other Studies

Other studies have reported that perceived slants are underestimates of true slants. The nonmonotonic function relating perceived slant to element size has been replicated in Ref. 3.

Constraints

- Relative importance of texture gradient elements under monocular viewing of small fields may not apply to binocular viewing of large fields.
- It is difficult to separate texture-gradient cues from linear perspective relations.

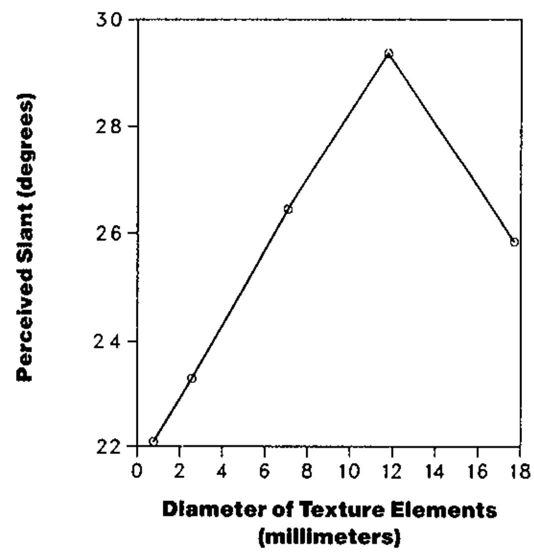

Figure 2. Mean slant judgments as a function of texture element size (Study 2). Texture gradient was at 43-deg slant (foreground at bottom of gradient) and viewed through an 11.4-deg aperture, with 20-mm separation between texture elements. (From Ref. 1)

Key References

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*2. Gibson, J. J. (1950). The perception of visual surfaces. *American Journal of Psychology, 63*, 367-384.

3. Gruber, H. E., & Clark, W. C. (1956). Perception of slanted surfaces. *Perceptual and Motor Skills, 6*, 97-106.

Cross References

5.105 Visual perspective and the specification of shape and distance;

5.108 Illusions of perceived size and distance;

5.112 Relation between perceived and physical distance;

5.113 Perception of the objective shape of slanted surfaces;

5.114 Optical and geographical slant;

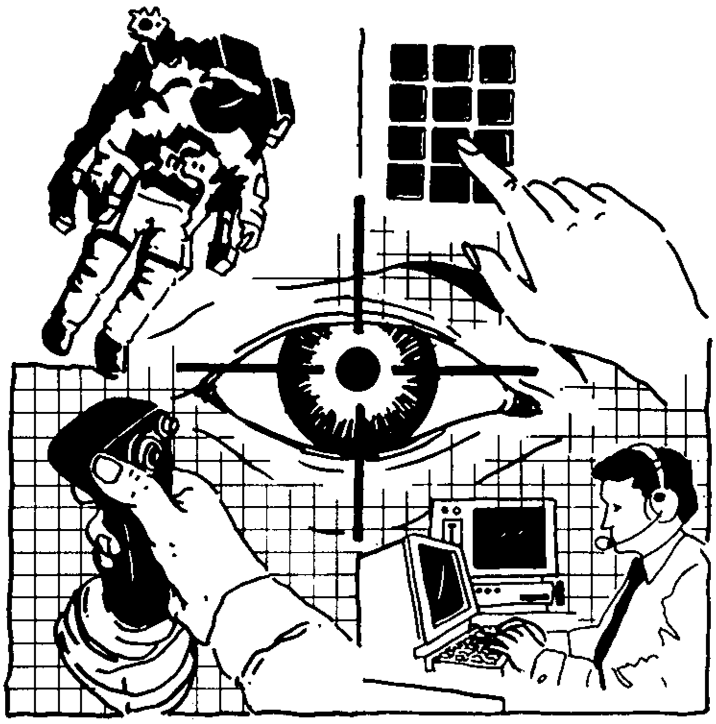
5.115 Representation of slant by linear perspective;

5.901 Monocular distance cues;

Handbook of perception and human performance, Ch. 21, Sect. 3.1

Notes

Section 5.2 Object Motion



5.201 Subject-Relative and Object-Relative Visual Motion

Key Terms

Cue conflict; eye movements; motion perception; simulation; subject-relative motion; tracking; visual position constancy

General Description

Two separate sources of information about the motion of objects are available to the observer: subject-relative motion and object-relative motion. Subject-relative motion gives the observer information about the absolute motion of the object relative to the observer and is drawn from retinal-image motion and from information about movement of the observer's own head and eyes. Object-relative motion information is available from the relative changes in the position of retinal images of objects. Alone, it reliably indicates that one or more objects are moving, but it does not specify a zero velocity point; therefore the information is ambiguous in the absence of subject-relative information. Other rules govern perceived motion in those situations (CRef. 5.301).

Observers are more sensitive to object-relative than to subject-relative motion. The minimum angular velocity at which motion can be detected is an order of magnitude lower (1-2 min arc of visual angle per second) when the target moves against a textured background than when it moves against a featureless or dark background (10-20 min arc/sec) (Ref. 3). The magnitude of differences in sensitivity between motion on textured and featureless background depends critically upon the conditions under which the threshold is measured (e.g., continuous to stop and go motion) and the type of threshold measured (e.g., minimum extent or minimum velocity) (CRefs. 5.203, 5.208, 5.209). In general, differences are minimized with short-duration, high-velocity targets where detection of change of position may not be critical to threshold (Ref. 1).

When cues conflict, object-relative motion dominates perception. The dominance of object-relative motion is most clearly illustrated by the classic demonstration of induced motion (Ref. 2; CRef. 5.301); for example, when a surrounding frame is displaced relative to a smaller stationary figure enclosed within it, the smaller figure appears to move. The configural interactions of object-relative motion predominate over subject-relative cues. It is interesting that, while the percept is faulty, it does not give rise to faulty tracking eye movements, even though the observer believes himself or herself to be tracking the target (Ref. 4).

Position constancy is the perception that an object is not moving even though the object moves with respect to the head or retina. It is fairly accurate during head movements and saccadic eye movements, and is frequently lost during pursuit movements. During head rotation and saccadic eye movements, stationary objects appear stationary and target displacements greater than 10-20% of angular rotation are accurately noted (Ref. 5; CRef. 5.603). During pursuit eye movements, stationary targets tend to appear to displace in the same direction in which the eye is moving. Target displacement detection shows similar bias. The degree of loss of position constancy can be considerable, but depends upon a number of factors (CRef. 5.215).

Key References

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Cross References

5.202 Image/retina and eye/head systems of motion perception;

5.203 Factors affecting threshold for visual motion;

5.208 Displacement thresholds for visual motion: effect of target duration;

5.209 Visual motion detection thresholds: effects of stationary referents;

5.215 Motion illusions with tracking eye movements;

5.301 Induced motion: determinants of object-relative motion;

5.603 Detection of motion during saccades: effect of axis of movement

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Notes

5.202 Image/Retina and Eye/Head Systems of Motion Perception

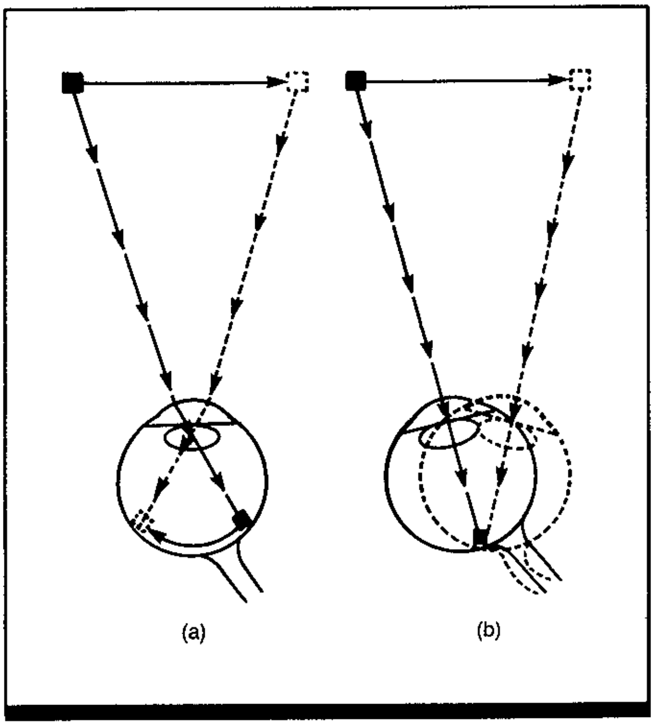

Figure 1. Object movement can be perceived (a) when the object image moves across the retina and the eyes are stationary (information from the image/retina system) or (b) when the retinal image remains stationary and the eyes move to follow the object (information from the eye/head system). (From Ref. 2)

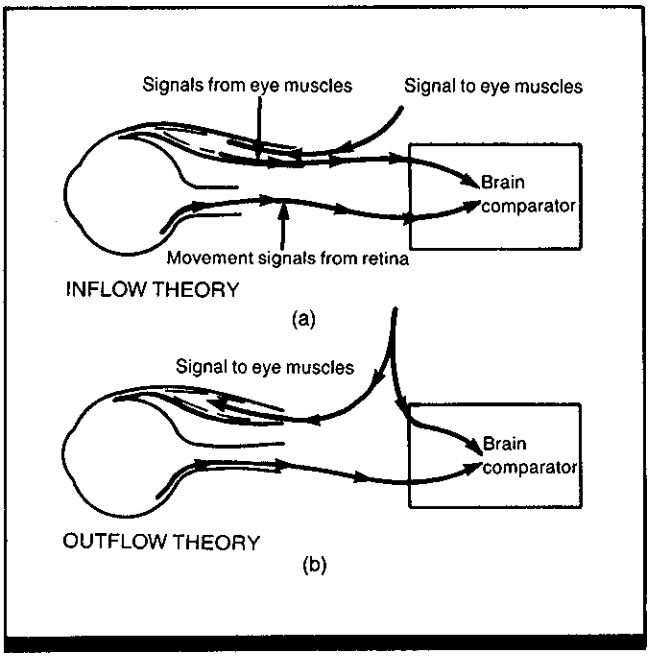

Figure 2. Two competing theories of eye/head system operation. Image/retina signals are interpreted by comparison with either (a) afferent signals from eye muscles (inflow theory) or (b) a corollary discharge of efferent signals that control eye movements (outflow theory). (From Ref. 2)

Key Terms

Apparent movement; corollary discharge; eye movements; eye-head system; image-retina system; inflow theory; motion perception; outflow theory; simulation

General Description

Two types of motion information, object-relative and subject-relative (CRef. 5.201), influence an observer's perception of motion. Object-relative motion involves motion of objects relative to each other (CRef. 5.301). Subject-relative motion involves the movement of objects relative to the observer. Two systems are important in determining whether subject-relative motion is perceived: the image/retina system that registers motion of an object's image on the retina and the eye/head system that registers self motion of the observer's head and eyes (Ref. 2). Generally the systems work together to ensure veridical perception of object motion and stasis (CRef. 5.201).

Neither the eye/head nor image/retina system is necessary or sufficient for motion perception. When a single luminous object moves on a featureless or dark background, the observer's eyes may remain stationary, causing the image of the object to move across the retina. Alternatively, the eyes may track the object, leaving the image stationary on the retina; then only motion information from the eye/head system is available to the observer (Fig. 1). In each case the percept is the same. If the luminous object is stationary and the eyes can be induced to track across it, both retinal/image and eye/head movement are produced; however, their signs cancel each other and the object appears stationary. Image/retina and eye/head movement signals are compared in computing the final object motion vector (Ref. 2).

Generally, information about movement in the eye/head system comes from eye movements; head movements are usually compensated for by the vestibulo-ocular reflex (but see CRef. 5.201).

There are two potential sources of information about eye movements. Inflow theory proposes that eye-position signals from kinesthetic receptors in the eye muscles are fed to a brain comparator. Alternatively, outflow theory proposes that the centrally originating signals that command eye movements send a corollary discharge to the brain comparator. The available evidence supports outflow theory. First, illusionary motion of stationary objects occurs when eyes

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are passively moved (pushed with fingers) so that only kinesthetic information is available about their motion (Ref. 2). Second, a retinally stabilized afterimage moves during eye movements in a dark room, but appears stationary if the eye is passively moved (Refs. 2, 3, 4).

Finally, it is possible to produce a corollary discharge signal without resultant eye movement and kinesthetic information (e.g., by paralyzing the eye muscles with curare). When this is done, the world appears to lurch when eye movements are attempted, presumably because corollary discharge signals are not compensated by cancelling image-retina signals (Ref. 3).

These systems are involved in perceived (a) stroboscopic motion (CRef. 4.401) with saccadic eye movements for which motion is only seen when information from both systems indicates a change of spatial position (Ref. 4); (b) motion during pursuit or tracking eye movements in which motion is only seen when two different retinal points are stimulated and is not seen when there is only eye/head motion (Ref. 5); (c) motion aftereffects (CRef. 5.212) which are seen when the eyes are stationary and only retinal image motion occurs. These aftereffects are not seen when tracking eye movements eliminate retinal image motion (Ref. 1).

Constraints

- Head movements that are independent of eye movements have not received much attention (CRef. 5.210).
- The comparator is error-prone; it can make small errors for stimulus velocity and direction of motion (CRef. 5.201).

Key References

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4. Rock, I., & Ebenholtz, S. (1962). Stroboscopic movement based on change of phenomenal rather than retinal location. *American Journal of Psychology, 75*, 193-207.

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Cross References

5.201 Subject-relative and object-relative visual motion;

5.212 Motion aftereffects;

5.301 Induced motion: determinants of object-relative motion;

5.401 Types of visual apparent motion

5.203 Factors Affecting Threshold for Visual Motion

Factor	Effect on Motion Perception	Sources
Target velocity	Threshold decreases significantly between 82 and 164 min arc/sec ($p<0.05$) and 41 and 164 min arc/sec ($p<0.02$)	CRef. 5.209
	The least angular-velocity difference discriminable between two objects is ~1-2 min arc of visual angle	Ref. 1
	The percent change in velocity for discrimination of a difference is at a minimum for rates of 1-2 deg/sec, and increases with higher target velocities	
	Threshold for detection of motion cessation decreases inversely with target velocity (without referents) at target velocities <1 deg/sec	Ref. 7
Duration of target exposure	There is a differential effect depending on presence or absence of referents. Threshold for motion detection is reduced as duration increases over a range of 0.12-16.0 sec	CRef. 5.209; 5.207
	A reduction of threshold with increased duration is rapid for short exposure times (0.5-4.0 sec), and asymptotes at ~16 sec (9 min arc/sec angular velocity)	Ref. 4
	Threshold decreases as target exposure time increases over a range of 40-1480 msec	CRef. 5.208
Extent of target movement	Target paths of equal length yield accurate velocity matches	CRef. 5.210
	Extent-of-motion thresholds vary inversely with velocity when there is no frame of reference	Ref. 8
	An increased target motion extent requires higher luminances to discriminate movement (up to critical target durations)	Ref. 3
	For given extents, there is a velocity limit beyond which movement cannot be discriminated	
	Threshold increases as distance traveled by a target increases over a range of 1.68-52.4 min arc	
Reference stimuli	Threshold for object-relative (with referents) motion is lower than threshold for subject-relative (no referents) motion	Ref. 8
	There is no effect of referents at target exposure times of 180 msec or less	CRef. 5.208
	There is no consistent effect of referents at 0.25-sec target exposure	CRef. 5.209
	Threshold decreases with stationary references at target velocities of 41, 82, and 164 min arc/sec at 16-sec exposure	
Size of motion field	Target velocity must increase proportionately as field size increases to be perceived as same velocity	CRef. 5.210
	Threshold ranges from 0.11-0.30 cm/sec (2-6 min arc/sec), depending on field dimensions	Ref. 2
Luminance level	Higher luminance levels become less effective as target exposure times increase over range of 0.12-16.0 sec	CRef. 5.207
	Threshold decreases with increased luminance when comparing 0.051 cd/m^2 and 1,592 cd/m^2	CRef. 5.209
Retinal location of target	Threshold increases as target moves from center to periphery of retina	Ref. 1
Target fixation or pursuit	Estimated target velocity is significantly greater with a fixation point	CRef. 5.217
	Estimated target velocity is reduced if visual pursuit is allowed	

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Key Terms

Motion perception; simulation; target acquisition; target displacement; tracking; velocity perception; visual referents

General Description

The threshold for visual movement perception is influenced by many factors (e.g., target velocity and distance, reference frames, visual fixation or pursuit). Motion thresholds are usually determined by asking observers to state direction of movement, to compare the velocity of a target stimulus to a standard stimulus, or to detect movement of a single target. The least discriminable difference in angular velocity of two targets is ~1-2 min arc/sec. The table lists factors known to influence movement perception, the direction and magnitude of the effect, and sources of more information.

Constraints

- These data must be interpreted carefully prior to applying them, as they were obtained under a wide variety of highly specific experimental conditions.

Key References

1. Bartlett, N., Brown, J., Hsia, Y., & Mueller, C. (1965). In C. Graham (Ed.), *Vision and visual perception*. New York: Wiley.

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Cross References

5.207 Perceived visual motion: effect of illumination and target exposure duration;

5.208 Displacement thresholds for visual motion: effect of target duration;

5.209 Visual motion detection thresholds: effects of stationary referents;

5.210 Visually perceived relative velocity: effects of context and extent of motion;

5.217 Perceived motion with tracking eye movements

5.204 Perceived Target Velocity in the Visual Periphery

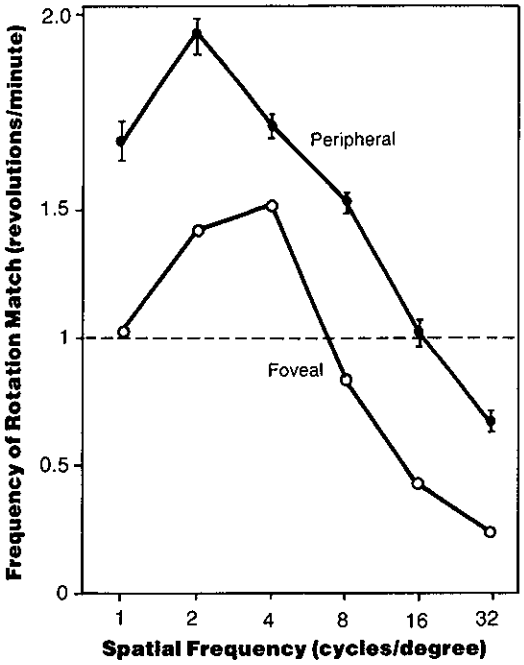

Figure 1. Frequency of rotation match as a function of spatial frequency for foveal vision (lower curve) and at an 11-deg distance from fixation (upper curve). Dashed line indicates the physical velocity of the stimulus. (From Ref. 4)

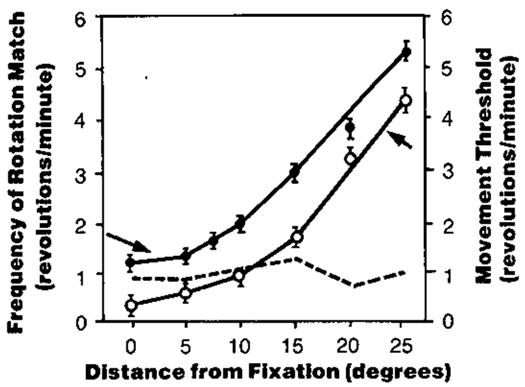

Figure 2. Frequency of rotation matches and movement thresholds for rotation at various distances from fixation (the arrows indicate the appropriate scales). Dashed line indicates difference between the two curves. (From Ref. 4)

Key Terms

Motion perception; peripheral vision; retinal location; rotary motion; simulation; target acquisition

General Description

The velocity of a moving target appears slower in the retinal periphery than in the fovea, probably because the threshold for the perception of movement is greater in the periphery than in the fovea.

Applications

Displays and operating situations in which the visual perception of velocities over a range of distances from fixation is important.

Methods

Test Conditions

- High-contrast, square-wave, reference grating with a spatial frequency of 1 cycle/deg of visual angle
- High-contrast, square-wave, target grating of variable spatial frequency (from 1-32 cycles/deg in one-octave steps)
- Gratings subtended 5 deg in diameter
- Both gratings mounted on turntables and rotated about their centers; frequency of rotation of reference grating set at one revolution per minute; frequency of rotation of target grating adjustable by potentiometer
- Ambient illumination at 17 cd/m^2

Experimental Procedure

- Method of adjustment
- Independent variables: spatial frequency of target grating, target's distance from fixation, in degrees of visual angle
- Dependent variables: frequency of rotation match, defined as frequency of target grating rotation required to make the apparent velocities of the reference and target gratings equal; threshold for perception of rotation
- Observer's task: adjust rotation speed of target grating so that the apparent velocities of the reference and target gratings were equal; rotation threshold for gratings determined by setting speed of target grating until rotation was just detectable
- 2 observers, with extensive practice

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Experimental Results

- For foveal stimuli, as the spatial frequency of the target grating increases, the matching frequency of rotation of the 1 cycle/deg reference grating increases to a peak at ~2-4 cycles/deg of visual angle, and then rapidly declines (lower curve, Fig. 1). At 16 and 32 cycles/deg, observers report that the grating appears stationary most of the time.
- For peripheral stimuli at an 11-deg distance from fixation, the frequency of rotation match increases to a peak at spatial frequencies of 2 cycles/deg, and then declines rapidly (upper curve, Fig. 1). Overall, this function is elevated above the function for foveal vision, indicating that a higher frequency of rotation in the periphery is needed to match apparent stimulus velocity in the fovea for two identical gratings. This implies that peripheral stimuli are perceived as rotating more slowly than foveal stimuli of the same spatial frequency.
- When both reference and target gratings are set at a spatial frequency of 1 cycle/deg, and the reference grating is rotating at 1 revolution/min, the frequency of rotation of the target grating needed to match the apparent velocity of the reference grating increases as the target grating's distance from fixation increases (upper curve, Fig. 2). Again, this implies that the peripheral grating is perceived as rotating more slowly than the reference grating.
- The threshold for movement of a grating increases as the grating's eccentricity increases (lower curve, Fig. 2). The apparent frequency of rotation is essentially constant with distance from fixation when rotation threshold is subtracted from frequency of rotation match (dashed line, Fig. 2). This implies that the increase in rotation threshold in the periphery is responsible for decrease in apparent velocity of peripheral stimuli.

Variability

Error bars present plus or minus one standard error.

Repeatability/Comparison with Other Studies

The results described here are less subject to problems of interpretation due to tracking eye-movements than earlier work employing linear motion (Ref. 4) because a rotating stimulus was used. The effects of slowing and stopping of perceived motion in the periphery, "time stopped-motion" illusion, have been reported earlier and appear to be very robust (Ref. 2). The increase in threshold for motion in the periphery has also been reported in earlier work (Ref. 1).

Constraints

- The results reported here apply only to slow and very slow motion. At high velocities, the reverse of the effects is reported (Ref. 4).

Key References

1. Aubert, H. (1886), Die Bewegungsempfindungen. *Pfluger's Archiv für Die Gesamte Physiologie Des Menschen und Der Tiere, 39,* 347-370.

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Cross References

1.307 Absolute sensitivity to light: effect of target area and visual field location;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.954 Disjunctive eye movements in response to peripheral image disparity;

5.203 Factors affecting threshold for visual motion;

5.205 Perception of motion in the visual periphery;

5.920 Stereoacuity: effect of target location in the visual field

5.205 Perception of Motion in the Visual Periphery

Key Terms

Motion detection; motion perception; peripheral vision; retinal location; target acquisition; tracking

General Description

Sensitivity to movement of a target decreases monotonically as the target moves farther and farther into the periphery. Despite this differential sensitivity to movement as a function of retinal location, movement in the periphery is more salient than movement in the center. It is easier to see a moving point in the periphery than it is to see a stationary line. If an observer fixates a point straight ahead and tries to view a stationary line off to one side, the line may disappear. This phenomenon is particularly strong at low levels of illumination, but occurs at high levels as well. When an image is stabilized it will disappear in the fovea as it does in the periphery when it is not stabilized. When the image is not stabilized, however, it appears in the periphery even though the eye wanders slightly during voluntary fixation. Small eye movements are less effective in refreshing information transmitted by the peripheral receptors. Since foveal regions are more sensitive to movement, however, stabilization of the image is required to produce the same disappearance. It follows that, with fixed gaze, objects are not visible in the periphery, though if the objects or eye should move, they become visible. This is not true of foveal images. Therefore, eye movements do not make foveal images more visible than they normally are and movement is not more salient in the fovea than it is in the periphery.

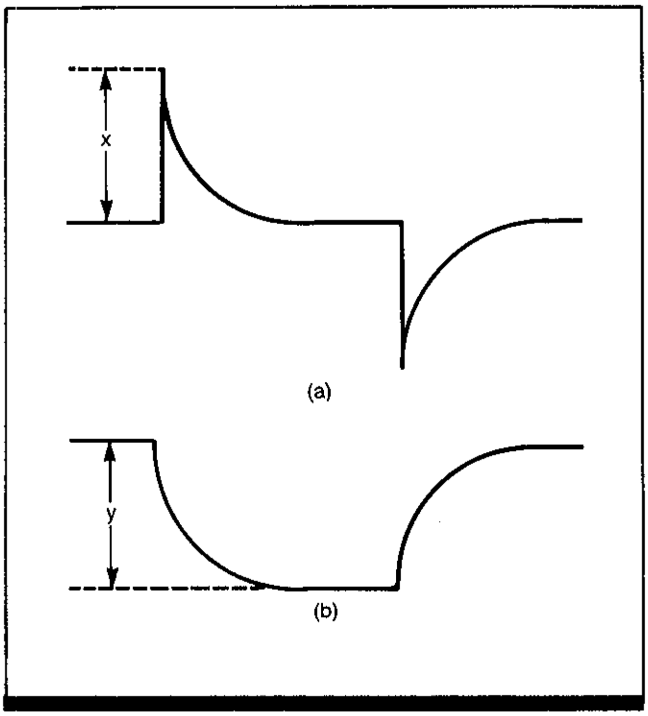

Figure 1. (a) Waveform of deflection of extrafoveally viewed spot (experimenter controlled) and (b) waveform yielded by perceptually matching deflection of foveally viewed spot to that of extrafoveally viewed spot (observer controlled). For perceptual match, $y = x$ and time constants are equal. (From Ref. 2)

Methods

Test Conditions

- Ramp waveform presented on a CRT display (Fig. 1a) with instantaneous (i.e., on the order of a few microseconds) deflections of spot or line through 1 or 2 deg of visual angle
- Slow returns to vertical coordinate via alternate exponential-spike waveforms of 25-msec time constant
- RC-filtered step deflection presented on a second CRT (viewed foveally) that allowed adjustments of amplitude and time constant to produce a perceptual match with the first waveform
- Displays viewed in room with normal lighting (i.e., at photopic viewing levels) for some experimental conditions and in dim lighting conditions for others

Experimental Procedure

- Precise method not specifically stated, probably method of adjustment
- Independent variables: retinal eccentricity of stimulus presentation, defined as foveal or 3-4 deg of visual angle extrafoveally
- Dependent variable: difference between adjustment of amplitude and time constant of waveform on one CRT to waveform on other CRT
- Observer's task: adjust amplitude and time constant of the second waveform to produce a perceptual match to the first
- Number of observers, trials, and degree of practice not specified

Experimental Results

- Displacement of spot was much larger than the static acuity threshold for 3-4 deg eccentricity.
- For foveal vision, waveform motion is accurately perceived. For extrafoveal vision, adjustment of the second waveform is such that rapid components of the first waveform appear not to have been perceived; that is, adjustment of the second waveform produces a configuration such as the one shown in Fig. 1b.
- If both CRT displays are viewed extrafoveally, their perceived motions still appear to match. This result also implies that only slow motions are transmitted to the motion detection system for peripheral stimuli.
- When the CRT displays are viewed under dimly lit conditions (i.e., scotopic viewing levels), the perceptual match between foveal and extrafoveal stimuli is destroyed. This implies that mainly the cone system is responsible for computing peripheral displacement on the basis of motion signals.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The study described reports that rapid displacements were not perceived, even though the spatial separation between points was above the static acuity threshold. This effect is complementary to another peripheral vision phenomenon in which two spots, flashed 50 msec apart, induce a sensation of movement, even if their spatial separation is below the static acuity threshold (Refs. 1, 3). These effects considered together imply that the systems for signaling motion and change of location are distinct.

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Constraints

- The effect reported here is produced only at photopic light levels.

Key References

1. Biederman-Thorson, M., Thorson, J., & Lange, G. D. (1971). Apparent movement due to closely spaced sequentially flashed dots in the human peripheral field of vision. *Vision Research, 11,* 889-903.

*2. Mackay, D. M. (1980). Illusory reversal of extrafoveally perceived displacement. *Nature, 284,* 257.

3. Thorson, J., Lange, G. D., & Biederman-Thorson, M. (1969). Objective measure of the dynamics of a visual movement illusion. *Science, 164,* 1087-1088.

Cross References

1.307 Absolute sensitivity to light: effect of target area and visual field location;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.954 Disjunctive eye movements in response to peripheral image disparity;

5.203 Factors affecting threshold for visual motion;

5.204 Perceived target velocity in the visual periphery;

5.920 Stereoacuity: effect of target location in the visual field

5.206 Sensitivity to Direction of Motion in the Visual Periphery

Key Terms

Dynamic visual acuity; motion detection; peripheral tracking; peripheral vision; peripheral warning signals; target acquisition; warnings

General Description

In the visual periphery, observers are approximately twice as sensitive to horizontal-axis movement as to vertical-axis movement. Absolute threshold for movement detection in the periphery is a nearly linear decreasing function of distance outward from a central eye fixation point. Figure 1 shows movement detection isograms for a circular pointer display.

Methods

Test Conditions

- Flat black aircraft-type instrument with white pointer 0.25 cm wide and 2.87 cm long located at random positions on interior flat black surface of a 203-cm diameter hemisphere; pointer luminance 6.4 cd/m^2; background luminance not specified, but at a photopic level; 1.2-cm cross at center of background used as fixation point; viewing distance 95 cm
- Two pointer displays used, one for clockwise and counterclockwise pointer movement, one for vertical and horizontal pointer movement; vertical/horizontal pointer movements limited to 3.5 cm
- 48 pointer positions in peripheral field tested
- Rate of pointer movement was systematically increased and decreased on alternate trials
- Condition presentation order randomly constructed

Experimental Procedure

- Method of limits
- Independent variables: rotary versus linear pointer movement, horizontal versus vertical pointer movement, location of pointer in peripheral visual field
- Dependent variable: rate of detectable pointer movement computed from average of three increasing and three decreasing rates
- Observer's task: fixate on cross at center of background; state if pointer is moving
- 10 airline pilots; ages 30-45

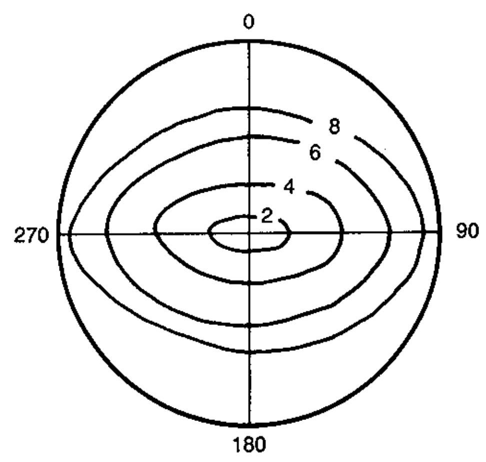

Figure 1. Absolute threshold isograms for detecting rotary movement in the periphery of the visual field. Numbers are rates of pointer movement in revolutions per minute. (From Ref. 4)

Experimental Results

- Clockwise and counterclockwise movement detection thresholds are not significantly different.
- Generally, vertical and horizontal detection thresholds are quite similar. Horizontal movement thresholds are slightly lower than vertical movement threshold in the area adjacent to the horizontal axis.
- All absolute movement threshold isograms are elliptical. Absolute thresholds for motion detection at a particular pointer movement rate extend approximately twice as far on the horizontal axis as on the vertical axis.
- For both rotary and linear pointer movement, absolute threshold increases as a linear function of the distance of the pointer from the center fixation point.
- Rotary and linear motion could not be compared quantitatively.

Variability

Judgments of absolute threshold were more variable for linear than for rotary motion.

Repeatability/Comparison with Other Studies

The elliptical shape of the absolute motion detection threshold isograms conforms closely to the patterns and extent of the color visual field.

Constraints

- Only a single, moving form was used in the study. Other research (Ref. 2) indicates that different forms will yield different motion thresholds.
- Different results may be obtained for stimuli of different color or luminance levels.

Key References

1. Biederman-Thorson, M., Thorson, J., & Lange, G. D. (1971). Apparent movement due to closely spaced sequentially flashed dots in human peripheral field of vision. *Vision Research, 11*, 889-903.

2. Gordon, D. A. (1947). The relation between the thresholds of form, motion, and displacement in parafoveal and peripheral vision at a scotopic level of illumination. *American Journal of Psychology, 60*, 202-225.

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Cross References

1.307 Absolute sensitivity to light: effect of target area and visual field location;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.954 Disjunctive eye movements in response to peripheral image disparity;

5.203 Factors affecting threshold for visual motion;

5.204 Perceived target velocity in the visual periphery;

5.205 Perception of motion in the visual periphery;

5.920 Stereoacuity: effect of target location in the visual field

5.207 Perceived Visual Motion: Effect of Illumination and Target Exposure Duration

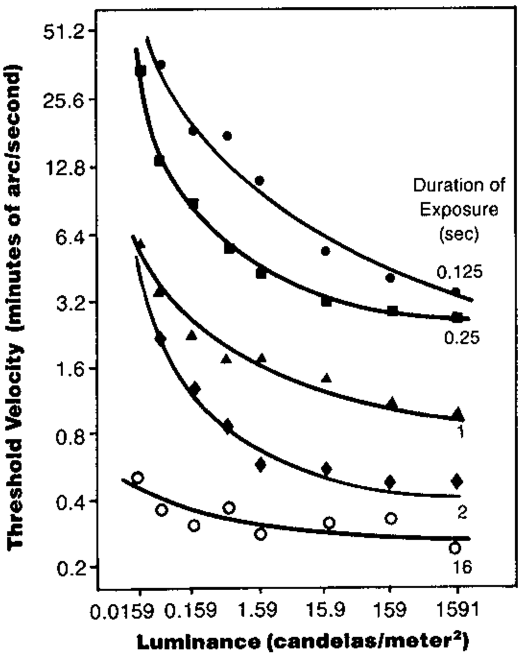

Figure 1. Threshold velocity for movement discrimination as a function of luminance; duration of exposure is the curve parameter. Plotted as the log of the mean of three observers. (From Ref. 5)

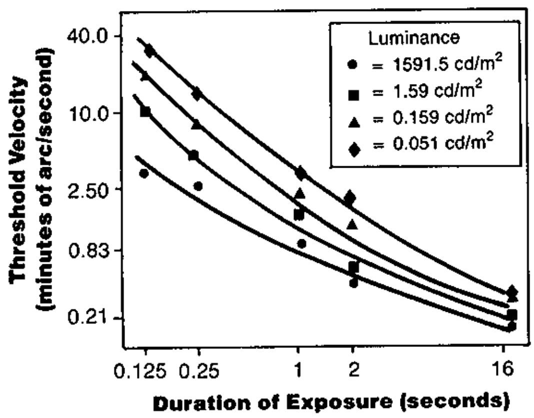

Figure 2. Threshold velocity for movement discrimination as a function of duration of exposure; target luminance is the curve parameter. (From Ref. 5)

Key Terms

Motion detection; motion sensitivity; simulation; training; velocity

General Description

Movement detection improves as target exposure time and illumination increase. The improvement in movement detection resulting from increased illumination is greater with shorter than with longer exposures. In general, increasing the target exposure time facilitates motion detection more than raising illumination does.

Applications

Discrimination of movement on visual displays; the design of visual displays to optimize conditions for movement detection; the selection and training of display operators in movement detection; the design of reticules and artificial field structure to aid pilots in visual search at high altitude.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- White rectangular targets subtending 15 min arc of visual angle; viewing distance 2.3 m (90.6 in.)
- Targets presented by means of belt apparatus and moved horizontally either left or right; adjacent targets separated by 45 min arc
- Targets viewed monocularly in dark room through black tube presenting visual field of 3.2 deg
- Eight target luminance levels ranging from 0.016-1591.5 cd/m^2 (0.005-50 mL); luminance increased over blocks of trials
- Five exposure times ranging from 0.125-16 sec
- Observers were dark-adapted for 10 min prior to each experiment

Experimental Procedure

- Ascending method of limits for velocity, used to reduce incidence of illusory motion
- Independent variables: target velocity, luminance level, target exposure time, direction of movement (right or left)
- Dependent variable: movement threshold, determined by increasing target velocity with luminance and exposure time held constant until motion perceived twice in succession
- Observer's task: report when and in what direction target movement was seen
- 3 paid male undergraduate students with normal vision and some practice

Experimental Results

- The discrimination of motion improves as luminance level is increased. This improvement is more marked for shorter than for longer target exposure times (Fig. 1). To test the significance of these tendencies, the data were analyzed by the orthogonal polynomial technique. The results indicate for the orthogonal luminance values of 0.05, 0.5, 5, 50, and 500 mL that the 0.125 and 0.25 durations are fitted by both linear ($p < 0.001$) and quadratic ($p < 0.05$ and $p < 0.01$, respectively) components, and the 2-sec duration by a linear component ($p < 0.01$); no components are significant for the 1- and 16-sec data.
- Motion discrimination improves as exposure time is increased from 0.125 to 16 sec (Figs. 1, 2).
- Exposure time is a more important variable than luminance (Ref. 5).

Variability

No specific information on observer variability was given. Individual performance initially was highly variable, but stabilized with practice. Data reported are similar to those obtained 6 months later under the same experimental conditions.

Repeatability/Comparison with Other Studies

The results of this study are supported by other investigators. In Ref. 2, the 4 observers were required to judge the direction of movement of a green spot of light (brightness level of 0.067 cd/m^2) on a dark screen. Targets were viewed monocularly at a distance of 183 cm. Target velocities ranged from 1.61-27.37 min arc/sec with a range of exposure times of 0.51-16.00 sec. Analysis of variance showed a significant decrease in threshold as exposure time increased ($p < 0.01$) with improvement leveling off at ~8 sec. The same general trend of improved movement detection with longer exposure times and higher luminances has been found by several other investigators. However, Refs. 3 and 4 reported that target luminance does not affect thresholds at moderate-to-high luminance levels for most combinations of stimulus variables. Instead, exposure duration and amount of displacement are the determining factors, and there is a tradeoff between the two factors.

Constraints

- The effect of increasing luminance is confounded with the effect of practice.
- Field of view is very limited and thus it may be difficult to extrapolate data to real world situations.
- A number of factors, such as target size, target location in field of view, and amount of practice, affect the perception of motion and should be considered in applying these data under different viewing conditions (CRef. 5.203).

Key References

1. Brown, R. H. (1955). Velocity discrimination and the intensity-time relation. *Journal of the Optical Society of America, 45,* 189-192.

2. Brown, R. H., & Conklin, J. E. (1954). The lower threshold of visible movement as a function of exposure-time. *American Journal of Psychology, 67,* 104-110.

3. Henderson, D. C. (1971). The relationships among time, distance, and intensity as determinants of motion discrimination. *Perception & Psychophysics, 10,* 313-320.

4. Henderson, D. C. (1973). Visual discrimination of motion: Stimulus relationships at threshold and the question of luminance-time reciprocity. *Perception & Psychophysics, 1,* 121-130.

*5. Leibowitz, H. W., & Lomont, J. F. (1954). *The effect of luminance and exposure time upon perception of motion* (WADC-TR-54-78). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD035163)

Cross References

5.203 Factors affecting threshold for visual motion

5.208 Displacement Thresholds for Visual Motion: Effect of Target Duration

Key Terms

Frame of reference; motion detection; simulation; target displacement; visual referents

General Description

When observers view linear motion in a frontal plane, the extent of motion (i.e., displacement) necessary for detection of motion is a U-shaped function of exposure duration. This relationship holds whether the motion is discrete (target is presented in two different spatial positions with a temporal interval between presentations), stop-go-stop (target is viewed in a stationary position prior to and following the motion interval), or continuous (constant motion during viewing period) with or without the presence of stationary reference objects.

Applications

Design and evaluation of visual displays; selection and training of display operators; improvement in operation performance by manipulating viewing conditions.

Methods

Test Conditions

- Luminous 2.4-min-arc spot presented using an oscilloscope covered with dark gray neutral filter; 12 x 12 cm oscilloscope screen located 75 cm from observer within truncated cone
- Ambient light of 1 lux at observer's eye; stationary target luminance 3.18 cd/m^2 (1 mL)
- Target viewed monocularly using head and chin rests
- Range of exposure times 40-1480 msec
- No fixation point, flashing lights at screen corners 0.5 sec prior to target presentation
- Stationary target duration: 10 msec for stop-go-stop discrete modes of presentation; all motion left to right; target motion started at center of screen
- Reference lines each side of motion track were 1.5 x 20 mm phosphorescent paper strips with 0.3-mm vertical black lines, 0.3 mm apart
- Three to four thresholds each session with ascending series of velocities; different exposure times for each threshold; mode of target presentation same within each session

Experimental Procedure

- Independent variables: exposure time; target velocity; presence or absence of reference lines; mode of presentation: continuous (target comes into view and leaves while moving), with or without stationary reference objects, and stop-go-stop (target is presented in two different spatial positions with a temporal interval between presentations)
- Dependent variables: displacement at threshold, calculated as the product of threshold velocity and exposure duration T (method of threshold determination not stated)
- Observer's task: report when motion was perceived
- 1 observer

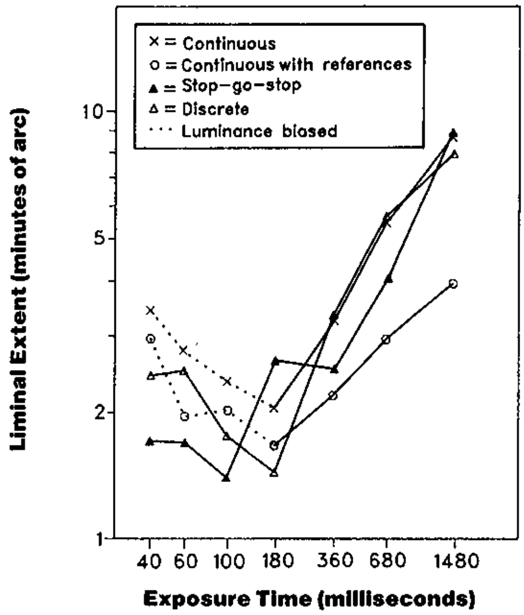

Figure 1. Extent-of-motion (displacement) thresholds for one observer as a function of exposure time for four modes of presentation. The dotted lines indicate data that are luminance-biased because of the time (300 msec) necessary for the CRT stimulus to reach maximum luminance. (From Ref. 1)

Experimental Results

- Extent-of-movement thresholds decrease for all modes of presentation as exposure times increase from 40 to 100-180 msec; thresholds for all modes increase for 180-1480 msec (Fig. 1).
- The presence of stationary reference lines has a greater influence on perception of continuous motion at longer exposure times (Fig. 1).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The data were analyzed with data of other investigators within the context of a motion detection model and found to be generally consistent.

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Constraints

- Experimental data are based on only 1 observer (author).
- Factors such as target size and location, amount of practice, visible referents, and luminance affect movement perception and must be considered when applying these data (CRef. 5.209).
- Field of view was very limited and therefore results may be difficult to extrapolate to real-world situations.

Key References

*1. Bonnet, C. (1975). A tentative model for visual motion detection. *Psychologia, 18*, 35-50.

2. Brown, R. H., & Conklin, J. E. (1954). The lower threshold of visible movement as a function of exposure-time. *American Journal of Psychology, 57*, 104-110.

3. Henderson, D. C. (1971). The relationships among time, distance, and intensity as determinants of motion discrimination. *Perception & Psychophysics, 10*, 313-320.

4. Leibowitz, H. W. (1955). Effect of reference lines on the discrimination of movement. *Journal of the Optical Society of America, 45*, 829-830.

5. Shaffer, O., & Wallach, H. (1966). Extent-of-motion thresholds under subject-relative and object-relative conditions. *Perception & Psychophysics, 1*, 447-451.

Cross References

5.201 Subject-relative and object-relative visual motion;

5.209 Visual motion detection thresholds: effects of stationary referents;

Handbook of perception and human performance, Ch. 17, Sect. 1.6

5.209 Visual Motion Detection Thresholds: Effects of Stationary Referents

Key Terms

Motion detection; relative motion; target acquisition; target displacement; velocity perception; visual search

General Description

Under certain conditions, the ability to detect target motion is increased when reference stimuli are provided. The detection of target motion also is enhanced with increases in target speed, luminance, and duration of exposure. Care must be taken to avoid the perception of illusory movement of targets at low velocities in the absence of a visible frame of reference.

Applications

Design and evaluation of visual displays; training of radar and related display operators; design of reticules and artificial field structure to aid pilots in visual search at high altitude.

Methods

Test Conditions

Study 1 (Ref. 2)

- Observers dark-adapted to lower luminance
- Square, white targets subtending 15 min arc of visual angle at viewing distance of 230 cm
- Targets on black background with space between targets subtending 45 min arc
- Monocular viewing through black tube that limited field to 3.2 deg of visual angle
- White vertical grid lines (when used) spaced 30 min arc apart
- Exposure times 0.25 or 16.0 sec
- Luminance levels 0.051 cd/m^2 (0.016 mL) or 1,592 cd/m^2 (500 mL)

Study 2 (Ref. 4)

- Observer-relative motion (movement of entire visual field with respect to observer; CRef. 5.201): for half the observers at each velocity, target was luminous outline square (264 min arc) surrounding a luminous disk (102 min arc); for other half of observers, the square alone was the target
- Object-relative motion (a pattern change brought about by movement of parts of visual field; CRef. 5.201): moving target was same square used for observer-relative condition; square surrounded a 184-min disk seen through mirror; disk was never displaced
- Monocular viewing into a movable, half-silvered mirror; displacements caused by movement of mirror
- Target displacement speed of 41, 82, or 164 min/sec
- No fixation required; observer told that disk or square might move left or right, in opposite directions, or whole pattern left or right
- Extent of target movement: object-relative, low and med speed group: 0.0, .3, .8, 1.3, 1.8, 2.3, 2.8 min visual angle; observer-relative, low and med speed group: 0.0, .8, 1.8, 2.8, 3.8, 4.8, 5.8 min visual angle; object-relative, high speed group: 0.0, .3, .55, .8, 1.3, 1.8, 2.3 min visual angle; observer-relative, high speed group: 0.0, .8, 1.3, 1.8, 2.8, 3.8, 4.8 min visual angle

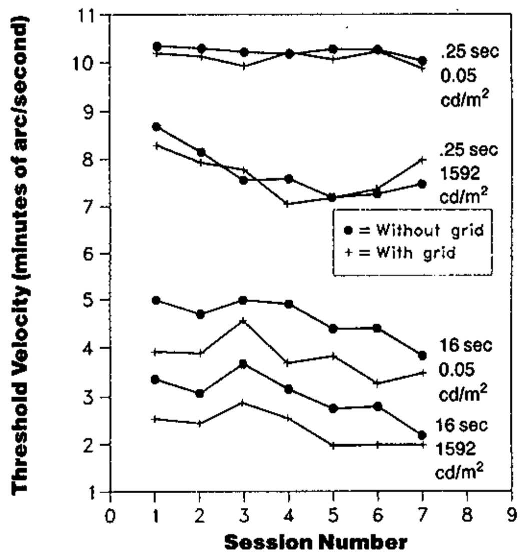

Figure 1. Changes in threshold velocity for detection of movement as a function of practice (session number) (Study 1). Curved parameters are duration of exposure, luminance, and the presence or absence of reference grid lines. (From Ref. 2)

Experimental Procedure

Study 1

- Method of limits; two-alternative forced-choice procedure; target speeds increased from subliminal value to speed at which motion correctly perceived twice in succession; ascending trials only
- Independent variables: exposure time, luminance level, presence or absence of reference grid lines
- Dependent variables: threshold velocity (mean velocity of four trials for longer exposure and six trials at shorter exposure)
- Observer's task: judge whether motion was toward right or left
- 8 inexperienced, paid observers

Study 2

- Method of constant stimuli; two-alternative forced-choice procedure
- Within-subjects design
- Independent variables: motion or no motion, extent of target motion, direction of motion, target velocity, presence or absence of reference square
- Dependent variables: percentage of target motions detected irrespective of direction; percentage of correct-direction minus incorrect-direction motion judgments; extent threshold, defined as extent at which correct-direction minus incorrect-direction motion judgments equalled 50%
- Observer's task: judge the presence or absence of motion and direction of movement; report whether disk or square appeared to move in object-relative situation
- 30 undergraduate observers, with some practice

Experimental Results

- The threshold for motion detection decreases with increases in either extent of motion or luminance. The presence of stationary referents (the grid lines) lowers consistent motion threshold for the 16-sec exposure by 48%, but has no effect for the 0.25-sec exposure (Fig. 1).
- For observer-relative motion, performance is better (extent thresholds are lower) for high-speed targets (1.4-min arc threshold) than for low-speed targets (4.4-min arc threshold).
- There is no effect of speed for object-relative motion (1-min arc threshold).
- At all speeds, performance is better (extent thresholds are low) for object-relative motion than for observer-relative motion, and the difference in performance increases with increasing speed of target motion.
- Thresholds for observer-relative and object-relative motion are correlated for both high- ($\rho = 0.68, p < 0.05$) and

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medium-speed ($\rho = 0.81$, $p < 0.05$) target motion. A 0.51 correlation for low-speed motion is not significant.

- Observers reported illusionary motion (false alarms) on approximately one-fourth of the trials for most groups and conditions.

Variability

No specific information on observer variability was given for Study 1. The analysis-of-variance technique was the same orthogonal polynomial method used in an earlier study (CRef. 5.207). For Study 2, the between-group variability was examined using the Kruskal-Wallis analysis of variance and the Mann-Whitney U test.

Repeatability/Comparison with Other Studies

Although the theoretical basis of movement perception for exposure times <0.1 sec is disputed, the results and general trends described in Studies 1 and 2 are supported by other investigations (Refs. 1, 3; CRef. 5.207). The beneficial effect of a reference framework cited in Study 1 is not supported when the movement is coincidental with the line of sight instead of perpendicular as in Studies 1 and 2 (Ref. 1). This discrepancy may be due to the shorter exposure times in the Ref. 1 study. As with other studies, illusory movement (autokinetic illusion) was thought not to affect the experimental results.

Constraints

- Auditory cue (click) caused by movement of mirror.
- Very limited field of view, and thus may be difficult to extrapolate data to real-world situations.
- Instructions to observers and feedback are very critical and can influence results, especially where external references are absent.
- Factors such as target size and location, amount of practice, and visible referents affect movement perception and must be considered when applying these data (CRef. 5.207).

Key References

1. Harvey, L. O., & Michon, J. A. (1974). Detectability of relative motion as a function of exposure duration, angular separation, and background. *Journal of Experimental Psychology, 103*, 317-325.

*2. Leibowitz, H. W. (1955). Effect of reference lines on the discrimination of movement. *Journal of the Optical Society of America, 45*, 829-830.

3. Leibowitz, H. W., & Lomont, J. F. (1954). *The effect of luminance and exposure time upon perception of motion* (WADC-TR-54-78). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD035163)

*4. Shaffer, O., & Wallach, H. (1966). Extent-of-motion thresholds under subject-relative and object-relative conditions. *Perception & Psychophysics, 1*, 447-451.

Cross References

5.201 Subject-relative and object-relative visual motion;

5.203 Factors affecting threshold for visual motion;

5.207 Perceived visual motion: effect of illumination and target exposure duration;

5.208 Displacement thresholds for visual motion: effect of target duration;

5.210 Visually perceived relative velocity: effects of context and extent of motion;

6.304 Role of reference frames in perception;

Handbook of perception and human performance, Ch. 17, Sect. 1.6

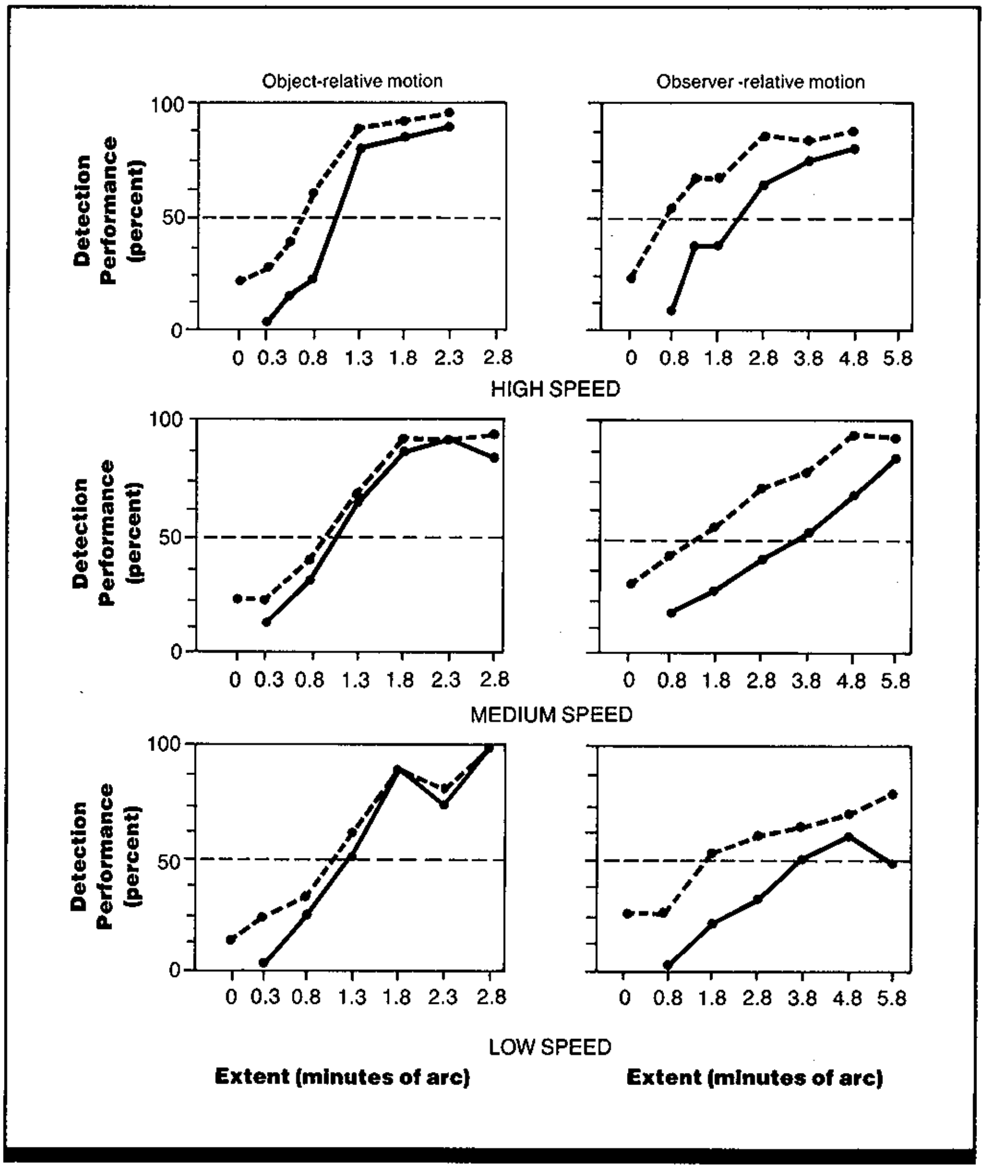

Figure 2. Performance as a function of target speed and extent of target motion in terms of percentage of motion responses to each stimulus irrespective of direction (dashed lines) and percentage of motion reports correct in direction minus percentage of motion reports incorrect in direction (solid lines) (Study 2). (From Ref. 4)

5.210 Visually Perceived Relative Velocity: Effects of Context and Extent of Motion

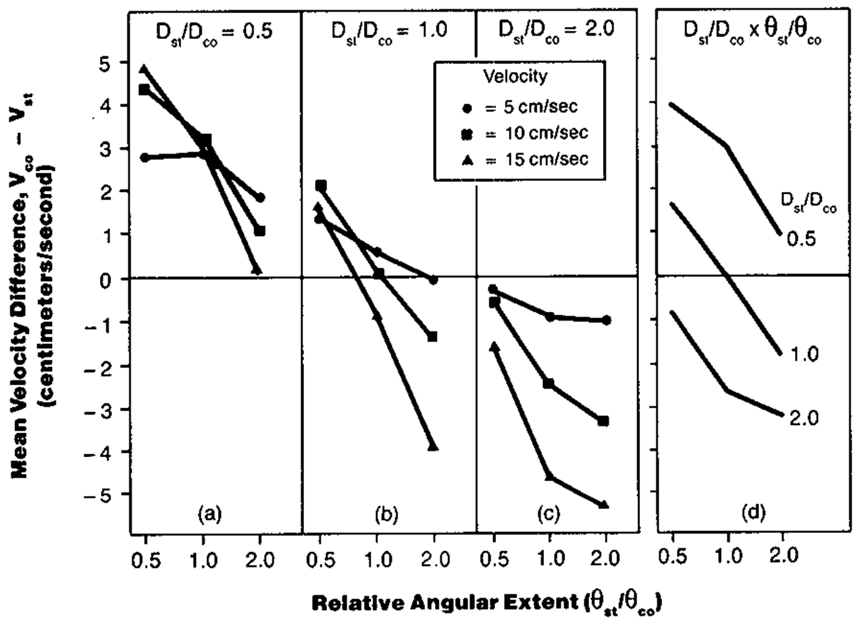

Figure 1. (a)-(c) Mean differences between comparison (adjusted by observer) and standard velocities as a function of the ratio of the angular extent covered by standard and comparison targets; Panels (a) (b) and (c) show three different ratios of distances to standard and comparison displays. (d) Data shown in (a)-(c) collapsed across different target velocities within each distance ratio. (From Ref. 3)

Key Terms

Field of view; motion constancy; motion perception; simulation; target acquisition; velocity transposition; visual context

General Description

Perceived velocity is dependent upon the angular extent and the nature of the visual field traversed. As the size of the field increases, the velocity of a moving object must increase proportionately if the object is to be perceived as moving at an equal rate. Perceived velocity is also influenced by the linear distance from observer to the target, and by the presence and/or dimensions of surrounding reference frames.

Applications

Design and layout of visual displays; field judgments of object velocity, such as in use of binoculars where there is no compensation for velocity magnification; tasks where an observer is required to detect small differences in target velocity.

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Methods

Test Conditions

- Two displays, viewed in total darkness and separated laterally by 90 deg, for each experiment; one was standard display and one was controlled by observer; displays could not be seen simultaneously
- A circular target light, 0.85 cm in diameter, optically rear-projected on each screen from Tektronix 604 monitor; target always started from left side and moved back and forth at a constant velocity over entire path until observer stated a velocity match was obtained with comparison target
- Luminous horizontal rectangular masks 12.5 × 4.2 cm or 37.5 × 12.5 cm used as reference frames for neither, only one, or both displays
- Viewing distance 1 m for Exps. 1 and 3; 1 and 2 m for Exp. 2
- Target traversed horizontal path of 7.13, 14.04, 20.56, or 26.56 deg of visual angle when viewed at 1 m
- Standard target velocity of 5, 10, or 15 cm/sec
- No fixation points; binocular viewing; 2.5-sec delay between trials; no target exposure time limit

Experimental Procedure

- Method of adjustment; randomized presentation blocked by condition
- Independent variables: target path length, viewing distance, presence or absence of reference frames, target velocity
- Dependent variable: accuracy of velocity match
- Observer's task: to match velocity of comparison display light to standard display light
- Observer instructed to use phenomenal velocity matches and not use counting or timing; observer told standard velocity would be constant during each trial but would vary between trials; observer terminated trial when velocity match made
- 24 different undergraduate students used for each experiment, with some practice

Experimental Results

- Target paths of equal length yield accurate velocity matches, but paths of unequal lengths yield large mismatches ($p < 0.001$). This is true whether targets are moving in complete darkness or are surrounded by same-size luminous frames.
- When frames are present, their effect on comparison velocity is a function of their relative size.
- Increasing the comparison path length by a factor of 3 increases the mean perceived velocity by ~33.8% when compared with the equal-path-length condition.
- For unframed displays (no framed displays were used), perceived relative velocity is influenced by angular velocity per unit of relative angular extent, rather than by relative linear or perceived extent.
- As shown in Fig. 1, relative angular extent, relative viewing distance to the displays, and velocity of the standard target all independently contribute to the values of the comparison velocity settings.
- Increasing the ratio of angular extents (e.g, by decreasing the comparison path length) yields a decrease in comparison velocity.
- Increasing the ratio of viewing distances (e.g., by decreasing the distance to the comparison display) yields a decrease in comparison velocity.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The results of Exp. 3 are constant with those of Ref. 1 regarding the effects of framework on velocity transposition. Results are also consistent with those of Ref. 4 and with the conclusion that perceived constancy of velocity can be understood within the context of the velocity transposition principle (Ref. 5). Additional supportive data are provided by Ref. 2.

Constraints

- A number of factors, such as target velocity and exposure time, visible frames of reference, viewing distance, illumination levels, and instructions to observers, must be considered when applying these data.
- Perceived velocity is inversely proportional to angular size of frame—only when frame is relatively isolated in field of view.

Key References

1. Brown, J. (1931). The visual perception of velocity. *Psychologische Forschung, 14*, 199-232.

2. Epstein, W. (1978). Two factors in the perception of velocity at a distance. *Perception & Psychophysics, 24*, 105-114.

*3. Epstein, W., & Cody, W. (1980). Perception of relative velocity: A revision of the hypothesis of relational determination. *Perception, 9*, 47-60.

4. Rock, I., Hill, A. L., & Fineman, M. (1968). Speed constancy as a function of size constancy. *Perception & Psychophysics, 4*, 37-40.

5. Wallach, H. (1939). On constancy of visual speed. *Psychological Review, 46*, 541-552.

Cross References

5.201 Subject-relative and object-relative visual motion;

5.203 Factors affecting threshold for visual motion;

5.209 Visual motion detection thresholds: effects of stationary referents;

5.215 Motion illusions with tracking eye movements;

5.217 Perceived motion with tracking eye movements;

Handbook of perception and human performance, Ch. 17, Sect. 6.0

5.211 Frequency Characteristics of Real and Induced Visual Motion

Key Terms

Apparent movement; induced motion; motion perception; oscillatory motion; simulation

General Description

Induced motion is the perceived motion of objects that are not actually moving, when other (usually surrounding) objects are physically moving instead (the surrounding moving objects are the uppermost and lowermost horizontal lines, *a* and *d* of Fig. 1a). The uppermost line moves upward while the lowermost line moves downward. Since they are moving in opposite directions, the two lines are described as exhibiting counterphase motion. This counterphase motion can induce an opposed counterphase motion of the inner lines *b* and *c* of Fig. 1a. These lines (*b* and *c*), are actually stationary. The threshold for perceiving motion by these stationary lines (induced motion) is two to three times higher than the threshold for real motion. The threshold for seeing real motion of the outer horizontal lines is between 25 and 50 sec arc of visual angle per sec. The induced motion cannot be seen when the up-down oscillation frequency of the outer horizontal lines exceeds frequencies of 2-5 Hz. At lower frequencies of oscillation, both real and induced motion require a minimal retinal velocity to be perceived. This is reflected in the fact that both types of motion share a common slope of − 1 when threshold amplitude is plotted against oscillation frequency. The real motion threshold will depend upon whether other objects or forms in question are near the moving object (Ref. 2).

Applications

Displays requiring the detection of motion, especially displays containing both stationary and moving elements, in which the moving elements could potentially induce motion in the stationary elements.

Methods

Test Conditions

- CRT display of four horizontal, parallel lines (Fig. 1a)
- Lines subtending 10 deg of visual angle, spaced 1 deg apart
- Outer lines 1.5 deg from foveal center
- Line luminance 0.5 cd/m^2
- Two outer lines driven in simple harmonic counterphase motion by sinusoidal generator
- Oscillation frequency of outer lines 0.2-20 cycles per sec
- Amplitude of oscillation adjusted by observer
- Viewing distance 57 cm; observer fixated center of display
- For induced motion, movement sensation used for threshold criterion was a faint "breathing" of the two inner lines for 3 observers; fourth observer (observer 3 in figure) employed the criterion of the entire four-line display as a compressing and expanding object, so that each inner line appeared to move in phase with the farther outer line, rather than counterphase with the nearer outer line

Experimental Procedure

- Method of adjustment
- Independent variable: oscillation frequency of outer lines (see observer task)
- Dependent variable: peak-to-peak threshold amplitude of outer lines, defined as the amplitude necessary to produce either the perception of real motion in the outer lines or induced motion in the inner lines (see observer task)
- Observer's task: for real motion of outer lines, adjust amplitude of moving outer lines so that motion of these lines was just detectable; for lower limit of induced motion adjust amplitude of moving outer lines so that apparent motion in stationary inner lines was just detectable; for upper limit of induced motion adjust oscillation frequency of moving outer lines so that apparent motion in stationary inner lines decreased to the point of no apparent motion
- 4 observers, with unknown amount of practice

Experimental Results

- Minimum threshold for real motion is an oscillation frequency of ~2 Hz. Beyond 20 Hz there is a lack of sensitivity for real motion (moving lines blur).
- Between 0.2 and 1.0 Hz, on a log-log plot, there is a slope of − 1 between threshold amplitude and oscillation frequency. This suggests that threshold is determined solely in terms of the velocity of the stimulus within the low-frequency range, regardless of frequency or amplitude.
- Minimum lower threshold for induced motion is an oscillation frequency between 1 and 2 Hz, depending on observer; minimum upper threshold is between 2 and 5 Hz, again depending on observer.
- Stated in terms of velocity, the minimum velocity for real motion is between 25 and 50 sec arc of visual angle per sec. The lower angular velocity threshold for induced motion is between 60 and 120 sec arc per sec, and the upper threshold is between 10 and 50 min arc per sec. Furthermore, the common slope on log-log paper of − 1 between amplitude and frequency for both real and induced motion suggests that they share some underlying property. The higher slope for high-frequency induced motion suggests that it does not depend upon the same stimulus property as real motion.
- In Fig. 1, the dashed areas represent conditions under which real motion is perceived. The white areas labeled "Induction" represent those conditions under which induced motion can be produced.

Variability

Precise range of error bars was not given, but probably represented plus or minus one standard deviation. Orientation of error bars is different for upper and lower limits of induced motion, because oscillation frequency was the dependent variable for the upper limit, but amplitude was the dependent variable for the lower limit.

Repeatability/Comparison with Other Studies

The finding of a slope of − 2 on a log-log plot between amplitude and frequency for upper limit induced-motion deter-

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mination is similar to amplitude/frequency limitations for the phi phenomenon, suggesting that they are functions of the same movement detection system in the brain (CRef. 5.401). The lower frequency limitations on induced versus real motion are consistent with earlier qualitative observations (Ref. 1). The looped curve obtained for induced motion is similar to the functions found for other phenomena with upper and lower limits (Ref. 5). The range obtained for minimum velocity for real motion is comparable to that obtained earlier (Ref. 2). The fact that thresholds for induced motion have been reported as lower (Ref. 1) or more variable (Ref. 3) in other studies is probably due to differences in stimulus configurations.

Constraints

- Precise threshold values are likely to vary depending upon observer strategies.
- Thresholds for real movement depend upon proximity to other stationary objects or visual referents. Threshold is high when moving object is in an empty field and low when it is close to other objects (Ref 2).

Key References

1. Duncker, K. (1938). Induced motion. In W. H. Ellis (Ed. and Trans.), *Source book of Gestalt psychology* (pp. 161-172). London: Routledge & Kegan Paul. (Original work published 1929).

2. Leibowitz, H. (1955). Effect of reference lines on the discrimination of movement. *Journal of the Optical Society of America, 45,* 829-830.

3. Mach, A., Fisher, C. B., & Fendrich, R. (1975). A reexamination of two-point induced movement. *Perception & Psychophysics, 17,* 273-276.

*4. Nakayama, K., & Tyler, C. W. (1978). Relative motion induced between stationary lines. *Vision Research, 18,* 1663-1668.

5. Tyler, C. W. (1975). Spatial organization of binocular disparity. *Vision Research, 15,* 843.

Cross References

5.203 Factors affecting threshold for visual motion;

5.208 Displacement thresholds for visual motion: effect of target duration;

5.209 Visual motion detection thresholds: effects of stationary referents;

5.401 Types of visual apparent motion;

Handbook of perception and human performance, Ch. 16, Sect. 1.

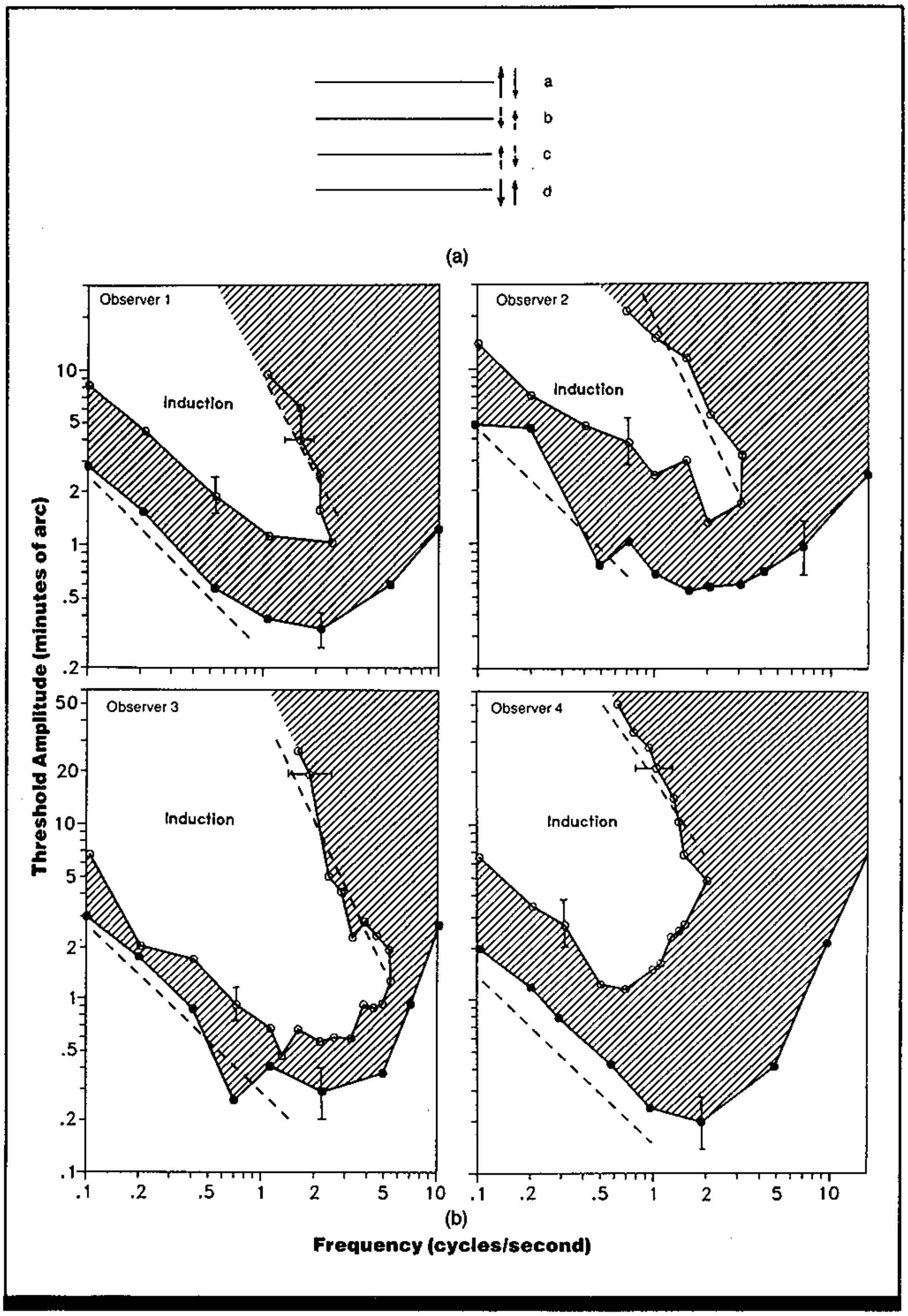

Figure 1. (a) Stimulus configuration used to induce apparent motion. Solid arrows indicate real motion; dashed arrows indicate induced motion. (b) Frequency characteristics of real and induced motion. Filled circles represent threshold amplitude for real motion in outer lines. Open circles represent upper and lower limits for induced motion. Lower dashed line represents a slope of −1, upper dashed line of slope of −2. (From Ref. 4)

5.212 Motion Aftereffects

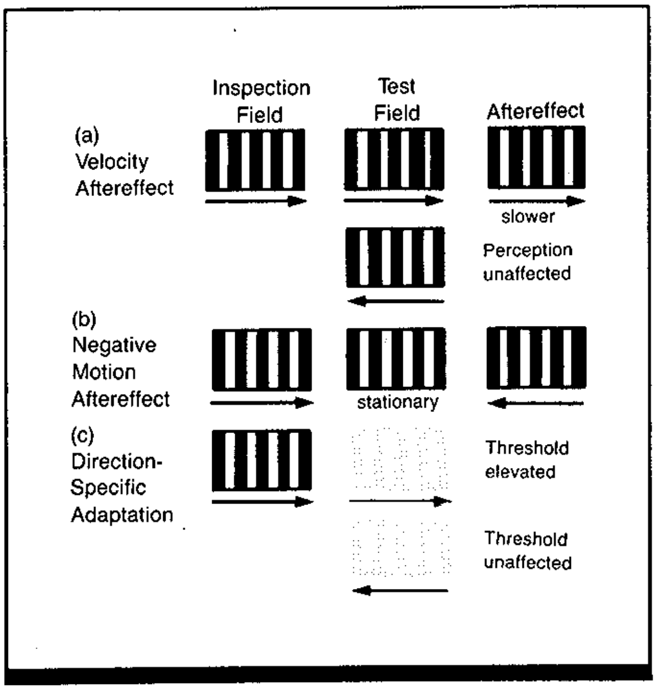

Figure 1. Three motion aftereffects described in the text. Arrows indicate the direction of movement. The dotted test field gratings in (c) indicate low-contrast gratings.

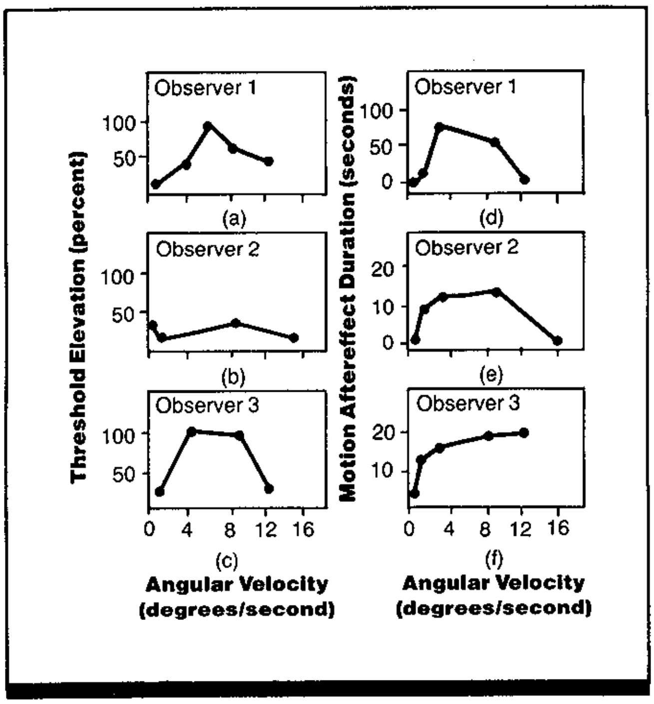

Figure 2. Threshold elevations and aftereffect durations for low-contrast moving bars presented as stabilized retinal images. (a)-(c) percentage threshold elevation calculated as 100 x [(mean nonreverse − mean reverse/mean reverse)] luminance settings for each of 3 observers as a function of angular velocity. (d)-(f) Aftereffect duration as a function of angular velocity for the same 3 observers. (From Ref. 4)

Key Terms

Apparent movement; motion aftereffects; motion perception; simulation

General Description

Motion aftereffects (MAE) refer to apparent changes seen in the motion of a stimulus (test field) after an observer has inspected a field of steadily moving contours (inspection field). Three perceptual effects can occur. (1) After prolonged inspection the velocity of the inspection field itself appears to slow down. In addition, the apparent velocity of a test field moving in the same direction as the inspection field will decrease, whereas the apparent velocity of a test field moving in a direction opposite that of the inspection field will be unaffected (Fig. 1a). These effects are three aspects of the velocity aftereffect (Ref. 4). (2) If the test field is stationary, it will appear to move in a direction opposite that of the inspection field (Fig. 1b). This is called the negative motion aftereffect (Ref. 5). (3) The threshold for motion perception in a low-contrast test field moving in the same direction as the inspection field will be elevated. However, the threshold for a test field moving in the opposite direction from the inspection field is unaffected (Figs. 1c, 2). This is called direction-specific adaptation (DSA) (Ref. 2).

Velocity effects are examined by means of a matching procedure. After adaptation, observers view the test field and matching field next to each other and are required to set the velocity for the matching field until the motion seen there appears equal in velocity to that seen in the test field. Direction-specific adaptation is investigated by having observers first adapt to an inspection field and then set the luminance of a test field until its contours are just detectable. Luminance thresholds are measured for test fields moving in both the same and in opposite directions as the inspection field. The results for a direction-specific adaptation study are depicted in Fig. 2.

These aftereffects presumably result from adaptation of motion analyzers tuned to different directions of motion. The rate of activity of the analyzers decreases when they are exposed to prolonged motion; the time to recover to baseline rates of activity is reflected in the duration of the aftereffect (Ref. 3).

The following factors have been shown to affect motion aftereffects: target contrast, lack of surround, ambient illumination, and viewing time. These effects are summarized in Table 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Operational situations and displays involving viewing of targets moving at constant velocities over prolonged periods of time such as viewing the road from a moving vehicle. This will result in MAE when gaze is directed toward stationary positions inside vehicle. After high-speed driving, a slower speed seems too slow.

Constraints

• Precise determination of aftereffect duration is difficult because it involves seeing motion or change in motion even though objects or pattern elements do not change position. Neural explanations interpret the decaying aftereffect as being masked by a background of neural noise, and therefore its perceived duration will be sensitive to noise level and observer strategies.

• Magnitude of velocity aftereffects can be determined by adjusting the direction and speed of the test pattern until the MAE appears stationary. However, because the aftereffect involves only apparent motion, landmarks used in the test pattern will continue to appear to move (Ref. 4). Furthermore, concentration on the nulling motion can result in adaptation to that motion and can influence the aftereffect (Ref. 1).

Key References

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Cross References

5.203 Factors affecting threshold for visual motion;

5.207 Perceived visual motion: effect of illumination and target exposure duration

Table 1. Factors affecting motion aftereffects.

Factor	Effect	Sources
Contrast	Increases in inspection field grating contrast up to ~3% result in rapid increases in the magnitude of the motion aftereffect (MAE); higher contrast increments up to 10.5% produce much smaller MAE increases. Increasing contrast of the test grating decreases MAE	Ref. 3
Surround	Absence of a patterned surround results in reduction or elimination of MAE	Ref. 1
Viewing time	As viewing time increases, velocity of inspection field decreases; thus MAE is operating on inspection field itself, which will in turn affect test field velocity	Ref. 7

5.213 Judgment of Impending Collision Between Targets in the Display Field

Key Terms

Air traffic control; nonuniform motion; safety; simulation; target acquisition; time to collision; visual acceleration; visual deceleration

General Description

When the paths of two moving objects intersect and the path of one is occluded before the point of intersection, observers most accurately predict a collision when both objects are moving at a constant velocity and no more than half of the track is occluded. Prediction is also accurate when one of the objects exhibits "natural" motion (acceleration followed by leveling to a constant velocity), but it is much less accurate when one of the objects exhibits constant acceleration or deceleration.

Applications

Situations in which observers must judge the likelihood of collision between two objects moving in the forward visual field (e.g., air traffic control).

Methods

Test Conditions

- Bright blue rings, 1.5 deg diameter, with paths intersecting in the middle of the display
- One reference ring moved from top to bottom of display at 9.6 deg/sec for total distance of 48 deg; second right exhibited different movements at average speed of 15 deg/sec starting 18 deg to the left of point of intersection and visible for 0.25 or 0.50 of the distance to the intersection
- Four types of movement: constant acceleration or deceleration, constant velocity, rapidly decreasing acceleration
- Temporal intervals between the arrival of the two rings at the point of intersection from 0 to ±360 msec

Experimental Procedure

- Method of constant stimuli
- Independent variables: type of motion, difference in time of arrival of rings at point of intersection, amount of occlusion of horizontal target
- Dependent variable: perceived time-difference between arrival of the two targets at the point of intersection
- Observer's task: to judge whether the horizontal target arrived at the point of intersection "before" or "after" the vertical target ("same time" judgments were not allowed)
- 11 observers

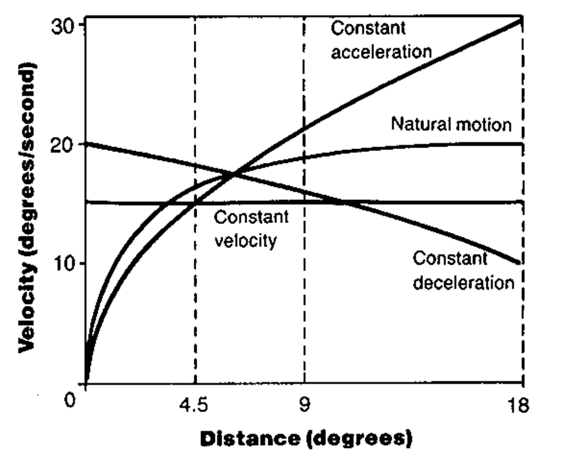

Figure 1. Target motions used, with velocity as a function of distance. Line at 18 deg corresponds to the position of intersection, and dotted lines at 4.5 and 9 deg correspond to positions of occlusion. (From Ref. 2)

Experimental Results

- Prediction of time of collision is most accurate when the horizontally moving targets exhibit either rapidly decreasing acceleration ("natural" motion) or constant velocity with relatively little occlusion.
- Time of collision is predicted too soon when the target decelerates.
- Time of collision is predicted too late when the target accelerates.
- Occluding either 0.25 or 0.50 of the horizontal path has little effect on accuracy of prediction, except when the target velocity is constant.

Variability

There is great variability between observers. The standard deviations of the predicted times of collision averaged 130 msec with the smaller occlusion and 180 msec with the larger occlusion.

Constraints

- The velocities studied are typically too great to be tracked accurately by the eye. Prediction may be much more accurate for slow velocities.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.214 Judgment of impending collision with approaching targets

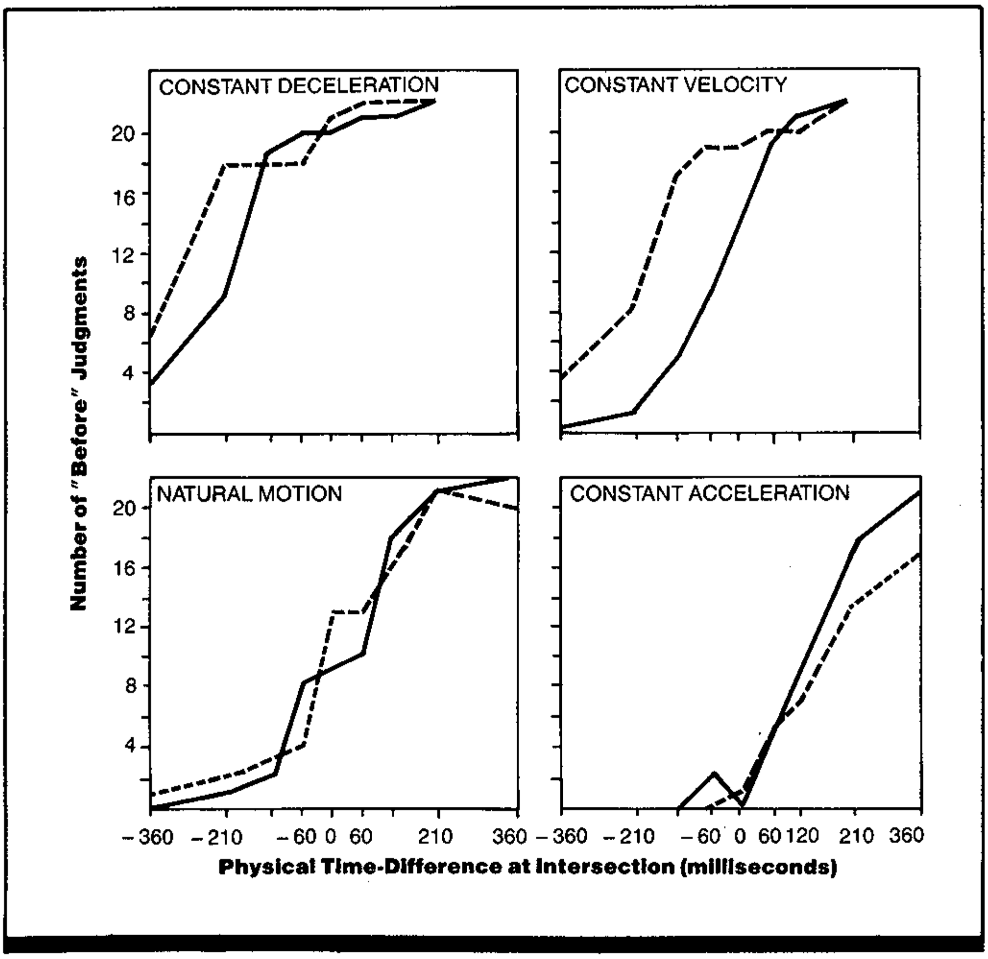

Figure 2. The number of times horizontally moving target was judged to arrive at the point of intersection before a vertically moving target when 0.50 of the horizontal track was visible (solid lines) and when 0.25 of its track was visible (broken lines). Negative time values indicate the horizontally moving target arrived at the intersection after the vertically moving target. (From Ref. 2)

5.214 Judgment of Impending Collision with Approaching Targets

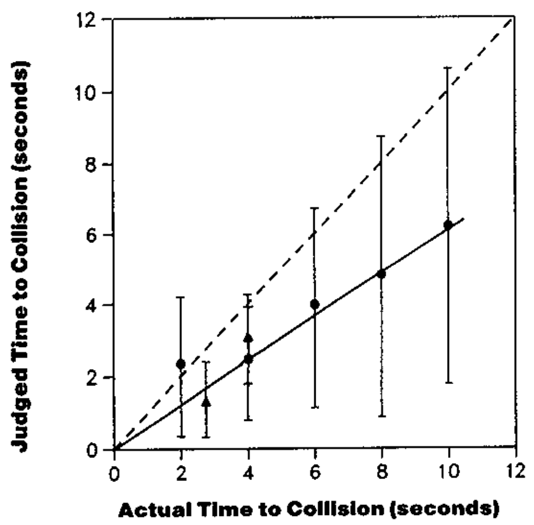

Figure 1. Judged time to collision as a function of actual time to collision. Vertical bars indicate standard deviations. Dashed line represents accurate judgment of time to collision. (From Ref. 1)

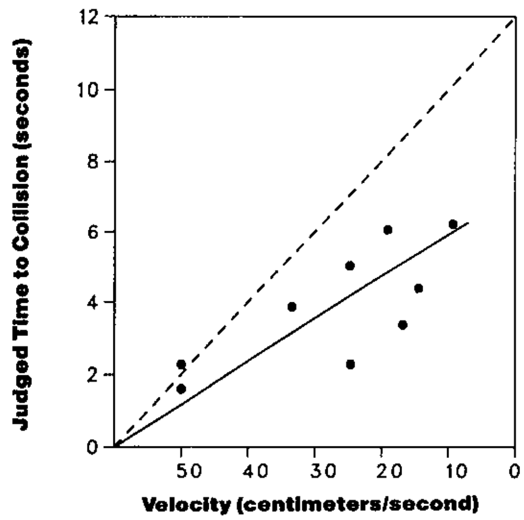

Figure 2. Judged time to collision as a function of object velocity. Dashed line represents accurate judgment of time to collision. (From Ref. 1)

Key Terms

Safety; simulation; target acquisition; time to collision; velocity

General Description

When an object is approaching from straight ahead, observers underestimate the time to collision. The amount of underestimation increases as the actual time to collision increases (Fig. 1) and as the velocity of the approaching object decreases (Fig. 2).

Methods

Test Conditions

- Black forms, 3 cm and 12 cm in diameter
- Background bisected into terrain and sky that were either both plain, both a grid, or one a grid
- Seven approach velocities of 18-90 km/hr
- Objects started approach from 1.2-2.66 m from observer
- Objects disappeared either 1 or 2 m from observer
- Viewing distance 4 m

Experimental Procedure

- Method of constant stimuli
- Mixed design
- Independent variables: target size, target velocity, type of background, length of approach track, distance from the observer at which target disappeared
- Dependent variable: error in judged time to collision
- Observer's task: push a button at the estimated time of collision with the approaching object
- 36 paid volunteers, ages 20-51 with 20/30 visual acuity or better

Experimental Results

- Time of collision is underestimated.
- Amount of underestimation increases as the actual time to collision increases and as the object velocity decreases.
- Results are not affected by target size, background detail, distances traversed, or approach velocities.

Variability

There is great variability in these judgments. Accurate judgments are typically within a standard deviation of the mean values.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The moving target was never closer than 1 m to the observer. When the distance is very short, estimates of time to collision can be very accurate.
- Stimuli were presented in a movie film; there were no three-dimensional stimuli.

Key References

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Cross References

5.213 Judgment of impending collision between targets in the display field;

Handbook of perception and human performance, Ch. 19, Sect. 2.2

5.215 Motion Illusions with Tracking Eye Movements

Key Terms

Aubert-Fleishl paradox; eye movements; Filehne illusion; Fujii illusion; illusory motion; motion perception; pendular whiplash illusion; pursuit eye movements; rebound illusion; simulation; spatial disorientation

General Description

A growing body of evidence indicates that the visual system suffers some loss in accuracy during pursuit eye movements in terms of position constancy (CRef. 5.201) and judging the speed and trajectory of moving objects (Refs. 9, 10, 11). The loss of accuracy in turn gives rise to a number of illusions unique to situations where tracking eye movements occur. The table describes a number of such illusions and conditions that influence their occurrence.

Applications

Environments where observers must judge or use information about object position, velocity, and trajectory while tracking moving targets.

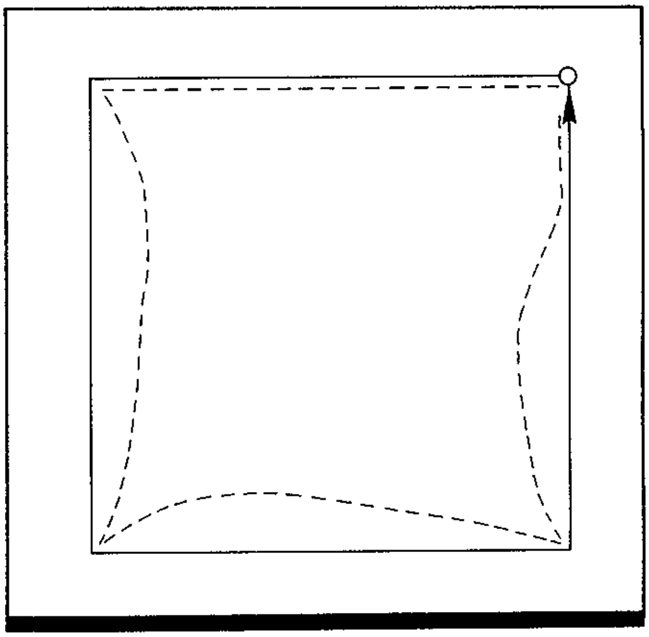

Figure 1. Actual (solid line) and perceived (dashed line) trajectories of a moving spot during pursuit eye movements. (From Ref. 4)

Key References

1. Carr, H. A. (1907). Studies from the psychological laboratory of the University of Chicago. *Psychological Review, 17*, 42-75.

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Cross References

5.201 Subject-relative and object-relative visual motion;

5.217 Perceived motion with tracking eye movements;

5.504 Elevator illusion;

Handbook of perception and human performance, Ch. 17, Sect. 3.4

Name of Illusion	Type of Distortion	Critical Conditions	Sources
Aubert- Fleishl paradox	A moving spot appears to move more slowly when tracked than when the eyes are stationary; estimates range from 10-40% reduction in velocity	Robust illusion, but strongest with pursuit of a harmonically oscillating target	Refs. 2, 10, 12
Filehne illusion	Stationary objects appear to move in the direction opposite to tracking eye movements	Robust illusion, strongest when tracking target is adjacent to stationary stimulus enhancing relative displacement	Refs. 10, 11
Pendular- whiplash illusion	Two points are equidistant from center and on opposite sides of a swinging pendulum; the tracked point appears to move more slowly and through a smaller angle than the untracked point; tracked point stops at extreme positions while other point appears to move	Has not been widely investigated in recent times	Refs. 1, 3
Fujii illusion	A spot that moves in a square trajectory has a distorted perceived trajectory (Fig. 1)	Pursuit movements cannot follow the abrupt direction changes, and therefore overshoot the corners	Ref. 4
Rebound illusion	A target moving in a straight path suddenly stops, but appears to rebound sharply backwards at point where it stops	As in Fujii illusion, pursuit movements overshoot at point of abrupt change	Ref. 8
Unnamed illusions	Afterimages appear to move in the direction of pursuit movements	Occurs with dark field, but visible with vivid afterimage while tracking in daylight	Ref. 7
	While tracking across a field of dynamic random-dot noise, a vague area of the field moves with the tracking movements	Occurs because some random set of dots is stationary on retina due to common motion with pursuit movements	
	A row of dots stroboscopically illuminated appears to move in synchrony with target being tracked	Dot display is ambiguous with regard to identity of dots from frame to frame; movement of dots is preferred interpretation during pursuit	Ref. 6
	Perceived trajectory of target relative to actual one is shortened 10-20% by pursuit	Produced under same conditions as Aubert-Fleishl paradox	
	Perceived trajectory of a circulary moving spot is a spirally shrinking circle or ellipse during pursuit	Illusion greatest at relatively slower velocities and relatively brief viewing time	Ref. 5

5.216 Autokinetic Illusion

Key Terms

Autokinetic illusion; corollary discharge; illusory motion; motion perception; stabilized images

General Description

When a dim spot of stationary light is observed in an otherwise dark room, the spot will appear to move about after a brief period. This phenomenon was first noted by early astronomers while star gazing, and was termed autokinetic motion by Aubert (Ref. 1). The illusion has been well studied and the table describes a number of its characteristics.

There is no generally accepted explanation for the illusion. One explanation attributes it to spontaneous shifts in apparent egocentric position in the dark (Ref. 2). There is, however, no independent evidence of such spontaneous shifts in egocentric position. More widely accepted explanations attribute the autokinetic illusion to eye movements. It has been suggested that the illusion might be caused by involuntary slow drifts during fixation (Ref. 7). This is supported by experiments with retinal stabilization, but it is contradicted by the greater magnitude of autokinetic motion and by demonstrations that a retinally stabilized (afterimage) and normal target move together (in phase) during autokinesis (Ref. 6). The most compelling explanation implicates corollary-discharge signals maintaining stable eye movements against differential fatigue of the eye muscles (Ref. 6). In general, these signals would not move the eyes but would compensate fatigue and imbalance-related drift. It is thus consistent with correlated motion of stabilized and unstabilized images. The mechanism of apparent motion due to corollary discharge in the absence of eye movements has been convincingly established (CRef. 5.202), but this mechanism remains to be established as causal in the autokinetic illusion.

Applications

Fixation of dim targets in dark environments.

Factor	Result	Sources
Magnitude of illusory motion displacement	Up to 30 deg maximal displacement are reported; average reports are 3-4 deg	Refs. 5, 8
Velocity	Estimates range from 12 min/sec to 15 deg/sec, a range of 75:1	Refs. 3, 5, 6, 8
Characteristics of motion over time	Motion can be perceived without displacement; speed and amplitude are generally not correlated; initially motion may be jerky but then smoothes out; prolonged viewing or fatigue leads to accentuated effects	Refs. 3, 4, 6, 7
Background characteristics	Illusion is most salient in dark room; presence of other objects reduces illusion	Ref. 6
Target position	Extreme gaze angle leads to immediate motion in the direction of ocular deviation	Ref. 3
Stabilized targets	Stabilization along horizontal axis greatly reduces reports of movement along that axis; stabilized (afterimage) and normal target will move in tandem	Refs. 6, 7
Set, individual differences	50% of naive observers fail to report illusion; alerting observer increases likelihood of report; one can influence deviation of motion or even convince observer that light is spelling words	Refs. 4, 6

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.202 Image/retina and eye/head systems of motion perception;

5.215 Motion illusions with tracking eye movements

5.217 Perceived Motion with Tracking Eye Movements

Key Terms

Apparent movement; Filehne illusion; motion perception; simulation; smooth pursuit eye movements; target acquisition; tracking; visual position constancy

General Description

When a moving target is being visually tracked, stationary background objects may appear to move in the opposite direction (the Filehne illusion, which is an apparent failure of position constancy). With target velocities ranging from 0-5 deg/sec, a stationary background appears to move in the opposite direction 61% of the time for long exposures (1.2 sec) and 58% for short exposures (0.2 sec). Background objects are judged stationary when they are moved in the same direction as the pursuit target at 0.96 deg/sec and 3.35 deg/sec for long and short exposures, respectively. The loss of position constancy of background objects during target tracking is accompanied by an underestimation of target velocity; the amount of underestimation is determined by target and background exposure time, as well as by background complexity, velocity, and direction of movement.

Applications

Design and evaluation of visual displays; selection and training of display operators; interpretation of displayed data; tasks where an observer is required to detect small differences in target velocity.

Methods

Test Conditions

Study 1 (Ref. 3)

- 0.5-deg-wide vertical line as visually pursued target on oscilloscope, with point as background object; point bisected target line when presented
- Background spot presented for 0.2, 0.33, or 1.2 sec
- Target line moved left or right at constant velocity (5 deg/sec) for 0.2- or 1.2-sec background-exposure times; 3 deg/sec for 0.33-sec exposure time; target traveled 7.5 deg before presentation of background point; background point moved in either direction at 0-5 deg/sec
- Counterbalanced order of conditions
- 35-cm viewing distance; binocular viewing; right-eye movements monitored by tracking double-Purkinje image; head rest and bite plate immobilized observer's head

Study 2 (Ref. 2)

- 0.6-cm luminous disk as visually pursued target; background was comprised of black vertical lines placed 0.6-1.3 cm apart and 0.6-1.3 cm wide; lines interspersed with black rectangles of 0.2-1.3 cm background; illuminated from rear; only target and background were visible
- 1-mm fixation target and a nonluminous comparison target used for some observations
- Target velocities of 3-10.5 deg/sec; background velocity varied from 0.25-1.0 deg/sec
- Viewing distance of target was 30.1 cm; distance between target and background 7.6 or 68.6 cm
- Fixation point used for some observations; monocular and binocular viewing; bite bar steadied observer's head

Experimental Procedure

Study 1

- Methods of limits with three-alternative forced-choice procedure
- Within-subjects design
- Independent variables: exposure time, direction and velocity of background movement, direction of target movement
- Dependent variables: threshold, determined when direction and velocity of background judged consistently as motion with or against target motion for three consecutive presentations
- Observer's task: track target from left to right and report if background point moved left or right or was stationary
- 6 paid observers with 20/20 visual acuity in each experiment, with some practice

Study 2

- Method of limits: three-alternative, forced-choice, randomized presentation for Exps. I and II; method of constant stimuli ascending and descending for Exp. III
- Mixed design for Exps. I and II; within-subjects design for Exp. III
- Independent variables: target velocity, separation of target and background, background velocity and direction, monocular versus binocular viewing, use of fixation target, use of a second target track (Exp. III)
- Dependent variables: estimated direction and velocity of background, thresholds based on results of 36 trials for Exp. I and II; velocity match of two moving targets based on 10 trials for Exp. III
- Observer's task: for Exps. I and II, report presence and direction of background movement; for Exp. III, track moving target, fixate on point, adjust speed of second target to first target speed
- 36 paid college students (Exp. I), 20 for Exp. II, 6 for Exp. III, with some practice

Experimental Results

Study 1

- A background point moving in the same direction as a target moving at 5 deg/sec will appear stationary, even if moving at a higher velocity, when the duration of presentation is shortened (e.g., a 0.96 deg/sec target will appear stationary with a 1.2-sec presentation, and a 3.35 deg/sec target with a 0.2-sec presentation). This difference is not due to gross differences in eye-movement velocities or in accuracy of tracking.
- When the target moved at 3 deg/sec for a 0.33-sec presentation of the background point, on average the point is judged stationary even when moving at 2.23 deg/sec.
- With a stationary background point and target velocity of 5 deg/sec, the Filehne illusion of movement (i.e., loss of **visual position constancy**) occurs 61% and 58% of the time for the 1.2- and 0.2-sec presentations of the background point, respectively.

Study 2

- Increasing background velocity yields increasingly accurate reports of background movement.
- For binocular viewing, the Filehne illusion of movement of a stationary background target occurs on ~38% of the trials when background and target are separated by 68.6 cm, but occurs infrequently when there is only a 7.6-cm separa-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

tion. (Only 44% of subjects reported the illusion in any condition.)

- For monocular viewing, illusionary movement in the direction away from the target is reported on 30% of the trials for all conditions (both 7.6 and 68.6 cm).
- The illusion affects reports for moving backgrounds; for several conditions, movement in the direction away from the target is reported correctly much more often than background movement in the same direction as the target.

Variability

No information on variability was given for Study 1. Analysis of variance was used to analyze results for Study 2. There are large individual differences, as only 16 of 36 subjects (44%) experienced the illusion on at least one trial (with a stationary background) in Exp. I of Study 2.

Repeatability/Comparison with Other Studies

Reference 1 supports the conclusions of Studies 1 and 2 that the loss of background position constancy during visual tracking is a function of eye movement and retinal-displacement information. Reference 4 supports Studies 1 and 2 in general, but demonstrates that the perceived movement of the background during visual tracking does not occur with saccadic eye movements.

Constraints

- A number of factors, such as target velocity, exposure time, ambient illumination, and viewing distance, must be considered when applying these data.
- No data on practice effects or age differences are reported.

Key References

1. Mack, A., Fendrich, R, & Sirigatti, S. (1973). A rebound illusion in visual tracking. *American Journal of Psychology,86*, 425-433.

*2. Mack, A., & Herman, E. (1973). Position constancy during pursuit eye movement: An investigation of the Filehne illusion. *Quarterly Journal of Experimental Psychology, 25*, 71-84.

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Cross References

5.203 Factors affecting threshold for visual motion;

5.210 Visually perceived relative velocity: effects of context and extent of motion;

5.215 Motion illusions with tracking eye movements;

5.604 Target localization during pursuit eye movements;

Handbook of perception and human performance, Ch. 17, Sect. 3.3

5.218 Motion Illusions

Key Terms

Apparent movement; depth perception; escalator illusion; interocular delay; motion illusions; Pulfrich effect; simulation; spatial disorientation

General Description

Figure 1 illustrates the conditions for an illusion called *apparent pausing*. Identical dots moving in opposite directions at constant speed appear to pause momentarily when they meet before continuing on their respective paths. For this illusion to occur, the dots must become coincident or at least touch. However, if the two dots are separated in apparent depth via the Pulfrich technique, pausing still occurs. The apparent pausing is assumed due to a vector averaging process; since the average velocity at the moment of coincidence would be zero, a perceptual pause is experienced.

A second motion illusion is called the *dynamic visual noise stereophenomenon*. A detuned television receiver shows a snowstorm of randomly twinkling points, known as dynamic visual noise. When such a receiver is viewed with both eyes, one of which has a neutral density filter in front of it, the displayed visual noise will appear to separate into two depth planes. The noise in the forward-protruding plane will appear to move in a direction from the unfiltered to the filtered eye; the noise in the recessed plane will appear to move in the opposite direction. The filter, by reducing retinal illuminance, is thought to produce an interocular delay resulting in a spatial disparity. This effect will occur even with those subjects who do not experience depth effects with static or dynamic random-dot stereograms.

The stereophenomenon produced by means of monocular filtering is similar to one produced by introducing real temporal delays into **haploscopic** displays (Refs. 3, 4); Fig. 2a illustrates the basis for the effect. The left and right eyes are shown viewing events at Time t_2. The spot at a transmitted by the right eye at Time t_1 (solid circle) is transmitted by the left (filtered) eye at time t_2 (open circle) because of the interocular delay introduced by the filter. If a second spot appearing at a' is transmitted by the right eye at Time t_2, the lateral retinal image disparity thus created will cause a spot to be perceived in a different depth plane at b. The monocular sequences of spots transmitted by the right eye at a (t_1) and a' (t_2) and by the left eye at a (t_2) and a' (t_3) are both preconditions for monocular apparent movement to the right associated with the spot at depth b. Figure 2b shows the reversal of the sequence shown in Fig. 2a. When the second spot appears to the left of a at a'', rather than to the right, reversal of both depth and movement occur. In a random display, the two sequences together produce the dynamic visual noise stereophenomenon. Illusory movement can also be seen by viewing a stationary display of shaded stripes, as shown in Fig. 3. This effect is called the *escalator illusion*. A majority of observers perceive motion in the direction from the dark to the light areas, and the left and right portions of Fig. 3 produce illusory movement in opposite directions. Repeated tests separated by 2-3 yr show high consistency. Real rotation of the figures at a slow rate (0.68 revolutions per min) increases illusory motion in the figure with dark-to-light shading in the direction of the rotation. At very slow rates of rotation (0.1-0.4 revolutions per min), rotation in a direction opposite to the dark-to-light shading will stop the illusory motion. The basis of the effect is unknown.

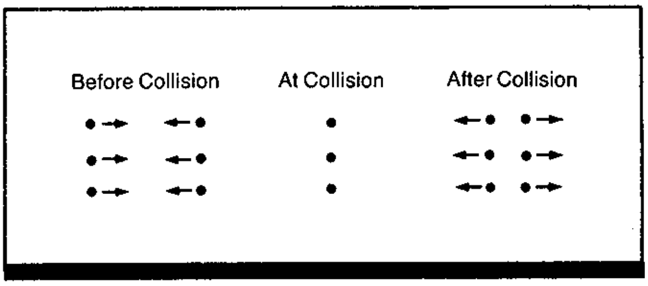

Figure 1. Stimulus for the *apparent pausing* illusion (see text). (From Ref. 2)

Constraints

- It is crucial for apparent pausing that the velocity of the dots remain constant; increasing velocity at collision nullifies the effect.
- When large disks are used instead of dots, apparent pausing will be experienced only with precise center-to-center alignment.
- The dynamic visual noise stereophenomenon has been demonstrated within the interocular delay range of 5-70 msec. The effect cannot be obtained with >70-msec delays.
- Perception of the escalator illusion is highly variable between subjects. The following groups have been distinguished: 24.9% report inconsistent movement or no movement; 59.0% report movement from dark to light shading; 6.5% report movement from light to dark shading; and 9.6% report movement sometimes in one direction and sometimes in the other.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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*5. Tyler, C. W. (1974). Stereopsis in dynamic visual noise. *Nature, 250*, 781-782.

Cross References

5.215 Motion illusions with tracking eye movements;

5.216 Autokinetic illusion;

5.219 Illusions of motion resulting from incorrect perception of depth;

5.220 Vernier offset in real and apparent motion;

5.221 Decomposition of composite motion;

5.802 Illusory spatial displacements;

6.306 Reversible or multistable figures;

Handbook of perception and human performance, Ch. 16, Sect. 3.4

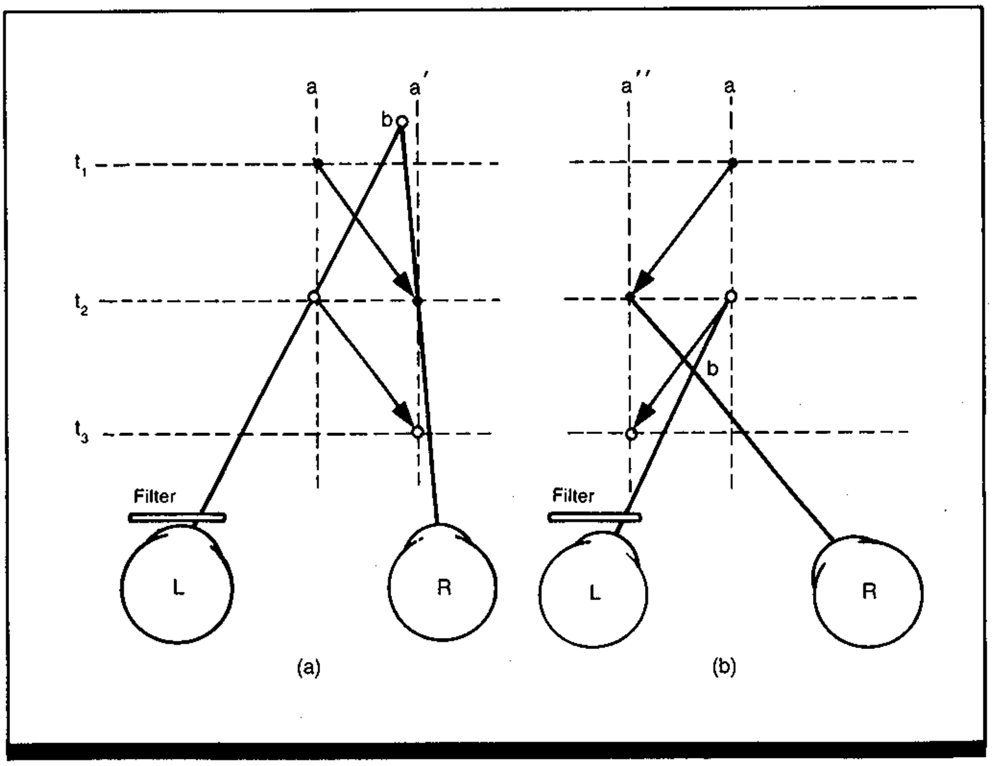

Figure 2. A sequence of stimulus presentations with temporal delays that yields an illusion similar to the *dynamic visual noise stereophenomenon* (see text). (From Ref. 5)

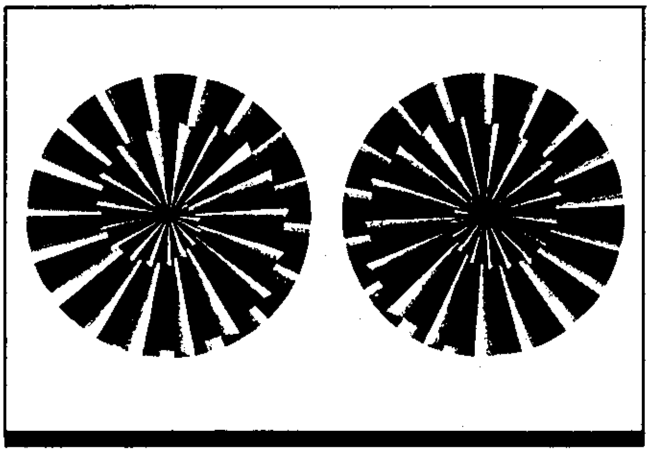

Figure 3. Stimuli that typically produce the *escalator illusion* (see text). (From Ref. 1)

5.219 Illusions of Motion Resulting from Incorrect Perception of Depth

Key Terms

Computer-generated imagery; depth perception; event perception; motion parallax, simulation

General Description

When an observer moves relative to a field of objects, the observer's motion leads to movement of the object's images on the observer's retina. Velocity and direction of the retinal image motion are determined by the observer's direction and speed of motion and the object's distance from the observer (CRef. 5.902), particularly when an observer moves laterally with eyes fixated on a distant point.

The velocity of retinal image motion is inversely proportional to the object's distance from the observer. This observer-induced image motion, known as motion parallax, provides potential information about depth, although it may be a weak indicator in isolation (Ref. 1). Nonetheless, parallax transformations consistent with the relative distances of objects are expected by the visual system. Where object depth is misperceived, the expectation of parallax transformations may lead to illusions of object motion with stationary objects (see table).

Table 1. Illusions of object motion with stationary objects.

Condition	Effect	Explanation	References
When viewing wireframe objects	When viewed monocularly, a wire object readily reverses perspective (the far face of the cube appearing near and vice versa) much as the outline Necker cube does. If the observer moves while perceiving the object in reversed perspective, the object appears to rotate.	For a given depth relation between two points, an associated parallax transformation should occur during observer movement (Fig. 1). In the example noted, the depth relationship is misperceived; hence, the associated parallax transformation does not occur. Instead, a parallax transformation consistent with the time depth relations occurs. This image transformation is consistent with object rotation, if the misperceived depth relationship were the time depth relationship.	Ref. 2
When viewing stereograms	When stereograms are viewed under conditions that permit head movement while the images are fused, parts of the image that appear relatively close to the viewer appear to move in the same direction as the head. Parts that are relatively far away appear to move in an opposite direction.	Because the display is flat, there is no parallax transformation between parts of the figure. The visual system interprets the absence of parallax transformation as a field of object motion which cancels the parallax transformations.	Ref. 2
During rapid observer motion	It is common to experience motion illusions during rapid vehicular motion. A common example is the child's belief that the moon follows the vehicle.	The distance of far away objects is often misjudged because many depth cues are not very sensitive at great distances. If distance is misjudged so that the object appears closer than it is, then stationary objects appear to follow the observer.	

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.901 Monocular distance cues;

5.902 Motion parallax;

5.904 Functional limits of various depth cues in dynamic visual environments;

Handbook of perception and human performance, Ch. 33, Sect. 4.4

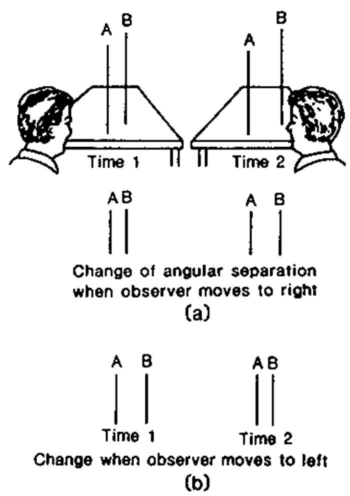

Figure 1. A rule of parallax. When a stationary object, or Contour B, appears to be behind another stationary object, or Contour A, and the observer moves to the right, the angular separation between A and B increases; if the observer moves to the left, the angular separation between A and B decreases. Therefore, if the depth relation between A and B is misperceived, for example reversed, then when the observer moves, the parallax change does not follow the rule for stationary objects, and an illusion of motion is perceived. (From Ref. 2)

5.220 Vernier Offset in Real and Apparent Motion

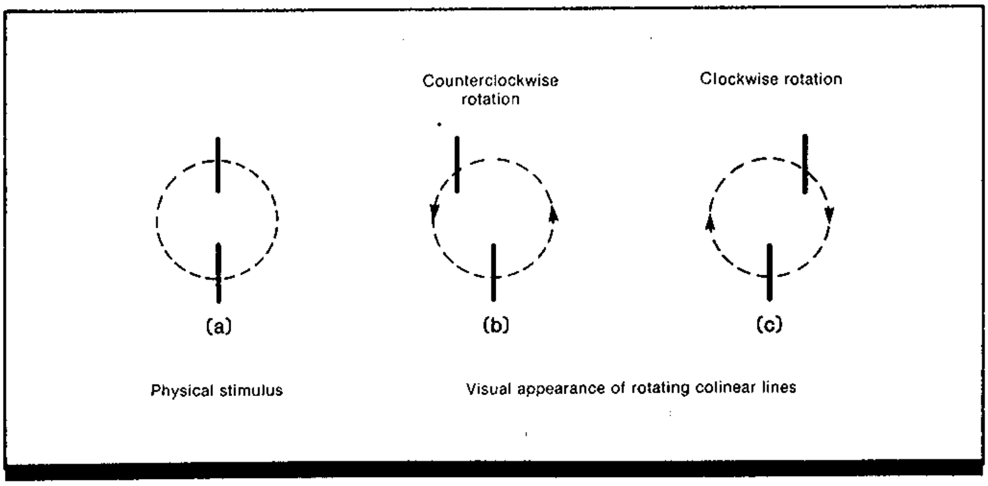

Figure 1. (a) Physical stimulus used in Study 1. (b), (c) Visual appearance of lines in (a) during rotation. (From Ref. 3)

Key Terms

Apparent movement; dynamic visual acuity; motion induced offset; rotary motion; rotation; vernier acuity; visual acuity

General Description

A vernier target rotating 0.7 revolutions per sec produces a perceptual distortion, such that two line segments that are colinear appear offset from each other by ~4 min arc of visual angle (Study 1). Furthermore, a vertical vernier target in apparent motion illuminated stroboscopically, so that upper and lower segments are presented colinearly, but separated in time such that the lower segment is illuminated 10 msec after the upper segment, causes observers to perceive the upper segment as leading the lower segment in motion (Study 2). This latter effect will occur only if the stimulus display is perceived as in motion.

Methods

Test Conditions

Study 1 (Ref. 3)

- Stimulus configuration as shown in Fig. 1; pair of vertical lines 24.8 min arc long by 0.13 min arc wide, separated by 16.6 min arc; luminance 13.62 cd/m^2
- Array of eight continuously lighted points arranged in a 1.9-deg circle; luminance 11.14 cd/m^2
- Target rotated clockwise or counterclockwise
- Stationary targets presented for 11, 275, or 1003 msec
- Viewing distance 5.24 m; CRT display in darkened room; observer's head stabilized by chin rest
- Beamsplitter placed in front of observer's eye to combine circular array and vertical lines
- Rotational velocity of vertical lines 0.7 revolutions per sec, accomplished by means of rotating Penchan prism

Study 2 (Ref. 1)

- Stimulus display on CRT as shown in Fig. 2; pair of vertical lines 1 deg long by 5 sec arc of visual angle wide; luminance 100 times detection threshold
- Uniform background luminance 5 cd/m^2
- Each line intensified for 50 μsec at 25-msec intervals at seven successive discrete stations (Fig. 4) each separated by 2.5 min arc; upper line always intensified 10 msec before lower line
- Direction of lines random between trials, starting 15 min arc left or right of fixation and ending at fixation

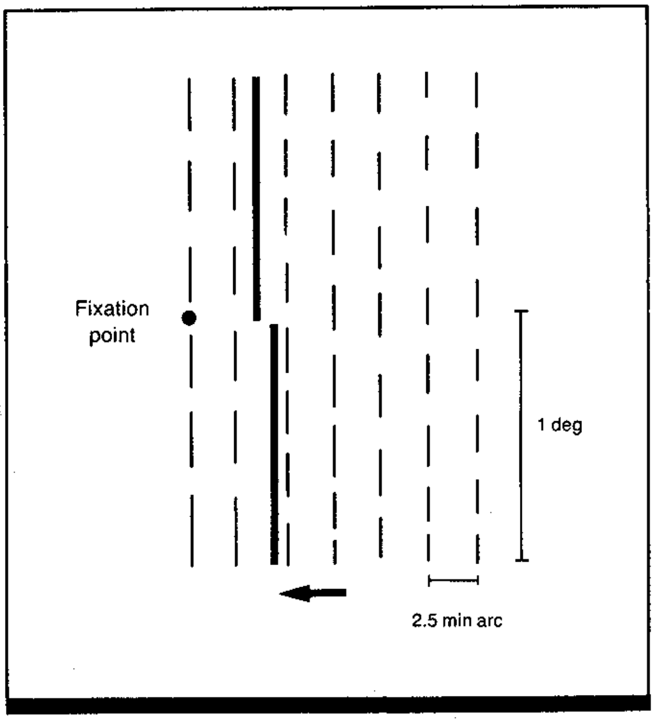

Figure 2. Stimulus presentation display used in Study 2. Dashed lines indicate seven locations for presentation. (From Ref. 1)

Experimental Procedure

Study 1

- Method of constant stimuli
- Independent variables: target rotation, target orientation in degrees, duration of presentation for stationary targets
- Dependent variable: point of subject equality (PSE), defined as min arc of vernier offset at which the two vertical lines appeared colinear
- Observer's task: report by means of manual switch closure the position of the top line relative to the bottom line
- 10 observers, with extensive practice

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Study 2

- Precise method not specifically stated, probably method of constant stimuli
- Independent variables: line segment (vernier) offset in sec arc; temporal or spatial offset, defined as line segments intensified at the same position but offset in time, or intensified at the same time and offset in space, respectively
- Dependent variable: vernier acuity, defined as 75% correct identification of the apparent offset of the top from the bottom segment (threshold calculated by **probit analysis**)
- Observer's task: identify the direction of the apparent offset of the top from the bottom line
- 2 observers, with extensive practice

Experimental Results

- In Study 1, the median point of subjective equality (PSE) to produce the appearance of colinearity for a target rotating clockwise is ~4 min arc to the left; for counterclockwise rotation the median PSE is ~4 min arc to the right (large solid circles, Fig. 3). This effect is greater than any obtained for stationary targets at different orientations (curves, Fig. 3). The symmetrical vernier offset is not a result of a change of stationary PSE with orientation, implying that the effect is caused by stimulation due to movement.
- The correlation between PSEs for the clockwise and counterclockwise conditions is −0.78.
- The effect may be produced by viewing a vernier target while rotating the head. Phenomenally, the effect will be experienced as a vernier offset in the direction opposite to the head rotation.
- In Study 2, vernier acuity for spatial offset is 6.6 sec arc of visual angle and 10.3 sec arc for the 2 observers; acuity for the temporal offset is 11.0 and 12.8 sec arc, respectively. Spatial acuity is slightly better than temporal acuity. Phenomenally, the upper line segment, intensifying prior to the lower segment, appears to be leading the lower segment, even though they are colinear. These results demonstrate that vernier offset can be detected from only temporal information, even when spatial offset information is not available, and that this detection is almost as precise as with the use of spatial information.
- When the experiment is repeated without using all seven stations leading up to fixation (so that only the last two bars containing offset information are displayed), observers are prevented from detecting temporal offsets. This implies that temporal offsets can be detected only when such a display is perceived to be in smooth motion.

Variability

In Study 1, the range of PSEs for the rotating target exceeded the range of PSEs for the stationary target. Correlation coefficients between the two measures of 0.77, 0.77, and 0.93 for 11-, 275-, and 1003-msec stationary target durations, respectively, indicate that 60-86% of the variance of the two measures is common to both. No information on variability was given for Study 2.

Repeatability/Comparison with Other Studies

The effect described in Study 1 has been reported by more than 50 observers (Ref. 3). Apparent motion effects of the type described in Study 2, in which stroboscopic motion is perceived as identical to real motion, are quite common (Refs. 2, 4, 5; CRef. 5.401). Temporal delays for minimum detectable apparent offset in Study 2 are very similar to those reported elsewhere (Ref. 6).

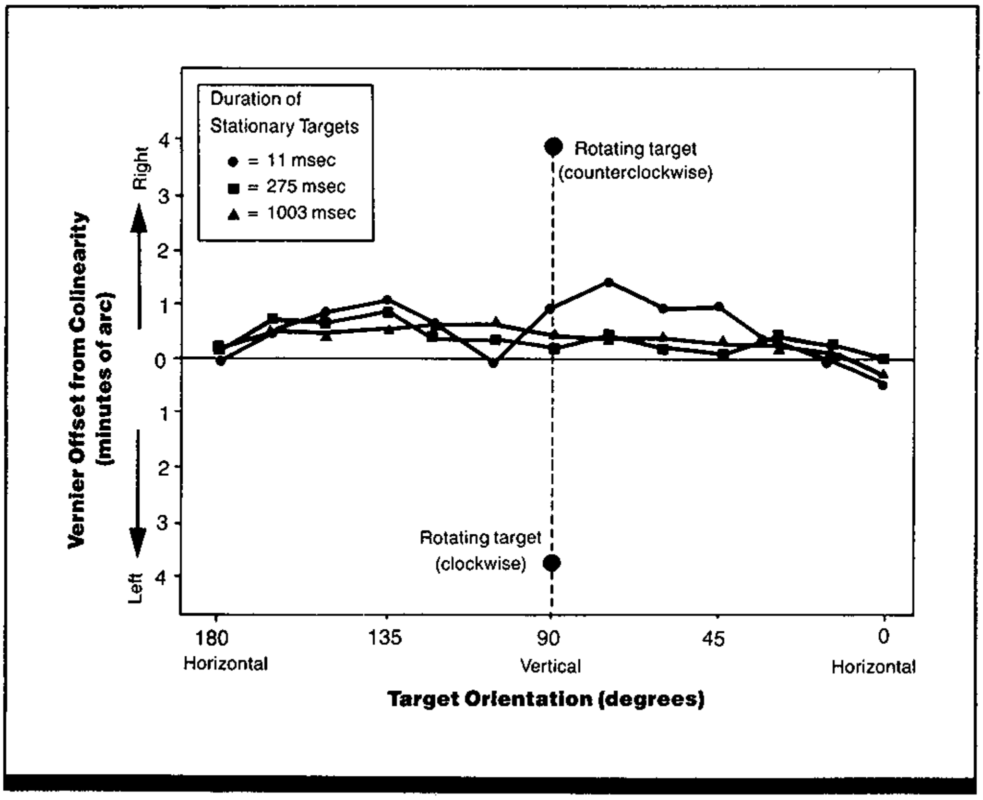

Figure 3. Median points of subjective equality (PSE) for stationary targets and for rotating targets (Study 1). The y-axis indicates the amount of offset necessary to make the two vertical lines appear colinear. (From Ref. 3)

Constraints

- Precise values for vernier acuity reported here will vary between observers.

Key References

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Cross References

1.607 Vernier acuity and orientation sensitivity: effect of adjacent contours;

1.610 Vernier acuity: offset discrimination between sequentially presented target segments;

5.302 Factors affecting induced motion;

5.401 Types of visual apparent motion;

Handbook of perception and human performance, Ch. 16, Sect. 3.4

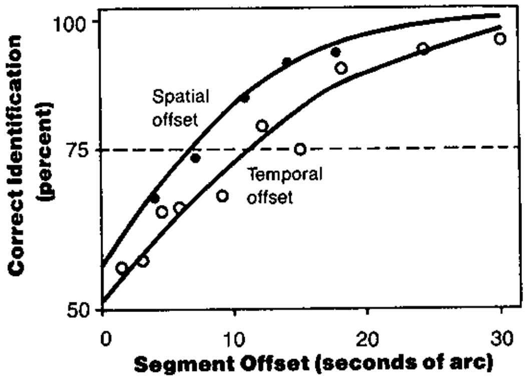

Figure 4. Percentage correct identification of spatial and temporal vernier offset for one subject (Study 2). Horizontal dashed line represents 75% accuracy criterion for threshold determination. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.221 Decomposition of Composite Motion

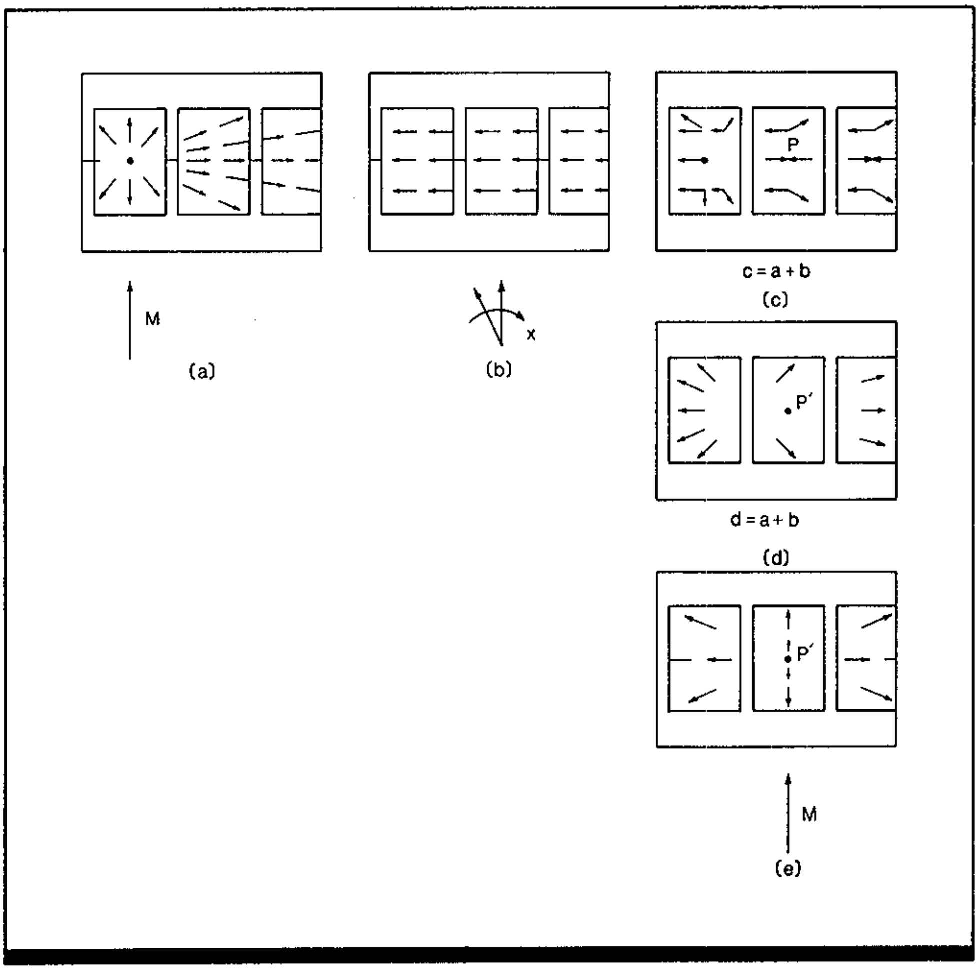

Figure 1. Compound motions. (From Ref?4)

Key Terms

Composite motion; information portrayal; lamellar field; motion analysis; motion perception; solenoidal field; visual simulation

General Description

Simple movements of a camera and/or viewer of a motion picture combine into complex motion patterns. Several theories have been offered to describe the perceptual information of composite motions. Figure 1 presents an example of the phenomenon of compound motions. Panels (a) and (b) present simple camera movements and Panels (c) and (d) are composites of these motions. Panel (a) shows the optical expansion pattern produced by a movement, *M*, toward the left wall. Panel (b) shows the optical flow pattern produced by a camera pan through angle *x*. In Panel (c), the camera (or viewer) pans through angle *x* while moving toward the left wall to keep the center of the middle wall fixed on the film (or retina). In this case, the fields shown in Panels (a) and (b) act on the same points. In Panel (d) the two fields at Panel (c) are summed, point by point, and the opposed vectors cancel at *P′*. Although *P′* is then stationary, the vectors in the display do not point back to *P′* and so it is not the center of expansion. *P′* will be both stationary and the center of expansion only if, as in Panel (e), the camera or viewer moves toward and sights on *P′*. It is an empirical question whether viewers can distinguish Fields (c) and (d) from Field (e); there is some evidence (Ref. 8) that they cannot.

In his analysis of motion picture perception, Gibson (Refs. 1, 2) cautions that picture perception, although having aspects in common with perception of the environment, may require a separate analysis. Although the camera is analogous to the eye, there are substantial differences. Gibson's approach to decomposing composite motions is to search for the invariant information in the optical flow field that is specific to a certain event. For example, a camera's or a person's approach to an object results in the magnification of the object plus a focus of expansion (or vanishing point) in the direction of the movement. When scanning a scene there is a progressive gain and loss (accretion and deletion) of textural elements at the leading and trailing edges of the field of view.

Johansson (Refs. 5, 6) has proposed a method of perceptual vector analysis in which any motion component that is common to all the objects in the field is separated perceptually from the relative motions among the objects. The relative motions in the display are treated as a perceptual unit and the common component is treated as a reference frame for the motion of this unit. Johannson also notes that locomotion (or camera motion in a motion picture display) is specified by a continuous flow of optical patterns over the whole retina; motions of an object in the display would correspond to only local flows over the retina.

Koenderink and Van Doorn (Ref. 7) separate the optical flow field into exterospecific (structure of the environment) and propriospecific (determined through observer's movement) components. Propriospecific components determine a solenoidal (source-free) field. This field is indistinguishable from rigid rotation and therefore it can be exactly cancelled by an eye movement. The exterospecific component yields a lamellar (curl-free or vorticity-free) field due to velocity components perpendicular and parallel to the plane. The position of singular points indicates the direction of movement with respect to plane. Unlike the solenoidal field, the lamellar field is unaffected by rotational movements of the observer. Movement information can be extracted by the observer by rejecting the vorticity of the field which will exclude eye or camera movement which would produce disturbance in the optical flow.

Key References

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Cross References

5.204 Perceived target velocity in the visual periphery;

5.211 Frequency characteristics of real and induced visual motion;

5.212 Motion aftereffects;

5.501 Displays providing self-movement information;

11.220 Canonical view: homogeneous and inhomogeneous translation of objects in the field of view;

11.221 Differentiation of targets in TV and cinematic displays

5.222 Perception of Rigid Versus Nonrigid Motion

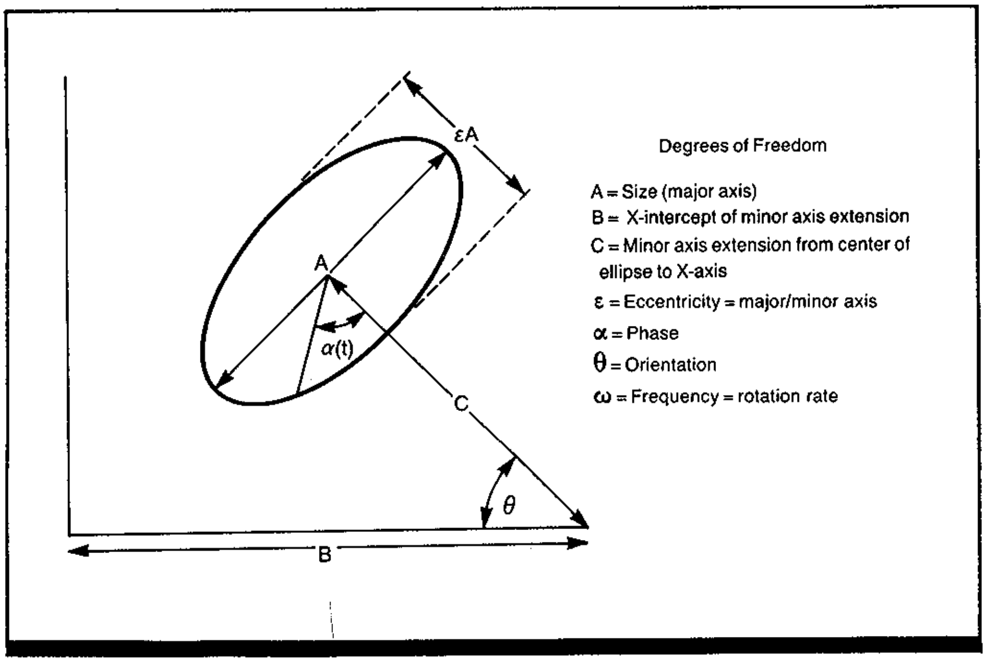

Figure 1. Parallel projection of a single point rotating about a fixed axis. The elliptical trajectory is described by seven parameters: size *A*, *x*-intercept *B*, distance *C* from the center of the ellipse of the *x*-intercept, and phase α at time *t*. (From Ref. 3)

Key Terms

Depth perception; motion perception; object rigidity; rotation perception; shape perception; visual simulation

General Description

What visual information is used and how accurately it is used in perceiving object shape and rigidity (or lack thereof) can be studied by mathematical analysis and laboratory studies. Two sets of cues provide information about rigidity: (1) all points on a rigid body that is rotating must move through three-dimensional space on circular paths and the centers of all paths must lie along a straight line perpendicular to each plane of rotation; (2) all points must traverse their paths at the same rotation rate (frequency).

Rotating bodies may be simulated by computer-rotated outline images on a (flat) CRT. With such a planar projection of three-dimensional motion, rigid motion is indicated when: (1) the projected images of all points on the object move about the projection surface along elliptical trajectories and the minor axes of these trajectories lie along a straight line; and (2) all of the points traverse their trajectories at the same frequency. It has been shown that rigid motion can be distinguished from nonrigid motion in such computer projections on the basis of four characteristics of the motion paths: frequency, orientation, eccentricity, and the *x*-intercept of a line formed by extending the minor ellipse axis to the *x*-axis (see Fig. 1). In theory, these four parameters are constant for rigid bodies, but not for nonrigid bodies. Eccentricity is the least effective cue to motion rigidity, because it is not constant when the rotating body is viewed in polar projection with the linear perspective axes retained.

For trajectory (path) analysis of the rigidity of a rotating object seen in parallel projection, the amount of each element's trajectory that is seen is the critical variable. Trajectory segments below 180 deg lead to deteriorating accuracy in discriminating rigid from nonrigid motion. Accuracy is also reduced with precession (rotation accompanied by axis wobble). The mathematical limitations of trajectory-based analysis information are consistent with the perceptual limitations of tests with observers.

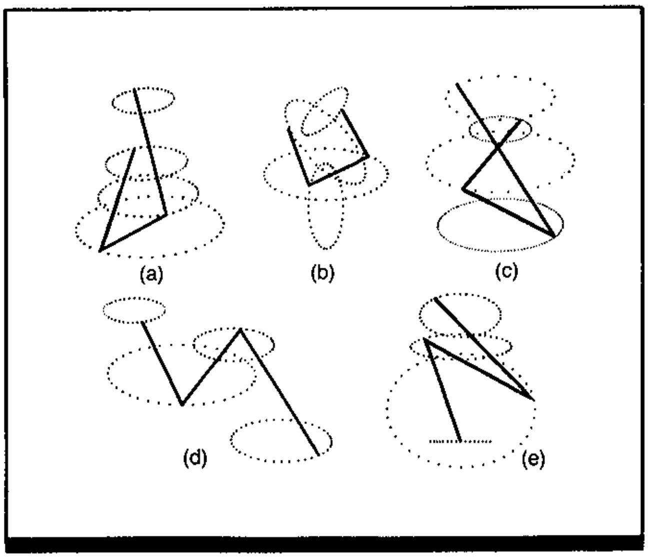

Figure 2. Five different classes of motion. Each ellipse is the image path under parallel projection of the endpoints of a straight line segment; the number of dots per ellipse is the number of time intervals to traverse the path. Case (a) is rigid motion because all paths have the same values of parameters θ, ω, *B*, and ε. (b)-(e) non rigid motion: ellipses with different (b) orientation ε, (c) frequency ω, (d) *x*-intercept *B*, and (e) eccentricity ε. (From Ref. 3)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Computer graphics and animation.

Methods

Test Conditions

Experiment 1

- Rigid and nonrigid simulated wireframe objects presented on a 16.5 x 21.6-cm Tektronix 611 CRT, binocularly viewed from 76.2 cm; objects rotated under computer control and appeared to move in three-dimensional space
- Objects formed by three line segments; each line segment made of eleven colinear points, with endpoints moving along elliptical or hypertrochoidal paths (Fig. 2)
- Randomly chosen motion parameters were: length of major axis A, distance C from x-intercept to center of ellipse, and phase α (Fig. 1); A varied from -1.52 to 3.06 cm; C from -3.05 to 3.05 cm; and α from 36 to 360 deg
- Figure 2 illustrates the five classes of rigid (a) and nonrigid (b)-(e) rotation; parameters constrained by rigid rotation (Fig. 2a) were fixed (eccentricity, $\epsilon = 0.375$; x intercept, $B = 0$; frequency, $\omega = 0.375$ Hz; and inclination of x-intercept of extended minor axis with x-axis, $\theta = 0$ deg); nonrigid rotation: (b) orientation, θ, from 0-135 deg; (c) rotation rates, ω, (frequency) from 0.092-0.55 Hz; (d) x-intercepts of extended minor axis (distance B) from -3.81 to 3.81 cm; and (e) eccentricities, ϵ, from 0-0.75
- Three presentation conditions: (1) slow rotation with rates listed above; (2) fast rotation with frequency of condition 1 doubled; (3) slow-rotation precession (axis wobble as a spinning top with frequency 0.275 Hz)
- Display frame rate of 44 frames/sec; simulated object reversed direction every 2.73 sec with reversal every three-quarter cycles for conditions 1 and 3 and every three half-cycles for condition 2
- Experiment 1: 180 randomly arranged trials with 20 rigid (a) and 10 each type of nonrigid (b)-(e) motion, with no feedback

Experiment 2

- Simulated objects reversed direction of rotation as in Exp. 1, except amplitude varied systematically among 18, 90, 180, and 270 deg
- Three classes of rotation: (a) fixed axis, frame rate 11 frames/sec; (b) fixed axis, 44 frames/sec; (c) moving axis, $\omega = \phi$ 1275 Hz, 44 frames/sec (conditions [d] and [e] of Exp. 1 not used).
- 300 trials using only one condition and single amplitude of oscillation; immediate feedback given after each response; within each condition sessions arranged in order of increasing difficulty

Experimental Procedure

(Experiments 1 & 2)

- Two alternative forced-choice procedure
- Independent variables: object rigidity; type of rotation
- Dependent variable: percent of correct responses
- Observer's task: decide if simulated motion seen in parallel projection is rigid or nonrigid
- Experiment 1: 180 randomly arranged trials with 20 rigid (a) and 10 each type of nonrigid (b)-(e) motion, with no feedback
- Experiment 1: 10 naive observers with some practice; Experiment 2: 3 paid observers with extensive practice

Experimental Results

- In Experiment 1, judgments of rigid versus nonrigid motion were 84.3% correct for rigid motion projections, and 82.5% correct for nonrigid motion projections. In case (e), where eccentricity was varied, there were 59% correct responses for fast rotation and 48% correct responses for precession (rotation with axis wobble). The results in Table 1 indicate observers are highly sensitive to trajectory-based information (under parallel projection) regarding rigidity and nonrigidity.
- In Experiment 2, subjects showed almost perfect performance in judging rotation about a fixed axis for 180 and 270 deg oscillation; performance was much poorer for only 18 deg. There was a dramatic drop in performance for rotation about a moving axis of rotation (condition [c]).

Variability

No information on variability was given.

Constraints

- Simulated objects of the class shown in Fig. 2b were noticeably larger than the other simulated objects; this could aid observers in identifying that set of nonrigid objects.
- More complex motions, such as translation of the rotating axis, would considerably complicate the analysis (Ref. 3).
- Some configurations that have reasonable interpretations as rigid rotating objects are perceived to have complex motions or to be nonrigid. A particularly well-known example is the Ames trapezoid (Ref. 1).

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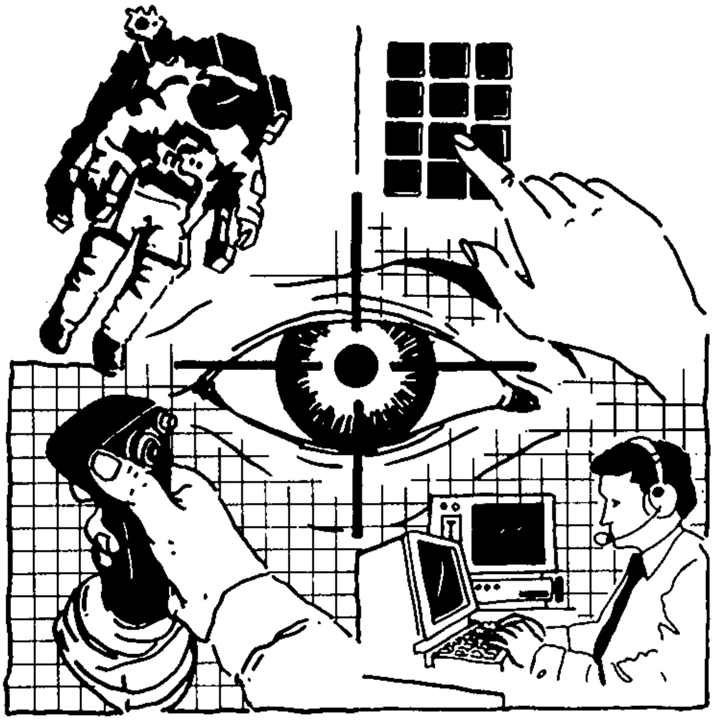
Table 1. Percentage of correct discriminations of rigid and non-rigid motion for each motion category (Experiment 1). (From Ref. 3)

Rotation			
Condition*	**Slow**	**Fast**	**Precession**
(a)	96.5	96.5	60.0
(b)	95.0	99.0	81.0
(c)	98.0	95.0	84.0
(d)	95.0	95.0	81.0
(e)	60.0	59.0	48.0
Mean	90.2		69.0
Number of observations	1200		600

* See "Methods" for description of motion conditions.

Notes

Section 5.3 Induced Target Motion



5.301 Induced Motion: Determinants of Object-Relative Motion

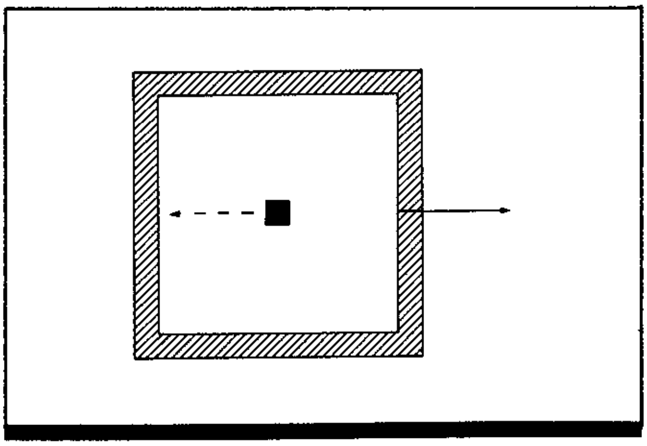


Figure 1. Classic induced-motion display. Actual motion indicated by solid arrow; perceived (induced) motion indicated by dashed arrow. (From *Handbook of perception and human performance*)

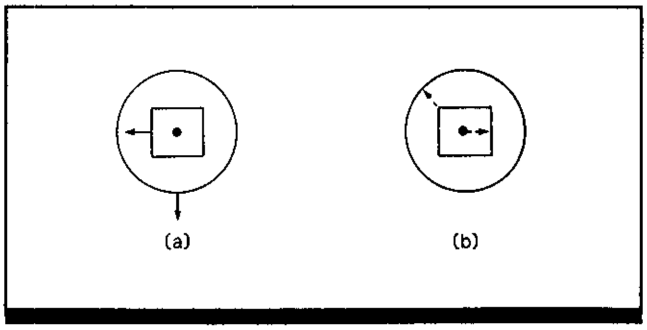


Figure 2. Multiple embedded frames. Arrows in (a) indicate actual motion; arrows in (b) indicate induced motion for slow actual motions. (From Ref. 11)

Key Terms

Computer generated imagery; induced motion; motion in depth; motion perception

General Description

Illusionary motion can be induced in the laboratory by moving a rectangular frame surrounding a stationary spot (with an otherwise dark field) from left to right; the stationary spot appears to move from right to left (Ref. 5). The same phenomenon is observable in nature, as when the essentially stationary moon appears to move as surrounding clouds move by it. Induced motion has generated experimental interest because it represents a simple and pure case of object-relative information dominating motion perception (CRef. 5.201), and thus can potentially reveal the rules by which object-relative information is processed. This entry discusses the conditions necessary for, and those that favor, induced motion. The different types of induced motion are introduced, common explanations briefly sketched, and some related phenomena are discussed. The factors that affect the illusion are summarized in another entry (CRef. 5.302).

Several conditions favor induced motion. Induced motion is most vivid when inducing and induced elements are the only elements in the display: textured background can reduce and destroy the illusion. If inducing elements are moving below their independent motion threshold, only induced motion will be seen. If above that threshold, the frame will appear to move and induced movement will also be seen. However, induced motion is lost when the inducing elements are moving at high velocity (Ref. 5). Generally, the induced element is surrounded by the inducing frame, but there are reports of induced motion when the inducing element is merely adjacent to the induced element (Ref. 4). The induced motion is more vivid as the surround contour is closer to the induced element (Ref. 8), but this relationship is more complex with complex displays (CRef. 5.302).

There are several varieties of induced motion. The minimum conditions for induced motion are two points of light with one moving below absolute motion threshold; either

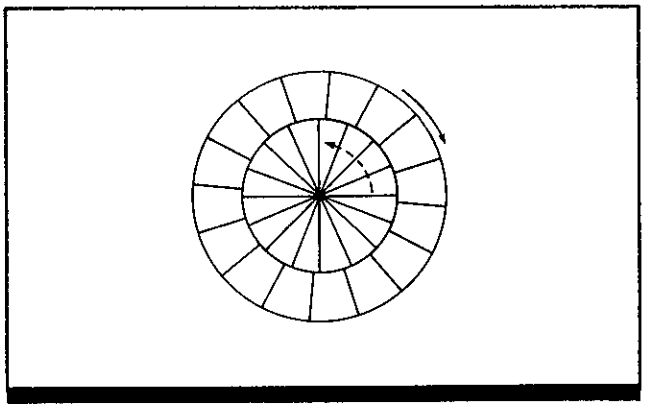


Figure 3. Rotary induced motion. Solid arrow indicates actual motion (of outer annulus); dashed arrow indicates induced motion (of inner disc). (From Ref. 5)

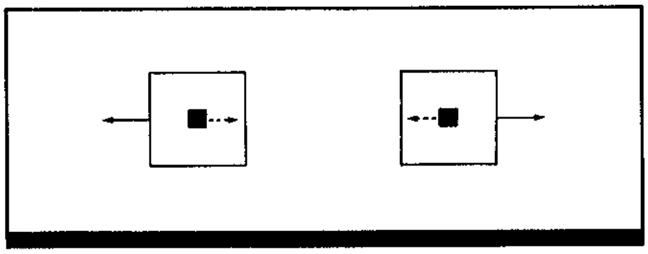


Figure 4. Simultaneously perceived induced motions in opposite directions. Solid arrows indicate actual motion; dashed arrows indicate induced motion. (From *Handbook of perception and human performance*)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

spot may appear to move (Ref. 5). The standard induction framework (Fig. 1) can be placed in a larger framework that can also move (Fig. 2). Reports of perceived motion of stationary targets are contradictory (Ref. 1; CRef. 5.302), but a number of reports claim that only the motion of the outermost frame affects the stationary target (which contradicts the adjacency principle).

Induced motion in depth (Ref. 6) occurs when a textured surface moving in depth behind a line induces apparent motion of the line in the opposite direction in three-dimensional space. Also, a looming and receding circle surrounding another will cause that circle to loom and recede in counterphase.

Rotary induced motion (Fig. 3) occurs when a spoked circle is surrounded by a spoked annulus and the annulus rotates. The central circle appears to rotate counterclockwise when the annulus is rotated clockwise.

Explanations of induced motion can be partitioned into two classes: subject-relative (i.e., observer-relative) and object-relative (CRef. 5.201). Subject-relative explanations propose that the illusory motion is due either to involuntary (hence unregistered) eye movements or to shifts in apparent median plane (Ref. 2). Both explanations are made untenable by demonstrations of simultaneous induced motion in opposite directions (Fig. 4; Ref. 7). Also, eye movements to an unseen auditory target are not affected by induced movement, which implies accurate registration of subject-relative eye position information during induced movement (Ref. 10).

Object-relative explanations attribute induced motion to an observer's assignment of motion to the stationary center object because of configural rules that favor perception of the background as stable (Refs. 5, 10).

Related Phenomena

When large parts of the visual field surrounding the subject are set in motion, illusory motion of the observer can occur (Ref. 5). This "induced motion of the self" is exploited in cinerama.

Simultaneous motion contrast occurs when a stationary contour surrounds the induced movement display. The stationary target no longer appears to shift position, but a paradoxical perception of movement without position change occurs (Ref. 3). The abstraction of structure from motion can occur when a large number of dots are in complex motion on the retina. The visual system uses configural rules to make the extent and direction of the underlying three-dimensional trajectories unambiguous (Ref. 9).

Applications

Design of environments and instruments where detection of signal motion is important.

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Cross References

5.201 Subject-relative and object-relative visual motion;

5.302 Factors affecting induced motion;

Handbook of perception and human peformance, Ch. 17, Sects. 4.2, 4.8, 4.10, 4.15

5.302 Factors Affecting Induced Motion

Factor	Effect	Sources
Minimal conditions for induced motion	Two points of light presented with one stationary and the other moving below absolute-threshold	Ref. 5
Background texture; stationary aperture around display	Induced motion is greatest with a homogeneous background and no visible aperture. There is a considerable reduction in illusion with a visible aperture	Ref. 3
Inducing elements do not surround target	Induced motion reported to be equally vivid when target was adjacent to frame as when within frame	Ref. 4
Multiple frames and targets	When a target is embedded in concentric frames that move independently of each other, the majority of studies report that the outer frame determines induced motion (but see Ref. 12)	Refs. 1, 2, 12
	With two standard induced-motion displays in different parts of the visual field, induced motion is perceived simultaneously in two different directions	Ref. 6
Eye movements	Induced motion can be produced with retinally stabilized targets. The effects of target fixation are contradictory, but, under some conditions, fixating the target reduces the illusion	Refs. 9, 11
Velocity of induction stimulus	At higher velocites, the vividness and apparent extent of induced motion are reduced	Refs. 5, 7, 14
Distance between target and induction stimulus	Induced motion decreases as separation between the target and frame contours increases. The relevant variable is perceived distance, as illustrated by putting the target and frame in different depth planes	Ref. 8
Stroboscopic induction stimulus	Good induced motion is produced using this method	Ref. 5
Dichoptic presentation of target and induction stimulus	Good induced motion is produced dichoptically	Refs. 1, 3
Prolonged observation of induced motion	10 min of exposure to harmonic-induced motion produces a 15% reduction in perceived target motion	Ref. 14
Unusual configurations	Induced rotary motion is produced with rotary induction stimulus; induced motion in depth is produced by frame moving in depth; induced motion of observer is produced when large parts of background are set in motion	CRef. 5.301
Individual differences	Observers differ markedly in their reports	Ref. 13

Key Terms

Eye movements; induced motion; motion perception

General Description

Induced motion refers to perceived movement of a stationary object; for example, a stationary spot surrounded by a rectangular frame will appear to move when the surrounding frame is set in motion. This illusion has generated considerable interest because it is a clear case where motion perception appears to be dominated by object-relative configural cues (CRef. 5.201). The table lists a number of configural and experimental factors or conditions that affect the illusion, summarizes their effects, and identifies sources of additional information.

Constraints

- There is still considerable controversy regarding some effects. This is particularly true for complex configurations and for near-threshold motion (Ref. 1, 11).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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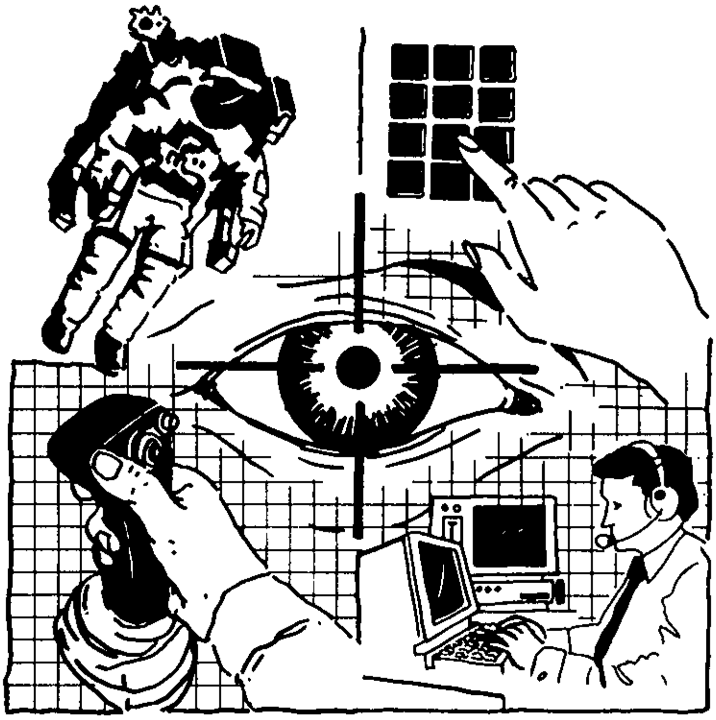
Cross References

5.201 Subject-relative and object-relative visual motion;

5.301 Induced motion: determinants of object-relative motion

Notes

Section 5.4 Apparent Object Motion (Stroboscopic Motion)



5.401 Types of Visual Apparent Motion

Key Terms

Alpha movement; animation; apparent movement; beta movement; delta movement; gamma movement; illusory self-motion; Kortes laws; motion perception; phi movement; simulation

General Description

The perception of motion can be produced by the sequential presentation of stationary stimuli; this is the basis of motion pictures, television, and all animated displays. One stimulus is presented from some duration (from ~10-400 msec) followed after a pause (from ~40-400 msec) by a second stimulus, sometimes at the same location, but more often at a different location. With the latter situation, an observer sees, under the proper conditions, only one stimulus moving from the first location to the second. The intensities and durations of the two stimuli, as well as their spatial and temporal separations, are all critical factors.

Several types of apparent movement have been described (Fig. 1):

- Alpha: a change in the apparent size of a stimulus light after it first appears or with repeated presentations (e.g., the second presentation appears to be a larger stimulus).
- Beta ("optimal"): smooth and continuous movement of a well-defined stimulus from one location to another; under the proper conditions, it is indistinguishable from real movement. Movement is seen when flash durations range from 5-200 msec, when temporal separations range from 10-200 msec, and at spatial separations ≤18 deg.
- Phi: the appearance of movement between two locations although no object appears to move. This is also known as "objectless" apparent movement. Beta movement becomes phi movement when the interval between the two stimuli becomes short, relative to the intensity and duration of the stimuli. Phi movement is mistakenly used interchangeably with stroboscopic movement.
- Gamma: the apparent expansion and contraction of a stimulus light when its intensity is raised or lowered. It appears that the border of the stimulus moves.
- Delta: reverse movement. This occurs when the intensity of the second stimulus is greater than that of the first (e.g., the "wagon wheel" effect)

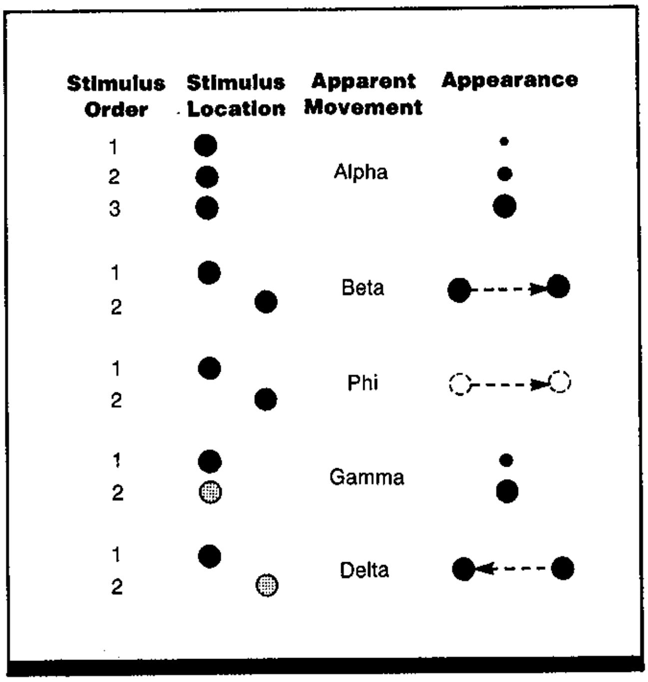


Figure 1. Types of apparent movement. In gamma and delta movement, the hatched disks are brighter than the solid ones.

Methods

Test Conditions

- Lights, black stimuli, geometric shape, and representations of everyday objects have all been used
- Stimuli have been projected or have been displayed in a tachistoscope or on a CRT

Experimental Procedure

- Method of adjustment
- Independent variables: target duration, intensity, size, separation, color, shape, observer's attitude, instructions
- Dependent variable: perception of movement
- Observer's task: to report movement of the stimuli

Experimental Results

- For beta movement in general, as the temporal separation of the two stimuli increases, either stimulus duration or intensity must be decreased or spatial separation must be increased, but there may be range limitations for this result.
- There is a critical level of target intensity for gamma movement for targets of all sizes; higher intensities are needed as target size increases.
- For delta movement, as the difference in intensity between the two stimuli increases, either the intensity of the second stimulus must be decreased, or the spatial separation or temporal separation must be increased.
- The duration of the first stimuli is more important than that of the second.
- Both small and large (20 deg) stimuli produce less compelling apparent movement than stimuli of intermediate size.

Variability

There are very large individual differences in the likelihood of reporting apparent movement. Quantitative thresholds for those who do report it may vary by 30%.

Repeatability/Comparison with Other Studies

Results are from several studies, but each study is usually concerned with only one type of movement.

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Constraints

- The stimulus parameters of duration, intensity, and separation that result in the perception of movement are related in a very complex way.
- The likelihood of reporting apparent movement is greatly affected by observer attitude.

Key References

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Cross References

5.402 Time, distance, and feature tradeoffs in visual apparent motion;

5.403 Temporal and spatial relationships in visual apparent motion;

5.405 Visual persistence and apparent motion

5.402 Time, Distance, and Feature Tradeoffs in Visual Apparent Motion

Key Terms

Apparent movement; Korte's laws; motion perception; simulation; visual persistence

General Description

When it is possible to see several paths of apparent motion in an ambiguous display, the path actually seen will depend upon linear tradeoffs between temporal and spatial separation of the elements in the display. Each path seen on its own gives clear apparent motion, but when presented simultaneously, the paths apparently compete and suppress one another. When paths are equiprobable, there is a log-linear relationship between time and distance. The path seen is unaffected by viewing distance, implying that the mechanism that selects the seen path is affected only by relative, not absolute, distances. The contributions of time and distance to path selection are independent. Furthermore, path selection is insensitive to the feature properties (e.g. shape, etc.) of stimulus elements.

Applications

Displays used to simulate motion.

Methods

Test Conditions

- Multiple-motion dot configurations of the type depicted in Fig. 1
- Dot rows displaced downward on CRT display by a distance v and rightward by a distance h, as depicted in Fig. 1
- Vertical distances (v) were 1.84, 2.45, or 3.06 mm at horizontal distances (h) 6.81 and 7.23 mm; v equals 0.82, 1.22, or 1.63 mm at h equal 5.11 and 5.32 mm; and v equals 0.41, 0.61, or 0.82 mm at h equal 3.83 and 4.04 mm
- Relative spacing between adjacent points on competing paths expressed as ratio d_n/d_1
- Four possible motion paths (P_1 - P_4), with transitions from P_1 to P_2, P_3, or P_4; range of t values included the transition time at which motion of the two possible paths was equiprobable
- Background luminance of display surface 0.058 cd/m^2

Experimental Procedure

- Method of constant stimuli with forced-choice response
- Independent variables: relative spacing between points on competing paths, defined by the ratio d_n/d_1; viewing distance (1 or 2 m)
- Dependent variable: transition time, ($t_{1,n}$) defined as the interflash interval at which transition from one motion path to a second motion path occurred
- Observer's task: report whether motion to the left or right was seen
- 168 trials for each combination of h and v
- 2 observers with extensive practice

Experimental Results

- For the largest t value, observers reliably reported that dominant motion was along path P_1; at the smallest value of t, motion reported was along P_2, P_3, or P_4 (where P_n is the path to the nearest dot in the row presented at the time T_n, n time intervals later).
- Transition time between two paths is an inverse linear function of the log of the ratio of the distances between successive points on competing paths (Fig. 2). In other words, there is a tradeoff between distance and time in determining which apparent motion path will be seen.
- Transition points for the two viewing distances differ only by 6%. This implies a scale invariance, in which only relative, not absolute, distances between points along com-

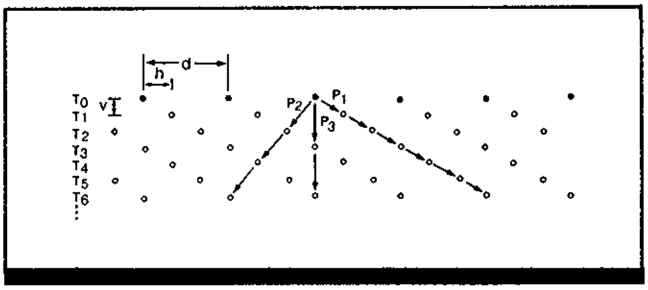

Figure 1. Ambiguous-motion stimulus configuration. Horizontal rows of dots were presented sequentially at times $T_0 \ldots T_n$. d is horizontal spacing of dots within a row; h is horizontal displacement and v vertical displacement across time intervals. Arrows show several possible paths of apparent motion. (From Ref. 1)

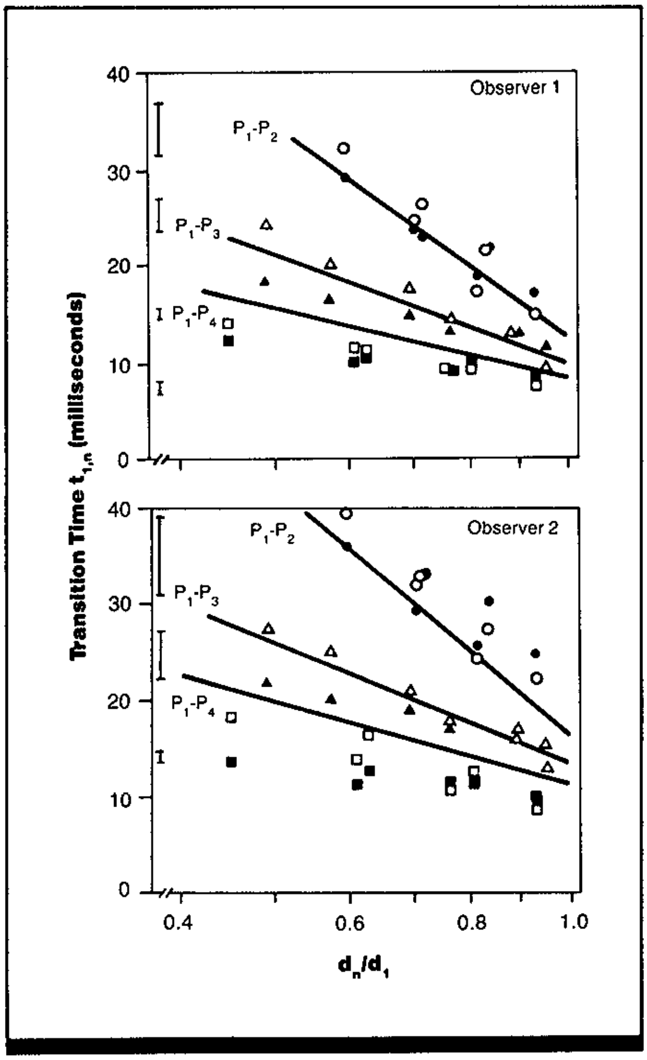

Figure 2. Transition times for 2 observers. Filled symbols are for 2-m viewing distance; open symbols are for 1-m viewing distance. Circles, triangles, and squares are for transitions between paths P_1, and P_2, P_3, and P_4, respectively. d_n/d_1 for the x-axis is the relative distance between two adjacent points on competing paths. (From Ref. 1)

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peting paths are important in determining which motion will be seen.

- In a related experiment, there is no consistent tendency to see motion between elements of like rather than unlike configuration. Hence the preference for motion along a particular path is insensitive to feature properties of the stimulus elements.

Variability

The error bars in Fig. 2 represent two standard deviations (SD) of the data in each of the four ranges of obtained data.

Repeatability/Comparison with Other Studies

The finding of tradeoffs between time and distance implies their separability, and is opposite to some of the original conclusions based on work on this topic (Ref. 2; CRef. 5.403). Later work produced qualitative results similar to those described here. Time-distance separability is also consistent with work using nonmoving but temporally modulated stimuli (Ref. 4). The finding of feature insensitivity is consistent with earlier work (Ref. 3). The precise function relating time and distance described here is new and is therefore not comparable to earlier work.

Constraints

- The log-linear relationship between time and distance is an adequate (but not the only possible) description of the data. It was chosen because it provided a simple form for the stimulus strength leading to a motion path preference (Ref. 1).
- Values for the temporal and spatial parameters obtained here and the relationship between them should be applied only qualitatively, as these values are observer-dependent.

Key References

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Cross References

5.401 Types of visual apparent motion;

5.403 Temporal and spatial relationships in visual apparent motion;

5.405 Visual persistence and apparent motion;

Handbook of perception and human performance, Ch. 16, Sect. 5.2

5.403 Temporal and Spatial Relationships in Visual Apparent Motion

Key Terms

Apparent movement; beta movement; Korte's laws; motion perception; simulation; stroboscopic motion

General Description

A visual stimulus such as a spot of light flashed first at one position and then at a nearby position will give an observer an impression of motion. Because no real movement has occurred, this effect is referred to as "apparent motion." The temporal and spatial properties of successive stimulus presentations required to produce optimal movement have been studied by Korte, and these relationships have been called Korte's Laws (Refs. 1, 2, 3). The four laws described are based on Korte's observations of a particular type of apparent motion, beta movement, which is the apparent movement of an object from one position to another (CRef. 5.401). For this description, *s* is the spatial distance between stimuli, and *l* is the luminance of the stimuli; *t* is the exposure time or duration of stimuli, and *i* is the temporal interval between stimuli. For optimal beta movement to be seen, threshold values of the various parameters are as follows:

1. *s* increases as *l* increases, with *t* and *i* held constant;
2. *s* increases as *i* increases, with *t* and *l* held constant;
3. *l* decreases as *i* increases, with *t* and *s* held constant;
4. *t* decreases as *i* increases, with *l* and *s* held constant.

The laws carry with them the implication that apparent motion will be seen only at certain values of the variables involved. For example, the first and second laws imply that the object apparently in motion is perceived at a constant velocity; the third law implies that the observer requires a fixed interval to perceive motion over a specified distance (Ref. 2).

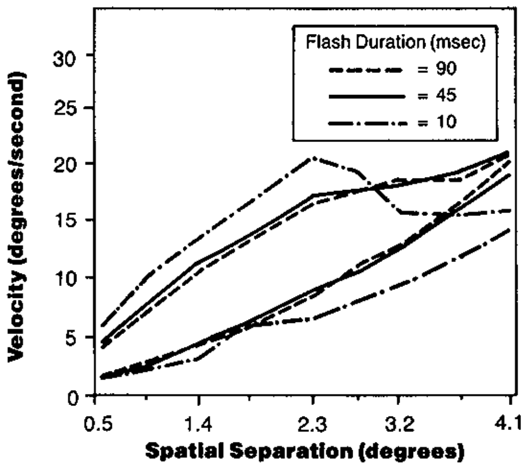

Figure 1. Calculated velocity of apparent motion display. Lower curves represent optimal motion; upper curves represent the impression of succession. (From Ref. 2)

Korte's laws should be viewed as working rules rather than as firm principles of high generality, as the term "law" implies. In practice, the visual system will tolerate departures from Korte's formulations and still yield perception of apparent motion. Figure 1 shows various relationships among the relevant variables that yield either optimal apparent motion (lower curves) or the appearance of successive separate presentations (upper curves).

Applications

Displays for the simulation of motion.

Methods

Apparent motion based on stroboscopically presented displays is used in television, movies, and computer graphics. In all of these media, static stimuli that differ slightly in spatial location and are presented in sequence at the proper rate, produce an impression of motion that is indistinguishable from real motion. Korte's laws (and similar formulations) (Ref. 3) can be applied to determine the proper temporal and spatial parameters to produce "good" apparent motion. For example, for two spots of light flashed on and off in sequence, large values of *i* will give the impression of a strobed display, whereas values of *i* that are too small will give the impression of two lights flashing in place simultaneously.

Empirical Validation

Korte's laws were based upon his original investigations into beta movement. He chose display parameters that produced good apparent motion, changed the value of one parameter to remove that perception, and then measured the values of other variables necessary to restore the optimal movement. Work that has employed the more conventional method of limits (Ref. 2) to determine the parameters necessary for optimal movement has produced results consistent with both the second and fourth laws. However, large changes in luminance do not result in the need to change other stimulus variables to maintain optimal movement; this is inconsistent with the first and third laws. The implication of constant velocity made by the first and second laws has also been shown not to hold (Fig. 1). This result also suggests that the visual system event responsible for apparent motion requires a certain relatively constant amount of time to occur, as velocity must increase to cover a greater distance in a fixed amount of time.

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Constraints

• The parameters necessary for optimal movement depend upon the amount of practice observers have had. Practiced observers report motion at values of i that result in either strobing or simultaneity for unpracticed observers (Ref. 1).
• Observers instructed that they should see motion will report motion under the same parameters that previously did not produce optimal movement (Ref. 1).
• The range of temporal and spatial values at which apparent motion may be seen has been shown to be different from that originally proposed by Korte. For example, optimal movement can be seen for values of i from 80-400 msec at certain values of t and s (Ref. 1). Apparent motion will also be seen over wide ranges of s, from 2-18 deg for binocular viewing (Ref. 5) and even at 100 deg for dichoptic presentation (Ref. 4).

Key References

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Cross References

5.401 Types of visual apparent motion;

5.402 Time, distance, and feature tradeoffs in visual apparent motion;

5.405 Visual persistence and apparent motion

5.404 Stroboscopic Apparent Motion

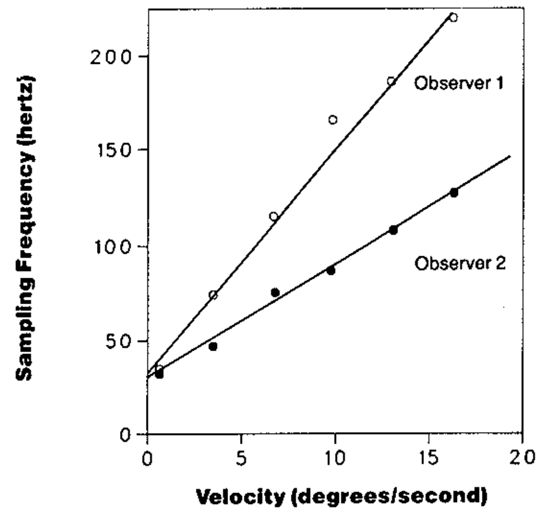

Figure 1. Critical temporal-sampling frequency for a moving line as a function of velocity (i.e., strobe threshold to yield smooth motion). The lines were fit by eye. (From Ref. 4)

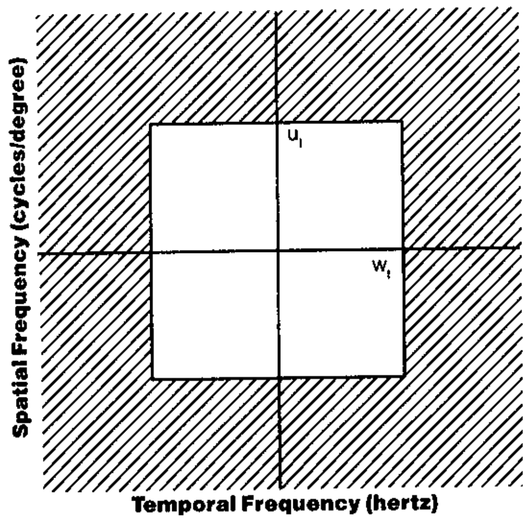

Figure 2. The window of visibility for spatial and temporal frequencies. The bounds u_l and w_l represent the limits of spatial and temporal frequency sensitivity, respectively. Combinations of spatial and temporal frequencies in the shaded region are invisible. (From Ref. 4)

Key Terms

Animation; apparent movement; motion perception; motion simulation; stroboscopic motion; visual persistence

General Description

A time-sampled (strobed) stimulus that varies rapidly in space and/or time may be perceived as a smoothly moving target. The critical sampling frequency for perceiving a strobed stimulus as a continuously moving image is a linearly increasing function of stimulus velocity; the faster a stimulus is moving, the greater the sampling frequency must be to detect stroboscopic motion. Stroboscopic apparent motion can thus be understood in terms of spatiotemporal filtering action of the visual system.

Applications

Displays in which continuous motion is simulated by stroboscopic apparent motion.

Methods

Test Conditions

- CRT display of a vertical line, 50 min long by 0.65 min wide; smooth line moved either left or right; observers fixated a point at the center of path of travel
- Horizontal velocity (*r*) of line from 1-17 deg/sec at the retina
- Sampling frequency for "smooth" stimulus was 1920 Hz
- Distance traveled by line was $1.25\sqrt{r}$ deg; duration was $1.25/\sqrt{r}$ sec
- Smooth and stroboscopic stimuli equated for time-average contrast at 200%
- Background luminance was 50 cd/m^2; viewing distance was 2 m

Experimental Procedure

- Two-interval forced-choice paradigm; stimuli blocked by velocity; presentation order and direction of motion randomized on each trial
- Independent variables: velocity of stimulus, defined in degrees per second at the retina
- Dependent variable: critical sampling frequency, defined as the sampling frequency at which continuous and stroboscopic motion are indistinguishable; critical sampling frequency estimated as that at which observer was correct 75% of the time
- Observer's task: choose which of two intervals contained a strobed stimulus
- 25 trials at each of five sampling frequencies, all at a single velocity
- 2 observers, with an unknown amount of practice

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Experimental Results

- Critical sampling frequency is a linearly increasing function of velocity. As velocity increases, the sampling frequency must also increase to perceive stroboscopic rather than smooth motion.
- The intercept of the function (~30 Hz for both observers) represents the temporal frequency limit for stroboscopic motion. The slope of the function (13 cycles/deg for observer 1 and 6 cycles/deg for observer 2) represents the spatial frequency limit for stroboscopic motion.
- The spatial and temporal frequency limits are relatively independent of each other. Together they delineate a "window of visibility"; components within the window are visible, and those outside the window are invisible (Fig. 2). Two stimuli will appear identical if their spatial and temporal frequency spectra are identical after passing through the window. The visual system may thus be described as a filter, such that spatiotemporal distributions of contrast that are identical after passing through the filter are indistinguishable. The results described here may be interpreted using these ideas.

Variability

No information on variability was given. However, this slope of critical sampling frequency as a function of velocity was >2:1 (6 vs 13 cycles/deg).

Repeatability/Comparison with Other Studies

The low estimates for the spatial frequency limit are reasonable considering the low contrast and brief duration of the stimuli. Classic demonstrations of apparent motion (Refs. 1, 3; CRef. 5.401) employ only two samples or two samples in repeated alternation, unlike the long sequences in the study described here. It has yet to be determined whether such displays are indistinguishable from real motion. Earlier filter theories were proposed simply in terms of temporal frequency (Ref. 2); the results described here extend theory to consider both spatial and temporal frequency components of a stimulus.

Constraints

- Computed values for the spatial and temporal frequency limits given here hold only for the viewing conditions described and should not be applied, except qualitatively, for different observers or under different viewing conditions.

Key References

1. Kolers, P. A. (1972). *Aspects of motion perception*. New York: Pergamon Press.

2. Morgan, M. J. (1979). Perception of continuity in stroboscopic motion: A temporal frequency analysis. *Vision Research, 19,* 491-500.

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Cross References

5.401 Types of visual apparent motion;

5.402 Time, distance, and feature tradeoffs in visual apparent motion;

5.403 Temporal and spatial relationships in visual apparent motion;

Handbook of perception and human performance, Ch. 6, Sect. 10.4

5.405 Visual Persistence and Apparent Motion

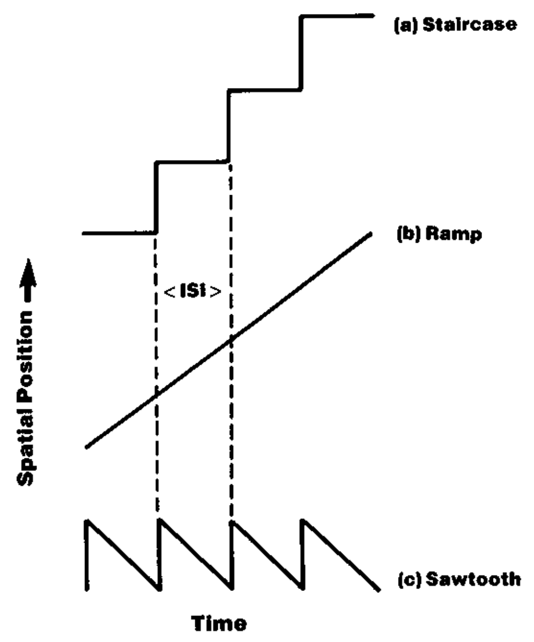

Figure 1. Stroboscopic staircase motion (a) can be decomposed into (b) a ramp component and (c) a sawtooth component. ISI (interstimulus interval) is the time between spatial jumps of the motion stimulus. (From Ref. 3)

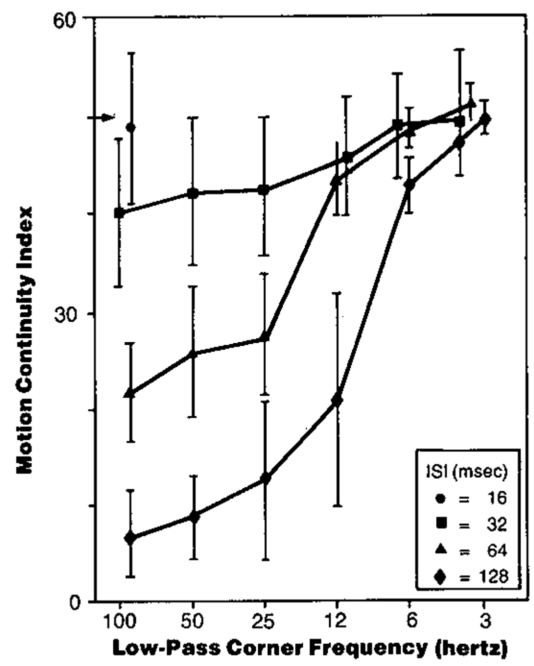

Figure 2. Perceived continuity of motion as a function of interstimulus interval (ISI) and low-pass corner frequency of filter through which stimuli were passed. The arrow at a motion continuity index of 50 indicates the point at which observers perceive presentations of the lagging stimulus as if on a continuous-motion trajectory joining the discrete space-time positions of the leading target. (From Ref. 3)

Key Terms

Apparent movement; motion simulation; simulation; visual persistence

General Description

An object moving in discrete spatial jumps is perceived to be moving smoothly, if the time between jumps is not too great. The apparent movement of successive static presentations of a stimulus can be decomposed into a sawtooth component and a ramp component. When the frequency of the sawtooth component exceeds 25 Hz, only the ramp component (smooth, continuous motion) is perceived. This effect is presumed due to the persistence of response in the motion analyzers which prevent the visual system from resolving higher frequencies, and in essence filter out frequencies greater than ~25 Hz. Smooth motion is perceived because the system interpolates momentary spatial positions that are the average of the persisting positions.

Applications

Displays and simulations designed to give the impression of continuous motion; specifically, filters may be applied to stimuli to remove those frequencies that would distinguish them from continuous motion, or stimulus parameters chosen so that the visual system will perform its own filtering.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Two horizontal bars, separated by 0.2 deg of visual angle, one to either side of central fixation; bars generated on oscilloscope screen and viewed through a 5-deg circular aperture; display luminance of 13 cd/m^2
- Bars moved in discrete spatial jumps of 0.75 deg (staircase motion) separated by interstimulus intervals (ISIs) of 32, 64, or 128 msec, with 8, 16, or 32 steps per cycle, respectively
- Staircase stimuli passed through analog filter prior to driving bars on oscilloscope screen; low-pass corner frequencies of 3, 6, 12, 25, 50, or 100 Hz; velocity of bar motion was 6 deg per sec; bar width of 0.3 deg
- Jumps of one bar temporally delayed relative to the other bar by a constant fraction (0.25) of the ISI
- Fundamental frequencies for stimuli of ISIs of 32, 64, or 128 msec were 7.80, 15.60, and 31.25 Hz, respectively; spatial frequencies were 1.30, 2.67, and 5.33 steps per deg, respectively

Experimental Procedure

- Method of adjustment, repeated measures design
- Independent variables: staircase interval (ISI), defined as the time between discrete spatial steps; low-pass corner frequency, defined as the lower limit of frequency components filtered out of staircase stimuli
- Dependent variable: Motion continuity index, $M = 100 (O/[O + T])$, where O is the observed spatial offset between bars and T is the theoretical setting of spatial offset when complete interpolation occurs
- Observer's task: adjust spatial offset between bars so that the temporal delay between bars would apparently be canceled and bars would appear aligned

Experimental Results

- Interpolation ratio is affected strongly only when temporal frequencies below 25 Hz are filtered out. Frequencies above 25 Hz have little effect on the ratio. This implies that the visual system itself filters out the sawtooth component of a staircase stimulus above ~25 Hz, leaving only the ramp component of motion, and resulting in the perception of smooth, continuous motion.
- Effects of ISI depend upon low-pass corner frequency of filter applied. When the fundamental frequencies of a stimulus are lower than the low-pass frequency of a filter, the filtering will not be able to produce complete interpolation because certain sawtooth components will remain. For example, a staircase of 128 msec ISI has a fundamental at 7.8 Hz and harmonics at 15.6 and 23.4 Hz, all below the 25-Hz low-pass limit, and thus such a staircase is relatively unaffected by such filtering, as these components will remain to serve as a distinction between staircase and continuous motion.

Variability

Error bars in Fig. 2 represent ± 1 standard deviation around the mean.

Repeatability/Comparison with Other Studies

These results relate to the phenomenon of vernier offset in apparent motion, in which colinear stimuli separated in time appear non-colinear, such that an earlier stimulus appears to spatially lead a later stimulus (CRef. 5.220). Other studies describe a tradeoff between time and distance in displays demonstrating apparent motion (Ref. 1; CRef. 5.402). The interpolation mechanism implies that apparent motion should not be seen with long spatial spans (i.e., greater than ~0.2 deg), but apparent motion has been reported with longer spans (Refs. 4, 5).

In a related study (Ref. 2), dark adaptation affected interpolation. A staircase of 30 msec ISI, shown to produce only intermediate interpolation under conditions of high luminance, yielded complete interpolation when luminance of display and surround was decreased by 2 log units. Decreased luminance is known to increase visual persistence, and therefore the result is consistent with the view that the filtering action of the visual system arises from inability of the system to resolve high frequencies.

Constraints

- Precise values for ISI and spatial frequencies of stimuli needed to produce apparent motion will vary with presentation conditions. As described here, for example, conditions that increase time constants in the visual system, such as decreased luminance, will increase visual persistence, and thus affect display parameters required for apparent motion.

Key References

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Cross References

5.220 Vernier offset in real and apparent motion;

5.401 Types of visual apparent motion;

5.402 Time, distance, and feature tradeoffs in visual apparent motion;

Handbook of perception and human performance, Ch. 16, Sects. 3 & 4; Ch. 22., Sect. 2.2.

5.406 Visual Apparent Motion: Effect of Perceptual Organization

Key Terms

Apparent movement; event perception; motion perception; perceptual organization; stroboscopic motion

General Description

Successive presentations of stimulus objects in separate locations can elicit apparent, or stroboscopic, motion. Perception of apparent motion depends on more than the retinal proximity of elements of the two stimuli, normally itself a powerful determiner of apparent motion (CRef. 5.401). Predicting the type and direction of motion depicted in successive stimulus presentations depends upon determining the identical objects or object parts across successive views; this task is called the correspondence problem. These interpreted correspondences are sometimes referred to as the phenomenal identity of the objects.

In general, apparent motion can be viewed as the outcome of a perceptual system that attempts to make sense of partial information about the environment.

Table 1 summarizes factors of the global organization of the percept that affect perceived motion of elements.

Key References

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Cross References

5.401 Types of visual apparent motion;

5.403 Temporal and spatial relationships in visual apparent motion;

5.405 Visual persistence and apparent motion;

Handbook of perception and human performance, Ch. 33, Sect. 4.1

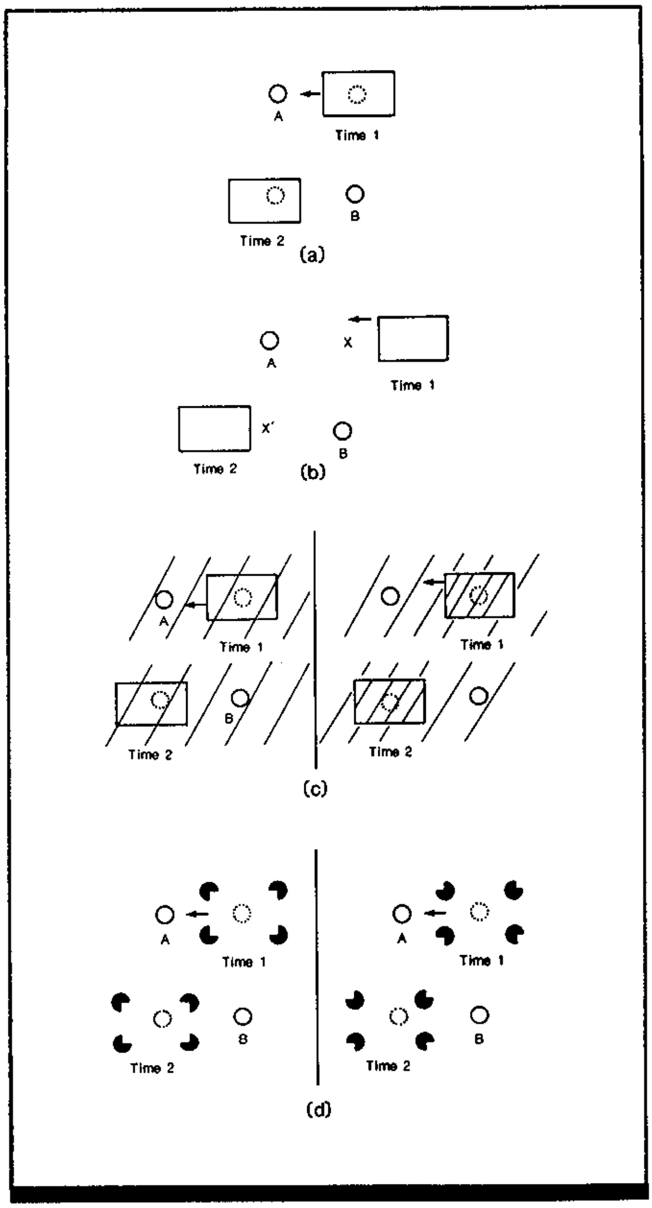

Figure 1. The conditions for apparent movement can be created by moving an object back and forth in front of two dots, alternately occluding one and revealing the other. When the moving object (a rectangle) is not visible, apparent motion is seen. (a) When the moving rectangle is visible, apparent motion is not perceived. (b) When the rectangle moves so far that, in its terminal portion, it does not occlude a dot but the dot still disappears, apparent motion is perceived. (c) When the moving rectangle appears to be only a perimeter, apparent motion is also perceived. (d) Even if the moving object is illusory, apparent motion is not seen (left). In a control condition for this effect (right), apparent motion *is* seen. (From *Handbook of perception and human performance*)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Organizational factors affecting apparent motion.

Factor	Description	Sources
Apparent motion occurs in the absence of retinal image motion.	If an observer follows a simple stroboscopic display (alternating lights) with his eyes so that the flashing lights always fall on the same retinal location, motion is still seen.	Ref. 3
By itself, the retinal image produced by eye movements is insufficient to support apparent motion.	If the eyes move back and forth across a flashing bar to produce the retinal pattern of the standard stroboscopic motion display, no motion is perceived	Ref. 3
Generally, global rather than local phenomenal identity determines the type of motion seen.	When observers view two equally spaced, colinear circles at positions 1 and 2, they perceive motion from *a* to *b* and from *b* to *c* under most conditions, despite the unchanging existence of a circle at *b*. 1 o o 2 o o *a* *b* *c*	Refs. 2, 5
Apparent motion occurs despite a clear difference in form (identity) of stimulus.	If an outline circle is presented and followed by a displaced outline square, the circle is perceived to move while simultaneously deforming into the square shape.	Ref. 1
With multiple objects in the field, similarity and proximity interact to determine phenomenal identities and apparent motion.	It is possible to construct formulas describing the interplay of proximity and similarity in apparent motion. However, for all but the simplest displays, this has not been accomplished.	Ref. 6
Apparent motion results from a problem-solving process incorporating the real world probabilities of events in interpreting intermittently viewed scenes.	Figure 1 illustrates the role of problem solving in understanding the events observed in producing or inhibiting apparent motion.	Ref. 4

5.407 Visual Motion Simulation by Displacement of Random-Dot Patterns

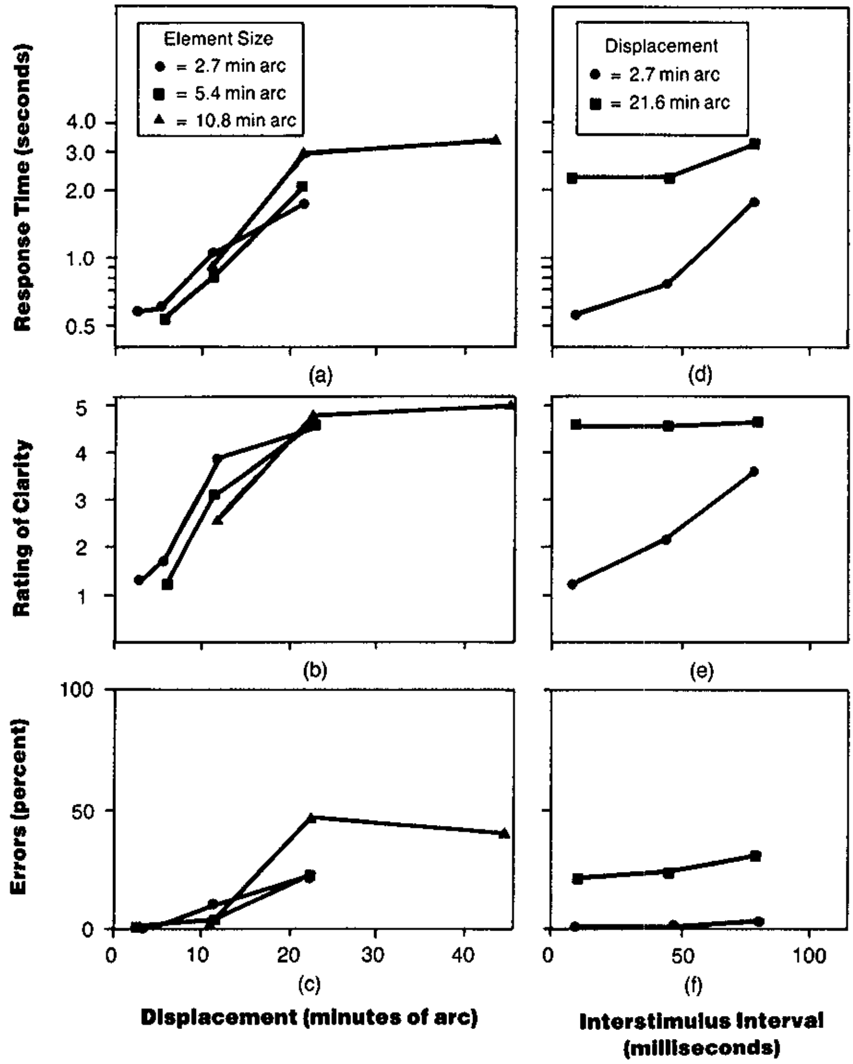

Figure 1: (a) Response time to report orientation of displaced rectangle as a function of displacement and element size; (b) ratings of clarity; (c) percentage of errors in reports; (d-f) same measures as a function of interstimulus interval and displacement. (From Ref. 2)

Key Terms

Animation; apparent movement; motion simulation; perceptual organization; random-dot patterns; simulation

General Description

Apparent motion is the name given to the illusion of continuous motion, produced by discontinuous displacement of static images. When such images are presented sequentially, they generate the sensory basis for motion pictures (CRef. 5.401). When the forms are recognizable, the phenomenon of apparent motion is robust over a wide range of interstimulus intervals (ISIs) and spatial displacements. When, however, the static images contain no recognizable forms, such as in random-dot stereograms (CRef. 5.915), then the conditions which produce apparent motion are more limited. With random-dot stereograms, displacement must be <15 min arc of visual angle and ISIs must be <80-100 msec.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

Experiment 1: Pattern Displacement

- Two grids of black or white elements with each element having an equal probability of being black and white
- Central rectangle identical in both grids, both displaced by *n* elements, the rest of the two arrays being uncorrelated; presented tachistoscopically
- Three element sizes: 2.7, 5.4, or 10.8 min arc; four values of displacement: one, two, four, or eight element widths (eight-element displacement not tested for two largest element sizes)
- Patterns presented in continuous alternation; 25 msec with 10 msec ISI
- Rectangular region oriented either horizontally or vertically
- Observer's task: depress horizontally or vertically

Experiment 2: Interstimulus Interval

- Conditions virtually identical to those in Exp. 1; one element size, 2.7 min arc, two values of displacement: 2.7, 21.6 min arc
- Three ISIs: 10, 45, 80 msec; pattern presented for 75 msec

Experimental Procedure

Experiment 1: Pattern Displacement

- Forced-choice and magnitude estimation
- Independent variable: displacement in min arc (element size multiplied by number of elements displaced)
- Dependent variables: number of errors in specifying rectangle's orientation, response time, ratings of boundary clarity
- Observer's task: depress button to initiate trial, release it when orientation was determined; indicate orientation (horizontal or vertical) of rectangle; rate border clarity on scale of 1-5
- 5 observers

Experiment 2: Interstimulus Interval

- Independent variables: pattern displacement, ISI
- Dependent variables: number of errors in specifying orientation, response time, ratings of boundary clarity
- 5 observers

Experimental Results

As displacement increases from 5-20 min arc of visual angle, response time increases ($p < 0.02$), clarity (as indicated by observers' ratings) decreases, and errors in reports of rectangle orientation increase (Figs. 1a, 1b, 1c). Displacement effects are similar for all element sizes.

- Performance deteriorates with increases in ISI from 1080 msec (Figs. 1d, 1e, 1f).

Variability

Analysis of variance used to test significance of response time data in Exp. 1.

Repeatability/Comparison with Other Studies

These results have been replicated (Ref. 1).

Constraints

- These results specifically apply to random dots and complex forms such as mazes (Ref. 4). While apparent motion does occur with larger displacements and ISIs, this may reflect a different, long-range mechanism seen with coherent forms (Ref. 2).

Key References

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*2. Braddick, O. J. (1974). A short-range process in apparent motion. *Vision Research, 14*, 519-527.

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Cross References

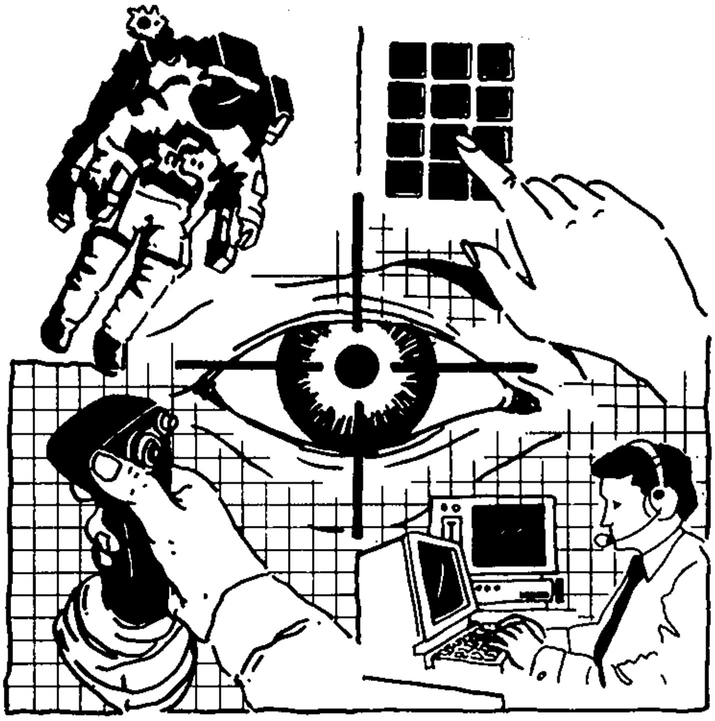
5.401 Types of visual apparent motion;

5.915 Random-dot stereoscopic displays;

Handbook of perception and human performance, Ch. 16, Sect. 4; Ch. 22, Sect. 2.2

Notes

Section 5.5 Self-Motion



5.501 Displays Providing Self-Movement Information

Key Terms

Ego-motion; motion pictures; peripheral vision; vection

General Description

Viewers of a motion picture can be made to feel as though they are moving when peripheral vision or large areas of the retina are stimulated. Self-movement is sometimes perceived by stationary observers when they view a stimulus in rotary motion. When observers sit in a striped drum that is rotating about the vertical axis, they perceive the drum as rotating for ~10 sec. Then the perception suddenly shifts and observers perceive themselves to be rotating in the opposite direction (Ref. 1).

When a display of random dots is placed on a disk facing an observer and it is rotated around the line of sight, the observer has the sensation of moving in the opposite direction and also tilts himself to the side opposite the direction of rotation (Ref. 2). Specifically, a small target disk with a vertical edge was placed in front of a larger disk with fixation at the midpoint of the edge. Fixation was monocular and the vertical orientation of this disk (the edge) was manually controlled by the observer. Subjects were tested at angular velocities of 50-130 deg/sec and instructed to keep the edge in a vertical orientation. The vertical edge itself appeared to tilt, an effect which increased rapidly during the first 20 sec of exposure and then remained relatively stable for the remaining 60 sec. When rotation stopped, the induced tilt decayed rapidly and then reversed direction. These effects occurred for all angular velocities; the full effect was reached at a velocity of 30-40 deg/sec.

Other experiments have used the same apparatus but block off portions of the pattern so that the observer sees a ring (rings vary in retinal eccentricity [distance from the fovea] and width [degree of visual angle subtended]). The magnitude of tilt increases with increasing field size and, to an even larger degree, with increasing eccentricity.

Linear motion can also induce the perception of self-movement. Even the small gliding motion of a swinging room, which consisted of walls and ceiling, severely disturbed the balance of a previously stationary subject (Ref. 4). An extension of this analysis using a moving room, investigated the effects of lamellar and radial optic array flow patterns on induced self-motion, and found that the retinal periphery did not mediate self-movement (information when the periphery was presented with an optical flow pattern that was radially expanding and contracting) (Ref. 5). Evidence was also found that some perception of self-motion could be induced by stimulating central portions of the retina.

The phenomenon of self-movement is also experienced when an observer is sitting on a moving train, looking forward. Even though most of the retina receives a projection from the stationary (relative to the observer) train and only a limited portion of the retina gets a projection from the side window, still the terrain is seen as stationary and the train (hence the observer) as moving (Ref. 3).

The feeling of self-movement in a motion picture viewer can be induced by using a large screen. One disadvantage, however, of enlarging the display is the loss of resolution that ensues. This would probably have little effect on peripheral vision, but could produce substantial degradation of central, foveal vision, especially in video displays. A second problem with using a large screen (and therefore an increased visual angle) is that displacements between contours in successive views may be produced which could disrupt the perception of smooth apparent movement.

Key References

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Cross References

5.502 Optical flow patterns and motion perspective;

5.503 Factors affecting illusory self-motion;

5.505 Oculogravic illusion;

Handbook of perception and human performance, Chap. 22

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.502 Optical Flow Patterns and Motion Perspective

Key Terms

Computer generated imagery; depth perception; motion analysis; motion parallax; motion perspective; optic flow pattern; simulation; video displays

General Description

Movement of an observer through space results in a regular transformation of the distribution of discernible points in the optic array of light that confronts the eye (Fig. 1). The differential flow of points relative to one another is a function of the velocity of the relative motion, the distance of each point or surface in question, and the arrangement or disposition of the surfaces in space relative to the viewer. These gradients of motion in the optic array are generally referred to as *motion perspective* to distinguish them from motion parallax, which is the relative optical motion of two isolated objects in space (CRef. 5.902).

Motion perspective contains a great deal of precise, potentially useful information regarding the path of motion of the observer as well as the slants and distances of the surfaces past which the observer is moving. Figure 2 shows the kinds of information available with various types of motion. In Fig. 2a the observer is moving laterally in a direction perpendicular to the line of sight (as shown by *M*), with the direction of gaze constant. For a surface at some slant with respect to the line of sight (such as the ground), points nearer to the observer move faster than points farther away; there is a smooth gradient of vectors to zero at infinite distance (approximated by the horizon). Nonslanted surfaces (approximated by surfaces *iii* and *iv* perpendicular to the line of sight) move uniformly faster, the closer they are to the observer.

Figure 2b shows lateral movement with the gaze fixed on a distant point *iv*. Here, there are two components of movement: the movement *M* of the viewer, which is responsible for the parallax, and the rotation of the eye, which is needed to keep point *iv* stationary on the retina. If rotation is confined to the *optic node*, it introduces only a uniform translation of the image (vector at *iii*) which modulates but cannot cancel the motion perspective due to the observer's motion *M*. If the horizon is assumed to approximate infinite distance, the vector at *v* equals *iii*. Note that while Figs. 2a, 2c, and 2d refer both to the optic array and to the image of the scene on the retina, Figure 2b pertains only to the retinal image, since the optic array refers to the pattern of light that confronts the eye at a station point and precedes the effects of changing the direction of gaze.

When an observer moves forward, the optic array contains a radially expanding flow pattern, and the focus of expansion of this pattern coincides with the point of aim of the observer's motion.

Figure 2c shows forward (radial) motion along the line of sight for a surface parallel to the motion (i.e., ground or floor). Points on the surface appear to expand outward from the aim point of the motion, with near points moving faster than more distant points.

Figure 2d shows forward motion along the line of sight

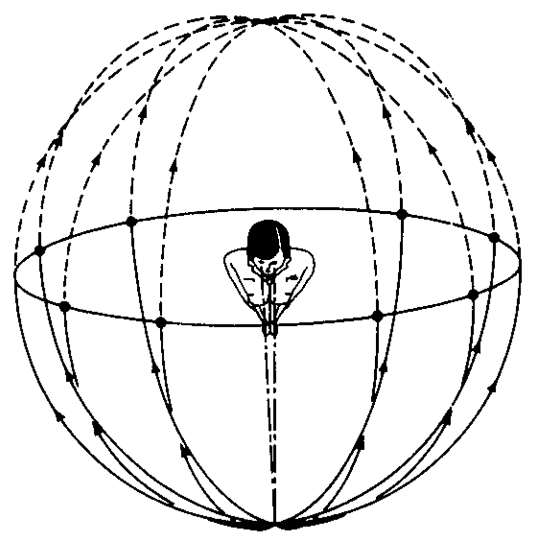

Figure 1. The direction of optical flow during forward motion. The visual scene appears to stream past as if protected on a spherical surface surrounding the observer's head. (From Ref. 1)

for a surface perpendicular to the direction of motion (i.e., wall). Notice that the point at which collision will occur if the movement is continued is itself the one stationary point in the field of view; it is also the center of the optical expansion pattern.

Characteristics of the optical expansion pattern provide information about the observer's motion with respect to objects in the visual scene. For example, symmetrical expansion of object contours outward from the focus of expansion indicates a collision course; asymmetrical expansion indicates a miss (Fig. 3). The impact point or aim point of the observer's motion is the one point in the optic array that remains stationary; all other points expand outward from this point with a velocity that depends on their distance from the aim point. Thus, in principle, observers could use the focus of expansion in the optic array to guide self-locomotion. In practice, however, the situation is more complicated, because the flow pattern in the retinal image is not always the same as the flow pattern in the optic array. This happens, for example, when moving observers do not look at their destination or gaze at a fixed angle to their destination, but rather look at some nearby feature in the world. In this important case, their eyes rotate continuously and add to the radial expansion pattern a translational velocity of the whole retinal image. This changes the flow pattern, and the focus of expansion may be displaced so that it no longer coincides with the aim point. In other cases the focus may be abolished altogether.

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In theory, the observer could separate the translational flow introduced by eye movements from the radial flow in the optic array and use the latter to guide self-motion. Some empirical tests have been made to see whether these motion components can be separated in practice. However, evidence is mixed regarding the observer's ability to locate and use the focus of optical expansion. When observers view a grating of vertical bars whose magnification increases so that the grating expands horizontally, they can locate the focus of expansion to within 1 deg. When a translational velocity is added to this display, however (simulating the case where the observer's gaze is directed away from the focus of expansion), observers' ability to locate the focus is essentially random, with accuracy much worse than 10 deg. Under certain conditions, introducing a motion perspective into the display so that velocity of expansion differs for different portions of the display serves to restore observer accuracy in locating the focus to within 1 deg (Ref. 9). In other words, with perspective in the display, the focus of expansion can be located even when translational velocity is present.

The considerations described above apply not only to the human observer, but to a camera moving through space as well. In this way, the film medium can produce the impression of motion and the depth cues contingent upon it.

—*Partly adapted from Refs. 4 and 7*

Applications

Displays to simulate motion and depth; situations in which human operators must detect the course of their motion or an object in motion relative to them (CRefs. 5.102, 5.214).

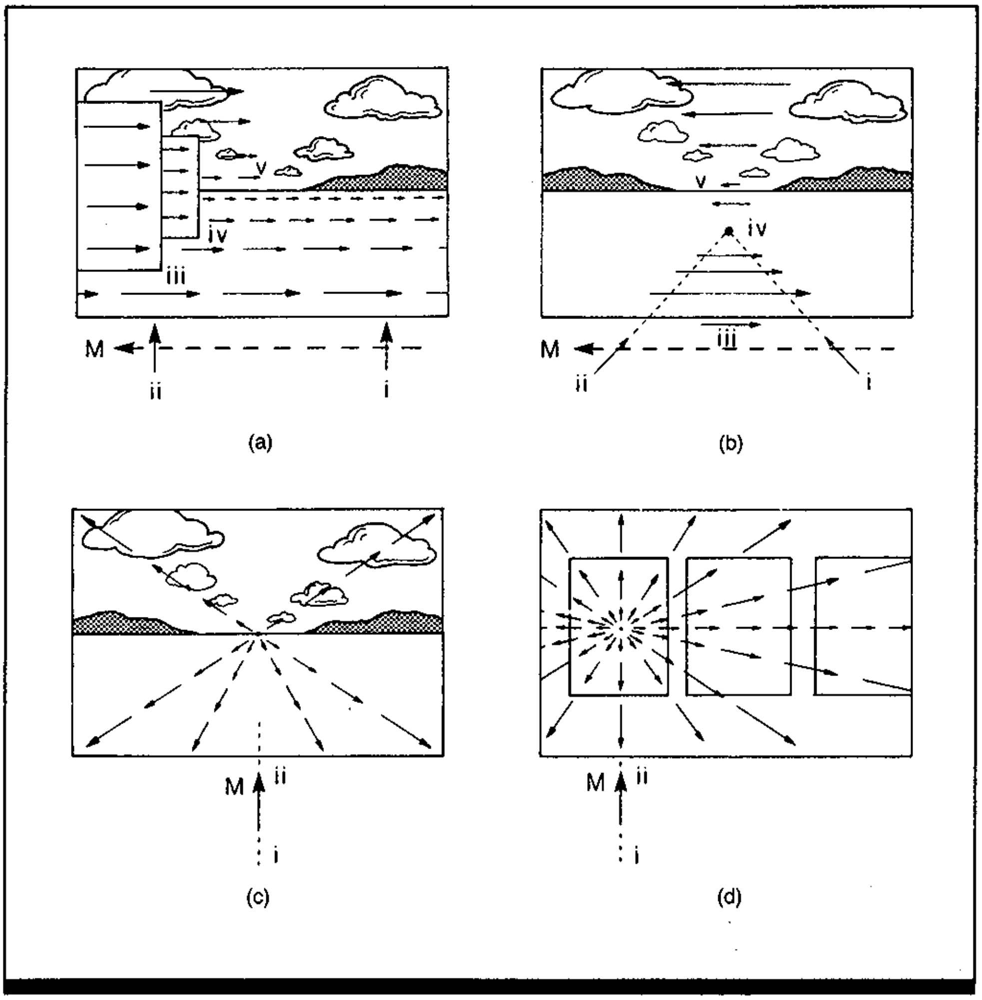

Figure 2. The components of motion perspective and the optical expansion pattern. In all of the scenes, the observer moves as shown by the arrow *M*, and the change in viewpoint is from *i* to *ii*. The solid arrows in each scene are motion vectors showing the magnitude and direction of motion of points at different locations in the optic array as the observer moves. (a) Lateral (leftward) motion with the gaze directed at the horizon and gaze direction constant. (b) Lateral motion with the gaze fixed on point *iv*. (c) Forward (radial) motion along the line of sight, surface parallel to *M* (ground or floor). (d) Forward motion toward a surface perpendicular to the direction of motion (wall). Note that panels (a), (c) and (d) refer to either the optic array or the retinal flow pattern, while panel (b) refers only to the retinal image. (From Ref. 4)

Constraints

• An array must possess texture or edges for these to be motion-produced information regarding depth relations.

• The texture elements being transformed by motion perspective must be detectable by the observer to be of use. For example, simulation display (such as video displays) that might lose texture, or computer-generated displays that lack texture, will not be adequate representational media for the use of perspective to simulate motion (Ref. 3). Even with detectable texture, the elements of texture must not be too small in the array or too far from *foveal* (central) vision to be of use (Ref. 5).

• Other motion-generated cues to depth include kinetic occlusion, kinetic shear, and projective shape transformations (CRef. 5.903).

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Cross References

1.240 Visual angle and retinal size;

5.102 Perception of impact point for simulated aircraft carrier landings;

5.214 Judgment of impending collision with approaching targets;

5.902 Motion parallax;

5.903 Kinetic occulsion and kinetic shear

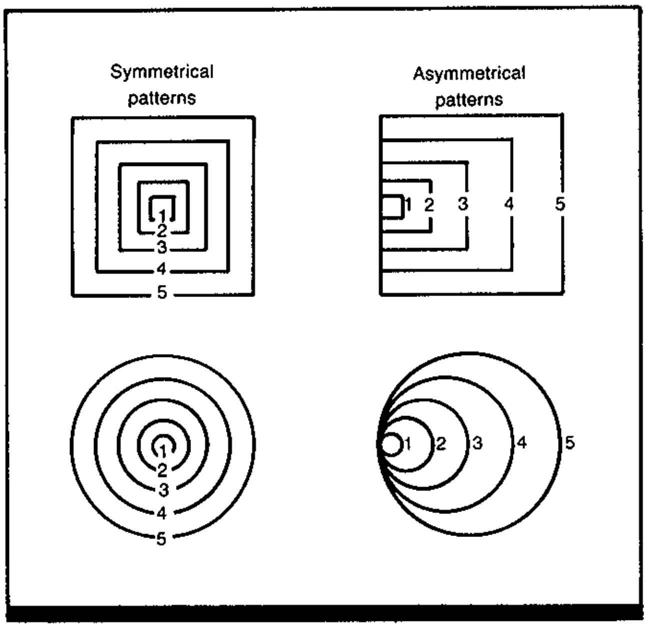

Figure 3. Successive momentary stimulus patterns (time increases from view 1 to view 5) for the perception of objects on a collision course with the observer (symmetrical patterns) and for objects on miss paths (asymmetrical patterns). (From Ref. 2)

Notes

5.503 Factors Affecting Illusory Self-Motion

Factor	Manipulation/Effect	Reference
Optokinetic nystagmus	Reversing motion of central small display with respect to large background has no effect	Ref. 3
Head tilt	Tilting head during illusion produces same Coriolis sensation as during real rotation	Ref. 5
Time for acquisition	When array begins rotating, it takes as much as 30 sec to experience self-motion as opposed to object motion	Ref. 3
Speed of acceleration	Accelerations <5 deg/sec^2 reduce illusion latency	Ref. 9
Accompanying body motion	Body motion in the same direction accentuates the illusion; in the opposite, cancels it	Ref. 12
Ménière's disease (labyrinthine disease)	Patients with higher thresholds for real self-motion in one direction have shorter latencies for illusory motion in that direction	Ref. 11
Scotopic versus photopic thresholds	Reducing luminance or acuity to scotopic levels has no effect	Ref. 8
Stimulus velocity	Increasing stimulus velocity to 90 deg/sec increases apparent self-motion velocity; further increases may stop the illusion	Ref. 10
Removing visual input after some exposure duration	Turning out the lights after the illusion has started produces first perception of motion in the same direction (positive aftereffect) and then in the opposite direction (negative aftereffect). Positive effects last up to 36 sec as stimulus exposure increases to 60 sec, and then decrease with longer exposures. Negative aftereffects increase with increasing stimulus duration up to 15 min	Ref. 2
Retinal location and distance of display	Peripheral displays are more effective as are more distant displays in producing the illusion	Ref. 4
Direction of rotation with respect to the body	Rotating a scene around the body produces perceived rotation; in the frontal plane, it produces perceived body tilt. Translatory visual motion yields perceived linear motion	Ref. 7
Proprioceptive cues	Turning in the dark or walking at the same rate as a moving platform produces illusory self-rotation in the opposite direction when stopped	Refs. 1, 6

Key Terms

Acceleration; circularvection; head tilt; illusory tilt; linear vection; motion aftereffects; optokinetic nystagmus; peripheral vision; posture; pseudo-coriolis sensations; simulation; spatial disorientation; vestibular system

General Description

Perception of self-motion is determined by both vestibular and visual input. Illusory self-motion is induced by visual movement alone, as when one is sitting in a stationary train watching a neighboring train pull out of the station. Illusory self-rotation induced by rotating scenes is called circularvection, while that produced by scenes moving in a flat plane is linearvection. The effects are not produced by optokinetic nystagmus, because nystagmus can be reversed by changing the direction of a small display inside a larger one without changing the direction of the illusion. Inclining the head during the illusion produces the same type of dizziness (pseudo-Coriolis sensations) as is produced by head tilting during real rotation (which produces Coriolis sensations). Illusory self-motion can occur regardless of eye movements in pursuit of a moving visual scene. It can also occur in the absence of visual input (in the dark) when a person is walking on a rotating platform at the same rate as the rotation but in the opposite direction. A rotating visual array initially produces perception of object motion, but illusory self-motion dominates after 30 sec or more. Slower rotation rates produce shorter latencies for the illusion and may eliminate the perceived object motion. Body motion in the direction of the illusory motion shortens the latency further, while that in the opposite direction destroys the illusion. Ménière's disease also affects the illusion. Peripheral vision is important for the illusion and therefore neither the degree to which the display is clearly focused nor reduction of illumination to subphotopic-suprascotopic levels affects the illusion. Velocity of illusory self-motion is proportional to stimulus velocity up to 90 deg/sec, beyond which the illusion may periodically not be experienced.

The illusion produces aftereffects if it has been experienced for a time and then the lights are turned off. It continues first in the same direction (positive) and subsequently in the opposite direction (negative), both following the time course of optokinetic nystagmus. When rotation produces vestibular input, it will outweigh the visual; with small actual motion or previous experience of the visual motion, visual and vertibular cues appear to be averaged. The illusion is induced more effectively by more distant and more peripheral visual displays than by closer or central ones. Self-motion illusions may be associated with illusory body tilt when a scene is rotated in the frontal plane and the observer is upright. The illusory tilt increases with stimulus velocity up to 15 deg/sec and is increased by inclining or inverting the head.

Linearvection, which is an illusory sensation of linear motion of the self produced by translatory motions of the visual scene, is affected by factors similar to those that affect rotary motions (see table).

Applications

When travelling at a constant velocity there are no vestibular cues to actual movement, and so perceived motion is determined by characteristics of the visual array. To avoid unfortunate consequences of illusory movement perception, it is important to be aware of the factors that produce the illusion.

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Cross References

1.917 Factors affecting the vestibulo-ocular reflex;

5.201 Subject-relative and object-relative visual motion;

5.203 Factors affecting threshold for visual motion;

5.502 Optical flow patterns and motion perspective

5.504 Elevator Illusion

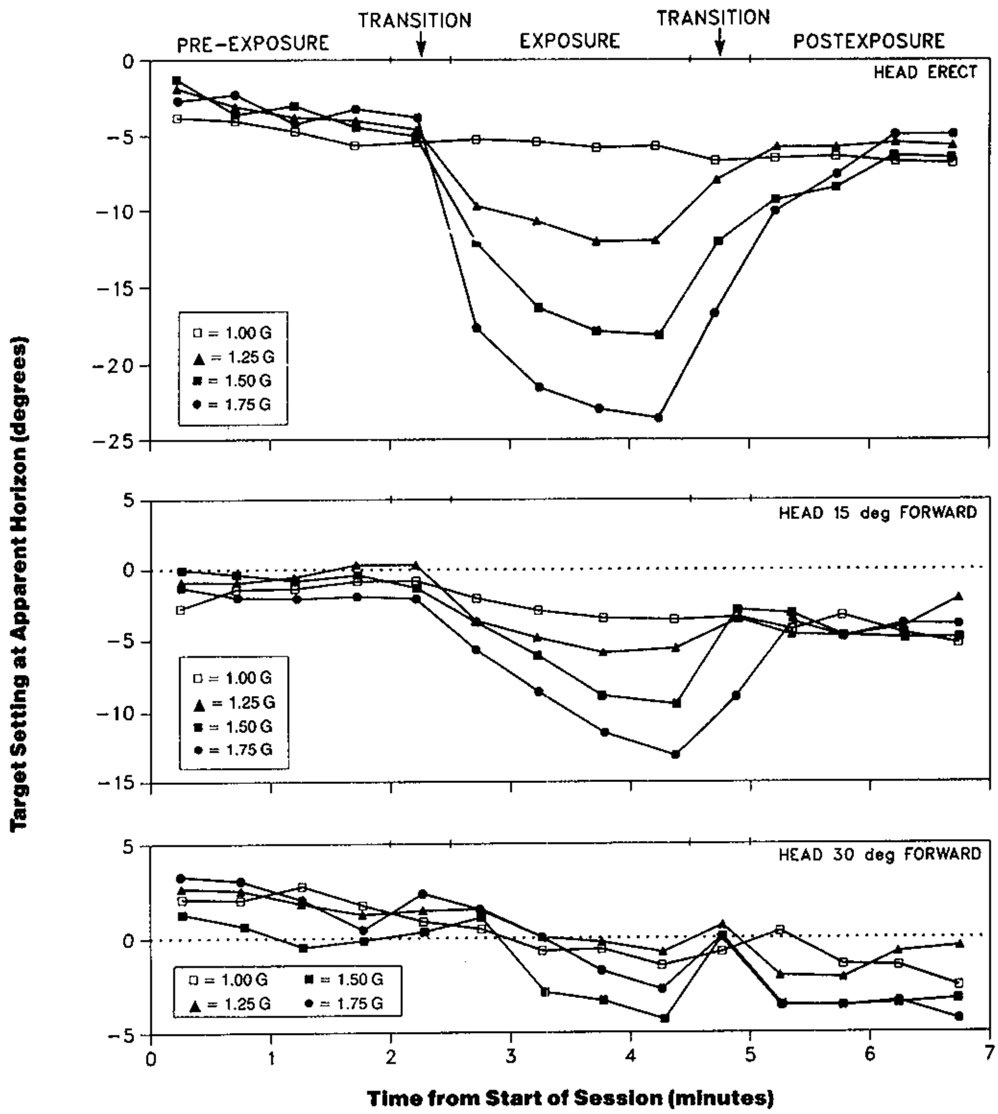

Figure 1. Settings of visual target to apparent horizontal as a function of G (vector sum of gravity and centripetal force on subject) and head tilt. Negative settings indicate an apparent rise in target. (From Ref. 1)

Key Terms

Elevator illusion; eye movements; gravitational-inertial force; labyrinthine disease; oculogravic illusion; otoliths; spatial disorientation; vertigo; vestibular system; visual direction

General Description

Stationary objects appear to rise as gravitational-inertial forces along an observer's body axis increase. This phenomenon is called the elevator illusion and is similar to the oculogravic illusion except that it requires an intact vestibular function (labyrinthine-diseased patients do not experience the elevator illusion.) The illusion is hypothesized to be based on a disruption of the normal balance between pro-

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prioceptive neck and vestibular mechanisms governing eye position at different head orientations. When the head is tilted and gravitational-inertial force is increased, the magnitude of the illusion increases with increasing force and decreases with increasing forward head tilt. No illusion is experienced at 30 deg of tilt, perhaps due to elimination of shearing force on the surface of the utricle or to changes on the forces on the eyeball.

Applications

Under flight conditions where the gravitational-inertial forces increase on the long axis of the body, the illusion might affect perception of fixated objects such as the instrument panel or an external object.

Methods

Test Conditions

- Gravitational-inertial forces of 1, 1.25, 1.5, or 1.75 G (vector sum of gravity and radial force of rotation) in Naval Air Development Center's human centrifuge; subjects strapped in; head positioned using bite board to be erect, 15 deg forward, or 30 deg forward
- Visual target was light annulus, 25 mm outer diameter and 5 mm thickness, viewed from 92 cm, subtending 1.6 deg of visual angle;
- Subject operated control switch to reverse target's direction

Experimental Procedure

- Method of adjustment
- Within-subjects design
- Independent variables: degree of head tilt; amount of gravitational-inertial force
- Dependent variable: position of target that subject judged to be horizontal
- Subject's task: adjust control switch so that target moved to apparent horizontal
- 9 male subjects, 19-32 yrs of age, experienced in centrifuge, with normal visual acuity and no labyrinthine disease

Experimental Results

- When head is erect or 15 deg forward, increases in gravitional-inertial forces cause subjects to lower targets (i.e., targets appear to rise).
- When head is 30 deg forward, subjects do not lower the target (i.e., the illusion is not experienced).
- The magnitude of the illusion is greater with increased gravitational-inertial force.
- With the head erect, the illusion changes 20.4 deg/G; with head pitched 15 deg forward, the illusion changes 9.1 deg/G.

Variability

Analysis of variance showed head pitch and G to be significant at 0.0001 level and their interaction significant at 0.01 level.

Constraints

- Labyrinthine-diseased patients do not experience the illusion.

Key References

*1. Cohen, M. M. (1973). Elevator illusion: Influences of otolith organ activity and neck proprioception. *Perception & Psychophysics, 14*, 401-406.

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Cross References

1.960 Factors affecting coordination of head rotation and eye movements;

3.210 Vestibular illusions;

5.202 Image/retina and eye/head systems of motion perception;

5.503 Factors affecting illusory self-motion;

5.505 Oculogravic illusion;

5.705 Visual factors influencing postural stability;

5.707 Postural stability: effects of illusory self-motion;

5.802 Illusory spatial displacements

5.505 Oculogravic Illusion

Key Terms

Elevator illusion; gravitorotational force; oculogravic illusion; posture; spatial disorientation; utricular maculae; vertigo; vestibular system

General Description

A vertical observer strapped to a horizontally rotating object, some distance from the center of rotation, is exposed to a centrifugal force acting radially. This force interacts with gravitational force to produce a resultant force that causes the observer to feel pressed downward and inclined in the direction of the resultant force. At the same time, any vertical visual object appears inclined in the same direction. If the observer faces in a direction tangential to the motion, these illusory inclinations occur in the **frontal plane**. If the observer faces towards or away from the axis of rotation, they occur in the **sagittal plane**. These kinesthetic and visual effects are known as oculogravic illusions.

In addition, a visual object in dark surroundings appears to move upwards while the observer is accelerated. This is know as the elevator illusion. If the observer's eyes remain closed until acceleration is complete, the visual object appears displaced when the eyes are opened by the same amount that it would have been displaced had the eyes been open all the time. On cessation of acceleration, the visual object appears to descend to its true position. An afterimage behaves in the same way, ruling out retinal image motion resulting from eye movements as the cause of the visual illusion.

When the room is bright and the observer fixates the walls rather than an object, and the change in direction of resultant force is ≥56 deg, the observer perceives the platform tilted upward and stationary and perceives himself motionless and on his back. At low levels of acceleration, conflict between visual and kinesthetic stimuli are resolved in favor of the visual stimuli, while at higher levels the nonvisual stimuli dominate.

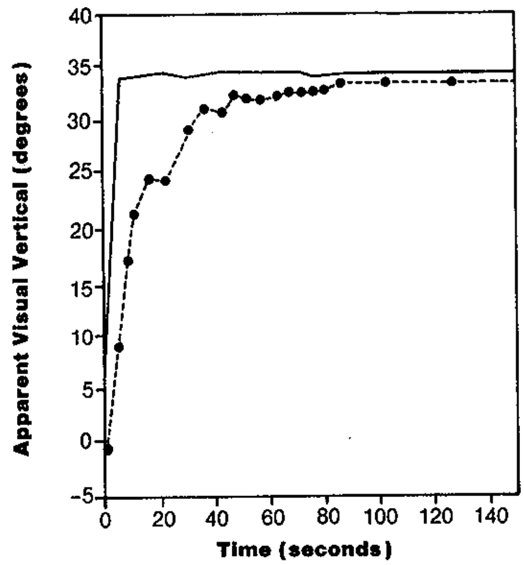

Figure 1. Degree of tilt of the apparent visual vertical from the subject's body axis as a function of elapsed time since the beginning of centrifugal rotation of the subject. The actual force acting on the subject is shown by the solid line. (From Ref. 2)

These illusions do not show adaptation to continued stimulation. The experience of acceleration lags behind the onset of the illusions by an average of 81 sec. The oculogravic and elevator illusions are related but not identical, because labyrinthine-diseased patients can still experience the former but not the latter, indicating that the vestibular system is not necessary for the oculogravic illusion.

Applications

The conditions under which the oculogravic and elevator illusions are experienced often occur in aviation and can produce illusory displacement of the flight crew, the aircraft, or the instrument panel (visual) relative to the aircraft. Awareness of the illusion can make these effects easier to correct and/or ignore.

Methods

Test Conditions

- Rotating platform 180 cm wide and 6.6 m from center to periphery suspended above 10-metric-ton, motor-driven flywheel; platform equipped with padded seat 5 m from center of rotation
- Subject strapped in with restraining straps and bite board to prevent body and head movements; seat rotatable about vertical axis from facing axis of rotation to 90 deg from axis of rotation
- Visual field either brightly lit or dark, with single collimated star or line of light

Experimental Procedure

- Independent variables: acceleration, body tilt, amount of exposure to illusion, visual condition (brightly lit room or objective visual display in dark or afterimage)
- Dependent variables: amount of perceived tilt, amount of perceived movement or displacement of visual display, time to report body or visual displacement relative to acceleration
- Subject's task: report perceived body tilt or visual movement or displacement of fixated object
- Healthy adult subjects of both sexes experienced with illusion

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Experimental Results

- Change in resultant force causes subject to perceive self, body support and visual vertical tilted firmly and smoothly in the direction of resultant force.
- Apparent angular motion is initially rapid and then slows down until subject is aware of no further change.
- Fixated star on line in dark or afterimage appears to rise with acceleration and descend with deceleration.
- Closing eyes during velocity changes stops apparent visual movement, but produces same visual displacement when eyes are reopened.
- When facing opposite center of rotation, subject experiences illusions that are the reciprocal of those experienced when facing center of rotation.
- When facing direction of rotation or opposite the direction of rotation, both the kinesthetic and visual illusions of tilt are away from the center of rotation.
- Subjects estimate angle of apparent rotation as identical to angle of resultant force: 1-deg change yields 50% correct and 3-deg change yields 100% correct.
- Exposure to up to 15 min of rotation does not alter magnitude of illusion.
- Subject's experience of illusion lags ~80 sec behind changes in velocity.

Constraints

- Reports indicate that labyrinthine-diseased patients experience illusions to a lesser extent than normal patients do.

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Cross References

3.210 Vestibular illusions;

5.504 Elevator illusion;

5.706 Postural stability: effects of retinal image motion;

5.707 Postural stability: effects of illusory self motion;

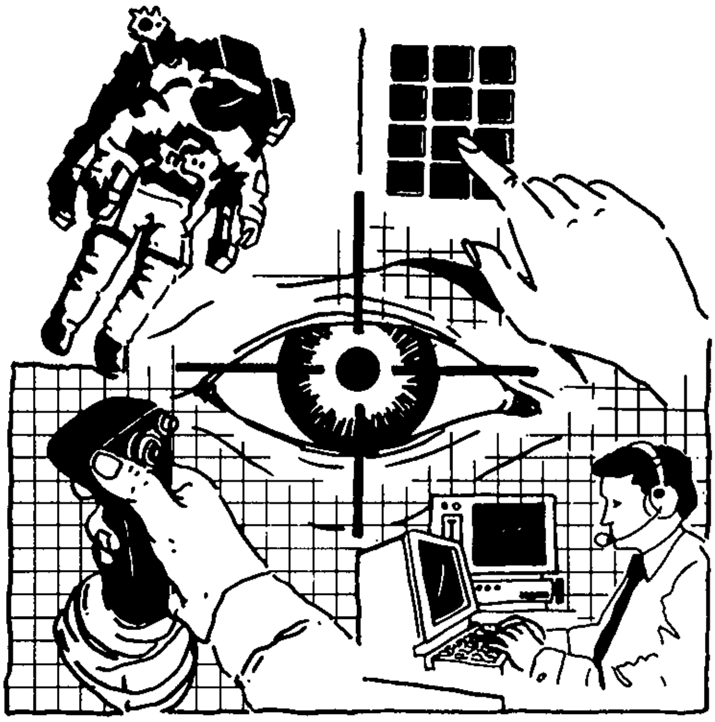
5.708 Illusory self-inclination;

5.802 Illusory spatial displacements;

Handbook of perception and human performance, Ch. 18, Sect. 5.7

Notes

Section 5.6 Visual Localization and Direction



5.601 Visual Localization and Perceived Visual Direction

Key Terms

Egocentric localization; object position

General Description

Localization of an object that is projecting an image on the retina requires that an observer have a system with which to describe the object's position. There are three classes of reports that an observer can make when localizing an object: (1) An object's position in reference to some direction that the observer perceives as centered on his own body is an egocentric report of visual direction. (2) Localizations referring to the position of a second object without explicit reference to the observer are called object-centered reports. (3) The third class of report, absolute identification, involves identifying an object's position without reference to either other objects or to the observer's egocentric system of directions.

Constraints

- Both egocentric and object-centered reports are subjective. Egocentric judgment depends upon perceived spatial relations among objects, just as object-centered localization does. Egocentric judgment is still referenced to an "object," although the object is a part or location of the observer's own body. Furthermore, a change in observer position will change egocentric localization, and has the potential to change the phenomenal positions of objects relative to each other. These ideas are demonstrated in Fig. 1. If the observer moves to the left, the egocentric localizations of object A change, but the visual direction of A relative to B does not change. If both the observer and object A move, but their physical relation remains constant, there is a difference in the object-centered visual direction of A relative to B, but no change in the egocentric localization of A. If A is moved, but the observer and object B remain stationary, then the change in egocentric direction of A is correlated with a change in the object-centered localization of A relative to B.
- Absolute identification is not really absolute, because observer position will be crucial in such identification when no other visual cues are present.
- Although the retinal projection does provide some information about object location, other sources of information must be taken into account. For example, a change in retinal position can occur either because the object has moved or the eye has moved, as illustrated in Fig. 2. Hence, there must be some channel for extraretinal eye position information in localizing objects.

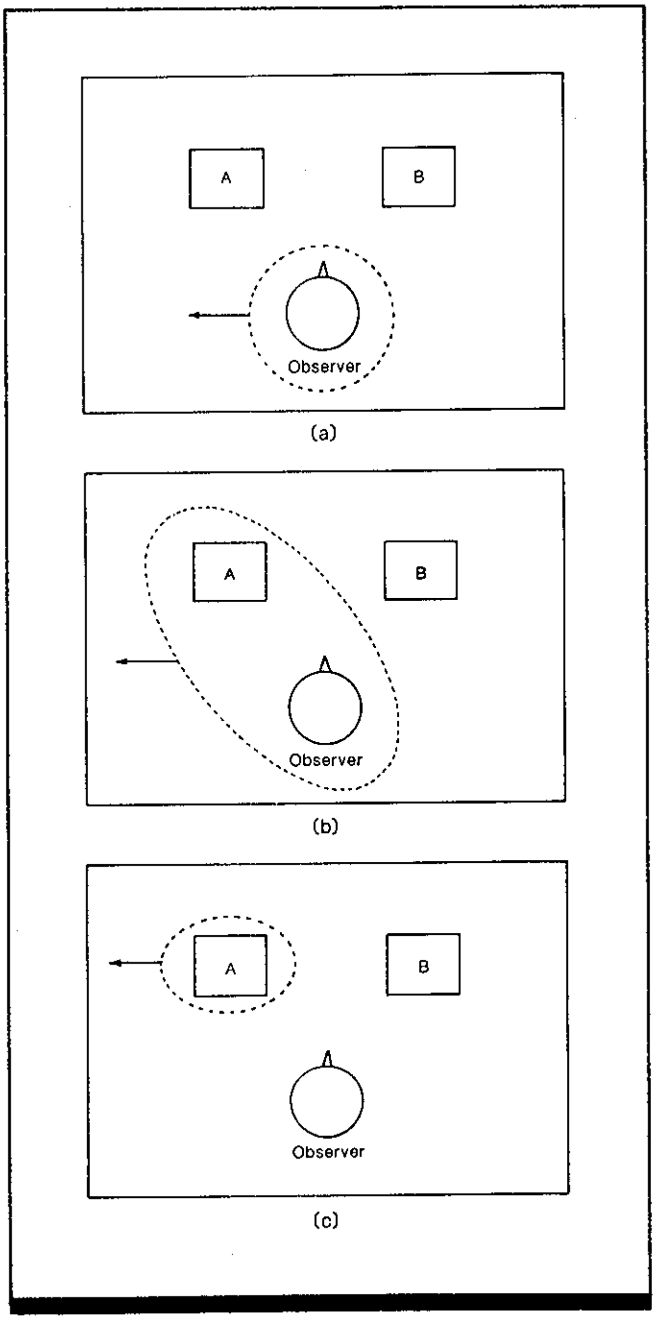


Figure 1. Observer located with respect to two objects. (From Ref. 1)

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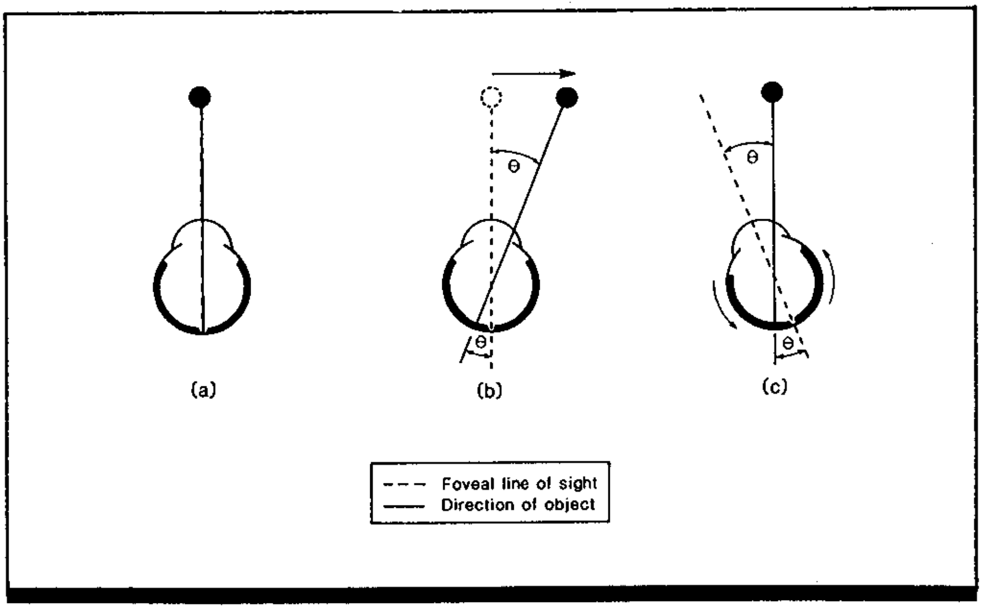


Figure 2. Identical shifts in original retinal location (a) may be produced either by (b) a change in object's position or (c) ocular rotation. (From Ref. 1)

Key References

*1. Matin, L. (1986). Visual localization and eye movements. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

Cross References

1.941 Gain of tracking eye movements: effects of target luminance and visual field location;

5.604 Target localization during pursuit eye movements;

5.606 Target localization accuracy: effect of gaze eccentricity;

5.1007 Spatial localization in the presence of intersensory conflict;

5.1010 Cross-model versus intramodal perception of distance and location;

7.407 Effect of signal target location on visual search;

9.202 One- versus two-handed reaching: effect of target distance and width;

9.205 Control movements: effects of direction

Table 1. Classes of visual localization.

Class of Report	Procedure or Technique	Example
Egocentric	Internal norm	Object's position described as "A is left of my median plane"
Object-centered	Simultaneous presentation of two objects	"A is to the left of B," with both A and B physically present
	Sequential presentation of two objects	"A is to the left of B," when A is presented before B, and is not visible when B is presented
	Intermodal	"The light A is to the left of the sound B"
Absolute identification	Absolute identification	Observer names light that was presented in otherwise dark room and was identical to other lights except in position; for example, naming "light number 7" in a row of 10 lights

5.602 Target Detection During Saccadic Eye Movements: Effects of Saccade Size and Timing

Key Terms

Apparent movement; eye movements; eye mediated-controls; motion perception; motion sensitivity; saccadic eye movements; saccadic suppression; spatial localization; target acquisition; target detection; visually-coupled systems

General Description

Detection of displacement is dramatically reduced for a brief period around onsets of saccadic eye movements. Detection of target movement is a monotonic function of the ratio of target displacement to saccade size (Figs. 1, 2), and detection is a U-shaped function of the time between saccade onset and target displacement (Fig. 3).

Methods

Test Conditions

Study 1 (Ref. 2)

- Eye movements of experimental observer recorded by electro-oculography and used to drive target displacement on oscilloscopes for both experimental and control observers
- As oscilliscope trace (2mm) served as the target and could move left or right in response to left-eye movements, and up, down, left, or right in response to right eye movements; gain control allowed the following target-movement/eye-movement ratios: 0, 1/20, 1/10, 1/5, 2/5, 1/2, or 1
- On each trial, control observer was always to fixate straight ahead while experimental observer fixated straight ahead, then fixated on cueing lamp 6.5 cm to left or right and held eyes in that position until instructed to again fixate straight ahead. Experimental observers were then to press one of four buttons indicating the direction of oscilliscope trace movement
- Stimulus conditions presented in randomized block fashion
- Observers in darkened rooms with heads steadied by bite bars; observers wore goggles so they could see trace, but not rest of oscilloscope screen

Study 2 (Ref. 1)

- Target was a row of 13 fixation points spaced 1 deg apart; each point identifiable by surrounding concentric circles and radiating lines; entire stimulus covered 13-deg square
- Screen background, fixation points, and lines at 0 log fL (3.426 cd/m^2); target background at 1.8 log fL (3.426 cd/m^2) (or 1.8 log fL as in source)
- Stimulus unpredictably moved 1, 2, or 4 deg left or right at 900 deg/sec while observer performed an irregular pattern of eye movements between fixation points; at least 1 sec between stimulus movements
- Eye movements monitored by photocells; observers light-adapted to stimulus prior to each experimental session

Experimental Procedure

Study 1

- Within-subjects design
- Independent variables: direction of target displacement, ratio of target displacement to extent of eye movement
- Dependent variable: percentage of correct reports of direction of target movement
- Observer's task: for both observers, to report direction of target movement by key press during interval between instructions to fixate straight ahead at beginning of trial and instructions to experimental observer to again fixate straight ahead
- 14 observers, paid university students

Study 2

- Independent variables: extent of target displacement, size of saccadic movement, time between saccade and target movement
- Dependent variable: percent of correct detections of displacement
- Observer's task: move switch to indicate detection of target movement
- 4 observers in 2-deg-displacement condition and 2 observers each in 1-deg and 4-deg conditions

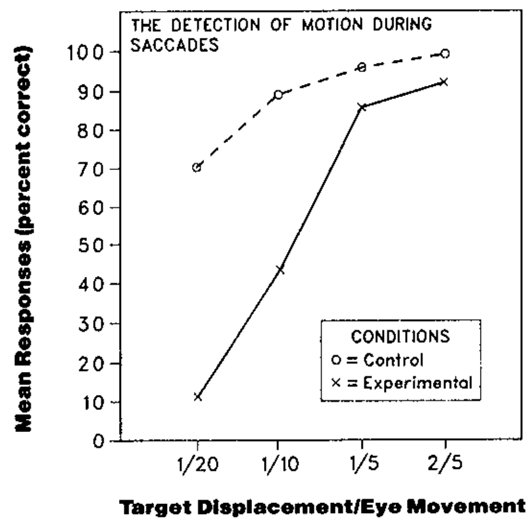


Figure 1. Percent correct detection of target movements during saccadic eye movements as a function of the ratio of the size of target movement to size of eye movement (Study 1). Target movements were yoked to saccadic eye movements of experimental subject (X—X) and independent of eye movements of control subject (0----0). (From Ref. 2)

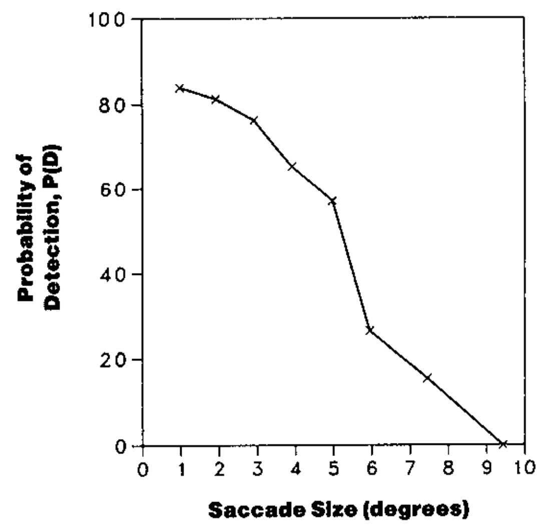


Figure 2. Probability of detection of 2-deg target displacements occurring within 10 msec before and 40 msec after the start of a saccadic eye movement as a function of the size of the eye movement (Study 2). (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• There is no difference in perception of independent target movements and those occurring during saccadic eye movements when the target movements are >1/5 the magnitude of the eye movements. Observers accurately report the direction of target movement (Fig. 1).
• Target displacements during eye movement that are 1/20 of eye movements are rarely detected, and consequently the object is perceived as motionless.
• Yoked target movements that are 1/10 of eye movements are seen roughly one-half the time (~43%), indicating that discrepancies of this size between eye and target movements may be close to threshold.
• Probability of detection of target movement is a U-shaped function of the time between onset of saccade and target movement, with maximum suppression occurring during the saccadic movement. The probability of detection at any particular point on the U-shaped curve is a function of the relative sizes of the target and eye movements.
• Target movements are not detected when they occur within 10 msec after a saccadic eye movement that is at least three times larger than the target movement.
• The relative directions of target and eye movements do not influence detection (CRef. 5.603).

Variability

Results in Study 1 were reviewed by analysis of variance and *a posteriori* use of the Scheffé procedure. Study 2 used a chi-square to test for significance of direction of target movement.

Repeatability/Comparison with Other Studies

A number of qualitative reports support the data (Refs. 3, 4, 5).

Constraints

• Other factors that affect detection of displacement have largely not been explored in this context.

Key References

*1. Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision Research, 15,* 719-722.

*2. Mack, A. (1970). An investigation of the relationship between eye and retinal image movement in the perception of movement. *Perception & Psychophysics, 8,* 291-298.

3. Sperling, G., & Speelman, R. (1966). Visual spatial localization during object motion, apparent object motion, and image motion produced by eye movements. *Journal of the Optical Society of America, 55,* 1575-1577.

4. Stark, L., Kong, R., Schwartz, S., Hendry, D., & Bridgeman, B. (1976). Saccadic suppression of image displacement. *Vision Research, 16,* 1185-1187.

5. Stark, L., Vossius, G., & Young, L. (1962). Predictive control of eye tracking movements. *Transactions of Human Factors Electronics, HFE-3,* 52-57.

6. Wallach, H., & Lewis, C. (1965). The effect of abnormal displacement of the image during eye movements. *Perception & Psychophysics, 1,* 25-29.

Cross References

1.935 Patterns and errors in saccadic eye movements: effect of visual task;

1.936 Timing and accuracy of saccades to briefly lit targets;

5.202 Image/retina and eye/head systems of motion perception;

5.215 Motion illusions with tracking eye movements;

5.603 Detection of motion during saccades: effect of axis of movement;

7.407 Effect of signal target location on visual search;

7.610 Threshold "detection lobe" curve;

7.611 Prediction of aircraft detectability;

Handbook of perception and human performance, Ch. 17, Sect. 3.2; Ch. 20, Sect. 2.3

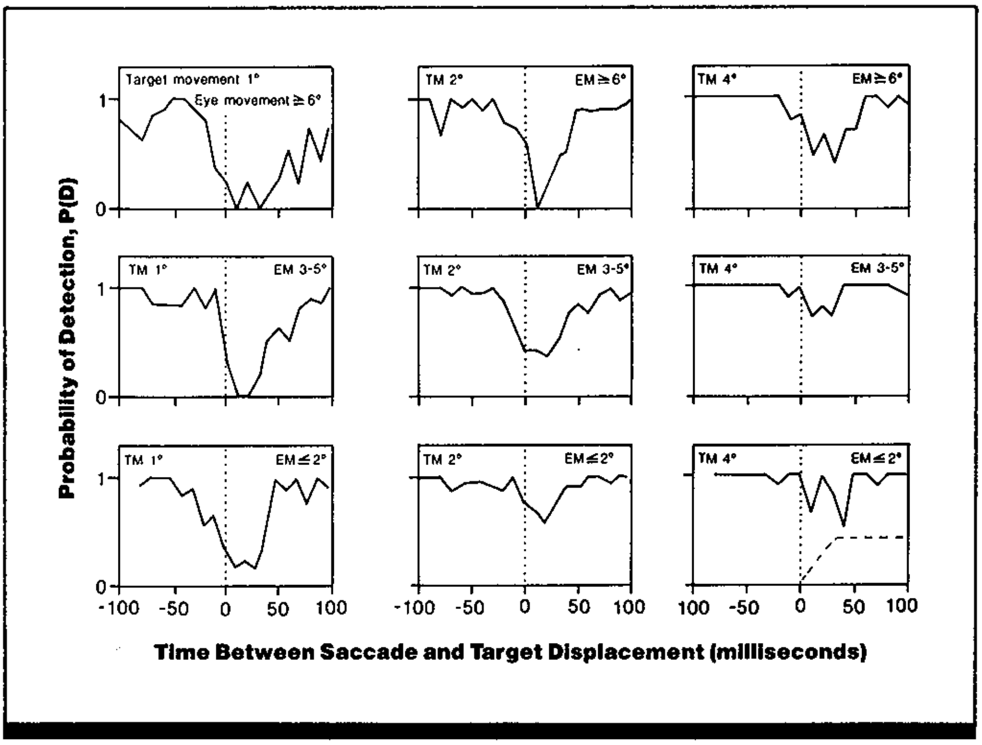


Figure 3. Probability of detection of target displacements as a function of the time between the saccadic eye movement and the target displacement (Study 2). The determining parameter for each curve is the relative size of the target and eye movements, with size of target movements organized by columns and size of eye movements organized by rows. The dashed line in the lower right cell represents a 6-deg saccadic movement. (From Ref. 1)

5.603 Detection of Motion During Saccades: Effect of Axis of Movement

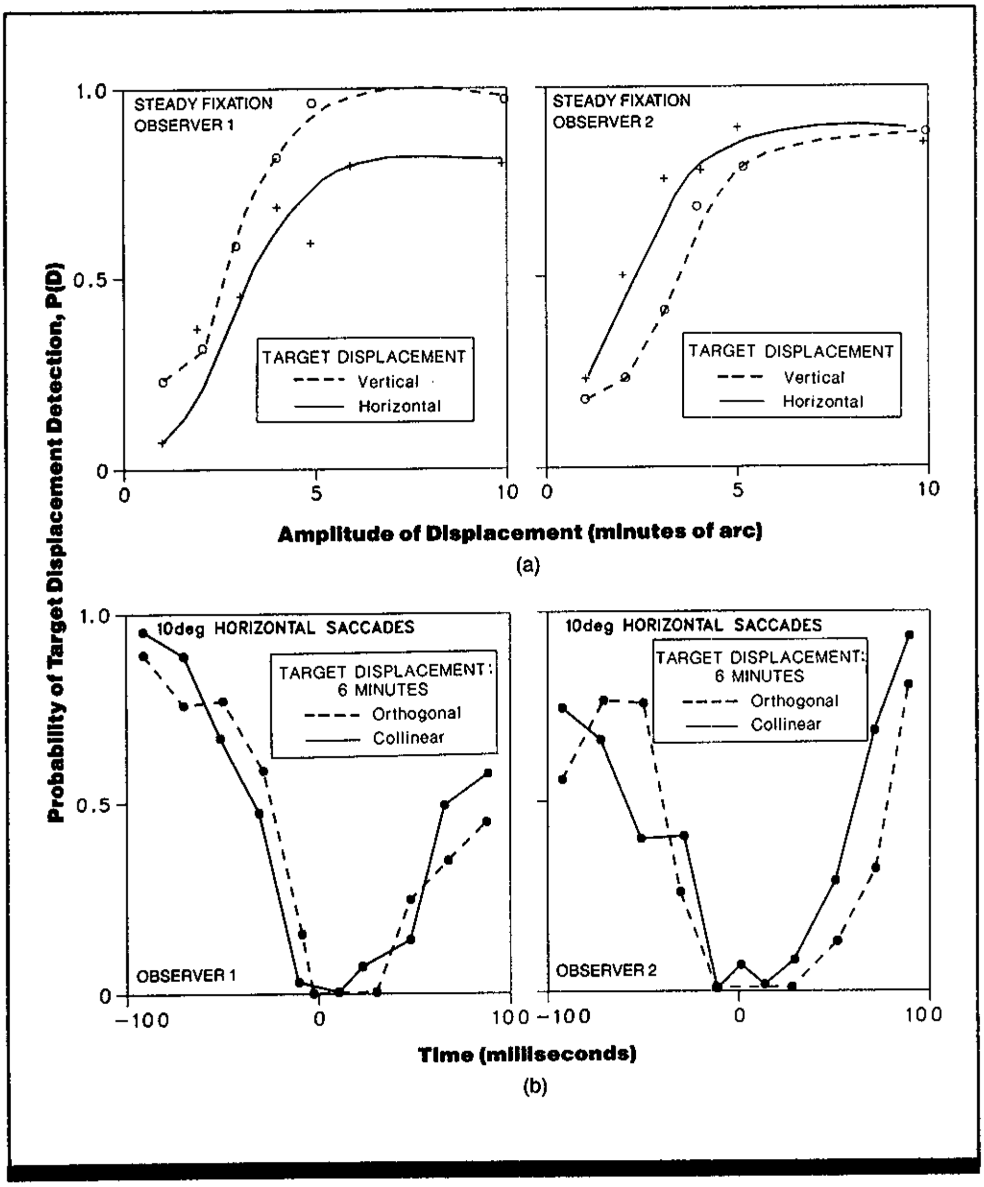


Figure 1. (a) Probability of target detection during steady fixations for two observers as a function of the amplitude of either vertical or horizontal target displacements. (b) Probability of target detection during 10-deg horizontal saccades (for the same 2 observers as in Fig. 1a) as a function of the time interval between the target displacement and the saccade (Study 1). (From Ref. 3)

Key Terms

Eye movements; eye-mediated controls; Ganzfeld; motion perception; saccadic eye movements; saccadic suppression; target acquisition; target detection; visually coupled systems

General Description

For a brief period of time during saccadic eye movements, the visual system is relatively insensitive to movements of visual targets (CRef. 5.602). This insensitivity is proportional to the size of the saccades: displacements <20% of saccade extent are generally not detected (Ref. 2), though the absolute magnitude of the suppression may depend on a number of factors (CRef. 5.602).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Whether suppression of image-displacement information is uniform for all axes of movement relative to the axis of the eye movement is somewhat controversial. There is a general consensus that suppression is uniform for displacements in the direction of or opposite to the direction of the eye movements along the axis of the saccade (Refs. 1, 2, 3, 4); the majority of studies find uniformity along all axes of displacement. One such study is described (Ref. 3), as well as a contrary result reporting greater suppression along the axis orthogonal to the saccadic eye movement (Ref. 4).

Applications

Design of systems that involve detection of movement of targets during continuous viewing.

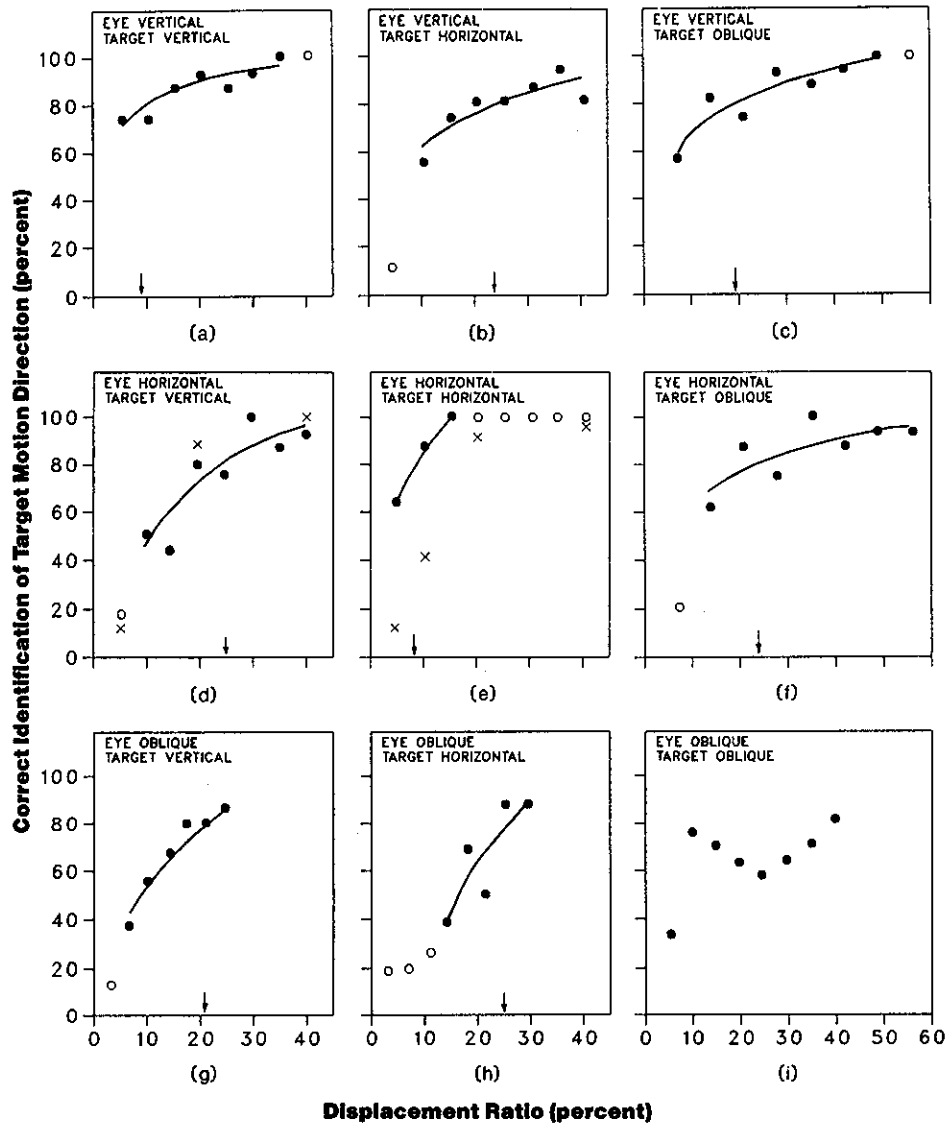


Figure 2. Percent correct identification of target motion directions during saccades as a function of displacement ratio (ratio of target displacement to eye movement) for different eye-movement and target-movement directions (Study 2). (From Ref. 5)

Methods

Test Conditions

Study 1 (Ref. 3)

- Target was a slightly defocused, 10-deg square containing a pattern of random dots projected onto a Ganzfeld; target luminance 1.8 log fL (2.33 log cd/m^2); target movement occurred randomly and asynchronously with eye movements; driven by mirror mounted on galvanometer; target displacement of 6 or 30 min
- Horizontal saccadic eye movements (observer moved eyes horizontally by alternate fixations between two vertical sides of square); horizontal or vertical target displacement
- Eye movements monitored by infrared photocell method; observers head steadied by bite bar; target viewed binocularly

Study 2 (Ref. 5)

- Target was 7-deg ring (oscilloscope image) on very dark background; target movements triggered by eye movements
- Ratio of target displacement to eye movement varied from 0-60%; target displacements were along four axes (horizontal, vertical, and obliques); eye movements independently made along same set of axes
- Eye movements monitored by infrared method; observers head steadied by bite bar

Experimental Procedure

Study 1

- Within-subjects design
- Independent variables: axis and extent of target displacements, interval between saccade and target displacement
- Dependent variables: percent correct detection of target displacements occurring within 100 msec of a saccade
- Size and axis of target displacement known to the observer and constant within a block of trials
- Observer's task: press button to indicate detection of target displacement
- 3 observers

Study 2

- Within-subjects design
- Independent variables: axis of target movement, displacement ratio (target displacement to eye movement), axis of saccadic eye movement
- Dependent variable: percent correct detection of axis of target displacement
- Observer's task: terminate trial when a target displacement was detected and report the axis of displacement
- 8 paid college students

Experimental Results

- In Study 1, for both 6 and 30 min of arc target displacements, target detection is almost completely suppressed from 20 msec before until 40-50 after saccade.
- Curves for horizontal and vertical displacements are very similar; thus there is no evidence of variation in detection for horizontal and vertical axes of displacement.
- In Study 2, when target-displacement axis differs from axis of eye movement, 80% threshold generally occurs at ~20% displacement ratio (target movement to eye movement).
- When target-displacement axis and eye-movement axis are the same for either the horizontal or vertical axis, the displacement ratio for the 80% threshold falls to 10%.
- Oblique movement yields an anomalously high threshold.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Findings of no anisotropy (variation in detection with direction) are reported in Ref. 2.

Constraints

- It is unclear at present under what conditions anisotropy is found.
- Volkmann (Ref. 5) found that there was not total saccadic suppression for weak light stimuli on a steady light fixation field.

Key References

1. Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision Research, 15*, 719-722.

2. Mack, A. (1970). An investigation of the relationship between eye and retinal image movement in the perception of movement. *Perception & Psychophysics, 8*, 291-298.

*3. Stark, L., Kong, R., Schwartz, S., Hendry, D., & Bridgeman, B. (1976). Saccadic suppression of image displacement. *Vision Research, 16*, 1185-1187.

4. Volkmann, F.C. (1962). Vision during voluntary saccadic eye movements. *Journal of the Optical Society of America, 52*, 571-578.

*5. Whipple, W., & Wallach, H. (1978). Direction-specific motion thresholds for abnormal image shifts during saccadic eye movement. *Perception & Psychophysics, 24*, 349-355.

Cross References

5.602 Target detection during saccadic eye movements: effects of saccade size and timing

Handbook of perception and human performance, Ch. 17, Sect. 3.3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.604 Target Localization During Pursuit Eye Movements

Key Terms

Apparent movement; eye movements; eye-mediated controls; motion illusions; pursuit eye movements; visual localization; visually coupled systems

General Description

Visual localization (CRef. 5.202) is impaired during pursuit eye movements, probably due in part to inaccuracies in eye position information generated during those movements. Observer judgments show little evidence of compensation for the changed position of the eye, when required to judge the relative position of targets presented sequentially in the course of a pursuit eye movement. These data, combined with evidence of motion illusions during pursuit movement (CRef. 5.215), demonstrate the potential for inaccurate target localization.

Methods

Test Conditions

- Both pursuit stimuli (a small moving point of light) and localization stimuli displayed on CRT viewed through a blue phosphor to reduce phosphor persistence
- Pursuit stimuli were upper and lower halves of a vertical line; separation of successive views equivalent to 9 deg/sec continuous movement; upper and lower halves appear misaligned if pursuit movements inaccurate
- Localization Stimulus 1 was the letter *y* flashed on right of screen; Stimulus 2 was a vertical line presented in one of five horizontal locations centered around spot where Stimulus 1 and Stimulus 2 appeared to be co-located
- Seven interstimulus intervals: 306 msec, 510 msec, 714 msec, 918 msec, 1122 msec, 1428 msec, and 1738 msec

Experimental Procedure

- Point of subjective equality determined by method of constant stimuli
- Independent variables: interstimulus interval, physical separation
- Dependent variable: percent judgments of relative position of Stimulus 2
- The staggered line pattern was set in motion, the observer commanded to follow it with her eyes. When fixation pattern reached midline, Stimulus 1 flashed, followed, at a variable interval in a variable position, by Stimulus 2. Observer judged whether 2 was to right or left of 1 by tilting joystick in appropriate direction
- Trials were separated by an interstimulus interval. Ten trials were run, in random order, at each of five separations
- 2 observers

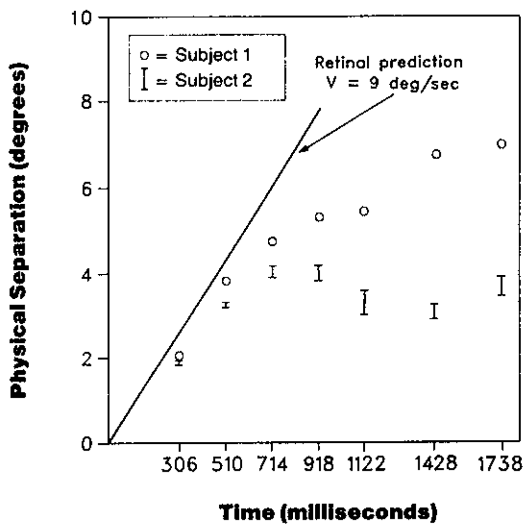


Figure 1. Visual direction during pursuit eye movement. Physical separation of two flashed lines reported to lie in the same visual direction whose presentations were separated by the time interval shown. The diagonal line is the locus of points for which the two lines would strike the same horizontal retinal location with accurate ocular pursuit. Data would fall along the abscissa with accurate position report. (From Ref. 1)

Experimental Results

- The apparent positions of the two stimuli are largely determined by their retinal positions at the short (306, 510) interstimulus intervals. Presence at times of apparent motion for short times was a factor. The longer intervals show, in Fig. 1, increasing compensation for the eye movement, with absolute error approaching an asymptote
- Eye compensation for position was never 100% for stimuli as long as 300 msec, although it increased with longer times intervals

Variability

Author reports data to be "highly variable" due to difficulty of judgments. No formal statistics reported.

Repeatability/Comparison with Other Studies

Results at short interstimulus intervals repeated in the same report, Ref. 1.

Constraints

- Large individual differences in asymptotic accuracy are evident in Fig. 1. These differences may be due, in part, to experience in related tasks.
- Author reports one can, at will, develop a set to produce data based on retinal location or on physical location. However, one cannot accurately report physical location (as above).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Stoper, A. E. (1967). *Vision during pursuit movement: The role of oculomotor information*. Doctoral dissertation, Brandeis University, Ann Arbor, Michigan.

2. Stoper, A. E. (1973). Apparent motion of stimuli presented stroboscopically during pursuit movement of the eye. *Perception & Psychophysics*, *13*, 201-211.

Cross References

1.945 Accuracy of tracking eye movements: effect of target velocity;

1.946 Accuracy of tracking eye movements: effects of target motion;

1.947 Visual tracking: effects of perceived versus real target motion;

5.202 Image/retina and eye/head systems of motion perception;

5.215 Motion illusions with tracking eye movements;

Handbook of perception and human performance, Ch. 20, Sect. 6.4

5.605 Target Localization During Pursuit Eye Movements: Effect of Intensity of a Brief Target

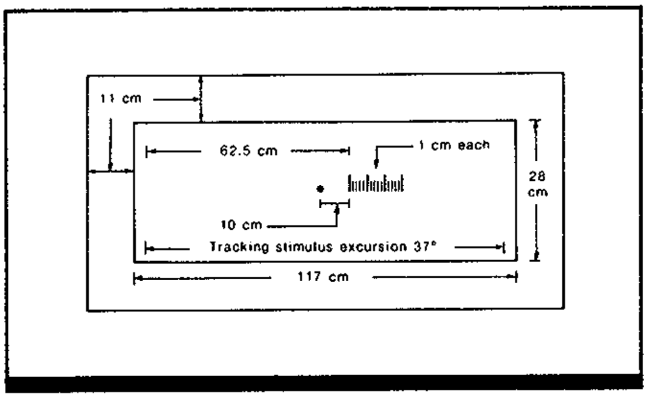


Figure 1. Stimulus display and scale projected on screen. (From Ref. 1)

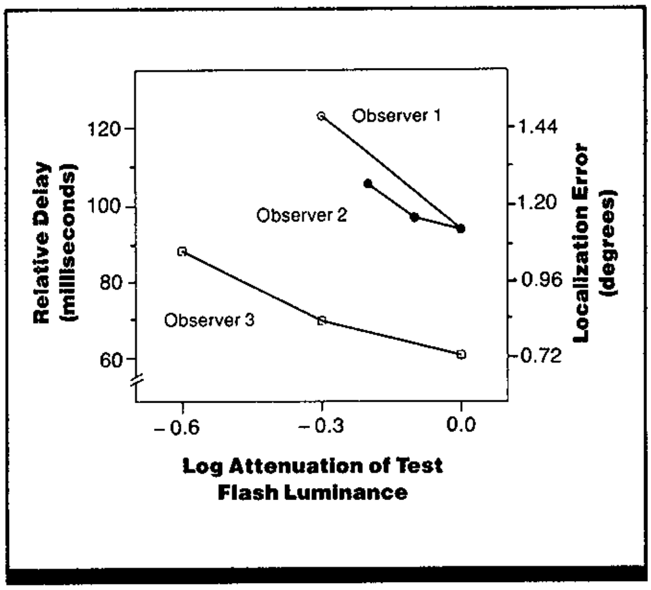


Figure 2. The influence of stimulus test flash luminance on error of localization of that flash and on visual latency (relative delay) during pursuit eye movements for three observers. (From Ref. 1)

Key Terms

Eye movements; pursuit eye movements; spatial localization; target detection; visual latency; visual localization; visually coupled systems

General Description

The intensity of a flash presented while observers track another stimulus with pursuit eye movements affects the accuracy with which that flash is localized. Errors of localization are consistent in the direction of the eye movements and decrease monotonically with increases in flash intensity.

Methods

Test Conditions

- Projected display (Fig. 1) consisted of 6 min arc of visual angle tracking spot moving from left to right across screen at constant velocity of 12 deg/sec
- Brief flash (<200 μsec) presented 3 min arc below tracking spot in region of hatch marks, to right of center screen; scale divisions on hatch marks ~0.035 deg; location of flash varied; attenuation of flash luminance varied from −0.6 to 0 log units

Experimental Procedure

- Method of constant stimuli
- Independent variable: location of flash with respect to hatch marks
- Dependent variables: reported location of flash, inferred visual latency (defined as delay between time of flash and observer's detection of flash, calculated from the actual position of the flash, the judged flash position, and the velocity of the eye movement)
- Observer's task: track moving spot with eyes; when flash appeared, call out particular hatch mark below which flash appeared
- 3 observers

Experimental Results

- A light flash during pursuit eye movement is mislocated in the direction of the eye movement; here, the eyes are moving from left to right and the flash is judged as being to the right of its actual position.
- As flash intensity increases, localization error and visual latency decrease monotonically (Fig. 2).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

When pursuit tracking velocity was varied from 5-14 deg/sec, localization errors were relatively constant regardless of tracking velocity (Ref. 1). A decrease in background luminance did not affect localization of a target flash (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Ward, F. (1976). Pursuit eye movements and visual localization. In R. A. Monty & J. W. Senders (Eds.), *Eye movements and psychological processes* (pp. 289-297). Hillsdale, NJ: Erlbaum.

Cross References

5.601 Visual localization and perceived visual direction;

5.604 Target localization during pursuit eye movements;

7.407 Effect of signal target location on visual search;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

9.206 Reaching hand movements: effect of varying visual feedback;

Handbook of perception and human performance, Ch. 20, Sect. 6.4

5.606 Target Localization Accuracy: Effect of Gaze Eccentricity

Key Terms

Eccentric gaze; eye movements; eye-mediated controls; intersensory perception; perceptual adaptation; target-directed movements; visually coupled systems

General Description

The ability to locate objects relative to egocentric position, such as when pointing or orienting, depends upon accurate registration of eye-head position. When the eyes are maintained in a gaze to one side of center, the apparent straight ahead shifts toward the direction of the gaze. The longer the duration of the eccentric gaze, the greater the magnitude of the effect.

Methods

Test Conditions

- Test stimuli were 101 individually illuminated LEDs, placed 1 deg apart in a circle, at the interocular axis
- Fixation light in a circle 1.54 cm above the interocular axis, at 12, 22, 32, or 42 deg to left and right of straight ahead; fixation maintained for 30, 60, or 120 sec
- Test lights illuminated starting from left or right; observer indicated whether test light was to left or right by pressing appropriate button; average point where response shifted from "left" to "right" or vice versa was apparent straight ahead
- Head fixed by bite board and head brace

Experimental Procedure

- Subjective straight ahead determined by a modification of method of limits
- Independent variables: extent and duration of eccentric gaze
- Dependent variable: position of apparent straight ahead
- 6 observers

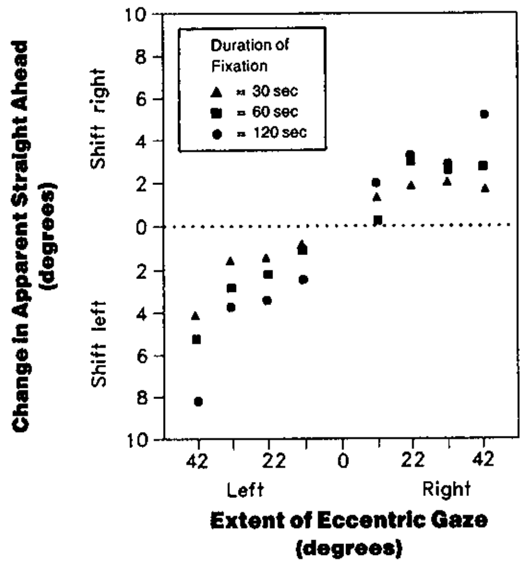


Figure 1. Apparent visual straight ahead as a function of duration and eccentricity of fixation. (From Ref. 3)

Experimental Results

- The greater the extent of eccentric gaze, the greater the shift in apparent straight ahead toward the direction of gaze (Fig. 1).
- The longer the eye is held in the eccentric position, the greater the magnitude of the aftereffect.
- These aftereffects are largely diminished after a 1.5-min delay (Ref. 3).

Variability

All results were statistically significant ($p < 0.01$); error bars were not shown.

Repeatability/Comparison with Other Studies

Prismatic adaptation studies support this result.

Constraints

- This is a quick decaying effect. Longer-term effects reported in some prismatic adaptation studies might result from other dynamics (CRef. 5.1103).
- Gaze eccentricity was also found to bias autokinetic movement (Ref. 2.).
- Observer was in darkness and could not see his own body during settings.

Key References

1. Kalil, R. E., & Freedman, S. J. (1966). Persistence in ocular rotation following compensation for displaced vision. *Perceptual and Motor Skills, 22,* 133-137.

2. Matin, L., Pearce, D. G., & MacKinnon, G. E. (1963). Variation in directional components of autokinetic movement as a function of the position of the eye in the orbit. *Journal of the Optical Society of America, 53,* 521, (Abstract).

*3. Paap, K. R., & Ebenholtz, S. M. (1976). Perceptual consequences of potentiation in the extraocular muscles: An alternative explanation for adaptation to wedge prisms. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 457-468.

Cross References

5.1103 Methods for inducing and measuring adaptation to prismatic displacement of the visual field;

5.1113 Prismatic displacement of the visual field: visual and auditory judgments of straight ahead;

5.1120 Factors affecting adaptation to loss of visual position constancy;

7.501 Factors affecting visual search with monochrome displays;

7.503 Effect of head and eye movement on target acquisition;

9.204 Blind positioning: effects of prior target exposure;

9.205 Control movements: effect of direction;

9.206 Reaching hand movements: effect of varying visual feedback;

9.208 Blind positioning accuracy: effect of target location;

9.210 Time and accuracy of fast control movements;

Handbook of perception and human performance, Ch. 25, Sect. 2.3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.607 Factors Affecting Target Localization

Key Terms

Egocentric localization; eye-mediated controls; frame of reference; Ganzfeld; proprioception; saccadic eye movements; saccadic suppression; target acquisition; target detection; target motion; target-directed movements; visual localization; visual position constancy; visual referents; visually coupled systems

General Description

There is evidence that observer-relative motion (no visual referents; CRef. 5.209) and position information are the principal determinants of pointing and related orienting responses. These responses are typically measured by having an observer view fixed or moving targets and background and then point to selected target locations under various experimental conditions. Target movement may be real or illusory. Accuracy of orientation may be determined by measuring responses such as shifts in subjective median plane, amount of target displacement, memory for target position, and pointing to the center of target or patterns. This table lists some factors known to influence position and orienting responses and cites entries or sources of more information.

Constraints

- These data must be interpreted carefully prior to applying them, as they were obtained under a wide variety of highly specific experimental conditions.

Key References

1. Bacon, J. H., Gordon, A., & Schulman, P. H. (1982). The effect of two types of induced-motion displays on perceived location of the induced target. *Perception & Psychophysics, 32*, 353-359.

2. Bridgeman, B., Kirch, M., & Sperling, A. (1981). Segregation of cognitive and motor aspects of visual function using induced motion. *Perception & Psychophysics, 29*, 336-342.

3. Bridgemen, B., Lewis, S., Heit, G., & Nagle, M. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 692-700.

4. Ludvigh, E. (1952). Possible role of proprioception in the extraocular muscles. *Archives of Ophthalmology, 48*, 436-441.

5. Miller, J., & Hall, R. (1962). The problem of motion perception and orientation in the Ganzfeld. In *Visual problems of the armed forces* (pp. 14-20). Washington, DC: National Academy of Sciences.

6. Sugarman, R., & Cohen, W. (1968). Perceived target displacement as a function of field movement and asymmetry. *Perception & Psychophysics, 3*, 169-173.

Cross References

5.203 Factors affecting threshold for visual motion;

5.208 Displacement thresholds for visual motion: effect of target duration;

5.209 Visual motion detection thresholds: effects of stationary referents;

5.210 Visually perceived relative velocity: effects of context and extent of motion;

5.217 Perceived motion with tracking eye movements;

5.601 Visual localization and perceived visual direction;

5.604 Target localization during pursuit eye movements;

5.606 Target localization accuracy: effect of gaze eccentricity;

5.1007 Spatial localization in the presence of intersensory conflict;

5.1010 Cross-modal versus intramodal perception of distance and location;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

7.407 Effect of signal target location on visual search;

7.501 Factors affecting visual search with monochrome displays;

7.505 Eye movements during visual search and pattern perception;

9.201 Fitts' law: movement time as a function of distance and accuracy;

9.203 Fitts' law: movement and reaction time as a function of target distance and size;

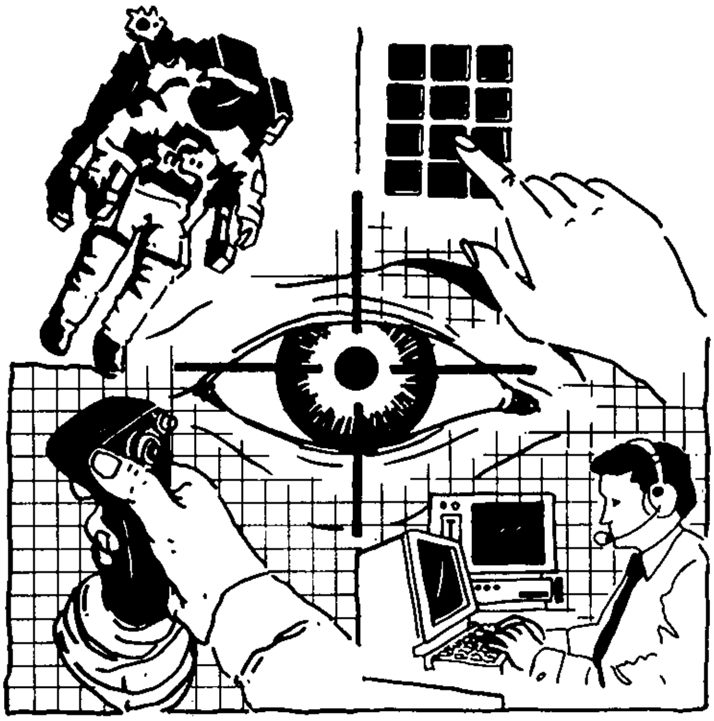
9.205 Control movements: effect of direction;

9.206 Reaching hand movements: effect of varying visual feedback

Factor	Effect on Orienting Response	Source
Type of target motion	When presented with induced linear step displacement or sinusoidal movement of a target on a display, the pointing responses of observers are significantly biased ($p<0.001$) toward an egocentric position (center of screen) rather than toward the apparent target position	Ref. 2; CRef. 5.217
Background movement	Background movement shifts the perceived position of a target on a visual display in the opposite direction for exposures as short as 3 sec	Ref. 6; CRefs. 5.210, 5.217
	Perceived target displacements are significant ($p<0.001$) for background movements of 7.5 and 22.5 deg	Ref. 6
	Perceived target displacements cannot be accounted for by field asymmetry alone	Ref. 6
	When the target is straight ahead, perceived displacement of a stationary target increases almost linearly with background displacement over a range of 7.5-30 deg	Ref. 6
Size of background	Perceived target displacement is decreased when a moving background is limited to a 15-deg field rather than a 30-deg field	Ref 6
Reference-frame movement	Moving and off-center stationary reference frames produce similar changes in a target's perceived location, as measured by pointing with an unseen hand	Ref. 1
	Moving a reference frame 8.7 cm altered the location by 77% of the frame movement, as measured by finger pointing (hand visible)	Ref. 1; CRef. 5.210
Saccadic eye movement	Target displacement information gained during a saccadic eye movement can be used by observers for motor-oriented tasks	Ref. 3; CRef. 7.505
	Observers can point to the center of a displaced visual field even though the displacement was not detected ($p<0.02$)	Ref. 3
	Saccadic tracking enhances the induced displacement effect: with two moving targets, the fixated one appears to move less	Ref. 2
	Saccadic suppression of detection of target displacement asymptotes at about ± 100 msec from saccadic onset	Ref. 3
	Observers can locate a target briefly flashed or displayed during a saccade	Ref. 3; CRef. 5.208
Position sense of the eye	Position sense of the eye is extremely poor and ocular movement >6 deg must occur for an observer to know (with high reliability) whether the eye is looking right or left	Ref. 4
	A stationary light viewed through a rotating mirror may be perceived as moving through an arc of 30-40 deg due to poor ocular position sense	Ref. 4
Body cues	Egocentric information (measured by pointing) is used by an observer to locate targets when visual displacement information is unavailable	Ref. 3
	Observers can center a single target in an illuminated unstructured field (Ganzfeld) within 6 deg of true center and within 2 deg of body center by using non-visual body cues	Ref. 5

Notes

Section 5.7 Postural Stability and Localization



5.701 Terminology Used to Describe Head and Body Orientation

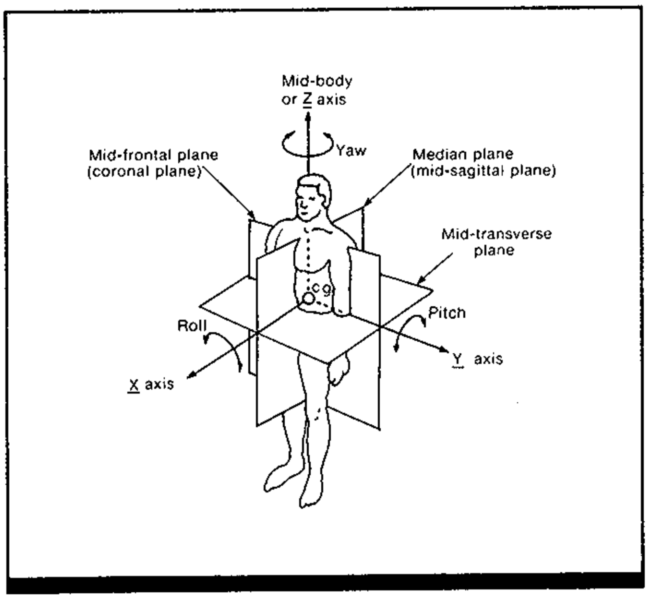


Figure 1. The principal planes and axes of reference of the human body. (From *Handbook of perception and human performance*)

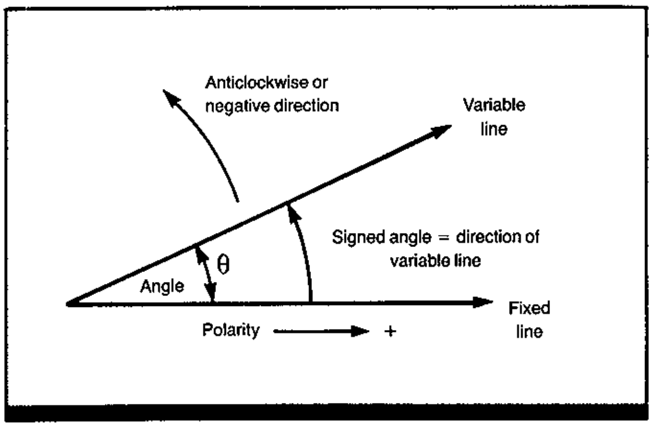


Figure 2. The basic geometric concepts of lines, angle, sign of rotation, polarity, and direction. (From Ref. 2)

Key Terms

Body axes; body orientation; center of gravity; egocentric localization; gravitational orientation; head tilt

General Description

Axes of the Body

By vertically and horizontally transecting the human body, we can identify three principal planes (coronal, sagittal, and transverse) which intersect at the body's center of gravity. Each of the planes can be considered to lie on an axis which corresponds to pitch, yaw, or roll movement (Fig. 1).

The intersection of the mid-sagittal plane and the mid-coronal plane forms the z-axis. This mid-body, vertical axis passes through the center of gravity of a standing body. Rotation about the z-axis is called yaw.

The intersection of the mid-frontal plane and the mid-transverse plane forms the y-axis. Rotation about the y-axis is called pitch.

The intersection of the mid-sagittal plane and the mid-transverse plane forms the x-axis. Rotation about the x-axis is called roll.

Orientation Concepts

Orientation of the human body in the environment and orientation of part of the body to other parts can be described in terms of fundamental geometrical concepts (Fig. 2):

1. two lines in a plane (one reference [fixed], one variable)
2. the sign of rotation of a point moving about a fixed point (clockwise or counterclockwise)
3. the polarity of a line (indicated by arrowhead)
4. a direction, which is the signed angle which a variable line makes with a reference line (usually θ)

Human Orienting Behavior

Specification of a human orientation behavior requires two lines or axes. For convenience, one axis is referred to as the standard (S) and another, the variable (V), depending on which is more often under the subject's control. Both axes may be external to the body, both may be internal, or one may be internal and the other external.

A classification of human orienting behavior (shown in Fig. 3) is composed of the following cases:

1. where both axes are external to the observer:
   a. judging angles (the relative orientation of two lines)
   b. judging direction (inclination to gravity, compass direction)
   c. setting a point to eye level (horizontal) (Note: One axis is anchored to the body at one point.)
2. where one axis is a body axis and the other an external line or reference axis:
   d. gravitational orientation of the body
   e. geographical orientation of the body
   f. egocentric: setting a line parallel with the body axis
   g. egocentric: setting a point to the median plane
3. where both axes are internal
   h. relative orientation of two body parts (kinesthesia)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- There are technical names for other planes and views, and the term *horizontal* is often substituted for *transverse*.

Key References

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2. Howard, I. P., & Templeton, W. B. (1966). *Human spatial orientation*. London: Wiley.

Cross References

3.201 The vestibular system;

10.1001 Techniques for body self-rotation without surface contact in micro-gravitational environments;

Handbook of perception and human performance, Ch. 18, Sect. 1.

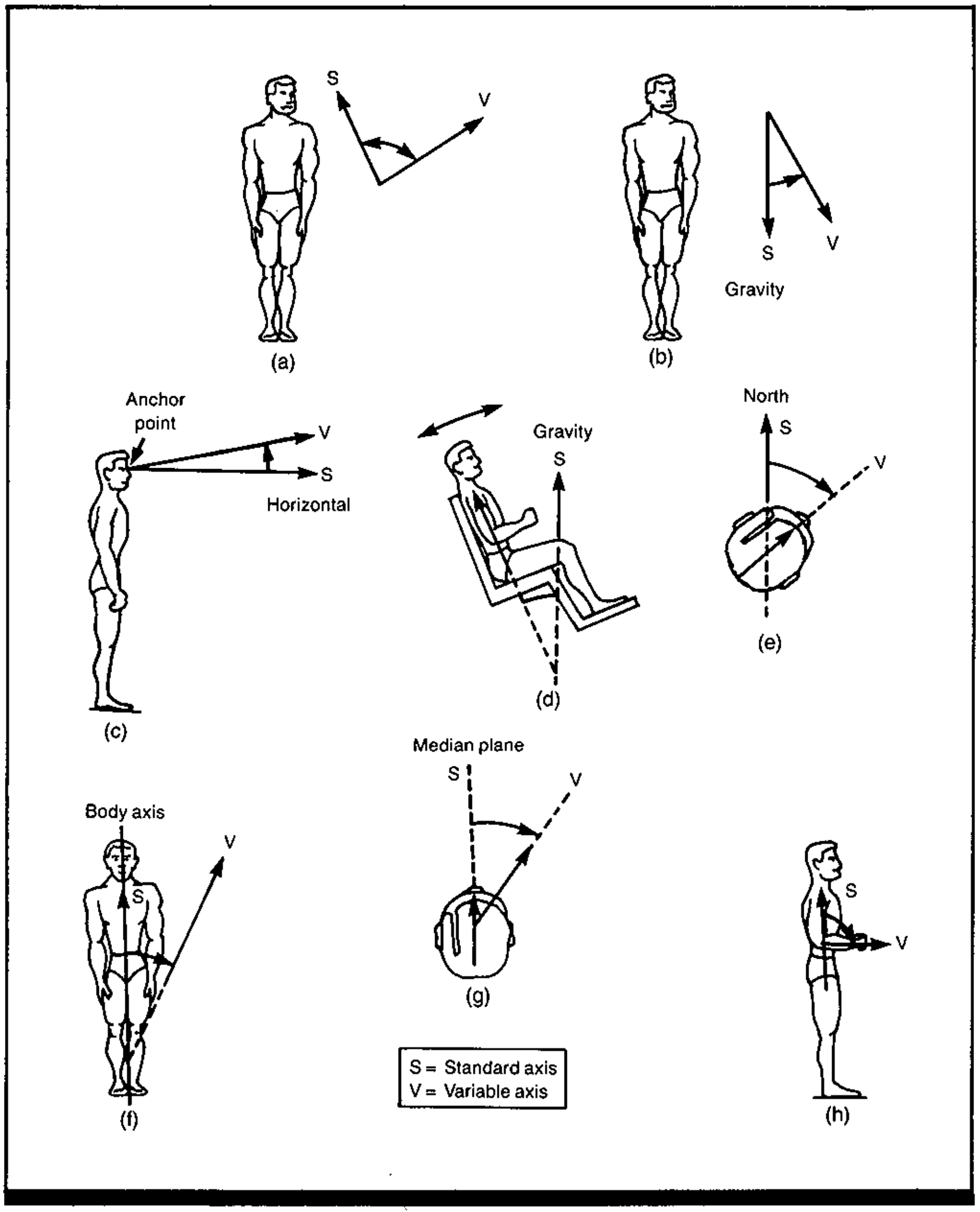

Figure 3. A classification of human orientation behavior. (From Ref. 2)

5.702 Regulation of Static Postural Stability

Key Terms

Body sway; myotatic response; otoliths, proprioception; semi-circular canals; somatosensory; vestibular system

General Description

The standing human body behaves much like an inverted pendulum, with most of its motion occurring about the ankle joint (although some motion occurs about the hip joint; Ref. 7). Body sway can be represented by its **power spectral density**, plotted as a function of frequency. The highest amplitudes of sway are between zero and 0.4 Hz, and the cut-off frequency is ~1.0 Hz. A small peak of sway activity in the 8- to 12-Hz band probably represents synchronous muscular tremor due to oscillation in the **myotatic reflex** (which has a 15-msec latency), but appears to play no specific role in maintaining an upright posture.

The main factors involved in static postural stability are somatosensory (passive stiffness of joint and muscles, and **proprioceptive**, such as the functional stretch reflex), vestibular (**semicircular canals** and **otolith organs**), and visual. Signals from these sources cooperate in the control of posture; their interaction helps to resolve ambiguities. The different types of signals are effective over different ranges of frequencies, with signals from the somatosensory system and the semi-circular canals effective at higher frequencies of body sway, while visual and otolith organ signals operate at the lower frequencies.

The table lists those factors that have been isolated as stemming from one of the systems, describes the factors and how they were isolated, gives their range or latency, lists factors known to alter the range, lists other constraints, and identifies sources of more information.

Table 1. Contributions of different systems to postural stability.

System	Description	Range/Latency	Factors/Constraints	Source
Somatosensory Passive stiffness of joints and muscles	When a muscle is slightly stretched by rotation of stabilometer platform, without inclination of body	Coefficient of stiffness range: 1.3-1.7 kg-m/deg	Is greater for taller or heavier subjects, or subjects with weights	CRef. 5.702
		The elastic torque generated by this degree of stiffness is sufficient to compensate for small deviations (amplitude: 0.1-0.2 deg; velocity: 0.6 deg/sec)	When inclination of body is added and the functional stretch reflex comes into play, range is 1.9-2.2 kg-m/deg	
Functional Stretch	When a muscle is stretched with greater amplitude, velocity, or regularity than can be compensated for by passive stiffness, and/or body sway is added to the stretch, supra-spinal reflex causes contraction of the stretched muscle and others associated with it to help maintain upright posture	120-msec latency	Although it may involve vestibular input, isolating the *sway* component from the stretch component causes first sign of response to be delayed until 200-300 msec	Ref. 6
			Can be eliminated by blockage of motor signals to contractile elements in muscle spindles	Ref. 6
			Is adaptive and can be affected by mental set of subject	
			Threshold of stretch reflex to passive flexion of soleus muscle is higher when muscle is relaxed than when it is voluntarily contracted	Ref. 3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

System	Description	Range/Latency	Factors/Constraints	Source
Vestibular	Body sway without ankle rotation eliminates proprioceptive input from muscle spindles	200-300 msec	Can be isolated from visual, but difficult to isolate from proprioceptive inputs	Ref. 5
	People with bilateral labyrinth loss do not lose their balance with eyes closed unless they must stand on one leg or in tandem position on rail			CRef. 5.704
	Vestibular inputs are often ambiguous, because of varying head position relative to rest of body		Ambiguities are resolved by vision or proprioception	Ref. 4
Visual	Subject enclosed in large illuminated box with walls and ceiling swaying	Moderate sway in direction of motion		Ref. 4
	Anomalous visual inputs	Peak destabilization at ∿0.1 Hz	No direct bearing on posture because rare in normal situations	
	Compare eyes open with eyes closed	Increases in sway with eyes closed confined to frequencies <0.3 Hz		Ref. 1
	Platform tilted sinusoidally at various frequencies (eyes open, eyes closed)	Stabilizing effects of vision are maximum at body sway of 0.3 Hz		Ref. 2
	Visually induced correction of posture	Occurs for sways of <2 deg with latency of 100-400 msec	The range listed involves vestibular and proprioceptive inputs	Ref. 4
	Illusory self-motion	Requires threshold displacement of >2 deg and latency of several seconds	This is probably range of visual imput	CRef. 5.707

Constraints

- Table 1 does not attempt to describe the many situations in which posture is maintained by cooperative action of more than one system.

Key References

1. Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: effects on self-motion perception and postural control. In *Handbook of sensory physiology. Vol. VIII* (pp. 755-804). New York: Springer.

2. Diener, H. C., Dichgans, J., Bruzek, W., & Selinka, H. (1982). Stabilization of human posture during induced oscillations of the body. *Experimental Brain Research, 45*, 126-132.

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*4. Howard, I. P. (1986). The perception of posture, self-motion, and the visual vertical. In K. R. Boff, L. Kauffman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

5. Nashner, L. M. (1971). A model describing vestibular detection of body sway motion. *Acta Otolaryngologica, 72*, 429-436.

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Cross References

5.703 Functional stretch reflex;

5.704 Postural stability: effect of vestibular ataxia;

5.707 Postural stability: effects of illusory self motion

5.703 Functional Stretch Reflex

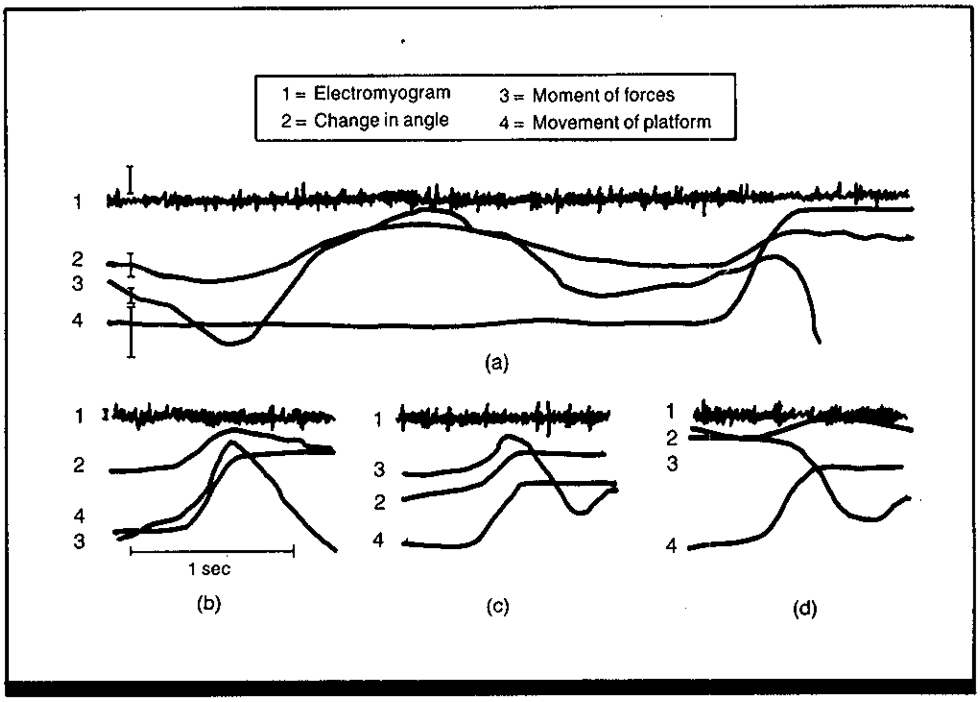

Figure 1. Electromyogram and stabilogram for ankle joint rotation alone. Time is 1 sec. (From Ref. 1)

Key Terms

Myotatic response; postural sway; proprioception; somatosensory; stretch reflex; supraspinal reflex

General Description

One of the factors affecting static postural stability is the responses of leg muscles induced by stretching, called the functional stretch reflex. Because it has a latency of 120 msec, involves other muscles besides the one stretched, and is absent in patients with spinal transections or postcentral lesions, it is considered a supraspinal reflex (at or above the level of the spine), rather than a myotatic response (Ref. 2). With ankle rotations of small amplitude and velocity, the reflex does not occur unless there is also some degree of body sway or inclination. The ankles of a standing person are rotated in the absence of body sway when the person walks on uneven ground. Under that condition, a reflex to muscle stretch would destabilize the person's posture.

Experimental rotation of an ankle joint, which stretches the triceps muscle, produces no functional stretch reflex. When body sway is added, the functional stretch does occur.

Methods

Test Conditions

- Subject stood on stabilograph fixed to a low rigid metal platform; platform rotated in sagittal plane (CRef. 5.701) with speed of 0.6 deg/sec, amplitude of 0.1-0.2 deg
- Platform rotation caused dorsal flexion of feet and stretching of sural triceps (ankle rotation condition, a 50-g load suspended from subject's belt was suddenly removed so that ankle joint changed as above, and body also swayed
- Electrical activity of muscles recorded by electromyogram (EMG) with surface electrodes
- For each subject several series of experiments were run, each experiment consisting of 20-30 runs

Experimental Procedure

- Independent variables: ankle only rotated, or ankle rotated and body swayed
- Dependent variables: EMG of sural triceps, change in moment of forces in ankle joint, change in the joint angle, amplification coefficient of stretch reflex (calculated as the ratio of change in moment of forces to change in joint angle)
- Subject's task: maintain postural stability
- Subjects: 5 healthy males (ages 25-50); heights ranged from 175-182 cm; weights ranged from 67-88 kg

Experimental Results

- Ankle rotation alone (Fig. 1) produces an increase in the moment of forces in the ankle joint (Trace 3, Fig. 1b, c), but sometimes the moment of forces remains unchanged or even decreases (Trace 3, Fig. 1d). There was no immediate change in the EMG of the sural triceps (Trace 1, Fig. 1), but 320 ± 50 msec after the start of movement, EMG amplitude fell.
- With unloading (ankle rotation and body sway), EMG activity increases (Trace 1, Fig. 2), joint moment increases (Trace 3, Fig. 2), and there is no inflexion of the stabilogram.

Variability

The ratio of change in the moment of forces in the ankle joint to change in the joint angle varies with height and weight of subject; range 1.3 ± 0.5 to 1.7 ± 0.4.

Repeatability/Comparison with Other Studies

If subjects are asked to stand with small forward inclination of the body, the electrical activity in the muscle increases on rotation (Ref. 1).

Body sway in the absence of muscle stretch caused by ankle rotation does not produce the functional stretch reflex (Ref. 4).

Constraints

- The functional stretch reflex should not be confused with the **myotatic stretch reflex**, which is intrasegmental.
- With more intense stimulation of ankle proprioceptors, the functional stretch reflex has been produced whether or not there is body sway (Ref. 3).
- The effectiveness of the stretch reflex in controlling postural sway varies with the frequency of body sway (Ref. 5).

Key References

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2. Howard, I. P. (1986). The perception of posture, self motion, and the visual vertical. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception.* New York: Wiley.

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4. Nashner, L. M. (1976). Adapting reflexes controlling the human posture. *Experimental Brain Research, 25*, 59-72.

5. Rack, P. M. H., Ross, H. F., Thilmann, A. F., & Walters, D. K. W. (1983). Reflex responses at the human ankle: The importance of tendon compliance. *Journal of Physiology, 344*, 503-524.

Cross References

5.701 Terminology used to describe head and body orientation;

5.702 Regulation of static postural stability

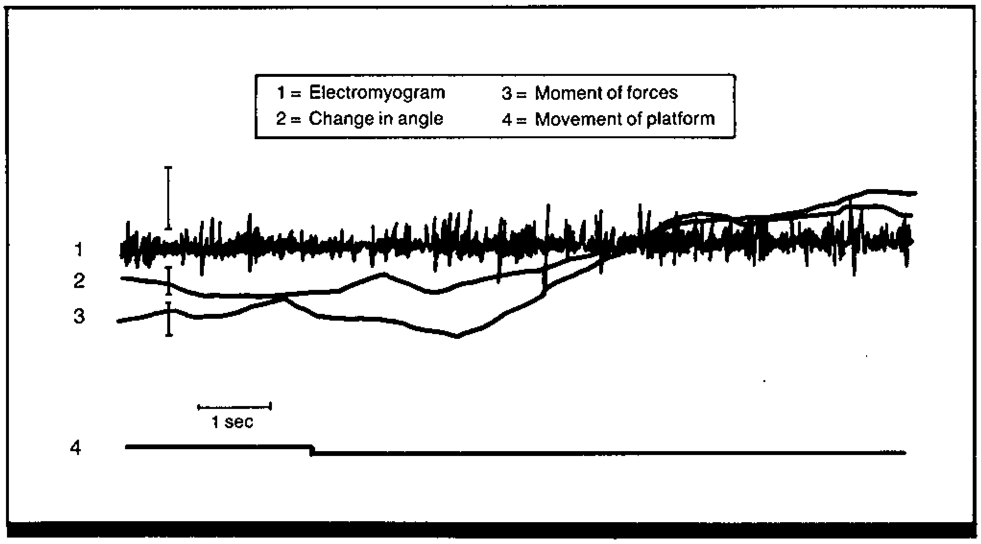

Figure 2. Electromyogram and stabilogram for ankle joint rotation with body sway caused by unloading. (From Ref. 1)

5.704 Postural Stability: Effect of Vestibular Ataxia

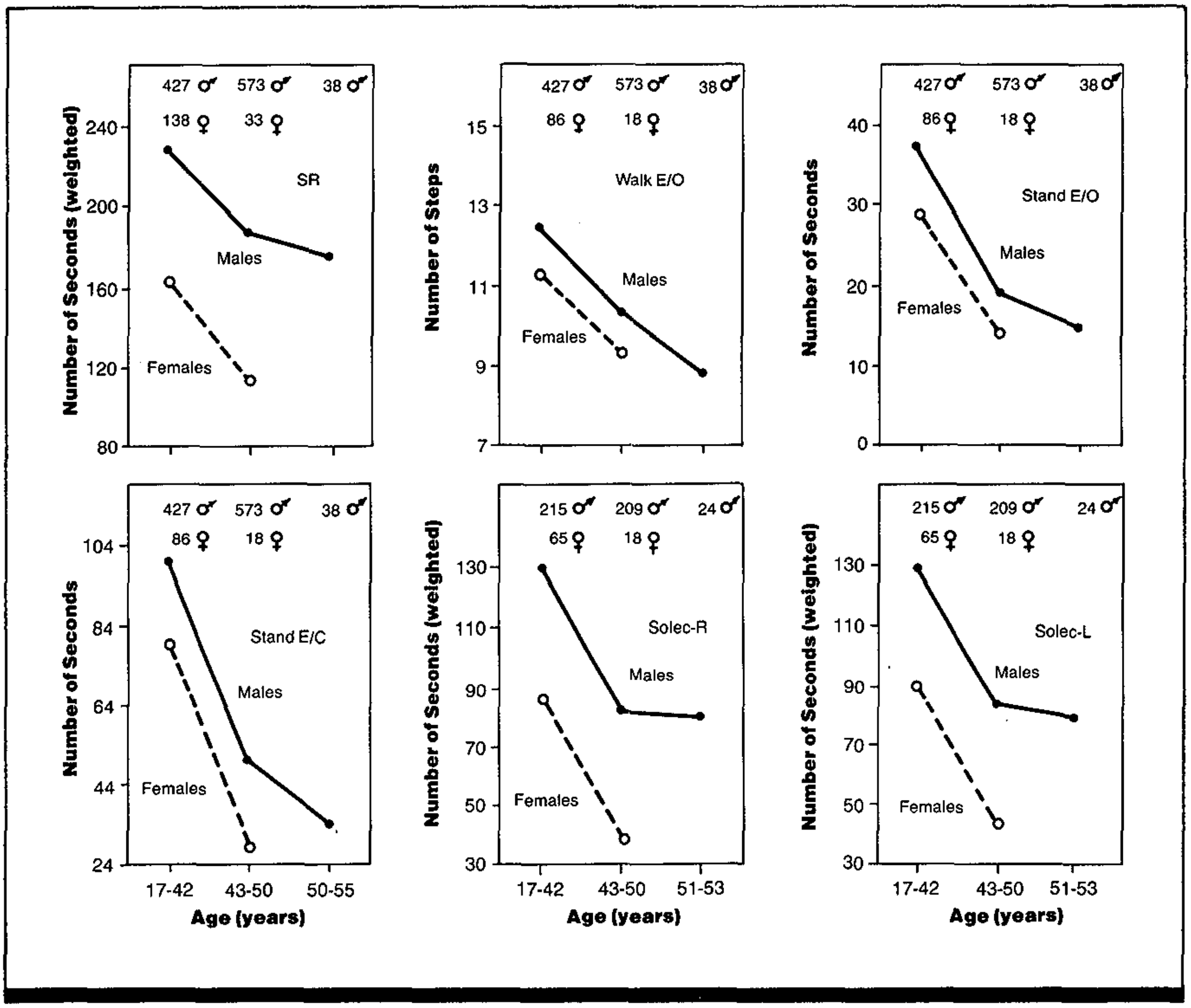

Figure 1. Performance on vestibular ataxia test battery as a function of chronological age and sex. See Table 1 for definition of acronyms. (From Ref. 2)

Key Terms

Body sway; labyrinth; proprioceptive cues; Romberg test; tandem walking; vestibular ataxia; vestibular system

General Description

Absence, disturbance, or loss of function of the vestibular apparatus (CRef. 3.201) affects one's ability to control static and dynamic aspects of postural stability. However, even with bilateral loss of labyrinthine function, normal postural stability can be maintained by the use of visual or proprioceptive cues, although individuals who are bilateral labyrinthine defective (BLD) have difficulty walking in the dark or over a mattress.

The standard Romberg test measures bodily sway of subjects whose feet are in a V position, and whose eyes are closed. Although visual cues cannot be used, proprioceptive cues are sufficient to maintain stability. Body sway is greater for those who are BLD than for normal subjects, but is within range of normal performance and is not severe enough to cause loss of balance. On other ataxia tests, BLD subjects also do not perform as well as normals; however, there are great individual, age, and sex differences in performance of normal populations (Fig. 1). Table 1 describes ataxia tests and scoring methods. Ten males with early vestibular loss due to meningitis or mastoiditis usually scored at or below the first percentile on these tests. Sixteen males with similar etiology, one 25-year-old athletic soldier, and four patients who had received streptomycin sulfate for Ménière's syndrome showed similar results. Eleven unilateral labyrinthine defectives (caused by surgery) and 94 individuals of both sexes suffering from vertigo showed performance levels between those of BLD and normal subjects.

Constraints

- Bilateral vestibular loss creates greater performance deficits than does unilateral loss on certain tasks long after the loss; there are greater deficits immediately after unilateral than after bilateral damage.
- BLDs did improve performance with practice on some tasks, but the improvement was not as great as for age-sex paired normals, and BLD performance never showed the smooth coordination shown by normal subjects on rail walking or tandem heel-to-toe tasks.
- BLDs do not suffer from motion sickness and react differently from normals to rotation and acceleration.

Key References

1. Birren, J. E. (1945). Static equilibrium and vestibular function. *Journal of Experimental Psychology, 35*, 127-133.

*2. Fregly, A. R. (1974). Vestibular ataxia and its measurement in man. In H. H. Kornhuber (Ed.), *Handbook of sensory physiology* (Vol. VI/2). New York: Springer-Verlag.

Cross References

1.910 Control-systems-analysis model of visual and oculomotor functions in retinal image stabilization;

1.918 Factors influencing visual suppression of vestibular nystagmus;

1.928 Gain of vestibular nystagmus: effect of object distance;

1.929 Vestibular nystagmus: effect of attention;

1.930 Vestibular nystagmus: effect of angular acceleration and deceleration;

3.201 The vestibular system;

3.209 Long-term adaptability of the vestibular system;

5.702 Regulation of static postural stability

Table 1. Tests for vestibular ataxia.

Description	Scoring
Sharpened Romberg (SR)—Stand on floor with eyes closed and arms folded against chest, feet aligned in strict tandem heel-to-toe position, body erect for 60 sec	Maximum of four trials; testing discontinued when criterion score of 60 sec was met on any trial; a score of 60 on first trial was weighted 4, and a perfect test score of 240 assigned; a perfect score on second trial was weighted 3 and 180 plus score on first trial assigned, etc.
Walk Eyes Open (Walk E/O)—Walk heel-to-toe on a rail 1.91 × 243.84 cm (3/4 × 96 in.) with feet in a tandem position with arms folded against chest, body erect	Number of steps taken with best three out of five trials (five per trial), maximum of 15
Stand Eyes Open (Stand E/O)—Stand in same position on the same rail for 60 sec	Best three trials out of five—maximum 180 sec
Stand Eyes Closed (Stand E/C)—Stand as in Stand E/O, except on a rail 76.2 × 5.69 cm for 60 sec	Same as Stand E/O
Stand One Leg, Eyes Closed, right and left (SOLEC-R, SOLEC-L)—Stand on each leg for 30 sec, arms folded, body erect; moving the standing foot from the start position was not permitted	Maximum of five trials, score of 30 on first was weighted 5, etc.; see scoring of SR above

5.705 Visual Factors Influencing Postural Stability

Key Terms

Illusory self-motion; retinal image motion

General Description

When an observer moves relative to the visual environment, the perceived changes exert a powerful effect (along with **vestibular** and **proprioceptive** inputs) on postural stability. Anomalous visual inputs can have a destabilizing effect on posture. The table lists some of the visual factors that influence the control of upright posture, describes their effects, and cites sources of additional information.

Constraints

- Interactions may occur between factors affecting the control of upright posture.

Key References

1. Amblard, B., Cremieux, J., Marchand, A. R., and Carblanc, A. (1985). Lateral orientation and stabilization of human stance: Static versus dynamic visual cues. *Experimental Brain Research, 61*, 21-37.

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Cross References

5.702 Regulation of static postural stability;

5.706 Postural stability: effects of retinal image motion;

5.707 Postural stability: effects of illusory self-motion

Factor	Effect	Source
Static and dynamic visual control of posture	A stationary, tilted scene can affect postural stability, but the major contribution comes from visual motion induced by body sway. The effectiveness of visual motion varies with the frequency of sway. Frequencies of visual motion of 3 Hz are least effective	Ref. 1
Motion of the visual environment	Normal visual inputs are most effective in stabilizing postural sway of frequencies 0.3 Hz or less. Postural responses to normal visual inputs have reaction times of 100-120 msec and can correct postural sways <2 deg. The stabilizing effects of anomalous visual inputs have a peak effect at ~0.6 Hz (for a large visual field rotating about the observer's line of sight)	Refs. 2, 3, 5, 6 CRefs. 5.702, 5.706
Type and location of visual motion	Postural stability decreases if visual acuity is severely degraded, that is, when high spatial frequency components are removed. Laminar visual motion destabilizes posture most when presented to the retinal periphery. Radial visual motion is more destabilizing when presented to the central retina	Refs. 7, 8
Illusory motion induced by visual tilt	Sensations of illusory self-motion require an angular displacement of at least 2 deg and have reaction times of several seconds	Refs. 3, 6 CRef. 5.707
Optical devices, such as reversing prisms, that reverse the direction of head-centered visual environment motion induced by head rotation, worn all the time for days	Postural stability is severely disturbed for several days	Ref. 4

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Notes

5.706 Postural Stability: Effects of Retinal Image Motion

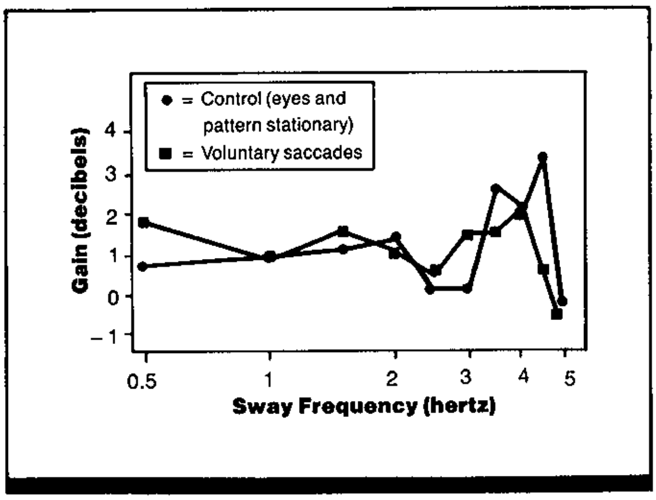

Figure 1. Frequency spectra of median gain in lateral sway under control conditions and with voluntary saccades. (From Ref. 2)

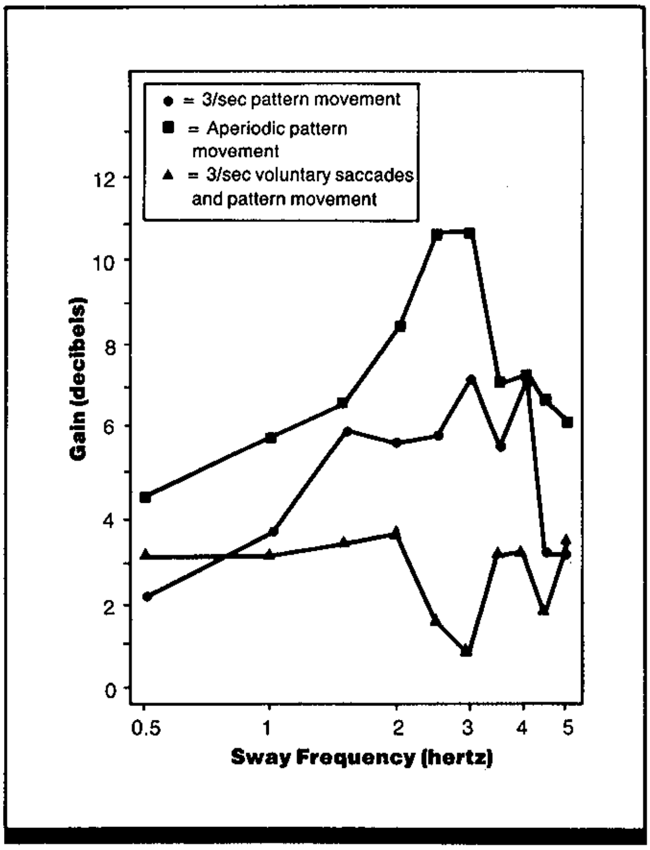

Figure 2. Frequency spectra of median gain in lateral sway caused by three-per-second pattern movement, aperiodic pattern movement, and three-per-second voluntary saccades with pattern movement. (From Ref. 2)

Key Terms

Body sway; retinal image motion; saccadic eye movements

General Description

Visual information influences postural stability; body sway depends on whether retinal image motion is voluntary or externally produced. Retinal image movement produced by voluntary eye movements (saccades) does not affect postural stability. When equivalent retinal image motion is produced by moving a pattern surrounding a subject, postural instability (body sway) results. Retinal image movement that is externally generated appears to signal the body that the body is moving. Aperiodic movement of the pattern causes greater body sway than does regular movement.

Methods

Test Conditions

• Subject viewed gray-and-white vertical square-wave grating pattern (180 deg of visual angle horizontal by 120 deg vertical; grating spatial frequency of 0.08 cycles per degree; two fixation lights near center, 4 deg apart; subject viewed whichever one was illuminated
• To direct voluntary saccades, fixation lights illuminated alternately (saccades directed either three times per second or aperiodically every few seconds)
• For externally produced retinal image motion, subject fixated one light and grating was moved to approximate saccade (4 deg in 33 msec)
• Subject stood on rigid plate mounted on strain gauges; as body's center of gravity shifted, forces on each gauge were measured; subject stood on one foot to enhance sway

Experimental Procedure

• Independent variables: production of retinal image motion (by saccades, by movement of stimulus, or both), schedule of retinal image motion production (regularly at three per second or aperiodically every few seconds)
• Dependent variable: ratio of test to baseline power spectra (gain in sway induced by test condition)
• Subject's task: stand on one foot and fixate illuminated light
• 13 adult subjects

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Experimental Results

- Results were normalized for individual differences by Fourier transforms of 2-sec sampling interval from 16- or 32-sec recording period. If a test condition has no effect, the test-to-baseline ratio is 0 dB; positive values on figure ordinates indicate larger sways during test conditions.
- Control data (sway when both pattern and eyes are stationary) do not differ from data from voluntary saccade conditions (regular and aperiodic); retinal image motion due to saccades does not influence body sway (Fig. 1). Fatigue increases baseline sway marginally at low frequencies and more markedly at 3.5-4.5 Hz.
- When the pattern surrounding the subject moves (Fig. 2), all sway component frequencies from 1-4 Hz show significant increases in gain, with the most reliable increase at 3 Hz.
- Under aperiodic pattern movement conditions, sway was so great that subjects began to fall and lowered the raised foot to prevent the fall.

Variability

Each frequency spectrum plots median gains (across subjects) derived from the average (within-subject) lateral sway power spectra. Confidence intervals (68% intervals of medians calculated nonparametrically) are ± 1.5 dB (for Fig. 1) and ± 2.0 dB (for Fig. 2).

Repeatability/Comparison with Other Studies

Early experiments indicated that moving one open eye with one's fingers while standing on one foot caused loss of balance (Ref. 1).

Constraints

- Without ocular recordings, it is not known if voluntary fixation was maintained as visual surroundings move.
- All measurements were made with subject standing on only one foot to increase body sway.

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Cross References

5.705 Visual factors influencing postural stability;

5.707 Postural stability: effects of illusory self motion

5.707 Postural Stability: Effects of Illusory Self-Motion

Key Terms

Illusory self-motion; linear vection; proprioception; self-motion; training simulation; visual scene movement; visual-vestibular interaction

General Description

A moving visual scene can induce a sensation of self-motion (vection). For illusory linearvection, several characteristics of moving visual scenes influence postural readjustments in the fore and aft direction (pitch): spatial frequency, velocity, location, and size relative to visual field, and direction of motion. In general, the postural readjustments induced by linearvection include inclination of the subject in the same direction as the visual scene movement, with a latency of 1-2.5 sec, followed by a plateau or steady state for the duration of the stimulus, and then an aftereffect when scene motion stops. Amplitude of postural change is logarithmically proportional to the image velocity and the spatial frequency of the inducing pattern, with saturation at highest image velocities due to a limit in image motion perception. The postural readjustment appears proportional to a low-pass filtering of the logarithm of velocity.

The frequency power spectra of postural sway caused by scene movement shows an increase over that caused by a stationary scene, especially at the low frequencies (0.02-0.2 Hz) and sharp peaks for 0.15-0.5 Hz.

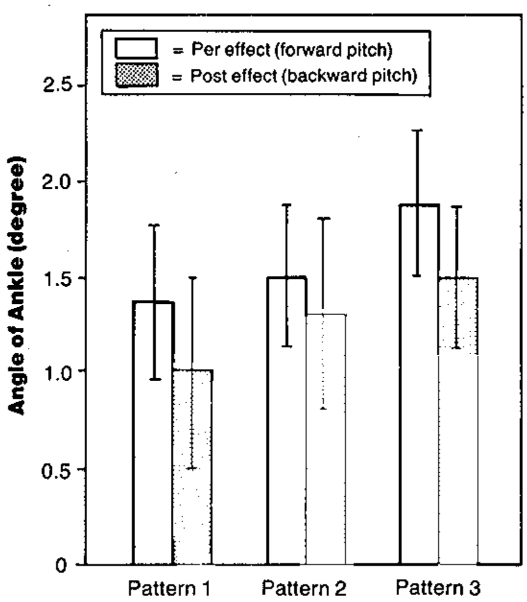

Figure 1. Amplitude of postural readjustment during observation of a visual stimulus moving forward at 0.25 m/sec (per effect) and after the stimulus motion has stopped (post effect) for each of three random patterns. (From Ref. 4)

Methods

Test Conditions

- Subjects stood erect and relaxed with hands at sides, attempted to maintain a vertical posture on a force platform, and to fixate a luminous point in center of screen
- Moving visual scene filled the greater part of peripheral and foveal fields of vision; scene projected upward onto horizontal screen (1.8 × 2.4 m) at 20 cm above eye level
- Three mirrors (one horizontal and other two 45 deg from vertical) were attached to the subject's head to create an optic tunnel
- Velocity of image from 0.027-2.7 m/sec; image movement toward or away from subject
- Various stimulus patterns at 0.8 contrast, particularly checkerboard patterns of black and white squares; spatial frequency equals number of squares per unit length (meter) in the anterior-posterior direction and varied from 0.36-3.75 cycles/m (sometimes reported as density in squares per m^2); temporal frequency (velocity times spatial frequency) equals number of squares passing a given point per second
- Each trial consisted of three periods: stationary scene for 100 sec (control), constant or sinusoidally modulated velocity for 50-200 sec, stationary scene for 100 sec (control)

Experimental Procedure

- Independent variables: direction (forward or back), velocity, or spatial frequency of stimulus pattern (image)
- Dependent variables: postural adjustment, ankle angle (as measured by angular potentiometer) and displacement of center of gravity, EMG for soleus and tibialis anterior muscles of each leg
- Subject's task: stand relaxed in vertical position
- 17 male and 13 female subjects (ages 25-35), with no known neurological disorders

Experimental Results

- 80% of subjects show clear postural readjustment to linear motion of the visual image.
- Change in body inclination is always in the same direction as image motion, irrespective of the localization of the image and its relative size.
- The amplitude of the postural readjustment, both the steady state induced during the stimulated (per effect) and the post-stimulation aftereffect, is dependent on the structure of the pattern presented (as shown at bottom of Fig. 1), with image velocity at 0.25 m/sec forward.
- The minimum velocity required to produce a postural change is <0.02 m/sec.
- Proximal stimuli are more effective than distal ones.
- The amplitude of the postural reaction is proportional to the total area of the moving portion of the visual field.
- For the same stimulus parameters, amplitude of inclination in the backward direction is ~25% less than in the forward direction.
- The transient postural "on" response has a delay (defined as time when excursion from baseline exceeds 10% of the maximum) of 1.2 ± 0.3 sec, and an exponential rise time yielding a time constant of ~2.2 sec.
- The "off" response delay (1.0 ± 4.0 sec) yields a longer time constant of ~4.2 sec.
- The amplitude of postural sway for moving scenes is greater than for static scenes, especially at low frequencies (solid line in Fig. 2).

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• One or several sharp peaks appear between 0.15 and 0.5 Hz (solid arrows in Fig. 2).
• Stimulation is often intensely disturbing to subjects and high scene velocities may induce fainting.

Variability

There are large individual variations. Of the 20% of subjects who did not show the effects at first, performing mental arithmetic induced a postural response in four of the six. Typical standard deviations are shown in Fig. 1, and power spectrum differences for two subjects are shown in Fig. 2.

Repeatability/Comparison with Other Studies

Similar results have been obtained with circularvection (Ref. 2) and with a linear motion of a suspended room (surrounding subjects) (Ref. 3).

Constraints

• Note that the time course for linear vection is slower than for actual tilt and is caused only by larger movements of the scene than for actual motion.
• Although a nearer visual display has a greater effect on vection and posture than a more distant display, the distant display has a greater effect when a far and near display are present at the same time (Ref. 1).

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Cross References

5.201 Subject-relative and object-relative visual motion;
5.502 Optical flow patterns and motion perspective;
5.503 Factors affecting illusory self-motion;
5.702 Regulation of static postural stability;
5.703 Functional stretch reflex;
5.705 Visual factors influencing postural stability;
5.708 Illusory self-inclination;
5.1011 Orientation perception in the presence of visual-proprioceptive conflict

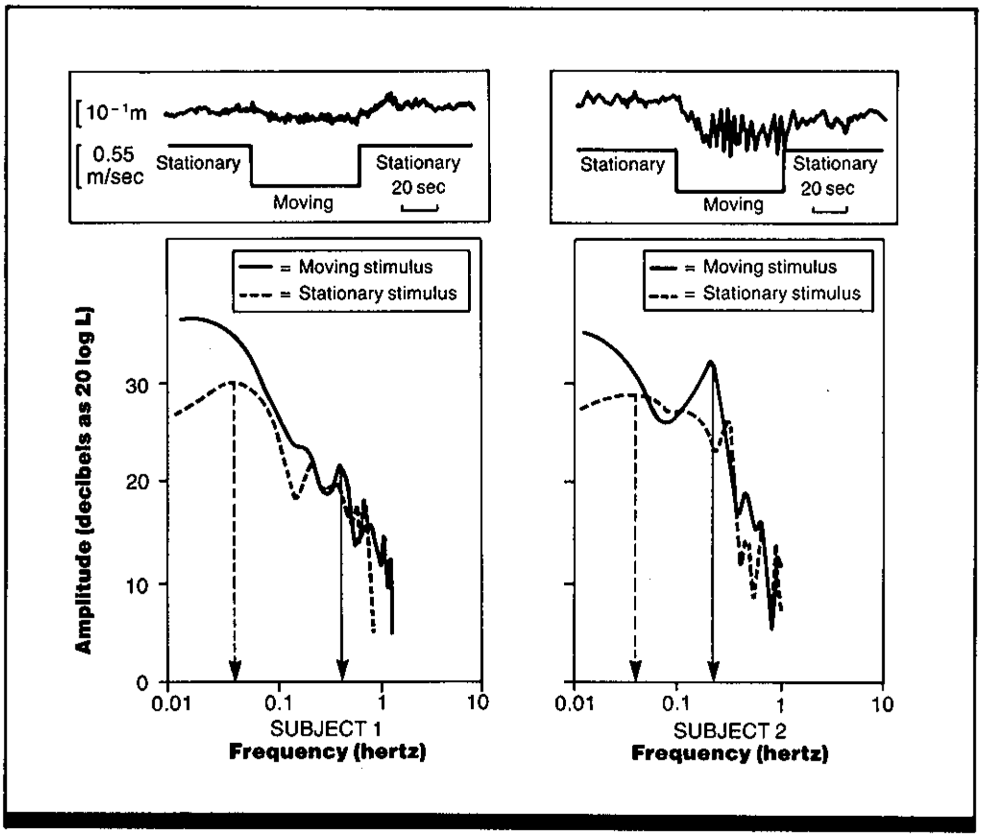

Figure 2. Typical power spectra for displacement *L* of center of gravity for two subjects viewing a stationary or moving (0.55 m/sec) checkerboard pattern (28.1 squares/m^2). Data for first quarter of exposure to moving stimulus are excluded. Arrows indicate peaks of spectral density. Top panels show displacement of center of gravity (top trace) and image velocity (bottom trace). (From Ref. 4)

5.708 Illusory Self-Inclination

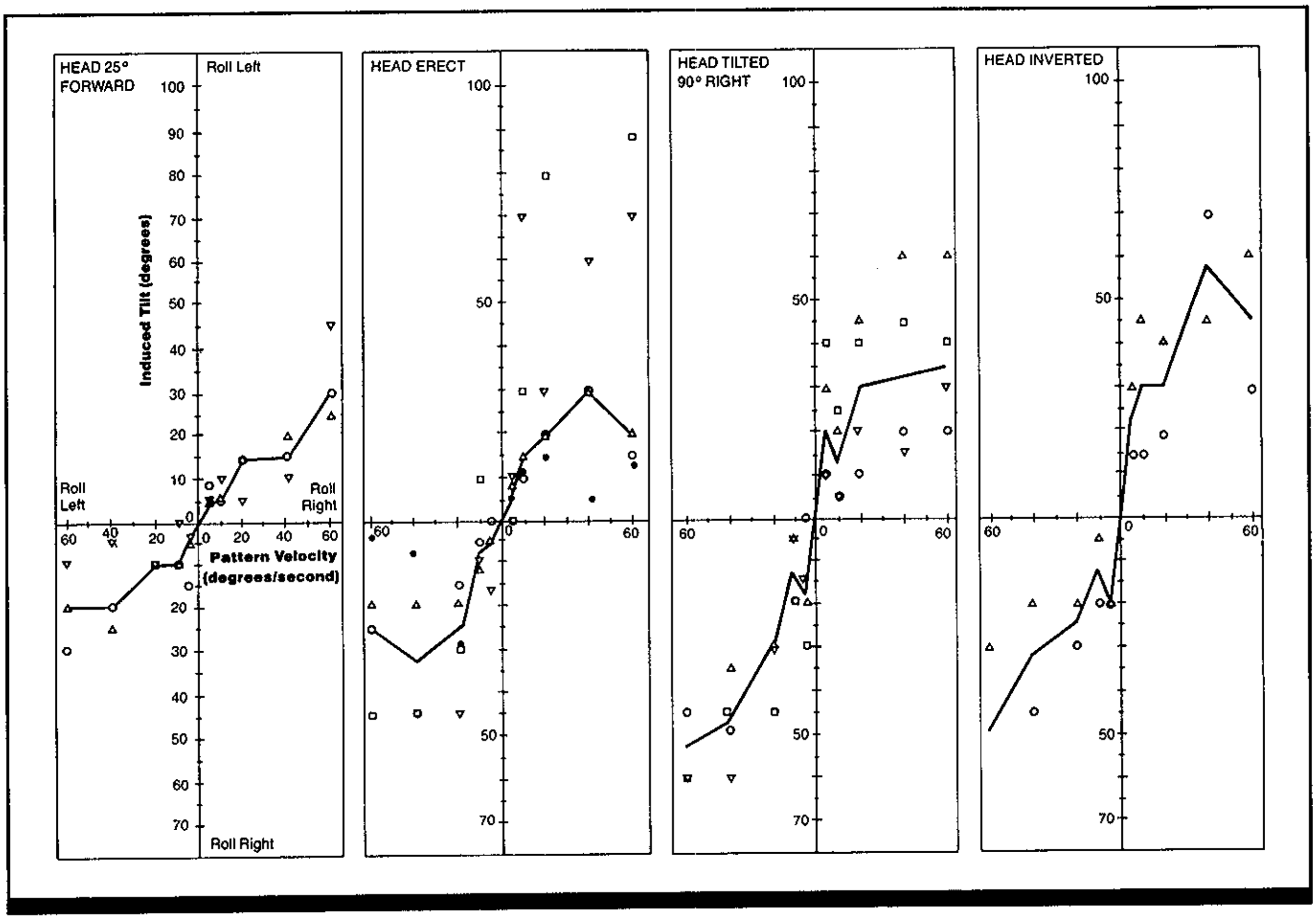

Figure 1. Perceived roll tilt angle produced by full-field rolling visual stimulus of varying velocities as a function of head position. Symbols indicate individual subject data and solid lines connect median values. (From Ref. 1)

Key Terms

Illusory self-inclination; scene rotation; self-motion; training simulation

General Description

A rotating visual scene can create an illusory sensation of self-inclination, and this induced sensation of body tilt is opposite to the direction of the moving scene. Thus, rotation of the visual scene to the left (counterclockwise roll) results in the sensation of body tilt to the right; rotation to the right (clockwise roll) produces the opposite effect. For a given velocity of upward or downward rotation (pitch) of the visual scene, the illusion of backward inclination is greater than that of forward inclination. For both roll and pitch movements, increasing the velocity of the rotating image produces increases sensation of tilt, to an asymptote of 40 deg/sec. The sensation of self-tilt is increased by inclining the head 90 deg or by inverting it.

Applications

In flight at constant velocities where there is no vestibular stimulus, the movement of the visual scene relative to the observer may create a sensation of illusory body movement. Maintaining erect head position and slow visual velocities will minimize this; otherwise, awareness of the potential illusion should help control for compensatory body movements.

Methods

Test Conditions

- Subjects tested in fighter aircraft simulator consisting of motionless jet cockpit inside 12-m diameter projection sphere; 1 subject in cockpit and remainder on edge of support platform ≥4.5 m from screen
- Visual scenes projected by point light source system; consisted of 464 randomly spaced and oriented black and white rectangles each subtending 2-3 deg of visual angle against white background
- Roll and pitch field velocities of ±5, 10, 20, 40, 60 deg/sec
- Subjects' head positions: erect, forward 25 deg, right ear down, head inverted (lying down with head backward over platform)

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Experimental Procedure

- Magnitude estimation
- Independent variables: head position, direction of pattern movement, type of pattern movement (roll or pitch), velocity of pattern movement
- Dependent variables: magnitude of induced body tilt, direction of induced body tilt
- Subject's task: view scene and report magnitude and direction of induced tilt
- 4 male 25-37-year-old trained subjects per experiment

Experimental Results

- The rotating movement of a visual scene produces a sensation of body tilt that is opposite the direction of the movement.
- Faster velocities of movement produce increased tilt sensations.
- Inverting the head produces greater tilt sensations than 90-deg head tilt which produces greater sensations than either head erect or head 25-deg forward positions.
- For a given velocity, downward pitch movement of the visual scene produces a backward tilt sensation that is more marked than the forward tilt sensation produced by upward movement.

Variability

Analysis of variance for head tilt effect with 0.05 significance level.

Key References

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Cross References

5.201 Subject-relative and object-relative visual motion;
5.502 Optical flow patterns and motion perspective;
5.503 Factors affecting illusory self-motion;
5.701 Terminology used to describe head and body orientation;
5.705 Visual factors influencing postural stability;
5.707 Postural stability: effects of illusory self-motion;
5.802 Illusory spatial displacements;
5.1011 Orientation perception in the presence of visual-proprioceptive conflict

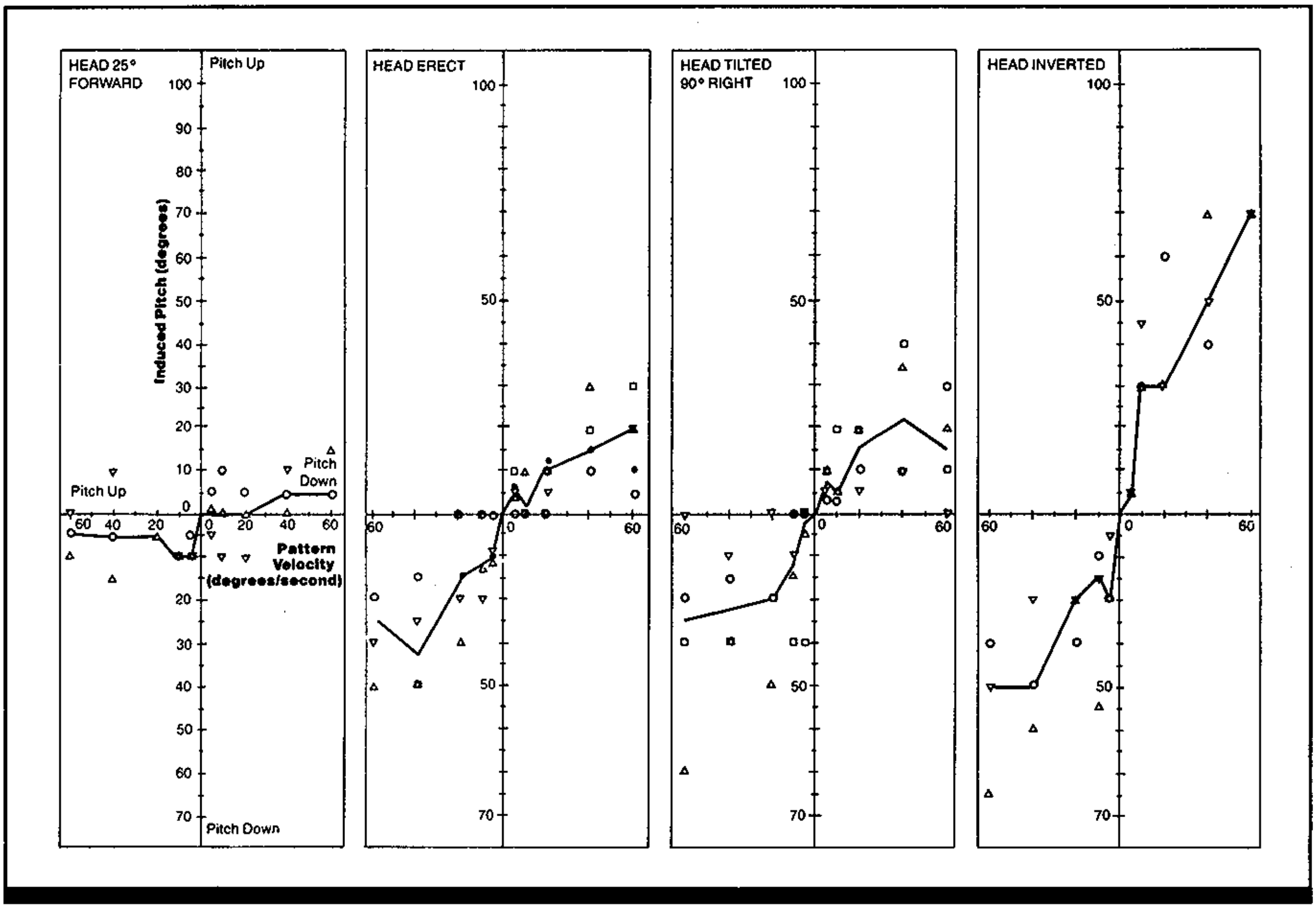

Figure 2. Pitch tilt angle produced by full-field pitching visual stimulus of varying velocity as a function of head position. Symbols indicate individual subject data and solid lines connect median values. (From Ref. 1)

5.709 Inversion Illusion

Table 1. Number of subjects (out of total tested) who experienced inversion illusion

Experimental Condition	Naive Normal Subjects	Experienced Normal Subjects	Labyrinthine Disabled Subjects
Head lower than feet	2/2	1/1	0/4
Negative G	2/2	1/3	0/4
Restrained	2/2	–	0/4

Key Terms

Gravitorotational force; inversion illusion; labyrinthine disease; visual-vestibular interaction; weightlessness

General Description

In weightless conditions, normal subjects perceive sudden up-and-down reversals that they may attribute to their own body position or to the vehicle. This is particularly true when the head is nearer than the feet to the floor of the vehicle and the subject is facing the front of the cabin in tunnel-like visual conditions, or when gravitorotational upright is 180 deg from visual upright, or when restrained. Labyrinthine-diseased patients do not experience similar effects. The illusion may be overcome with experience or with sufficient time to think about the situation.

Methods

Test Conditions

- KC-135 (Boeing 707) and C-13 1B (Convair) aircraft having ballistic trajectories (parabolic flight) with 20-30 sec weightless period followed by pullup generating 2 *G* and 12-16 sec weightless period with pullup of 2.5 *G*, respectively
- Experiment 1: Subject assumed head-down position with respect to aircraft (facing long axis of aircraft) in weightlessness within 2-6 sec
- Experiment 2: Subject stood on overhead of aircraft while exposed to small negative *G* loading for few seconds
- Experiment 3: Subject restrained with respect to cabin at either upright, 30, 60, or 90-deg tilt in weightless phase of parabolic flight

Experimental Procedure

- Independent variables: head-foot position, *G*-loading, body tilt, labyrinthine-diseased or normal subject
- Dependent variables: perceived body or aircraft position
- Subject's task: assume correct position (Exp. 1) and report perceived body position
- 7 normal subjects (ages 19-39 yr) and 4 meningitis-caused labyrinthine-disabled subjects (ages 25-34 yr); 3 of 11 subjects with extensive experience in weightlessness; all experienced with parabolic maneuvers

Experimental Results

- Normal subjects who assume the head-down position when entering weightlessness experience the inversion illusion (i.e., identified "down" as where their feet were).
- Naive subject identified aircraft as upside-down and self as upright when weightless and head down.
- When experiencing negative *G*, all labyrinthine-disabled subjects and 2 of 3 sophisticated normal subjects appropriately identified themselves as upside-down in upright aircraft.
- 2 naive and 1 sophisticated subject experienced illusion of upright self and upside-down aircraft with negative *G*.
- Normal, but not labyrinthine-disabled, subjects experienced inversion illusion under restraint on entering weightlessness and return to headup on pullout in all body tilts and trials.

Repeatability/Comparison with Other Studies

Russian cosmonauts report similar experiences.

Constraints

- Clearly labyrinthine disease and experience affect the illusion.
- The illusion can be corrected if the experience lasts a sufficient length of time.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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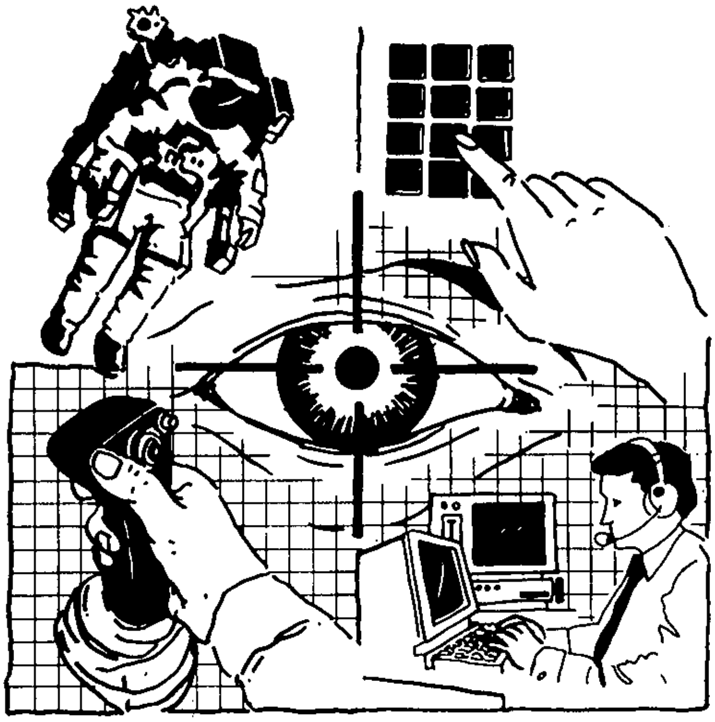
Cross References

3.210 Vestibular illusions

Notes

Section 5.8 Orientation



5.801 Factors Affecting Judgment of the Visual Vertical

Key Terms

Body rotation; body tilt; eye torsion; frame of reference; gravitoinertial force; head tilt; illusory tilt; linear acceleration; linear oscillation; orientation perception; postural aftereffects; rod and frame test; rotation; tactile cues; target acquisition; tilt aftereffect; vernier acuity; visual vertical; weightlessness

General Description

Judgments of the visual vertical are affected by the environment, the status of the observer, and whether the judgment is made relative to the environment or to the observer's body. Such judgments are typically made visually by estimating the angle of a test line with respect to the **subjective vertical**, or by adjusting the test line to match the subjective vertical. Tables 1-4 describe (1) the precision of judgments of visual vertical, (2) the effects of frame of reference on judgments of visual vertical, (3) the effects of body tilt, head tilt, and eye torsion on judgments of visual vertical, and (4) the effects of gravity on judgments of the visual vertical. The tables list some of the factors that influence judgment of the visual vertical, indicate the effect of each factor, and cite sources of additional information.

Constraints

- Interactions may occur between factors affecting judgment of the visual vertical, but such interactions have not generally been studied.

Table 1. The precision of judgments of the visual vertical.

Factors	Precision	Sources
Setting a line to the vertical (or horizontal)	Observers can set a luminous line in dark surroundings to the vertical or horizontal with a precision of 1 deg or less	Refs. 21, 44
Precision of judging the vertical	There is less variability (more precision) in judgments associated with vertical (and horizontal) lines. On 75% of all trials observers can detect when a line subtending 0.5 deg at the eye is ~0.5 deg from the vertical. At orientations other than the vertical (or horizontal), the precision of judgments is worse than 1 deg. However, judgments are more precise at orientations of 45 deg with respect to the vertical than at intermediate orientations	Refs. 2, 10, 16, 23, 39, 43
Effect of body tilt on the precision of judging the vertical	The precision of judgments of the visual vertical is highest when the body is in its normal upright posture and decreases with increasing tilt of the body. The tilt effect is greatest when observers are immersed in water and somasthetic inputs are eliminated	Refs. 18, 25
Vernier acuity and vertical (and horizontal) lines	Vernier acuity (the ability to detect the alignment or non-alignment of two straight lines with their proximal ends separated by a small space), is better for vertical (or horizontal) lines than for lines of other orientations	Refs. 20, 22, 24
Water submersion	The precision and accuracy of setting a line to the vertical under water are much the same as in air for body tilts up to 90 deg. Beyond 90 deg the variability of settings becomes relatively larger, reaching a maximum value when observers are in the inverted position	Refs. 32, 33, 40
Use of cushions that weaken tactile cues	Under normal conditions of gravity, the use of cushions that weaken tactile cues has been found not to affect the precision of judgments of the visual vertical unless the observer is tilted. Tilting observers results in a judgment decrement	Ref. 30

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Table 2. The effects of frame of reference on judgments of the visual vertical.

Factors	Effects	Sources
Tilted frame of reference (with rod-and-frame test)	When observers were asked to face a model room tilted 22 deg and to set a rod contained within it to appear vertical with respect to gravity, they displaced the apparent vertical position of the rod an average of 15 deg in the direction of the tilt of the room. Similar effects were produced when the test rod was seen within a large tilted luminous square in completely dark surroundings A problem with many applications of the rod-and-frame test is that crucial variables have not been controlled. These include stability of the head, starting position of the rod, speed of rotation of the rod, and exposure time. Furthermore, the test is often scored in terms of the unsigned deviation from the true vertical, a measure which confounds the item of prime interest, namely the constant error, with variability	Refs. 4, 14, 19, 31, 44
Size of tilted frame	The apparent vertical is displaced more by a frame that subtends a large angle at the eye than one which subtends a small angle. For example, a frame that subtended <10 deg at the eye, irrespective of its distance, was found to displace the apparent vertical by only 2 deg, whereas a frame which subtended 40 deg produced an effect of 8 deg	Ref. 9
Depth of separation of rod from frame	Increasing the depth separation of the rod and frame in the rod-and-frame test decreases the effect of the frame on the setting of visual vertical	Ref. 11
Addition of polar features to frame	The addition of polar features (features that indicate the top and bottom of objects) to an otherwise bare box tilted at 45 deg displaces the location of the apparent vertical position of a rod 17 deg in the direction of the polar axis. However, the addition of polar features does not have much effect for larger angles of tilt of the box When the projected image of an outdoor scene is tilted, the apparent vertical is displaced in the direction of the polar axis (the axis joining the "top" and "bottom" features of the scene) up to a 75-deg tilt of the scene, at which angle the tilt illusion is zero. This is not the case, though, when observers view scenes through prisms; then, even at an angle of 75 deg, the test rod is still displaced in the direction of the tilted frame	Ref. 36
Rotating annulus-shaped display	An annulus-shaped display of a given area rotating in the frontal plane about the fixation point displaces the apparent vertical more when it is in peripheral regions of the visual field than when it is closer to the center of the field	Ref. 15
Rotating background	The illusory tilt of a test line increases as the angular velocity of the display increases; the mean size of the effect increases to an asymptotic value of 15 deg when the angular velocity of the 130-deg background reaches 30 deg/sec. At each velocity, the apparent tilt of the test line reaches its steady level after ~18 sec and returns to its normal position in about the same time after the background stops rotating	Ref. 7
Observer strapped to bed	When observers are strapped to a bed, the orientation of the bed becomes the factor determining the precision of judgments of the visual vertical only when the bed is tilted 90 deg or more	Ref. 17

Table 3. The effects on body tilt, head tilt, and eye torsion on judgments of the visual vertical.

Factors	Effects	Sources
Head angle position	Displacement of the visual vertical is larger when the head is tilted into a position where the utricles of the vestibular system are less sensitive	Ref. 6
Abrupt cessation of body rotation	When a body has been rotating about its x-axis for some time and is then suddenly stopped, there is an apparent displacement of a vertical line in the direction opposite to that of the rotation of the body. This effect decays over a period of a minute or two and is replaced by the typical Müller or Aubert effect. The Aubert effect is more prominent when the head is tilted rapidly rather than slowly	Refs. 37, 38 CRef. 5.804
Backward inclination of the head	Apparent inclination of a vertical line occurs in the median plane of the head as the head is inclined backward. The variability of estimates of the vertical increases with increasing tilt of the head as well as with increasing tilt of the whole body	Refs. 8, 25, 26
Linear oscillation	If an observer is oscillated along a linear path, the illusory changes in body tilt and in the visual vertical are much less than when the observer is actually tilted, by an amount that produces an equivalent displacement of the utricle. For example, going from 0- to 30-deg static tilt results in a subjective change of 25 deg, whereas an oscillation producing the same utricular displacement results in only an 8-deg change	Refs. 29, 35
Voluntary induced eye torsion	It has been found that voluntarily induced eye torsion is accompanied by a corresponding shift in the apparent vertical. However, the effects of voluntary eye torsion may not be the same as those produced by involuntary torsion	Ref. 1
Aftereffect of head tilt (and body tilt)	When the head has been returned to a vertical position after being tilted for some time, the apparent vertical positions of the head and of a luminous line are displaced up to 6 deg in the direction of head tilt. The size of the postural effect is about the same as the size of the visual effect for head tilts up to ~20 deg, but the size of the visual effect exceeds that of the postural effect for larger head tilts. The size of both effects depends on how long the head is held in the tilted position, and both decay exponentially after the head is returned to its normal posture. When the whole body is tilted, visual and postural aftereffects are produced that resemble the aftereffects of tilting the head alone	Refs. 3, 5, 34, 41, 42 CRef. 5.708

Table 4. The effects of gravity on judgments of the visual vertical.

Factors	Effects	Sources
Weightlessness	Based on studies of astronauts aboard space flights, some researchers have concluded that performance on tasks requiring judgment of the vertical was the same as under normal gravity conditions. However, others have criticized this conclusion as the observers remained in the same position while being tested and could use the Z-axis of the body as a referent	Ref. 13
Displacement of gravitoinertial force	When observers seated sideways in an aircraft are accelerated so that the force is displaced 28 deg, the observers display a displacement of the visual vertical of ~16 deg	Ref. 12

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Cross References

1.652 Orientation-selective effects on contrast sensitivity;

1.957 Factors affecting countertorsion of the eyes;

5.607 Factors affecting target localization;

5.705 Visual factors influencing postural stability;

5.708 Illusory self-inclination;

5.804 Body tilt: effects on perceived target orientation (the Aubert and Müller effects);

5.1114 Perceptual effects of inversion and left-right reversal of the visual field;

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

5.1120 Factors affecting adaptation to loss of visual position constancy;

5.1124 Effect of underwater environments on perception;

6.304 Role of reference frames in perception

5.802 Illusory Spatial Displacements

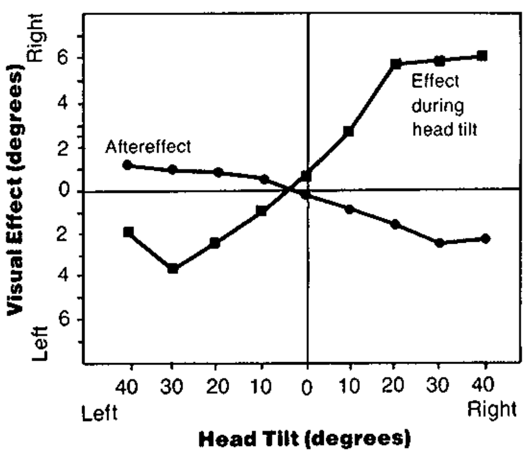

Figure 1. Deviation of visual vertical during and after various angles of head tilt (Study 1). (From Ref. 2)

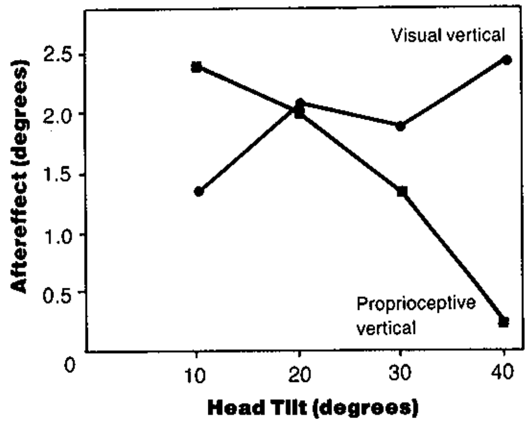

Figure 2. Magnitude of visual and proprioceptive vertical aftereffects as a function of degree of head tilt (Study 3). (From Ref. 4)

Key Terms

Boresight angle; egocentric localization; head tilt; illusory spatial displacement; postural aftereffects; proprioceptive vertical; sighting accuracy; target acquisition; tilt aftereffect; visual fixation; visual vertical

General Description

When the head is tilted from vertical, judgments of visual vertical are affected both during the displacement and for a brief period after the head is restored to the vertical (visual-spatial aftereffect). During head tilt, apparent vertical (position of a line judged to be vertical) deviates in the direction opposite the head tilt, but after 3-min exposure to tilts of up to 40 deg in either direction and return of head to upright, apparent vertical is displaced between 2 and 6 deg in the direction of previous head tilt, with greater deviations for greater head tilts up to 30 deg. (Note that the *description* of the effect is reversed for lines that are truly vertical: truly vertical lines will first appear to be inclined in the same direction as head tilt, and then be displaced in the direction opposite to the previous head tilt after the head is returned to upright.) As the duration of head tilt increases, the aftereffect increases, up to an asymptote of 2 min; the aftereffect also shows an exponential decay reaching an asymptote after 2 min. Judgments of proprioceptive vertical (judgments of head position) correspond to judgments of visual vertical at 20 deg of head tilt in both magnitude and direction; however, the judgments at 10, 30, and 40 deg suggest different mechanisms.

When the eyes are deviated for a period from visual straight ahead, there is an aftereffect on their subsequent resting position in the direction of the deviation that lasts up to 30 sec. Visual straight ahead is also judged displaced in the direction of the previous fixation.

Applications

Tilting the head or deviating the eyes for a short period causes errors in judgments of visual spatial location and grasping. Knowledge of the illusions can allow for corrections in reports of sightings by observers under those conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

Study 1 (Ref. 2)

Dimly lighted (6.6 cd/m^2)
152 × 0.9-mm light bar, 182 cm from eyes; head upright or tilted 10, 20, 30, or 40 deg right or left for 2-3 min

Study 2 (Ref. 5)

Light bar 154 × 6 mm, 180 cm from subject's eyes; 30-deg head tilt for 15, 30, 45, 60, 75, 90, 105, 120, or 180 sec and same durations after return to vertical

Study 3 (Ref. 4)

78 × 3-mm line of light, 120 cm from subject's eyes with head tilt at 10, 20, 30, or 40 deg

Study 4 (Ref. 3)

Eyes fixated at deviations of 2, 12, 22, 32, or 42 deg left or right from center line of sight

Experimental Procedure

- Method of adjustment (Studies 1, 3, 4); identification (Study 2)
- Independent variables (across studies): amount of deviation of eyes or head, duration of deviation, interval following deviation
- Dependent variables (across studies): deviation of visual object judged to be vertical, deviation of judged visual straight-ahead, or judgment of actual head tilt
- Subject's task: point to visual straight ahead, or adjust line of light to appear vertical or at same angle as head
- 30 subjects (Study 1), 4 subjects (Study 2), 12 subjects (Study 3) and 6 subjects (Study 4)

Experimental Results

- Tilting the head produces an aftereffect in which a truly vertical line appears displaced in the opposite direction from head tilt.
- Magnitude of the aftereffect is a function of the amount of head tilt, up to ~30 deg (Fig. 1).
- The visual aftereffect is in the opposite direction from the visual effect during head tilt (Fig. 1).
- At 20-deg head tilt, visual and proprioceptive aftereffects are about equal, but they deviate at greater or lesser head tilts (Fig. 2).
- Magnitude of the visual aftereffect exponentially increases with duration of head tilt and exponentially decreases with delay after head tilt, with asymptotes at ~2 min.
- Shift in apparent visual straight ahead is a linear function of amount of deviation of the eyes with direction equal to the direction of deviation (Fig. 3).

Variability

Studies 1, 2, and 3 used analysis of variance to test significance of results.

Key References

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*4. Wade, N. J., & Day, R. H. (1968). Apparent head position as a basis for a visual aftereffect of prolonged head tilt. *Perception & Psychophysics, 3*, 324-326.

*5. Wade, N. J., & Day, R. H. (1968). Development and dissipation of visual spatial aftereffect from prolonged head tilt. *Journal of Experimental Psychology, 76*, 439-443.

Cross References

1.960 Factors affecting coordination of head rotation and eye movements;

3.210 Vestibular illusions;

5.106 Classic geometric illusions of size and direction;

5.220 Vernier offset in real and apparent motion;

5.801 Factors affecting judgment of the visual vertical;

5.804 Body tilt: effects on perceived target orientation (the Aubert and Müller effects);

Handbook of perception and human performance, Ch. 11, Sect. 6.2

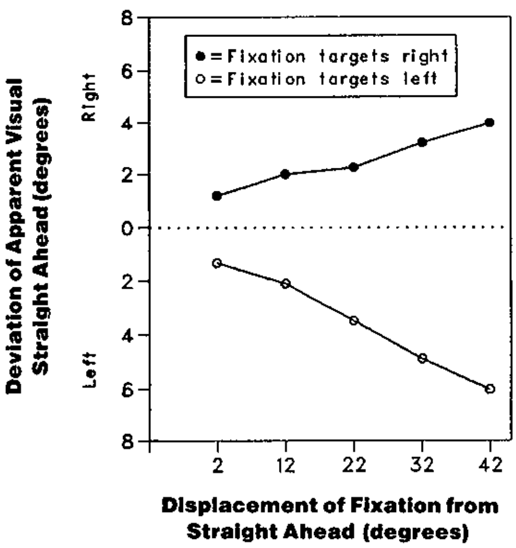

Figure 3. Deviation of apparent visual straight ahead as a function of displacement of fixation from straight ahead (Study 4). (From Ref. 3)

5.803 Perceived Displacement of the Horizon with Head Tilt and Visual Display Rotation

Key Terms

Cyclofusional eye movements; eye torsion; gravitational frame of reference; head tilt; horizon; ocular torsion; visual field rotation

General Description

Tilting the observer's head or rotating a visual display around the observer's line of sight will induce eye torsion and a displacement of the apparent horizon. The effects of head tilt and display rotation are additive for eye torsion, but interact for horizon estimates.

Methods

Test Conditions

- Visual display was ring of visual noise (white dots ranging from a small fraction of a deg to 2-3 deg of visual angle in size randomly distributed on black background) subtending 130 deg; circular white central target subtended 32 deg and bisected by a black stripe
- Visual display either stationary or rotated at angular velocity of 20 deg/sec; illumination provided by shielded incandescent lamps maintaining space-averaged luminance of 15.195 cd/m^2
- Head maintained in vertical or tilted position by bite bar; head tilts ranged from 45 deg clockwise to 45 deg counterclockwise in increments of 15 deg
- Targets viewed through +3.5 diopter color-corrected lens 10.5 cm in diameter placed 18.0 cm from the target; observer's eye always centered on optical axis such that corneal surface located within 1-2 mm from lens surface
- Eye torsion (residual ocular torsion, CRef. 1.959) measured by having observer align target stripe parallel to bar-shaped afterimage projected by slit-shaped horizontal strobe flash attached to biteboard with head in vertical position

Experimental Procedure

- Method of constant stimuli
- Independent variables: magnitude of head tilt, direction of head tilt, magnitude of visual field rotation, direction of visual field rotation
- Dependent variables: amplitude of eye movements, direction of eye movements, magnitude of target alignments, direction of target alignments
- Observer's task: use control knob to rotate circular central target until black stripe appeared horizontal
- 6 male observers, undergraduate college students with unknown amount of practice

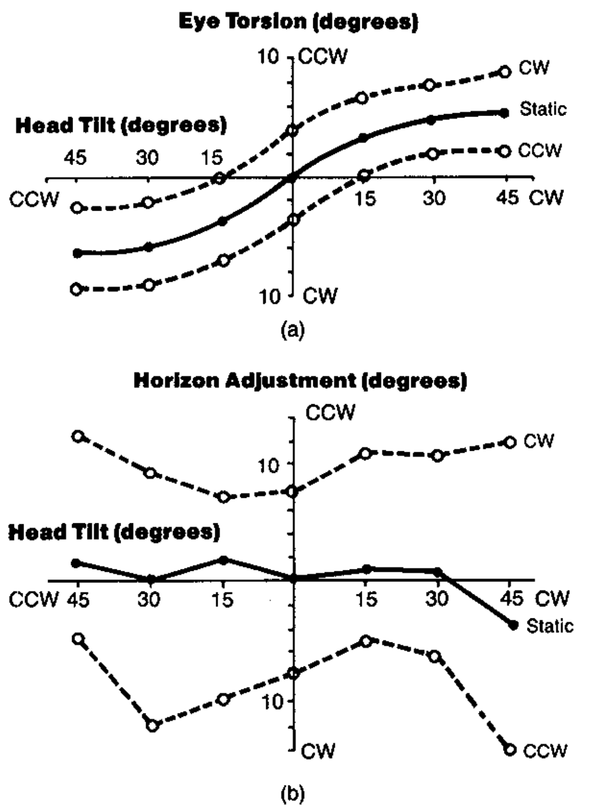

Figure 1. (a) Mean amplitude of directional ocular torsion as a function of head tilt for clockwise (CW) and counterclockwise (CCW) visual field rotation and no visual field rotation (static). (b) Mean magnitude of directional horizontal target alignment, expressed as deviation from true horizon for same three rotation conditions as Fig. 1a. (From Ref. 5)

Experimental Results

- Irrespective of the direction of either visual field rotation or head tilt (i.e., no change, clockwise, or counterclockwise), mean amplitude of torsional eye movements (torsions) varies directly as a function of magnitude of head tilt (Fig. 1a).
- Irrespective of the direction of visual field rotation, mean amplitude of optic torsion is always in a direction opposite the direction of head tilt (e.g., as head tilt increases in a clockwise [CW] direction, mean amplitude of optic torsion increases in a counterclockwise [CCW] direction) (Fig. 1a).
- Irrespective of the direction of visual field rotation, no functional relationship is found between mean magnitude of horizon displacements and magnitude of head tilt (Fig. 1b).
- Irrespective of either direction or magnitude of head tilt, mean amplitude of ocular torsion is always greater than mean horizon displacement. Furthermore, under three conditions of head tilt (15 and 45 deg CWW, and 45 deg CW), horizon displacement is commonly in the direction opposite the direction of ocular torsion. Thus, it appears that observers tend to compensate for torsional eye movements when subjectively estimating horizontal under head-tilt conditions.
- Although for each of its conditions the functional relationship between visual field rotation and ocular torsion monotonically increases the effect of visual field rotation on horizon displacement is a far more intricate one that appears functionally dependent on a complex interaction among magnitude and direction of head tilt as well as direction of visual field rotation.
- Summarizing, the results provide no evidence of a simple

relation between the function relating torsional eye movements to horizon estimates and the interaction of head tilt and visual field rotation.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other investigators have reported comparable results (Refs. 1, 2, 3, 7) and/or formulated similar conclusions (Refs. 6, 7) based on independent investigations.

Key References

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2. Dichgans, J., Held, R., Young, L. R., & Brandt, T. (1972). Moving scenes influence the apparent direction of gravity. *Science, 178*, 1217-1219.

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Cross References

1.957 Factors affecting countertorsion of the eyes;

1.958 Eye movements induced by head and body movements;

1.959 Eye torsion in response to lateral head tilt;

1.960 Factors affecting coordination of head rotation and eye movements;

5.606 Target localization accuracy: effect of gaze eccentricity;

5.607 Factors affect target localization;

5.705 Visual factors influencing postural stability;

5.801 Factors affecting judgment of the visual vertical;

5.802 Illusory spatial displacements;

5.804 Body tilt: effects on perceived target orientation (the Aubert and Müller effects);

Handbook of perception and human performance, Ch. 10, Sect. 3.5

5.804 Body Tilt: Effects on Perceived Target Orientation (the Aubert and Müller Effects)

Key Terms

Aubert effect; body tilt; gravitational vertical; Müller illusion; visual localization; visual vertical

General Description

As the body of an observer is tilted vertically, the ability to orient a test line so that it is aligned with gravitational horizontal or vertical decreases. As body tilt increases, the apparent horizontal (or vertical) inclines in a direction opposite that of body tilt and the truly horizontal (or vertical) appears to tilt in the same direction as body tilt (Müller E-phenomenon). With greater body tilt, the effect declines until there is no deviation from actual horizontal. As tilt increases beyond ±80 deg, apparent horizontal (or vertical) inclines in the same direction as body tilt and true horizontal (or vertical) appears to tilt in the direction opposite that of body tilt (Aubert A-phenomenon).

Methods

Test Conditions

- Subject harnessed into chair that could be tilted around its fore-aft axis up to ±90 deg from upright
- Optical system that provided a line target of collimated light was attached to chair's tilting ring; a round knob was used by subject to adjust position of line target
- Subject's left eye covered; target appeared directly in front of right eye; subject was rotated with eyes closed at velocity of 1.5-2 deg/sec to each of 19 positions ranging from −90 deg (left) to +90 deg (right) in 10-degree intervals; direction of tilt alternated and magnitude randomized; when subject opened eyes, room was completely dark and luminous target line had been randomly offset

Experimental Procedure

- Independent variables: direction and degree of body tilt from vertical
- Dependent variables: mean standard deviation of target setting from gravitational horizontal (constant error)
- Subject's task: set line to gravitational horizontal
- Each subject tested at all 19 settings on each of 13 consecutive days
- 3 adult male subjects with normal hearing and normal vestibular function

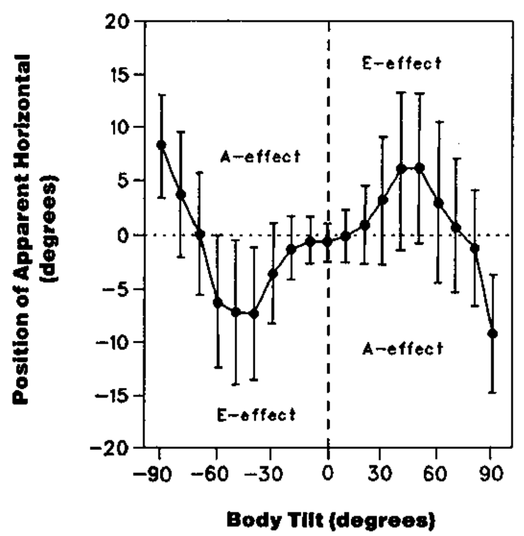

Figure 1. Mean position of the apparent horizontal as a function of body tilt, with standard deviations indicated by vertical bars. (From *Handbook of perception and human performance*, based on Ref. 2)

Experimental Results

- When subjects are close to upright (within ±20-40 deg of body tilt), there is no significant difference between apparent horizontal and gravitational horizontal.
- Beyond this range, the apparent horizontal (position of a line judged to be horizontal) inclines with increases in body tilt (E-effect), reaching a limit at 50 deg of tilt; then the effect declines to reach a point of no deviation at ~60-80 deg.
- Further increases in tilt produce an increasing deviation in the apparent horizontal in the same direction as the body tilt (A-effect).
- Setting of the apparent horizontal varies as much as 10 deg from gravitational horizontal.

Variability

Bars in Fig. 1 represent ±1 standard deviation. There was considerable intertest and intersubject variability.

Repeatability/Comparison with Other Studies

Similar curves have been produced by tilting of head alone (Ref. 1) and for vertical as well as horizontal lines.

Constraints

- There are large individual differences in the presence, magnitude, and symmetry of the effects.
- That left and right tilt were alternated may have had a different effect than if direction and degree were randomly presented.
- The illusion of tilt can be dispelled if the room is not dark and items in the environment can be used as a frame of reference.
- When the head is moved quickly, there is a delay of a few seconds before the illusion occurs.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Graybiel, A., & Clark, B. (1962). Perception of the horizontal or vertical with head upright, on the side, and inverted under static conditions and during exposure to centripetal force. *Aerospace Medicine, 33*, 147-155.

*2. Miller, E. F., Fregly, A. R., van den Brink, G., & Graybiel, A. (1965). *Visual localization of the horizontal as a function of body tilt up to ±90° from gravitational vertical* (NSAM-942. NASA Order No. R-47). Pensacola, FL: Naval School of Aviation Medicine.

Cross References

3.202 Dynamics of the otolith organs;

3.210 Vestibular illusions;

5.801 Factors affecting judgment of the visual vertical;

5.805 Illusions of perceived tilt;

Handbook of perception and human performance, Ch. 18, Sect. 5.7

5.805 Illusions of Perceived Tilt

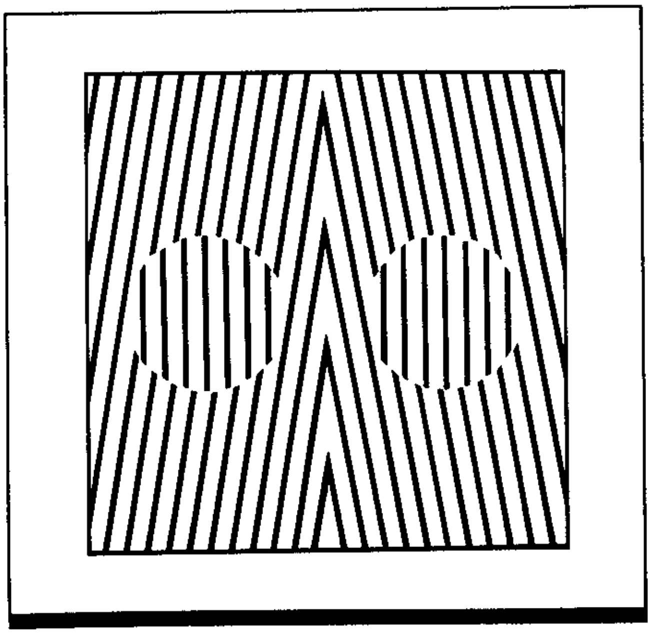

Figure 1. Demonstration of tilt contrast. Although the lines in the two discs are vertical, they appear tilted in directions opposite to the adjacent, background lines of contrasting tilt. (From Ref. 3)

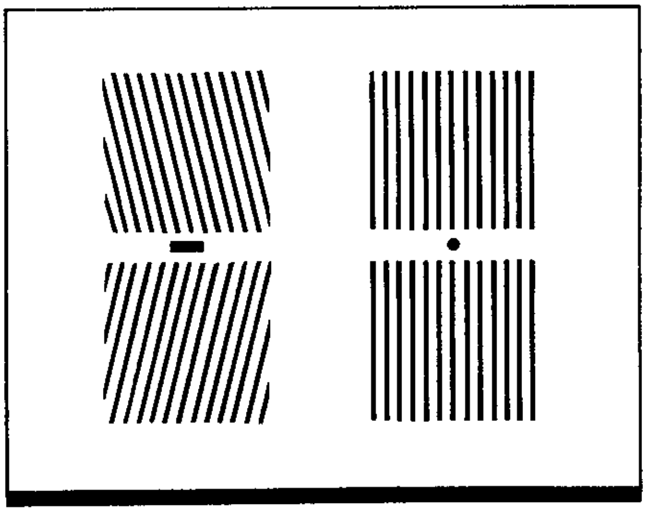

Figure 2. Demonstration of the tilt aftereffect. Inspect the small black rectangle on the left for ~30 sec, then transfer gaze to the dot on the right. Each test grating should appear to tilt in the opposite direction to the corresponding inspection grating. (From Ref. 5)

Key Terms

Induction; orientation perception; spatial vision; tilt aftereffect; tilt contrast; tilt illusion; visual simulation

General Description

The apparent orientation, or tilt, of a given line (test line) is affected by a neighboring line (induction line) with a different tilt. The tilt illusion refers to the perceived tilt of the test line in a direction opposite that of the induction line. When the two lines are presented together, the illusion is called tilt contrast. When the two lines are presented consecutively, with the induction line preceding the test line, the illusion is called the tilt aftereffect.

The illusions are at a maximum, ranging from 1.5-4.1 deg arc of visual angle (Refs. 1-4), when the angle between the induction and test lines is between 10 and 20 deg. Angles less than 5 deg are underestimated (the effect is called angle assimilation) as are angles between 60 and 90 deg (the indirect effect) (Ref. 2). The illusions can be produced by luminance gradients and by color differences alone (Ref. 1).

Inspection of the induction line for as briefly as 5 sec generates a sizable aftereffect with an asymptote being reached in ~45 sec; the aftereffect lasts for several minutes after the induction line has been removed (Ref. 2). The illusions are also found with gratings and are maximized when the induction and test gratings are of the same spatial frequency (Ref. 3). The extent of interocular transfer, although greater than zero, is not well defined in the literature (Ref. 4). However, the illusion is still present when the test line is shown to one eye and the induction line to the other. The illusion does not extend beyond a region of 1 deg arc from the induction line or grating.

Applications

Any situation in which fine orientation discrimination must be made in presence of other lines or gratings of different orientation

Constraints

- Difference in orientation of induction and test lines or gratings, spatial frequency of gratings, length of inspection period for induction line, color differences in induction and test lines, and many other factors can influence the extent of the tilt illusions and, therefore, must be considered in applying the general principles about the phenomena to specific viewing conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Elsner, A. (1978). Hue difference contours can be used in processing orientation information. *Perception & Psychophysics, 24,* 451-456.

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6. Ware, C., & Mitchell, D. E. (1974). The spatial selectivity of the tilt aftereffect. *Vision Research, 14,* 735-737.

Cross References

1.623 Visual acuity and contrast sensitivity: effect of age;

1.652 Orientation-selective effects on contrast sensitivity;

3.210 Vestibular illusions;

5.801 Factors affecting judgment of the visual vertical;

5.802 Illusory spatial displacements;

Handbook of perception and human performance, Ch. 7, Sect. 3.2; Ch. 18, Sect. 5.4

5.806 Non-Visual Discrimination of Surface Orientation: Haptic Aftereffects

Table 1. Aftereffect as a function of angle of convergence/divergence. (From Ref. 1)

	Angle of Convergence/Divergence (degrees)					
	11.25	22.5	37.5	45	67.5	90
Mean (degrees)	2.50	3.25	4.79	5.11	7.60	6.67
Standard deviation (degrees)	3.24	2.26	3.81	4.50	4.84	4.39

Key Terms

Haptic aftereffects; haptic discrimination; non-visual spatial discrimination; parallelism; tactile controls; tilt; touch

General Description

After a period of feeling two divergent (or convergent) surfaces, parallel surfaces are perceived as convergent if the previous experience was with divergent surfaces, and divergent if the previous experience was with convergent surfaces. This is true even though subjects are capable of determining haptic parallel within 3-4 deg if there has not been any immediately previous experience with non-parallel surfaces.

Methods

Test Conditions

- Each of two upright 12 x 21 cm boards could be rotated about its own axis on the midline of its surface; the boards were 14 cm apart at their axes
- Slant of each board adjusted by experimenter prior to subject's placing a hand on each board, or adjusted by pressure from subject's palm resting on the board
- Subject seated on circular stool at circular table containing apparatus mounted on a circular base; subject's arm shielded by a curtain that prevented viewing of the apparatus; subject was not blindfolded
- Trials alternated between divergent and convergent to prevent the build-up of cumulative error in perception of parallel; for experiments varying exposure time and recovery time, subject placed hands palm down on the table during the recovery period
- Timing of trials varied across experiments

Experimental Procedure

- Between-subjects design
- Independent variables: direction of non-parallelism (divergent or convergent), degree of non-parallelism, duration of non-parallel exposure, duration of recovery period from previous opposite trial
- Dependent variable: aftereffect, measured in terms of degrees from parallel (i.e., amount of error)
- Subject's task: hold palms on converging or diverging palmboards, then adjust palmboards to parallel; for control subjects, set palmboards to parallel without any previous convergent or divergent exposure
- 12 subjects per experiment, except 18 subjects for exposure-time manipulation; 24 control subjects

Table 2. Aftereffect as a function of duration of adaptation exposure. (From Ref. 1)

	Duration of Adaptation Exposure (seconds)				
	12	18	27	40	60
Mean (degrees)	9.79	8.82	8.84	8.82	8.99
Standard deviation (degrees)	4.36	4.21	4.88	4.71	5.23

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 3. Aftereffect as a function of duration of recovery period from the previous trial. (From Ref. 1)

	Duration of Recovery Period from Previous Trial (seconds)				
	0	7	14	28	56
Mean (degrees)	4.43	6.18	5.97	5.81	6.12
Standard deviation (degrees)	5.74	4.20	3.34	4.58	5.52

Experimental Results

- The mean and standard deviation of the aftereffect generally increases as the degree of previously experienced convergence or divergence increases (Table 1).
- The magnitude of aftereffect is similar for nonparallel exposure durations ranging from 12-60 sec (Table 2).
- There is little difference between aftereffects for a 7-sec and 56-sec recovery period between trials. However, there is a decrease in aftereffect when no rest period is allowed (Table 3).

Variability

All experimental subjects had aftereffects.

Repeatability/Comparison with Other Studies

Other experiments in this series indicate that aftereffects also occur in each hand separately.

Constraints

- There were no statistical analyses of differences among conditions or among subjects.

Key References

*1. Gibson, J. J., & Backlund, F. A. (1963). An aftereffect in haptic space perception. *Quarterly Journal of Experimental Psychology, 15*, 145-154.

Cross References

5.807 Kinesthetic perception of parallelism: effect of target separation and distance from the body;

5.808 Haptic and visual perception of target orientation

5.807 Kinesthetic Perception of Parallelism: Effect of Target Separation and Distance from the Body

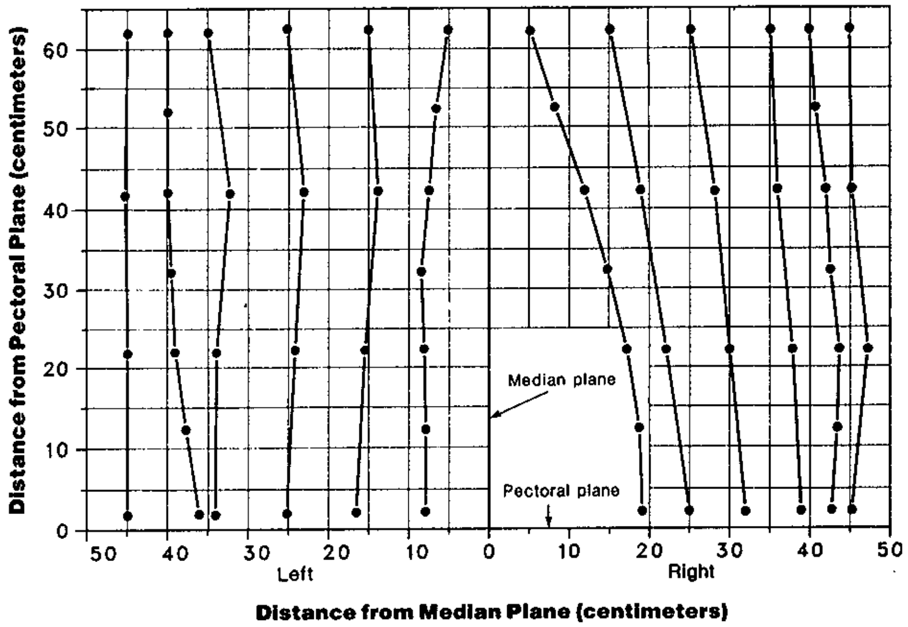


Figure 1. Judged position of parallelism as a function of distance from body and separation of anchors. (From Ref. 1)

Key Terms

Joint perception; kinesthetic judgment; parallelism

General Description

When two threads (anchored to a horizontal plane in front of the subject and symmetrical to the body's median plane) are anchored and adjusted at various distances from the body so as to feel kinesthetically parallel to each other, the two lines formed by the threads increasingly diverge as the points of anchoring are closer to the body. This divergence from parallel decreases as the distance separating the farthest points of anchoring for the two lines increases. The divergence is asymmetric with respect to the body's median plane, as shown in Fig. 1.

Methods

Test Conditions

- Once each trial, subject pulled two threads of equal length taut, toward the pectoral plane, adjusting the threads so they were subjectively, kinesthetically parallel with each other and to the median plane of the subject's body
- Threads were of fixed length (~20-25 mm) and anchored onto a wood board by pins
- Distances between thread anchor points ranged from 100-900 mm in 100 or 200 mm steps
- Anchor points for threads were 2-62 cm from pectoral plane
- Several trials conducted at each factorial combination of anchor point separation distance and anchor board position; at each anchor point separation distance the mean of ten judgments of parallelism determined anchor point separation distance at subsequent (next closest to pectoral plane) anchor board position
- From the means of the ten judgments, lines of subjective parallelism were constructed for each level of the anchor point separation variable
- The distance between largest anchoring point separations was varied within each set of trials
- No information on visual feedback provided to subject

Experimental Procedure

- Independent variables: separation between points of anchor for the two threads, distance from subject's pectoral plane at which measurements were taken
- Dependent variable: judgment of parallelism, as measured by distances (left and right) from median plane
- Subject's task: pull two threads taut, toward the pectoral plane, adjusting the threads so that they were subjectively, kinesthetically parallel to each other and to the median plane of subject's body
- Ten judgments per distance from pectoral plane
- 5 subjects

Experimental Results

• When two threads anchored equidistant from the body's median plane are adjusted to kinesthetically parallel positions at distances away from the subject's body (the pectoral plane), the result is a series of lines that tend to diverge as the distance separating the anchor points for the first trial (the one farthest from the body) decreases.

• Divergence from parallel increases when anchoring points are closer to the body.

• Divergence from parallel is asymmetric with respect to the median plane of the body.

Variability

Data for individual subjects were reported, but statistical variability was not computed.

Constraints

• Subjects were apparently blindfolded, but this is not reported.

Key References

*1. Blumenfeld, W. (1936). The relationship between the optical and haptic construction of space. *Acta Psychologica*, 2, 125-174.

Cross References

5.806 Non-visual discrimination of surface orientation: haptic after effects;

Handbook of perception and human performance, Ch. 31, Sect. 4.2

5.808 Haptic and Visual Perception of Target Orientation

Key Terms

Cross-modal judgment; haptic discrimination; oblique effect; orientation perception; spatial orientation

General Description

When the orientation of an unseen rod is adjusted with one hand to match the orientation of another unseen rod felt with the other hand (haptic judgments), matching error is about twice as large as when the rods are visually inspected. In both modalities, error is much greater for matching oblique orientations than for horizontal or vertical orientations. For haptic judgments, oblique error is greater for matches made when standard and comparison rods are felt simultaneously rather than successively. For visual judgments, oblique error is greater for successive inspection of standard and comparison stimuli.

Methods

Test Conditions

- Two 8 x 203 mm stimulus rods were mounted 482 mm apart (at their centers) and positioned in front of and parallel to the subject's body; experimenter set standard rod's orientation between 0 deg (vertical) and 315 deg (degrees increasing clockwise); subject adjusted comparison rod to a perceptually equivalent orientation
- For haptic judgments, one hand inspected the standard rod and the other hand inspected (and set) the comparison; for visual judgments, luminous stimuli were viewed in an otherwise dark room; the comparison rod was adjusted by remote-control
- For stimulus judgments, standard and comparison rods were presented at the same time; for delayed comparison, the standard rod was viewed or felt for 5 sec, and the comparison rod was viewed or felt and then manipulated after a 10-sec interval

Experimental Procedure

- Method of adjustment
- Repeated measures factorial design
- Independent variable: stimulus orientation, haptic or visual inspection, simultaneous or successive comparison
- Dependent variable: mean absolute error, defined as difference (in degrees) between standard and comparison orientations
- Subject's task: through remote control, adjust a comparison rod to the visual perceived orientation of a standard rod; haptically adjust a comparison rod to the haptically perceived orientation of a standard rod
- 7 male and 9 female university students, half tested first visually and half haptically; prior to testing, all subjects familiarized with standard orientations

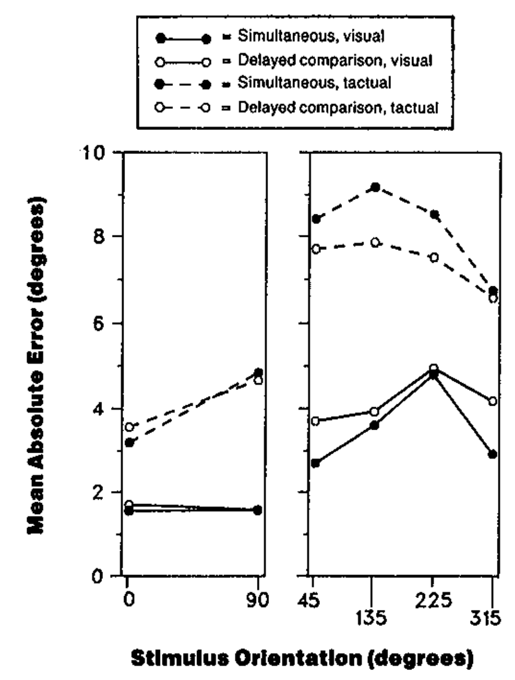


Figure 1. Mean absolute error for reproducing stimulus orientation by vision and touch (haptic mode) for simultaneous and successive presentations of the standard and the comparison. (From Ref. 3)

Experimental Results

- Error in touch matching stimulus orientation is about twice as large as visual matching error.
- For both vision and touch, error for matching oblique orientations is significantly greater ($p < 0.01$) than error for matching horizontal or vertical orientations.
- For haptic judgment, error on oblique orientations is greater when standard and comparison stimuli are inspected simultaneously. For visual judgment, error on oblique orientations is greater for successive inspection. For both modalities, accuracy in reproducing horizontal and vertical orientations is similar for the simultaneous and successive conditions.

Variability

An analysis of variance was used, but mean-square errors were not reported.

Repeatablity/Comparison with Other Studies

Similar results are reported in Ref. 2. Visual problems with oblique orientations are reviewed in Ref. 1.

Constraints

The experimental session lasted 2-1/2 hr, but any fatigue effects should have been offset by counterbalancing the conditions and randomizing the order of trials.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: The "oblique effect" in man and animals. *Psychological Bulletin, 78,* 266-278.

2. Lechelt, E. C., Eliuk, J., & Tanne, G. (1976). Perceptual orientational asymmetries: A comparison of visual and haptic space. *Perception & Psychophysics, 20,* 463-469.

*3. Lechelt, E. C., & Verenka, A. (1980). Spatial anisotropy in intramodal and cross-modal judgments of stimulus orientation: The stability of the oblique effect. *Perception, 9,* 581-589.

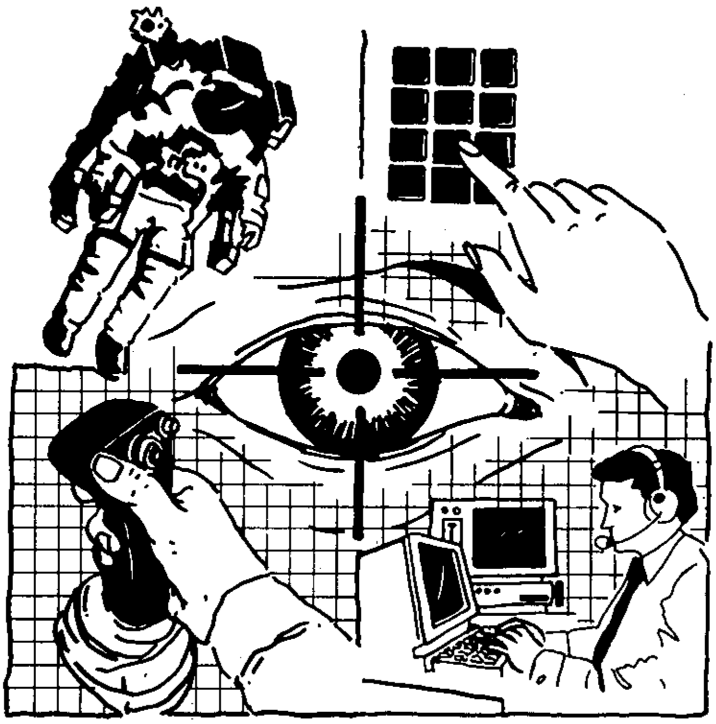
Cross References

6.608 Haptic discrimination of letter forms: effect of orientation;

Handbook of perception and human performance, Ch. 31, Sect. 4.5

Notes

Section 5.9 Depth Perception



5.901 Monocular Distance Cues

Key Terms

Accommodation; aerial perspective; brightness; depth perception; distance vision; interposition; kinetic occlusion; kinetic shear; linear perspective; monocular depth cue; motion parallax; motion perspective; retinal size; shadow; streaming; texture gradient; three-dimensional displays

General Description

Vision is usually **binocular**. Because the two eyes are separated in the head, each eye receives a slightly different view of the visual scene. This slight difference in each eye's image (known as **lateral retinal image disparity**) is a primary cue to depth. However, an observer using only one eye has available a number of other cues to depth and distance. These **monocular** cues alone can produce satisfactory depth and distance judgments. For example, one-eyed individuals and equipment users with monocular viewing devices usually function quite well. Moreover, monocular cues are useful at distances where binocular cues are ineffective.

The accompanying table lists a number of monocular distance cues. In most natural environments, many different monocular cues are present simultaneously and provide redundant information about depth and distance. The observer is generally unaware which cues he or she is using or the relative contribution of a given cue.

Cue	Description
Interposition (occlusion, obscuration, contour interruption	An object partly covering another appears closer A powerful and dominant relative distance cue
Motion perspective (motion parallax, monocular movement parallax)	With observer motion, the images of objects at different distances move across the retina at different velocities (CRefs. 5.502, 5.902) With lateral head motion, objects at different distances have different relative angular motion; closer objects move faster With observer movement, the images of objects further than fixation move in the same direction as the observer, while the images of objects closer than fixation move against the line of observer motion The angular rate of image motion increases as the distance of the object from fixation increases A powerful distance cue
Streaming	A special case of motion parallax With rapid motion, details blur, giving an appearance of flow or streaming terrain Streaming velocity decreases with distance and increases with rate of locomotion Streaming velocity is greatest perpendicular to the direction of locomotion and decreases with increasing angle from perpendicular; streaming is not apparent for straight-ahead fields
Linear perspective	A constant distance between points in the visual field subtends a smaller angle with increasing distance Parallel tracks, power lines, and roads appear to narrow (converge) with distance
Perspective change	Movement past objects produces continuous change in perspective as viewpoint changes Less change with greater distance
Texture gradient (texture density gradient, texture density, texture compression)	A special case of linear perspective With roughly uniform texture, texture density increases with distance, producing a smaller, smoother texture

Cue	Description
Aerial perspective (atmospheric attenuation)	Atmosphere scattering and absorption reduce brightness contrast, and color saturation of objects with distance, making distant objects bluer Works only at long ranges and in normal atmosphere
Brightness	Without other distance cues, the brighter of two objects appears nearer Small or point sources diminish in brightness with distance
Vertical position (relative height, height in plane)	Objects lower in the visual plane appear nearer; those closer to the horizon appear farther away
Familiar size (relative size)	Objects of known size which appear small or subtend a small visual angle at the retina are distant
Detail clarity (optical resolution, detail resolution)	With increasing distance, small details disappear Does not require atmospheric loss of either contrast or color saturation; this distance cue is based on **visual acuity**, learning, and familiarity with the object
Accommodation (eye focus)	Change in thickness of lens of the eye to form sharp images of objects at different distances This weak cue may only be effective for distances <4-12 ft
Light and shade (highlighting, shadowing)	The shadow of one object on another is a relative distance cue Shading is a cue; highlights indicate protruding surfaces (bumps), shadows indicate receding surfaces (dents, craters), depending upon the direction of illumination
Kinetic occlusion	Similar to interposition, except for moving objects or observer The surface of a near object moves to conceal or reveal parts of a surface farther away (CRef. 5.903)
Kinetic shear	Relative movement parallel to an edge between two surfaces causes an abrupt change in the alignment of textural elements at the edge, indicating that the two surfaces may lie at different depths (CRef. 5.903) Requires that textures be present

Applications

Use of equipment under conditions where binocular distance cues are absent or ineffective.

Constraints

- The relative effectiveness of the various depth cues differs with distance and conditions. For example, motion parallax can be a very strong distance cue, depending upon rate of motion. At short distances, it may be a much stronger cue than relative size, but at long distances, relative size is a more effective cue. Interposition, when present, tends to be the dominant cue.
- In central vision, under favorable conditions and for observers with excellent **stereoacuity** (12 sec of visual arc), **stereopsis** (a binocular depth cue), can provide a meaningful cue to distances up to ~450 m. In the presence of both binocular and monocular cues, stereopsis is the most effective distance cue in central vision up to ~65 m. In peripheral vision, stereopsis is less effective, and motion parallax, a monocular cue, may be more effective.
- Several kinds of monocular cues usually are present simultaneously. Monocular cues may indicate only relative, not absolute, depths or distances.
- Individuals differ greatly in accuracy of judgments based only on monocular cues.

Key References

1. Gold, T. (1972, June). The limits of stereopsis for depth perception in dynamic visual situations. *Seminar Proceedings of the Society for Information Display, 2,* 399-406.

2. Haber, R. N., & Hershenson, M. (1973). *The psychology of perception.* New York: Holt, Rinehart, & Winston.

3. Woodworth, R. S., & Schlossberg, H. (1954). *Experimental psychology.* New York: Henry Holt.

Cross References

5.502 Optical flow patterns and motion perspective;

5.902 Motion parallax;

5.903 Kinetic occlusion and kinetic shear;

5.905 Lateral retinal image disparity;

7.221 Attentional and decision-making factors in component and compound tasks

5.902 Motion Parallax

Key Terms

Depth perception; distance vision; motion parallax; three-dimensional displays

General Description

Motion parallax refers to changes in the projective relations among objects in the visual field due to an observer's motion. Motion parallax will occur even if the observer is stationary and the scene is moving or is in simulated motion (Ref. 2), and is an important cue to depth. Motion parallax is illustrated in Fig. 1. At the observer's original location L_1, the retinal projections of the point of fixation P_2, an object at the nearer point P_1, and an object at a farther point P_3 all overlap, since all three points are in line. When the observer moves to L_2, while maintaining fixation at P_2, the relationship among the retinal projections of the near, fixation, and far points changes. An object at P_1 appears to move in a direction opposite the observer's line of motion, while an object at P_3 appears to move in the same direction as the observer's line of motion. The fixation point is not displaced on the retina.

A different state of affairs occurs when fixation is shifted to P_3. An object at P_2 and an object at P_1 now both move against the observer's line of motion. If fixation were moved still farther away, to some point beyond P_3, objects at points P_1, P_2, and P_3 would all appear to move in a direction opposite to the observer.

The direction in which the retinal image of an object moves relative to the fixation point therefore indicates whether the object is nearer or farther than the observer's fixation point. Further depth information is gained from the size of the displacement of the retinal image. The fixation point serves as an anchor, since its retinal projection will not be displaced. Objects close to the fixation point, whether on its near side or far side relative to the observer, will show smaller retinal displacement than objects more remote from the fixation point (Fig. 2).

Motion parallax contains information about both the direction and the magnitude of depth relative to the fixation point. Its use as a depth cue depends in essence upon the ability of the observer to detect the relative angular velocities of two objects. Objects whose retinal images move in the same direction as the line of motion of the observer and that display large retinal displacements are farther from an observer's fixation point than those moving in that direction but displaying smaller displacement: in this case, both objects would be on the "far" side of the observer's fixation point. Objects whose retinal images move in the opposite direction to the observer's line of motion and display large retinal displacements are closer to the observer than those moving in that direction but displaying smaller displacements; in this case, both objects are on the "near" side of the observer's fixation point. When the retinal images of two objects move opposite to each other as a result of the observer's motion, the observer is fixating at some distance between the two objects. The object moving opposite the observer's line of motion is clearer than the object moving in the same direction as the observer.

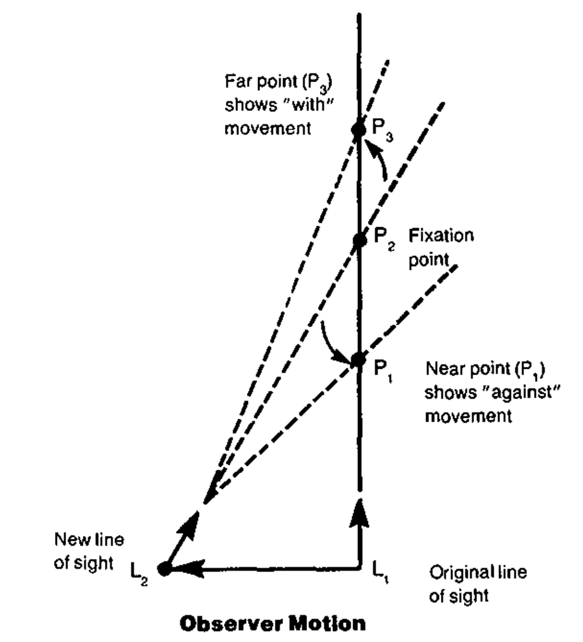


Figure 1. Changes in the retinal projections of object at near (P_1) and far (P_3) distances when the observer fixates some intermediate point (P_2) and moves from L_1 to L_2. (From Ref. 1)

The motion parallax described above is most correctly called relative motion parallax, because it depends upon relative retinal displacements of two or more objects. Theoretically, an observer could use parallax cues to gauge object distance if only a single object were involved and the observer moved relative to it. Such motion parallax is referred to as absolute motion parallax. In this case, the observer would have to register both the translatory component of the eye's movement and the visual direction of the object. However, with only a single object present, information about the observer's translation and the angular velocity of the object's retinal displacement would have to come from nonvisual sources (probably **proprioception**; Ref. 2).

Applications

Visual displays that simulate motion and depth.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Motion parallax can also be described in terms of relative motion in the optic array rather than relative motion on the retina (Ref. 2).
• Dynamic visual environments place functional limits on the use of motion parallax as a depth cue (CRef. 5.904). Furthermore, illusions of motion will occur during incorrect depth perception (CRef. 5.219).
• Other depth cues exist for an observer in motion. Motion perspective is related to motion parallax (CRef. 5.502). Kinetic occlusion and shear also result from observer motion (CRef. 5.903).
• Evidence of an observer's ability to employ absolute motion parallax as a depth cue is mixed (Ref. 2).

Key References

*1. Haber, R. N., & Hershenson, M. (1973). *The psychology of visual perception*. New York: Holt, Rinehart, & Winston.

2. Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

Cross References

5.219 Illusions of motion resulting from incorrect perception of depth;

5.502 Optical flow patterns and motion perspective;

5.903 Kinetic occlusion and kinetic shear;

5.904 Functional limits of various depth cues in dynamic visual environments;

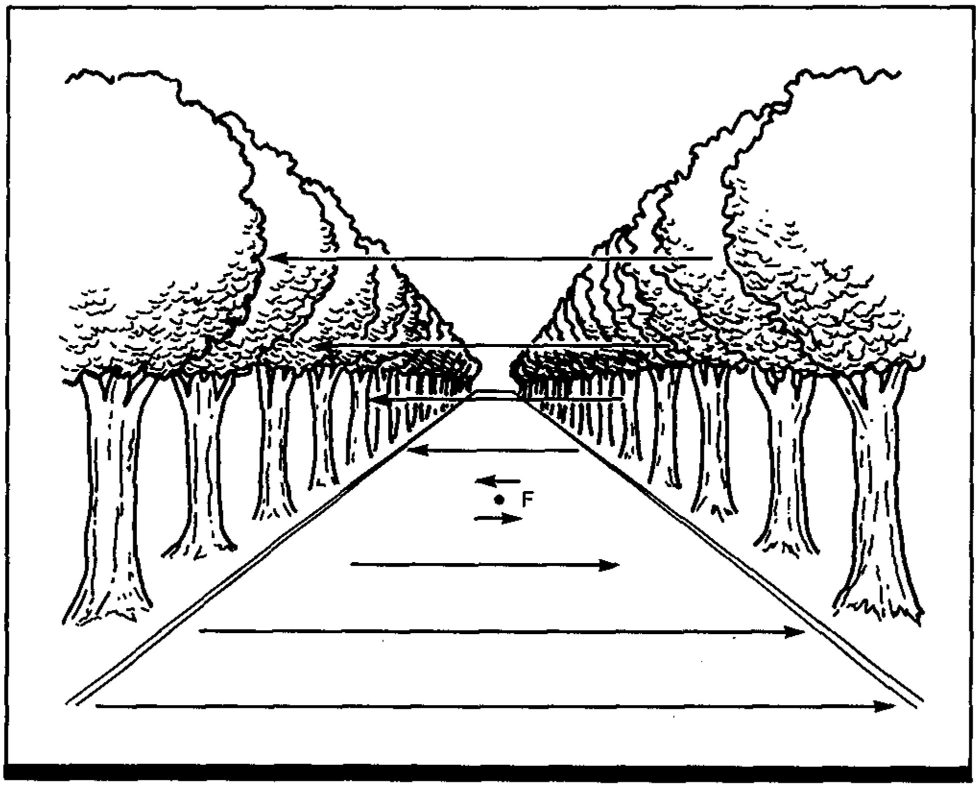


Figure 2. Relative retinal displacements for an observer moving from right to left, looking to the right and fixating at an intermediate distance *F*. Arrows represent relative displacement of the retinal image, with arrow direction indicating direction of displacement and arrow size indicating magnitude. (From Ref. 1)

5.903 Kinetic Occlusion and Kinetic Shear

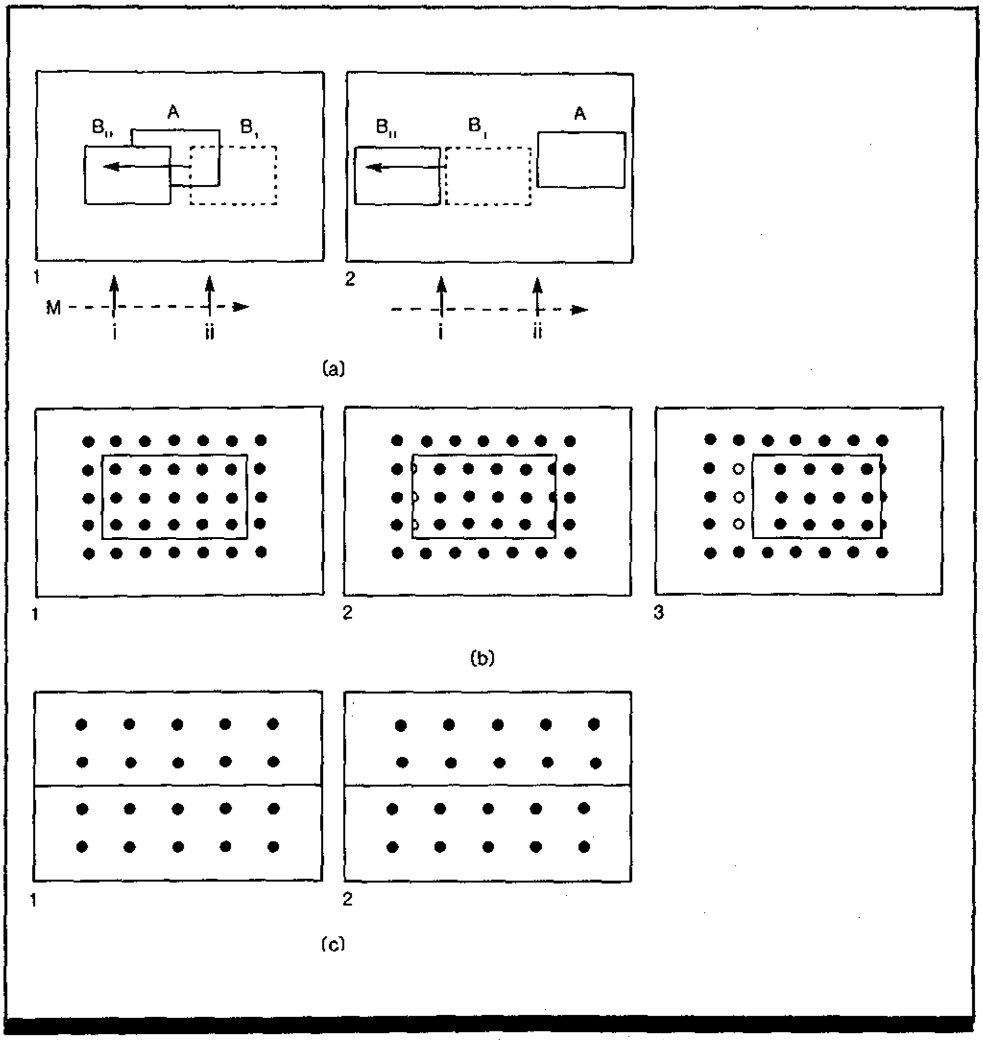


Figure 1. (a) Kinetic occlusion. Panel 1: The occlusion of rectangle A by rectangle *B* is changed as the observer moves from point *i* to point *ii*. Panel 2: Occlusion does not occur when the observer moves from *i* to *ii*; occlusion could occur, however, if viewpoint or extent of motion were changed. (b) Kinetic occlusion of textured surfaces. Occlusion as from Panel 1 to Panel 2 specifies that the smaller rectangle is viewed through an aperture; occlusion as from Panel 1 to Panel 3 indicates that the smaller rectangle is in front of the larger one. (c) Kinetic shear. Abrupt change in the alignment of surface elements is characteristic of separable surfaces and, often, of surfaces at different depths. (From *Handbook of perception and human performance*)

Key Terms

Depth perception; kinetic occlusion; kinetic shear; monocular depth cue; three-dimensional displays

General Description

Motion-generated depth cues may be separated into three classes based on the kind of information they provide regarding the depth of objects in the visual field. Motion parallax (CRef. 5.902) and motion perspective (CRef. 5.502) provide information about the direction of depth (whether object *A* is closer or further than object *B*) as well as a scale with which to gauge distance (how much further or closer it is). Signed depth cues provide an indication of the direction of depth relations, but no information about scale. That is, a signed depth cue will provide an observer with information that object *A* is closer than object *B*, but will not indicate how much closer. An unsigned depth cue indicates a depth difference and relative motion, but not the direction of the depth difference.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Kinetic occlusion is a signed depth cue. Kinetic occlusion occurs when the surface of a near object moves to conceal or reveal parts of a surface farther away. In Panel 1 of Fig. 1a, as the observer moves from point *i* to point *ii*, rectangle *B* appears to move from B_i to B_{ii}. Rectangle *B* is perceived as being in front of Rectangle *A* since *B* occludes a portion of *A*; the part of rectangle *A* that is hidden changes as the observer moves. In Panel 2 of Fig. 1a, the observer has no cue as to the depth relations of *A* and *B*, as kinetic occlusion did not occur. The kinetic occlusion in Panel 1 could have been produced by the relative motion of *A* and *B* projected to a stationary observer, by movement of the observer relative to fixed objects *A* and *B*, or by a combination of these two.

Kinetic occlusion may also occur with textured surfaces, as in Fig. 1b. For Panels 1 and 2, the pattern of disocclusion and occlusion indicates that the surface indicated by the smaller rectangle is to the rear, and is viewed through an aperture in the large rectangle. Occlusion that proceeds as from Panel 1 to Panel 3, however, specifies that the smaller rectangle is in front.

Figure 1c illustrates the unsigned depth cue of kinetic shear. When the edge between two objects is visible, any relative movement parallel to that edge will cause an abrupt change in alignment of elements at the edge. This is a characteristic of separable surfaces, and could indicate that the surfaces lie at different depths. However, because the observer does not see surface parts being concealed or revealed, there is no indication as to which surface is closer. Hence kinetic shear is an unsigned depth cue, providing information that a difference of depth exists, but no information as to the direction of that difference. Direction of depth relations depends upon other sources of information (Ref. 1). As with kinetic occlusion, shear can be the result of either a stationary observer and moving surfaces, fixed surfaces with an observer moving relative to them, or a combination.

Applications

Displays to simulate motion and depth; situations in which the observer must detect differences in depth between objects.

Constraints

- Neither kinetic occlusion nor kinetic shear is an inevitable outcome of motion; they depend upon spatial layout, point of view, and extent of movement.
- The use of kinetic occlusion and shear as depth cues depends strongly upon where the observer is looking. When the gaze is directed only 4 deg from the active edge in an experimental display, detection of depth direction drops to chance levels (Ref. 3).
- Kinetic shear does not necessarily indicate a depth difference. Two surfaces could be equidistant from an observer and still be in motion to produce the misalignment resulting in shear.

Key References

1. Farber, J.M., & McConkie, A.B. (1979). Optical motions as information for unsigned depth. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 494-500.

*2. Hochberg, J. (1982). How big is a stimulus? In J. Beck (Ed.), *Organization and representation in perception*. Hillsdale, NJ: Erlbaum.

3. Hochberg, J., Green, J., & Virostek, S. (1978). *Texture occlusion requires central viewing: Demonstrations, data, and theoretical implications*. Paper presented at the American Psychological Association Convention, Toronto, Canada.

4. Kaplan, G. (1969). Kinetic disruption of optical texture: The perception of depth at an edge. *Perception & Psychophysics, 6*, 193-198.

Cross References

5.502 Optical flow patterns and motion perspective;

5.901 Monocular distance cues;

5.902 Motion parallax;

Handbook of perception and human performance, Ch. 22, Sect. 1.3

5.904 Functional Limits of Various Depth Cues in Dynamic Visual Environments

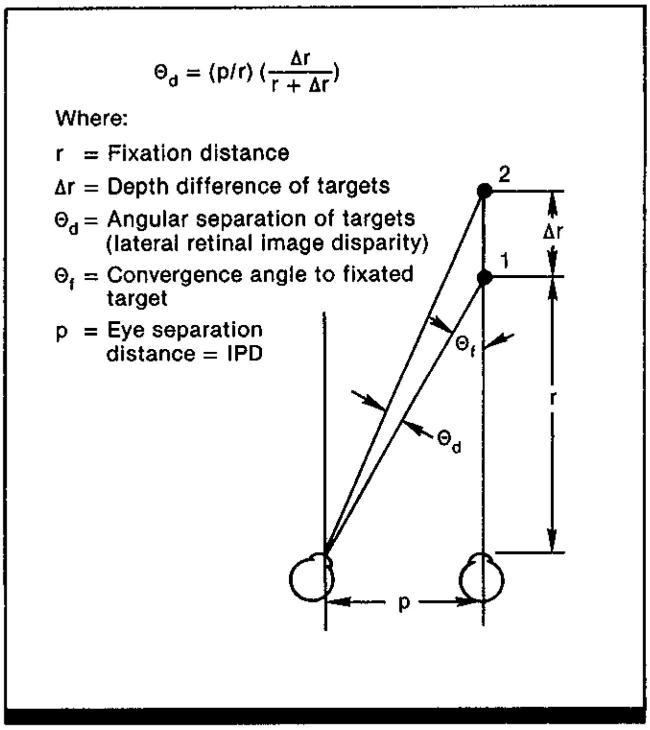


Figure 1. Geometry of stereopsis. (From Ref. 1)

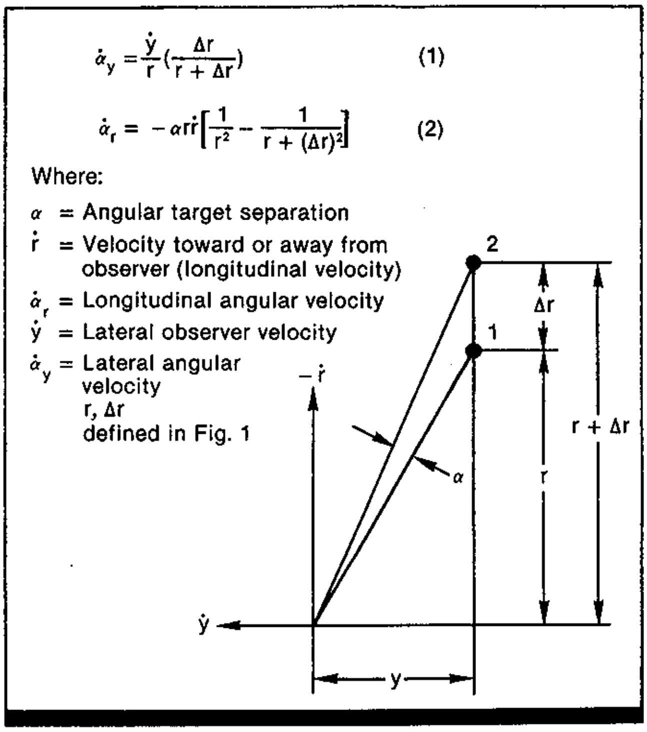


Figure 2. Geometry of motion parallax. (From Ref. 1)

Key Terms

Binocular depth cue; depth perception; distance vision; monocular depth cue; motion parallax; retinal image disparity; retinal size; stereoacuity; three-dimensional displays

General Description

Several **monocular** and **binocular** visual cues normally are available for use in judging distance to objects. However, these cues are functional only over limited and varying distances. To compare the relative effectiveness of cues over a range of distances, the incremental depth threshold (smallest detectable difference in depth between targets) is calculated for a given distance. The visual cue with the lowest incremental depth threshold value at that particular distance is the most effective cue at that range. The model presented here (Ref. 1) estimates functional distance for 3 cues: **lateral retinal image disparity**, motion parallax (CRef. 5.902), and differential retinal size. Its purpose is to estimate the far limits of **stereopsis** as a visual cue for depth perception in dynamic visual settings, considering the presence of monocular cues, such as differential retinal size and motion parallax.

Figure 1 shows the basic geometry for stereopsis. Incremental depth (Δr) is determined for a given fixation distance (target distance) r, binocular disparity θ_d, and interpupillary distance p, by

$$\Delta r = r^2\left(\frac{p}{\theta_d} - 1\right)^{-1}$$

Setting θ_d equal to the stereoscopic threshold for human observers and solving for Δr yields the smallest difference in the depth of two targets at a given fixation distance that can be detected on the basis of retinal disparity cues.

Figure 2 shows the basic geometry for motion parallax. For a given lateral velocity $\dot{y}$ and longitudinal velocity $\dot{r}$, the angular rates $\dot{\alpha}_y$ and $\dot{\alpha}_r$ provide the respective motion parallax cues (see Fig. 2). Incremental depth is given by

$$\Delta r_{\dot{y}} = r^2\left[(\dot{y}/\dot{\alpha}_y) - r\right]^{-1}$$

and

$$\Delta r_{\dot{r}} = \{[(\dot{\alpha}_r/\alpha r\dot{r}) + (1/r^2)^{-1}] - r\}^{1/2}$$

Setting $\dot{\alpha}_y$ and $\dot{\alpha}_r$ equal to angular velocity thresholds for human observers and solving for $\Delta r_{\dot{y}}$ and $\Delta r_{\dot{r}}$, respectively, yields the smallest difference in the depth of two targets at a given fixation distance that can be detected on the basis of motion parallax cues.

As target distance changes, so does the angular size of the image of that target on the retina. Thus, changes in retinal image size can serve as a cue to depth. Incremental depth threshold for differential retinal size (Δr_ϵ) is determined by

$$\Delta r_\epsilon = (\Delta\epsilon/\epsilon)r$$

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

where $\Delta\epsilon/\epsilon$ is the relative size-change threshold (i.e., smallest detectable increase or decrease $\Delta\epsilon$ in image size ϵ as a proportion of ϵ).

Figure 3 represents depth thresholds as a function of distance. The two binocular curves are based on a low stereoscopic threshold (θ_d = 10 sec arc) for foveal vision and a high threshold (θ_d = 70 sec arc) for peripheral vision. The motion parallax functions are based on lateral and closing velocities of 1 knot and motion parallax thresholds (detectable angular velocity) of 100 sec of arc/sec. The differential retinal size function assumes a threshold of $\Delta\epsilon/\epsilon = 0.05$.

Principles of functional cue utility that follow from Figure 3 are: For static peripheral viewing, stereoscopic cues are functional to 9.2 m (30 ft) (point *A*), with retinal size being the dominant cue beyond that range. For static foveal viewing, stereoscopic cues are functional to a distance of 264 m (point *B*). For dynamic peripheral viewing with 1 knot lateral velocity, motion parallax is dominant to a distance of ~49 m (point *C*), beyond which retinal size cues are more functional. For dynamic peripheral viewing with 1 knot longitudinal speed and targets approximately 10 deg below or to the side of the directed motion, motion parallax is the dominant cue to 17.4 m (point *D*). With foveal fixation, stereoscopic cues dominate at distances up to 6.4 m.

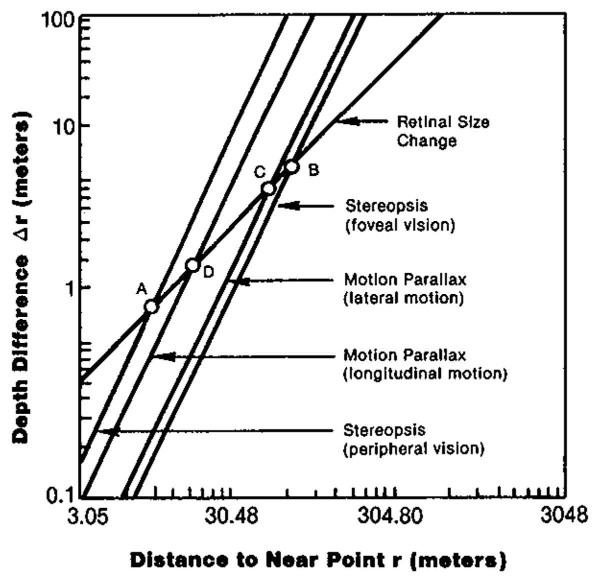


Figure 3. Depth thresholds as a function of distance for various visual cues. (From Ref. 1)

Applications

The design of economical visual target acquisition systems by determining dominant visual cues at varying predicted target distances, so that irrelevant cues can be eliminated from the design. Improved observer training through directed cue attending (guided practice) in specific target acquisition situations. The equations can be used to estimate distance over which depth cues are most effective.

Empirical Validation

The model has not been empirically validated, but all threshold data are derived from empirical data.

Constraints

- Several relevant distance cues are not included in the model. These include monocular cues of interposition, perspective, accommodation, and texture gradient, and others (CRef. 5.901). In principle, the model can be expanded to include these cues.
- Significant individual differences in threshold values indicate that specific cue transition distances are applicable only to the average observer.

Key References

*1. Gold, T. (1972). The limits of stereopsis for depth perception in dynamic visual situations. *International Symposium & Seminar (72E06)*, Vol. II. New York: Society for Information Display.

2. Gold, T., & Perry, R. F. (1972, March). *Visual requirements study for head-up displays* (JANAIR 700407). Washington, DC: Office of Naval Research. (DTIC No. AD741218)

Cross References

5.103 Pilot judgments of distance, height, and glideslope angle from computer-generated landing scenes;

5.502 Optical flow patterns and motion perspective;

5.901 Monocular distance cues;

5.902 Motion parallax;

5.905 Lateral retinal image disparity

5.905 Lateral Retinal Image Disparity

Key Terms

Binocular depth cue; binocular image registration; depth perception; double vision; retinal image disparity; three-dimensional displays

General Description

Lateral retinal image disparity (δ) refers to the difference in the relative position of the visual images of an object on the two retinas due to lateral separation of the eyes. Within limits ($\delta < 10$ deg) retinal image disparity gives rise to the appearance of depth relative to the point of fixation. Targets at larger disparities may be seen as double images (diplopia) with no accompanying sensation of depth (or only one image may be seen and the other suppressed; CRef. 5.930).

Geometric Definition of Lateral Retinal Image Disparity

Retinal image disparity, δ_1, of point P with respect to point F is equal to the difference between the **convergence angle** required to fixate F and the convergence angle required to fixate P (Fig. 1); that is

$$\delta_1 = \alpha_1 - \alpha_2 \qquad (1)$$

where α_1 and α_2 are the convergence angles associated with F and P, respectively. Point P has convergent (or crossed) disparity (δ is negative) relative to point F because the eyes converge in moving from F to P (Fig. 1). For points more distant than F, disparity is divergent (uncrossed) (δ is positive). These relationships hold for all targets that fall on or near the line of sight to the fixation point.

When the disparity of P is measured with respect to fixation, then δ is termed the *absolute disparity* of point P. By definition, a fixated point F has a disparity of $\delta = 0$ deg. The *relative disparity* between point P and any other part in the visual field may also be calculated.

Retinal disparity is also defined as the sum of the visual angles subtended in the left and in the right eyes by the lines of sight to points F and P (Fig. 1). That is,

$$\delta_1 = p + p' \qquad (2)$$

where p is the visual angle between the images of points F and P in the left eye, and p' is the visual angle between images of the two points in the right eye.

Relation Between Lateral Retinal Disparity and Depth

The relation between retinal disparity and depth of a target in real space (distance from target to plane of fixation) varies as a function of viewing distance. Retinal disparity has a one-to-one correspondence with distance of a target from fixation plane *as long as convergence angle is held constant*. However, a given disparity may yield various depth sensations, depending on the viewing distance (convergence angle). Conversely, a given depth may give rise to various disparities when viewing distance (convergence angle) is changed.

Figure 2 shows how depth varies with retinal disparity for different viewing distances. Note that the functions are different for convergent and divergent disparities

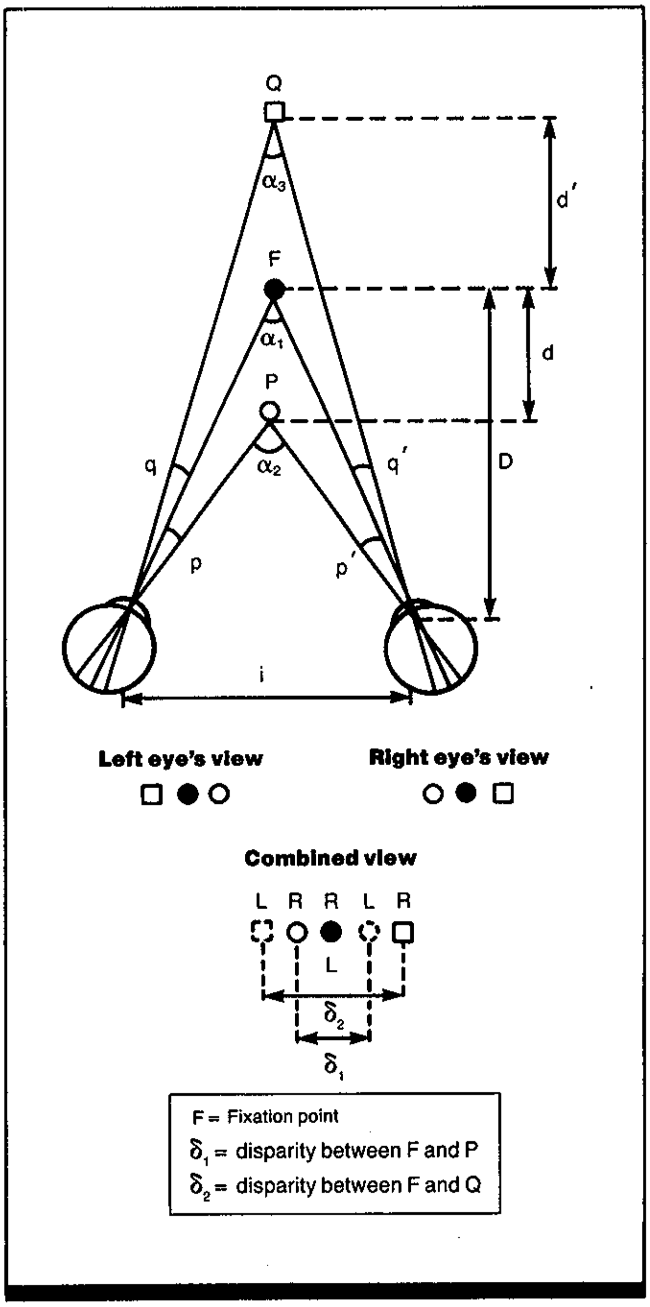


Figure 1. Lateral retinal image disparity.

(representing points nearer and further than fixation, respectively).

Calculation of Angular Disparity and Depth

The relative disparity of two targets a known distance apart (and, conversely, the apparent depth between two targets with a given relative disparity) can be calculated from Eq. 1 and the definition of convergence angle (CRef. 1.808). Table 1 gives formulas for calculating relative disparity and

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depth for both symmetric and asymmetric convergence angles based on the approximation that, for a small angle, measured in radians, $\alpha \approx \tan \alpha$. Errors of approximation are <1% for an angle <10 deg (fixation distance >75 cm), and less for smaller angles.

Applications

The limiting range of stereoscopic vision — that is, the maximum distance at which the relative depth between targets can be discriminated on the basis of disparity information alone — varies with interpupillary distance (IPD) and stereoacuity (minimum detectable disparity difference). This limit has been calculated to be between 200 and 450 m, depending on the values assumed for IPD and stereoacuity. The maximum distance at which disparity is an effective cue is much less, however, because of interaction with other depth cues. A realistic value for normal observers is ~65 m for central vision and ~9 m for peripheral vision.

Constraints

- Disparity/depth relationships shown in Table 1 and Fig. 2 are theoretical limits; empirical functions may depart from these values, depending on individual differences, viewing conditions, etc. (CRef. 5.916).
- For δ greater than ~3 deg, perceived depth is related only qualitatively to δ, and Eq. 4 (Table 1) does not give valid estimates of *empirical* (perceived) depth. It can be used to calculate *normative* (theoretical) depth.

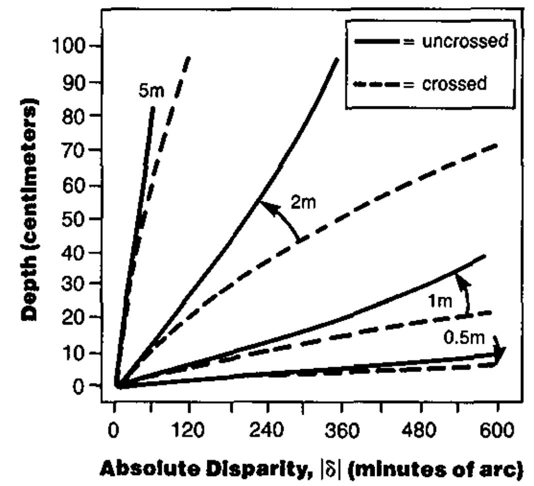

Figure 2. Depth as a function of retinal disparity.

Key References

1. Gulick, W. L., & Lawson, R. B. (1976). *Human stereopsis: A psychophysical approach* (pp. 8-59). New York: Oxford University Press.

2. Hochberg, J. (1971). Perception II. Space and movement. In J. W. Kling & L. A. Riggs (Eds.), *Woodworth & Schlosberg's experimental psychology* (3rd ed., pp. 475-482). New York: Holt, Rinehart & Winston.

Cross References

1.808 Convergence angle;

1.952 Vergence eye movements: eliciting target characteristics;

1.954 Disjunctive eye movements in response to peripheral image disparity;

5.910 The horopter: locus of points with no retinal image disparity;

5.916 Perceived depth as a function of lateral retinal image disparity;

5.930 Limits of stereoscopic depth perception

Table 1. Formulas for calculating disparity and depth.

To calculate	For known	Use formula	Eq.
Disparity	depth	$\delta = id/(D^2 + dD)$	(3)
Depth	disparity	$d = \delta D^2/(i - \delta D)$	(4)

Key:
δ = disparity in radians
i = IPD
D = distance to fixation point
d = distance from target to fixation point (by convention, taken as positive for targets further than fixation and negative for targets closer than fixation)

5.906 Vertical Retinal Image Disparity

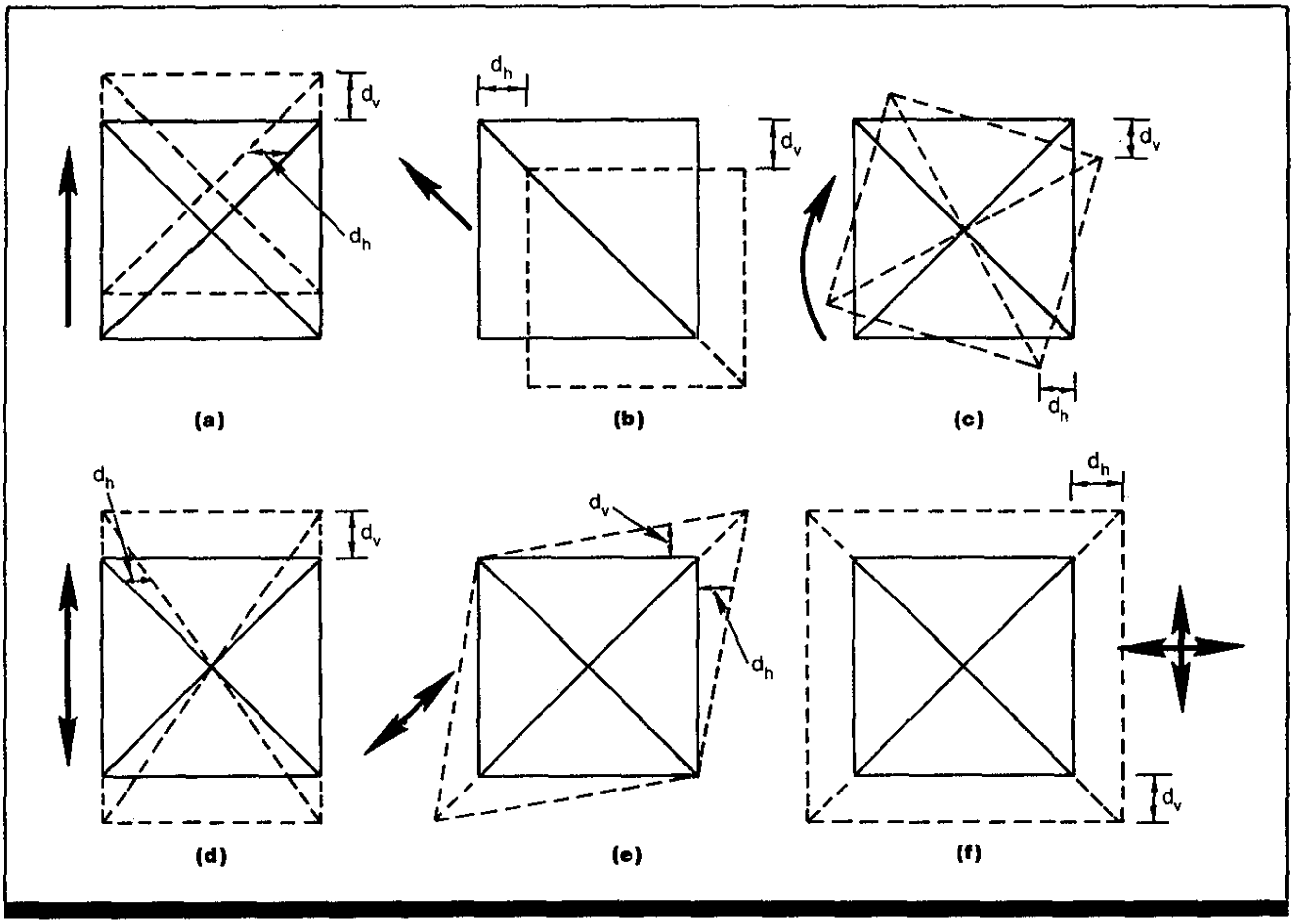

Figure 1. Some types of distortion of one eye's image which cause vertical disparities: (a) vertical meridional misalignment; (b) oblique meridional misalignment; (c) rotational misalignment; (d) vertical meridional magnification; (e) oblique meridional magnification; (f) overall magnification.

Key Terms

Binocular image registration; interocular magnification difference; rotational misaligment; three-dimensional displays; vertical misalignment; vertical retinal image disparity

General Description

Vertical retinal image disparity is the vertical difference in retinal location of the two eyes' images of a single object, contour, or point. In this respect, it is the same as **lateral retinal image disparity** rotated 90 deg. But vertical disparity has different perceptual consequences, since it does not play the significant role in visual function that lateral disparity does for **stereopsis** and vergence eye movements (eye movements to change fixation distance). Vertical disparities may arise in many ways, especially in specialized **binocular** displays. Figure 1 illustrates some ways to distort one eye's view (half-field) relative to the other which produce vertical disparity. One half-field is represented by the solid figure, the other by its dashed counterpart. In each case, d_v indicates vertical disparity while d_h shows the horizontal disparity that may also exist with such distortions. The arrows to the left of each figure indicate the direction of misalignment or magnification. Note that such distortions of the half-fields may exist for single contour elements within an otherwise binocularly correspondent display.

Vertical disparities generally arise under natural viewing conditions only from differential meridional or overall magnification effects of spectacle lenses (CRef. 5.909), or from an overall magnification difference that occurs when viewing an object at near distance (see Fig. 2) that is significantly closer to one eye than the other. The relative paucity of natural vertical disparities is an optical consequence of the eyes' being only horizontally separated in the head.

Because the eyes make only small involuntary compensatory eye movements to align small vertical disparities on

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corresponding points of the two retinas, vertical diplopia (double vision) arising from disparities greater than ~2 diopters (0.573 deg of visual angle) is generally more salient and disturbing than diplopia arising from horizontal disparities, which can be resolved at will by horizontal vergence eye movements. Also, diplopia arising from vertical disparity is more salient and uncomfortable in the presence of a complex background such as a real-life scene than against simpler, more homogeneous backgrounds. Experimentation with such displays has produced the recommendation that vertical disparity not exceed 3.4 min (Ref. 1).

Despite the discomfort that vertical disparity produces, many observers can adapt to 2-6 diopter (~1-3 deg) vertical field disparity produced by prisms and achieve single vision within 2-16 min after putting on the prisms (Ref. 4). Removal of the prisms also produces diplopia and discomfort which requires time to dissipate.

Stereopsis is valid in the presence of vertically disparate half-images (up to 25 min disparity), at least when the vertical disparity is confined to the test object and fixation is not disturbed (CRef. 5.927). However, stereopsis may be degraded in the presence of vertical field disparity, especially when there has been insufficient time to adapt (CRef. 5.928).

Although vertical disparities contain little useful information about depth and are not generally used for its computation, there is one anomalous situation in which they are thought to give rise to apparent depth, the induced effect; there are, however, explanations for the effect that do not rely on vertical disparity (CRef. 5.909).

Applications

Stereoscopic and autostereoscopic displays in which the two eyes' views differ spatially or may undergo differential distortion, and all displays at close distances when one eye is much closer to the display than the other.

Constraints

- Tolerance for vertical disparities varies widely among individuals.
- There are circumstances, generally with oblique contours, in which disparity which has been produced by vertical magnification or displacement in one eye may be interpreted as horizontal disparity by the visual system (see Fig. 1).

Key References

1. Gold, T., & Hyman, A. (1970). *Visual requirements study for head-up displays* (JANAIR Report No. 680712). Washington, DC: Office of Naval Research. (DTIC No. AD707128).

2. Harker, G. S., & Henderson, A. C. (1956). Effect of vertical misalignment of optical images on depth judgments. *Journal of the Optical Society of America, 46*, 841-845.

3. Lawson, E. A. (1972). Vertical disparities. *British Journal of Psychology, 63*, 265-270.

4. Ogle, K. N., & Pragen, A. deH. (1953). Observations on vertical divergences and hyperphorias. *Archives of Ophthalmology, 49*, 313-334.

Cross References

1.955 Fusional eye movements in response to vertical disparity;

5.905 Lateral retinal image disparity;

5.909 Binocular differences in image size and shape (aniseikonia);

5.927 Stereoacuity: effect of vertical disparity;

5.928 Response time and accuracy of depth judgments: effect of vertical disparity

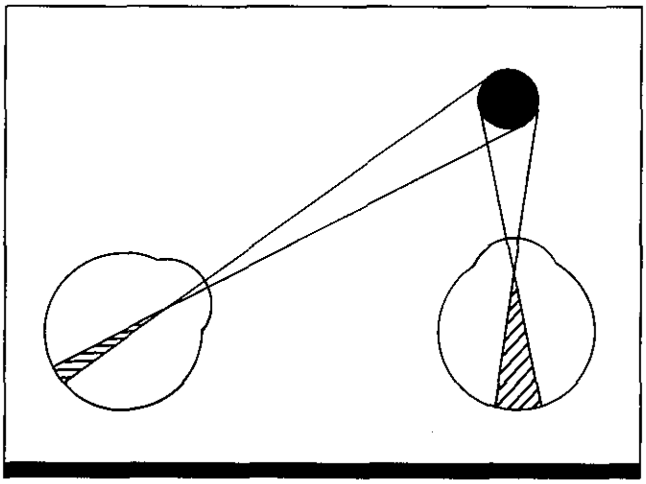

Figure 2. Objects closer to one eye than to the other will be differentially magnified on the two retinas, producing vertical image disparity.

5.907 Retinal Image Disparity Due to Image Magnification in One Eye

Key Terms

Aniseikonia; binocular image registration; double vision; interocular magnification difference; interocular size difference; retinal image disparity; three-dimensional displays

General Description

When one eye's view is magnified relative to the other's view, some combination of vertical, horizontal, or orientation disparity is produced, depending on whether magnification is overall or meridional, and if meridional, on the axis of expansion. Examined here are basic cases of vertical, horizontal, and overall magnification. In Fig. 1, *ABCD* is a square in the unexpanded eye. Point *B* is the focus of expansion. Horizontal magnification relocates *C* and *D* to C_h and D_h respectively, and adds Δh horizontal disparity to the field of view. Similarly, vertical magnification relocates *A* and *D* to A_v and D_v and adds Δv vertical disparity. Overall magnification displaces *A* to A_v, *C* to C_h, and *D* to D_o, and produces both horizontal and vertical disparity. Linear values of these disparities can be calculated from

$$\Delta v = mv$$

$$\Delta h = mh$$

where *v* and *h* are vertical and horizontal distances from the focus of expansion, and *m* is the amount of image magnification expressed as a percent times 100 (i.e., linear magnification).

Meridional magnification also adds orientation disparities to all oblique lines in the field of view, e.g., between *BD* and BD_v for vertical magnification, and *BD* and BD_h for horizontal magnification. Overall magnification does not add orientation disparity.

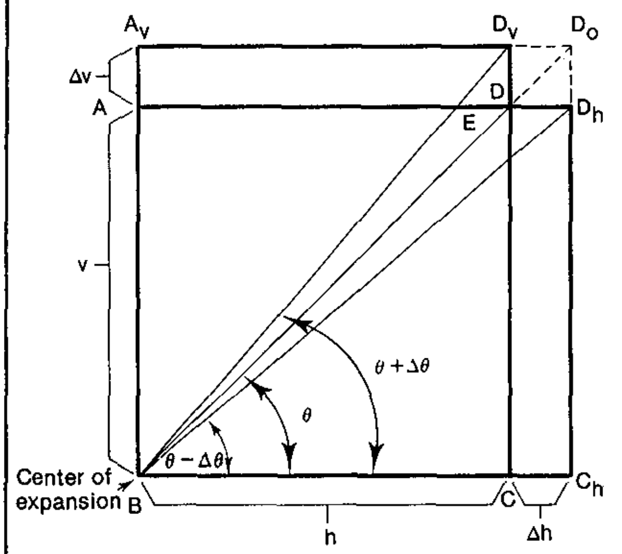

Figure 1. The relationship between overall, vertical, and horizontal magnification of one eye's view and retinal image disparity.

Note that vertical magnification results in spurious horizontal disparities along oblique lines, e.g., along *DE* and all other points connected by lines parallel to *DE* that are on *BD* and BD_v (CRef. 5.909).

Applications

Stereoscopic and autostereoscopic displays where the half-fields differ in size or shape.

Key References

1. Arditi, A. (1986). Binocular vision. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

2. Ogle, K.N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

Cross References

1.956 Eye torsion: effects of angular disparity in binocular display patterns;

5.905 Lateral retinal image disparity;

5.906 Vertical retinal image disparity;

5.908 Retinal image disparity due to image rotation in one eye;

5.909 Binocular differences in image size and shape (aniseikonia);

5.924 Stereoacuity: effect of target orientation

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Notes

5.908 Retinal Image Disparity Due to Image Rotation in One Eye

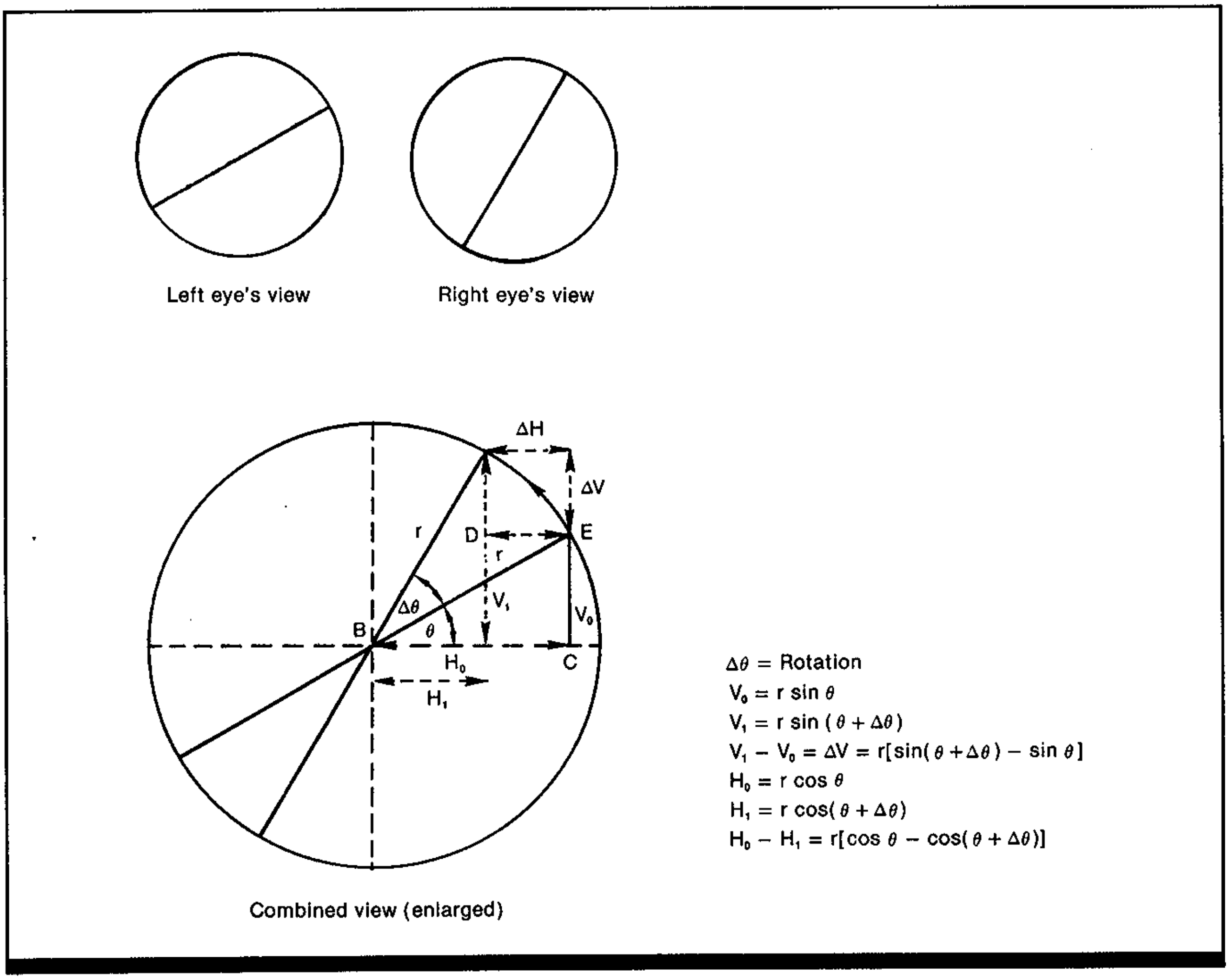

Figure 1. The relationship between orientation disparity and vertical and horizontal disparity.

Key Terms

Binocular image registration; cyclofusion; double vision; interocular orientation difference; retinal image disparity; rotational misalignment; three-dimensional displays

General Description

Rotation of one eye's image results in retinal orientation differences for all points in the **binocular** field of view except for a point at the center of rotation. The apparent depth resulting from this orientation disparity depends on two factors: (1) the difference in orientation between the images to the two eyes ($\Delta\theta$) and (2) base orientation (θ). Orientation disparity ($\Delta\theta$) may be computed in terms of the resultant horizontal and vertical linear disparities (i.e., ΔH, ΔV) using the following formulas:

$$\Delta H = r[\cos\theta - \cos(\theta + \Delta\theta)]$$

$$\Delta V = r[\sin(\theta + \Delta\theta) - \sin\theta],$$

where r is the distance from the center of rotation to the point in the unrotated half-field, θ is the orientation of the unrotated image in deg, and $\Delta\theta$ is the amount of rotation.

Applications

Stereoscopic and autostereoscopic displays where the half-fields differ in rotational alignment.

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Constraints

- Formulas give only absolute value of disparity. **Divergent disparities** are commonly assigned positive values and **convergent disparities**, negative values.
- Note that disparities produced by rotation are of opposite sign above and below the center of rotation.

Key References

1. Arditi, A. (1986). Binocular vision. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception*. New York: Wiley.

2. Ogle, K. N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

Cross References

1.956 Eye torsion: effects of angular disparity in binocular display patterns;

1.957 Factors affecting countertorsion of the eyes;

5.907 Retinal image disparity due to image magnification in one eye;

5.909 Binocular differences in image size and shape (aniseikonia);

5.913 Tolerance for image rotation;

5.924 Stereoacuity: effect of target orientation;

5.927 Stereoacuity: effect of vertical disparity

5.909 Binocular Differences in Image Size and Shape (Aniseikonia)

Key Terms

Aniseikonia; binocular image registration; geometric effect; induced effect; interocular magnification difference; interocular shape difference; interocular size difference; retinal image disparity; three-dimensional displays

General Description

Aniseikonia is a condition in which the image of an object in one eye differs in size and/or shape from the image of the same object in the other eye. Persons with normal vision generally have a small degree of aniseikonia due to individual refractive or sensory anomalies of the eye (Fig. 1). The most common cause of significant aniseikonia, however, is the differential image magnification produced by wearing corrective lenses that have a different refractive power for each eye when lenses are not close enough to the eye. Contact lenses produce much less aniseikonia than spectacles because they are worn closer to the **optic nodes** of the eyes and result in less magnification. **Binocular** visual displays may also introduce aniseikonic distortion.

Even relatively small image size differences in the two eyes can lead to difficulties in binocular fusion, to distortions of stereoscopic spatial localization, and to eye discomfort and other physical symptoms (see Table 1).

Clinical studies (Ref. 2) have found the following relation between the magnitude of image size differences and the physical and perceptual effects in individuals with aniseikonia:

Size difference	Effects
1-2%	Can cause eye discomfort, fatigue, other symptoms listed in Table 1
>3%	Associated with definite impairment of binocular vision
>5%	Binocular vision is imperfect or absent

When images are different sizes in the two eyes, one side of the visual field may appear farther away than the other side, objects on one side may appear larger, and object shape may be distorted. Such distortions of spatial vision are generally worse for near vision than for far vision. The distortions usually disappear when the lenses producing the aniseikonia are worn constantly. In experimental studies, observers wearing lenses which magnified the image of one eye relative to the other by as much as 5% adapted to the spatial distortions within 3-4 days (Ref. 6). Unlike the spatial distortions, however, clinical symptoms, such as eye discomfort and headaches, do not always abate with prolonged wearing of lenses producing aniseikonia, and may be intense enough, in some observers, to prevent continued use of the lenses.

Differential image magnification may be meridional (along one axis only), as produced by a cylindrical lens, or overall, as produced by a spherical lens. All overall and meridional magnification differences, regardless of axis, can be equivalently described by a sum of horizontal and vertical magnification difference components. Horizontal magnification differences produce an apparent tilting of the visual field known as the *geometric effect* (Fig. 2). Vertical magnification differences produce what is known as the *induced effect*, an apparent tilting that is equal, but opposite to, that produced by horizontal magnification differences.

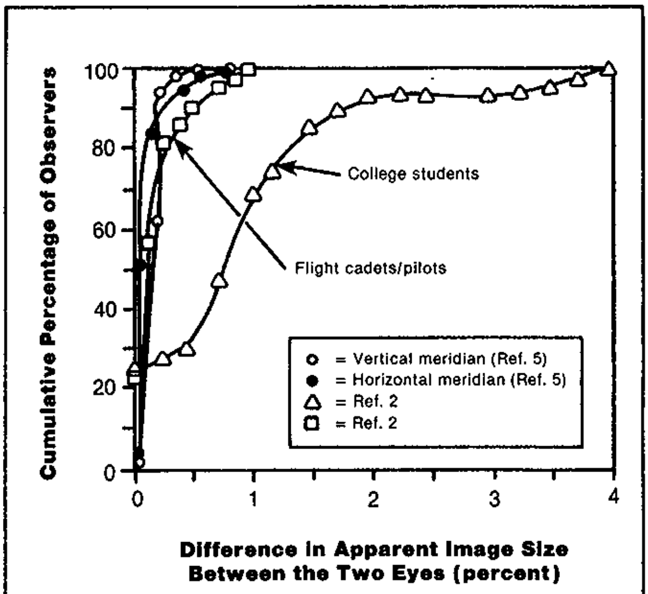

Figure 1. Normally occurring image size differences for two population groups. In Ref. 6, 280 cadets and instructor pilots were tested for aniseikonia using an eikonometer; all subjects were tested without corrective lenses. In Ref. 2, 107 flight cadets and 341 college students were examined; no procedural details were given (presumably, observers did not wear corrective lenses during measurements). (Data from Refs. 2 and 5)

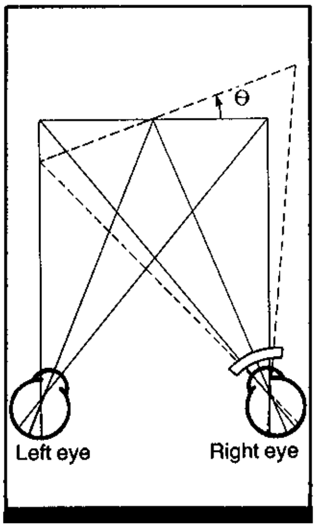

Figure 2. Apparent rotation of frontoparallel plane when horizontally magnifying lens is placed over the right eye (geometric effect). (From *Handbook of perception and human performance*)

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The tilt generally reaches a maximum when magnification difference in the eyes is 6-8%. Figure 3 shows the magnitude of both effects in terms of the apparent rotation (angle θ in Fig. 2) of the frontoparallel plane as a function of lens magnification difference.

Since small equal vertical and horizontal magnification differences have equal but opposite effects, their sum (overall) magnification has a cancelling, and thus zero, effect in terms of apparent tilt. Hence, image size differences arising from spherical lens power differences in the eyes ordinarily do not produce distortions of apparent tilt in the visual environment.

The induced effect is widely believed to have different causes than the geometric effect, since vertical magnification differences produce **vertical retinal image disparities**, which ordinarily do not give rise to the perception of depth (see Ref. 1). Reference 1 explains the induced effect in terms of spurious **horizontal disparities** that can be produced by vertical magnification of oblique contours (CRef. 5.907).

Applications

Stereoscopic and autostereoscopic presentations where left and right eyes' views may differ in size or shape, and viewing situations in which the observer wears spectacle lenses, especially those differing in cylindrical refractive power.

Constraints

- Differences in ocular image size occur normally with **asymmetric convergence** because the right and left eyes are at different distances from a target that is off the midline; the effects discussed here apply to anomalous image size differences that are not encountered in normal visual experience.
- If overall or vertical magnification differences are large, stereoacuity may be reduced (CRef. 5.927).
- The induced and geometric effects have been studied for meridional magnification differences only up to ~20%.

Key References

1. Arditi, A., Kaufman, L., & Movshon, J. A. (1981). A simple explanation of the induced size effect. *Vision Research, 21*, 755-764.

2. Burian, H. M. (1943). Clinical significance of aniseikonia. *Archives of Ophthalmology, 29*, 116-133.

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5. Ogle, K.N. (1939). Induced size effect. II. An experimental study of the phenomenon using restricted fusion stimuli. *Archives of Ophthalmology, 21*, 604-625.

6. Ogle, K.N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

Cross References

5.907 Retinal image disparity due to image magnification in one eye;

5.927 Stereoacuity: effect of vertical disparity

Table 1. Some possible clinical symptoms caused by image size differences in the two eyes. (After Ref. 2)

Symptoms
Eye discomfort (burning, itching, etc.)
Eye fatigue, especially in close work and while watching moving objects
Headaches
Photophobia (abnormal visual intolerance of light; i.e., light is uncomfortable)
General nervous fatigue or nervous tension, sleepiness, gastric symptoms
Motion sickness

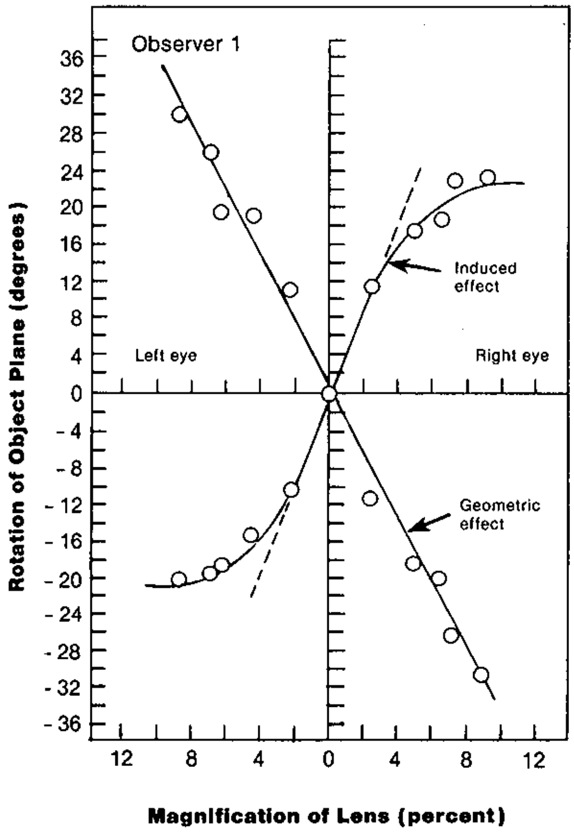

Figure 3. Magnitude of apparent rotation as a function of meridional (afocal) lens magnification and axis of lens (induced effect = vertical magnification, geometric effect = horizontal magnification). With lens over one eye, observer viewed random pattern of paint splatters on glass "object plane" at distance of 40 cm. As measure of apparent tilt, pattern rotated about vertical axis until it appeared frontoparallel. Curves are fit by eye. Positive rotation represents clockwise divergence from frontoparallel, as viewed from the top. (From Ref. 5)

5.910 The Horopter: Locus of Points with No Retinal Image Disparity

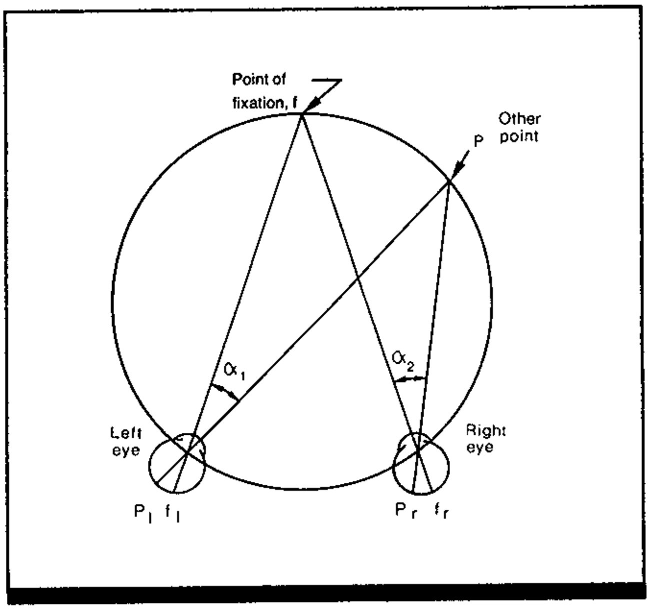

Figure 1. The Vieth-Müller circle, which is an important theoretical horopter. The circle is the locus of points for which $\alpha_1 = \alpha_2$. It is also shown in Figs. 2 and 3 for comparison. (From *Handbook of perception and human performance*)

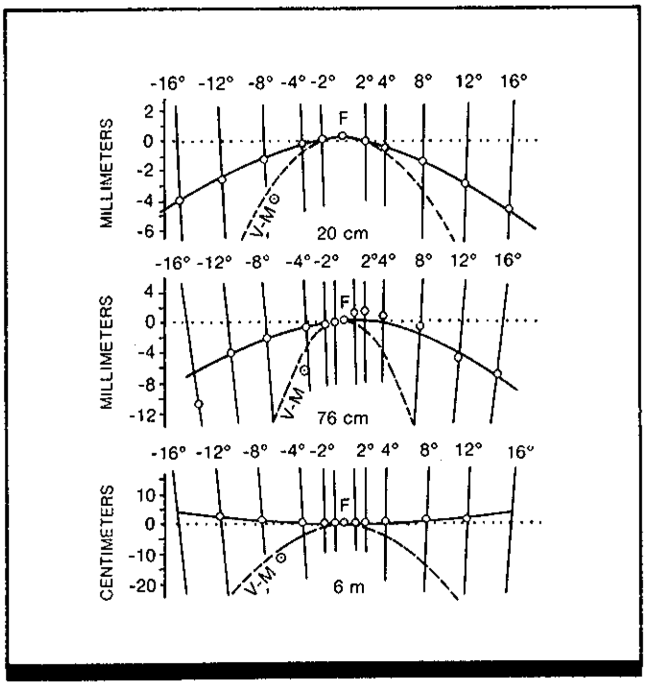

Figure 2. The apparent frontoparallel longitudinal horopter for one observer at three observation distances. The vertical axis has been magnified to accentuate deviations from true frontoparallel. *F* is the point of fixation; *V-M* is the Vieth-Müller circle. (After Ref. 2)

Key Terms

Longitudinal horopter; single vision; three-dimensional displays; vertical horopter; Vieth-Müller circle

General Description

The horopter is a surface in space that contains all points having zero **lateral retinal image disparity**; as such, it locates all spatially correspondent points on the two **retinas** with regard to **binocular** viewing. Only the horizontal section of this surface, the *longitudinal horopter*, has been studied in detail.

Figure 1 shows a historically significant theoretical longitudinal horopter, called the *Vieth-Müller circle*. This circle is the locus of all points such that visual angles α_1 and α_2 are equal. It is not an empirically accurate horopter because the assumptions of the Vieth-Müller model about the eye's true shape, optics, and mechanics are not valid.

Several techniques have been used for empirically determining the longitudinal horopter and none yield results corresponding with the Vieth-Müller circle. If the locus of apparently frontoparallel points is the criterion for retinal correspondence, then the shape of the horopter is highly dependent on viewing distance; the shape approaches the Vieth-Müller circle at short distances, becomes flatter with increasing distance, and is slightly convex at long distances (Fig. 2). These data were collected from an observer who

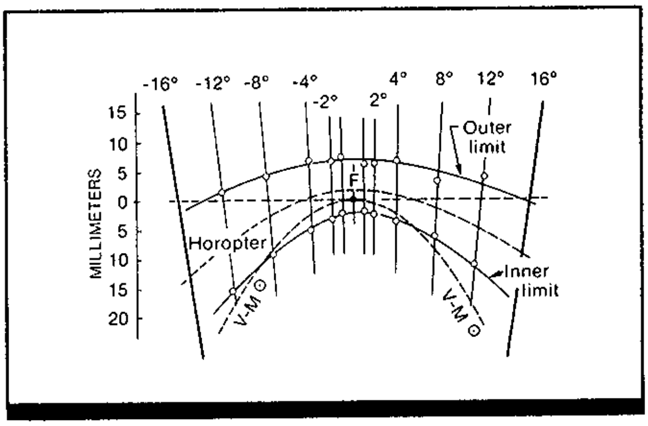

Figure 3. The single vision longitudinal horopter for one observer at one distance, as the mean of inner and outer limits of single vision. Vertical axis is magnified by a factor of 2. *F* is the point of fixation; *V-M* is the Vieth-Müller circle. (After Ref. 2)

adjusted a series of rods at a range of positions in the periphery until each appeared parallel to a fixated vertical rod in the center. While the changing shape of the apparent frontoparallel plane with distance is interesting, there is little reason to believe that retinally correspondent points would arise from a plane, given the curvature of the retinas.

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Figure 3 shows an empirical longitudinal horopter based on the criterion that images arising from correspondent points appear single. Here the observer also fixated a central rod, but in this instance adjusted the peripheral rods both backward and forward until they appeared double (diplopic). The horopter surface is the mean of the near and far limits of single vision (CRef. 5.911).

Figure 4 shows an empirical longitudinal horopter derived from measurements now believed to be the most valid horopter criterion. This *nonius horopter* is derived as follows: the observer fixates a central rod and attends to a peripheral vertical rod that has one part (e.g., the top) visible to one eye and other part (e.g. the bottom) visible to the other eye. Sliding the peripheral rod to and fro in depth changes the apparent horizontal vernier alignment of its top and bottom portions because the relative horizontal position of the rod's images on the two retinas changes due to retinal disparity (CRef. 5.905). The observer sees no depth in the rod, but adjusts it until the horizontal position on the two retinas appears in alignment. This is repeated for peripheral rods at a range of positions. In units of retinal disparity (not shown), there is a flattening of the nonius horopter with increased viewing distance; that is, distant peripheral points require less (crossed) disparity to be functionally correspondent than do near peripheral points.

Another section of the horopter surface that has been studied is the *vertical horopter*, which is a set of retinally correspondent points of zero disparity along the vertical meridian. The vertical horopter (Fig. 5) is highly dependent on viewing distance. At short distances, it is vertical; at long distances it is horizontal; and at intermediate distances, it is tilted back, that is, points in the upper part of the field need to be more distant than the fixation point to be retinally correspondent, whereas points in the lower part require crossed disparity. These data were collected using horizontally separated flashing lights with one visible to each eye; the observer fixated a point straight ahead. When the lights were misaligned in the two eyes, there was apparent motion (CRef. 5.401) between the lights that could be nulled by adjusting the lights' relative horizontal position.

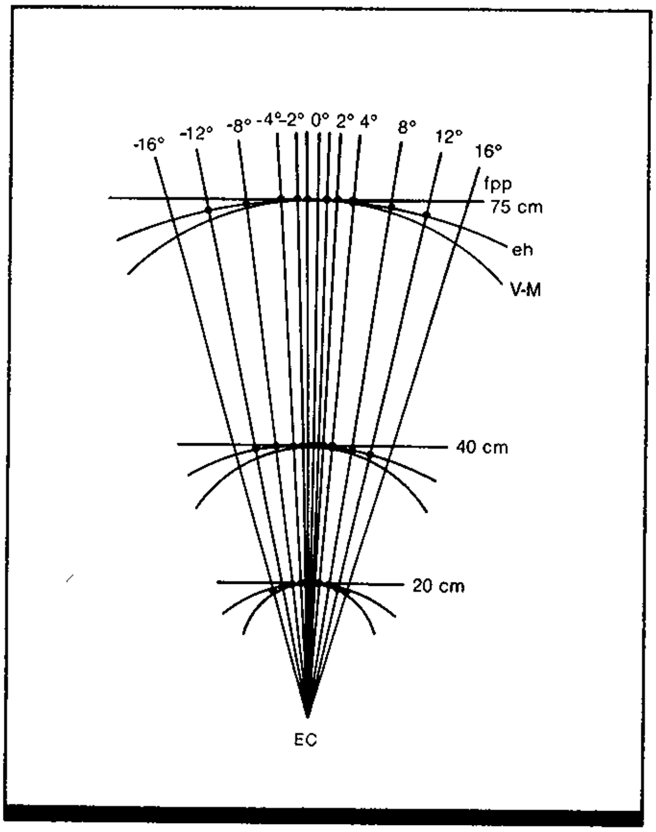


Figure 4. The nonius horopter for one observer at three observation distances. *fpp* is the true frontoparallel plane; *eh* is the empirically determined horopter; *V-M* is the Vieth-Müller circle; *EC* is the ego center halfway between the two eyes. (From Ref. 3)

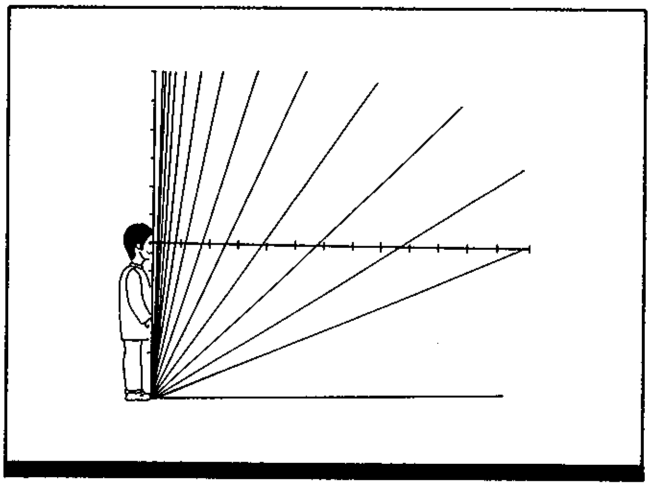


Figure 5. The vertical horopter is a straight line passing through the point of fixation and a point on the ground directly below the eyes. A line which falls on the horopter will cast images on the retinas which are oriented obliquely at opposite orientations about the vertical and which have increasingly crossed disparity in the lower visual field. (From Ref. 1)

Applications

Wide angle stereoscopic and autostereoscopic displays.

Constraints

- Horopters define the shape of the zero disparity surface only in the absence of other cues to depth.
- There is no clear relationship between the nonius horopter and apparent depth.
- All of the data shown here were collected on highly practiced observers.

Key References

1. Nakayama, K. (1970). Geometrical and physiological aspects of depth perception. In S. Benton (Ed.), *Three-dimensional imaging. Proceedings of the Society of Photo-Optical Instrument Engineers, 120*, 2-9.

2. Ogle, K. N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

3. Shipley, T., & Rawlings, S. C. (1970). The nonius horopter—I. History and theory. *Vision Research, 10*, 1255-1262.

Cross References

1.809 Phoria;

5.401 Types of visual apparent motion;

5.905 Lateral retinal image disparity;

5.911 Limits of single vision;

Handbook of perception and human performance. Ch. 23, Sects. 3.1, 3.2

5.911 Limits of Single Vision

Key Terms

Binocular fusion; double vision; Panum's fusional area; retinal location; single vision; three-dimensional displays; visual field location

General Description

Singleness of vision refers to the tendency for an object located nearer or farther than the plane of fixation to appear as single despite spatial differences between the eyes' images of it (**retinal lateral image disparity**). The amount of retinal disparity that can exist while a person still perceives an object as single defines the area of single vision, or *Panum's fusional area*. The response bias of the observer to report what is known to be a single object as being perceived as single makes it difficult to quantify singleness of vision. Many different methods of measuring single vision limits have been used, yielding estimates between 0 and several tens of min arc of visual angle disparity at the fovea. Double vision, or diplopia, is discomforting and may cause headache and blurred vision, but it does not generally occur in normal observers except when viewing large vertical disparities or orientational disparities with large vertical disparity components (CRef. 5.906) which occur only with stereoscopic or autostereoscopic presentation. Diplopia thresholds are equivalent to measurement of one dimension of the fusional area.

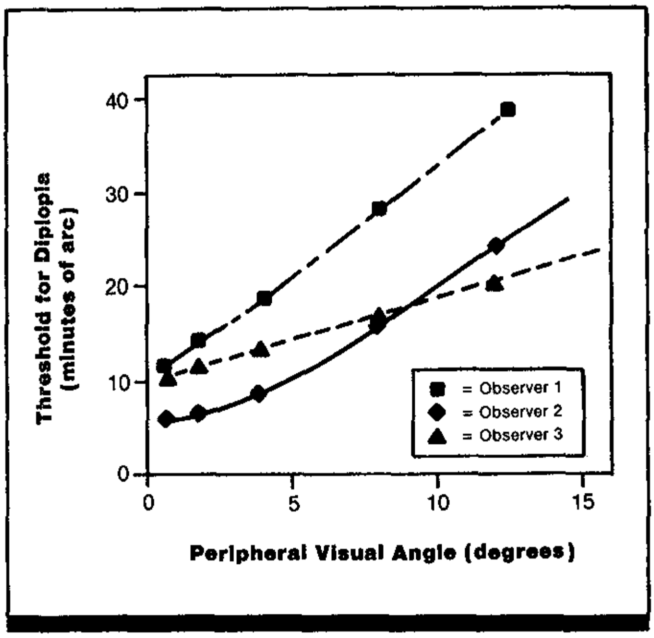


Figure 1. The horizontal extent of Panum's area (diplopia threshold) as a function of target distance from fixation for 3 observers. (From Ref. 4)

Applications

Stereoscopic or autostereoscopic display designs.

Methods

Test Conditions

• Observer viewed 24 peripherally located vertical rods against white background on horopter apparatus (CRef. 5.910) while fixating central rod; rods spaced 1, 2, 4, 8, 12, and 16 deg on either side of fixation; each rod 0.32 mm diameter; 40-cm viewing distance
• Track-mounted rods moved inward and outward by observer using randomly staggered handles out of view

Experimental Procedure

• Independent variable: mean retinal eccentricity (distance between target and point of fixation) of rod in two eyes
• Dependent variable: half the distance between near and far limits of single vision, expressed in angular measure
• Observer's task: set position of rods to near and far limits of single appearance
• 3 practiced observers

Experimental Results

• Diplopia threshold (Panum's area) increases monotonically with target distance from fixation (eccentricity); the probability of double vision increases with eccentricity.
• Means of data indicate that, for eccentricities of 5-6 deg and above, threshold is ~3% of the angle of eccentricity, on average.

Variability

Large variability between subjects; within-subject variability not known.

Repeatability/Comparison with Other Studies

Findings are qualitatively similar to those of most studies. Specific estimates of diplopia thresholds are widely variable, within and between both subjects and studies.

Constraints

• The underlying physiological basis of single vision is not known. There is a neural fusion of similar spatial contours, and binocular suppression is involved (CRef. 1.805).
• Measurements of diplopia or of Panum's area may not necessarily generalize to natural viewing conditions. Despite the ubiquity of horizontal retinal disparities above diplopia threshold, for example, observers rarely report seeing double; one image is suppressed.
• Reference 1 suggests that diplopia thresholds depend on the steepness of local disparity gradients rather than on absolute retinal disparity.
• Practice effects are known to strongly influence diplopia thresholds.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Burt, P., & Julesz, B. (1980). Modifications of the classical notion of Panum's fusional area. *Perception, 9*, 671-682.

2. Kaufman, L., & Arditi, A. (1976). The fusion illusion. *Vision Research, 16*, 535-543.

3. Mitchell, D. (1966). A review of the concept of "Panum's fusional areas." *Americal Journal of Optometry, 43*, 387-401.

*4. Ogle, K.N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

Cross References

1.805 Spatial extent of binocular suppression;

5.905 Lateral retinal image disparity;

5.906 Vertical retinal image disparity;

5.910 The horopter: locus of points with no retinal image disparity;

5.930 Limits of stereoscopic depth perception;

Handbook of perception and human performance, Ch. 23, Sect. 5.2

5.912 Tolerance for Vertical Disparity

Key Terms

Binocular image registration; double vision; Panum's fusional area; retinal location; single vision; three-dimensional displays; vertical misalignment; vertical retinal image disparity; visual field location

General Description

The largest magnitude of **vertical retinal image disparity** that can be tolerated without producing double vision (i.e., the diplopia threshold) increases with target distance from fixation (retinal eccentricity). There is wide variation in diplopia thresholds and rate of increase for different observers, methods, and threshold criteria.

Applications

Stereoscopic and autostereoscopic displays, especially those with a vertical magnification component in one eye.

Methods

Study 1 (Ref. 1)

Test Conditions

- Fixation pattern and horizontal test lines of variable disparity presented on CRT **stereoscope** apparatus; 105-cm viewing distance; target 1.8 log units above visibility threshold; 15-deg background mask at 3 cd/m²
- Fixation pattern was three concentric squares with sides of 1, 1.2, and 1.4 deg, a 2-min arc of visual angle central horizontal line and 10-deg vertical line (broken by the fixation squares in **foveal** condition)
- Test line was 30 × 1 min arc in foveal condition, 110 × 1 min arc in eccentric viewing condition; 160-msec flash presentation of target lines
- Observer's head fixed by a biteboard

Experimental Procedure

- Method of constant stimuli
- Three-alternative forced-choice classification
- Blocked by eccentricity condition
- Independent variables: vertical disparity, target distance from fixation
- Dependent variable: mean disparity at which observer no longer reported unequivocal singleness of target line
- Observer's task: report whether target line appeared "unequivocally single," "unequivocally double," or "neither unequivocally single nor unequivocally double"
- 2 practiced observers, with excellent **visual acuity** and **stereopsis**

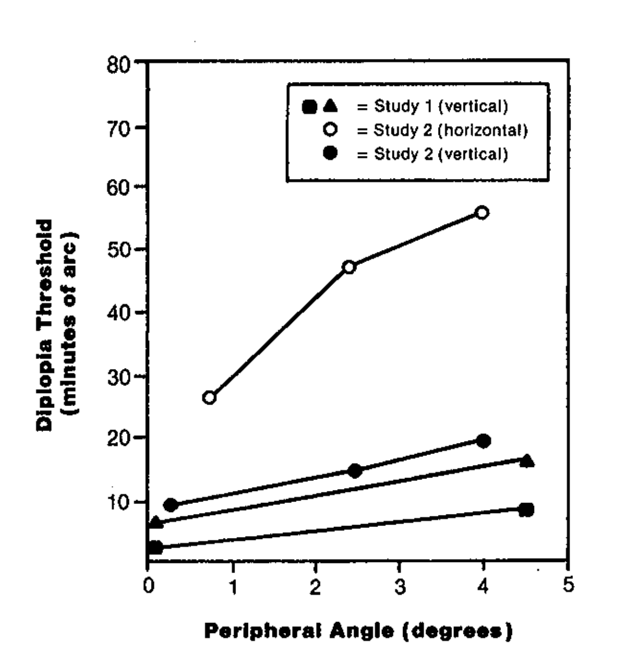


Figure 1. Vertical diplopia thresholds as a function of target distance from fixation. Horizontal diplopia thresholds from Study 2 are shown for comparison. (Study 1: data from Ref. 1; Study 2: data from Ref. 2)

Study 2 (Ref. 3, reported in Ref. 2)

- Vertical or horizontal parallel line stimuli presented at constant separation in one eye's view in stereoscope; separation varied in other eye's view; other details of test conditions and procedure not reported in Ref. 2.

Experimental Results

- Thresholds for double vision (diplopia) increase monotonically with increased angular distance from fixation (retinal eccentricity).
- Diplopia thresholds for horizontal disparity from Ref. 2 are included for comparison: vertical diplopia thresholds are lower and increase at a lower rate than horizontal diplopia thresholds.
- Data for 2 observers from Ref. 1 show lower thresholds and lower rate of increase with retinal eccentricity, probably due to different response criteria (CRef. 5.911).
- Vertical diplopia thresholds are similar when target image is displaced vertically from fixation as well (not shown).

Variability

Given for data of Ref. 1 only, standard deviation is between 0.333 and 0.5 of the threshold value. High variability among observers.

Constraints

- These diplopia thresholds are half the extent of Panum's fusional area, since the area demarcates the region of single vision over both signs of disparity (i.e., left eye superior and right eye superior), but diplopia thresholds and size of Panum's area are often confused in the literature.
- Diplopia thresholds are rarely, if ever, measured outside 5 deg eccentricity.
- When the task is to discriminate vertical disparity from zero disparity, even lower vertical diplopia thresholds are obtained than are shown here; presumably they are lower in the periphery as well.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Duwaer, A.L., & Van den Brink, G. (1981). What is the diplopia threshold? *Perception & Psychophysics, 29*, 295-309.

*2. Mitchell, D.E. (1966). A review of the concept of "Panum's fusional areas". *American Journal of Optometry, 43*, 387-401.

3. Volkmann, A.W. (1849). Die stereoskopischen Erscheinurgen in ihrer Beziehung zu der identischen Netzhautpunkter. *Albrecht von Graefe's Archiv fur Ophthalmolgie, 45*, 1-100.

Cross References

1.955 Fusional eye movements in response to vertical disparity;

5.906 Vertical retinal image disparity;

5.911 Limits of single vision;

5.927 Stereoacuity: effect of vertical disparity;

5.928 Response time and accuracy of depth judgments: effect of vertical disparity

5.913 Tolerance for Image Rotation

Key Terms

Binocular image registration; cyclofusion; double vision; interocular orientation difference; rotational misalignment; single vision; three-dimensional displays

General Description

The maximum rotational misalignment between the two half-images of a **stereoscopic** display that can be tolerated without producing double images (diplopia) is inversely related to target size. Tolerance for rotational misalignment has been shown to be greater for displays containing 50 parallel lines than for single-line displays.

Applications

Stereoscopic and autostereoscopic displays.

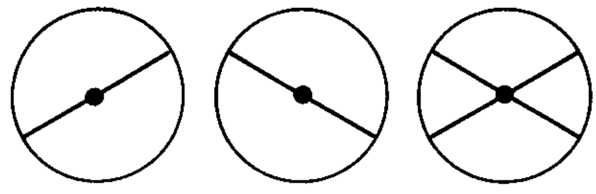


Figure 1. Rotational misalignment (extorsion). (From Ref. 4)

Methods

Test Conditions

- Target of single horizontal line or 50 parallel lines; targets presented at optical infinity on face of circular light box 10.5 deg of visual angle in diameter with luminance of 513.94 cd/m^2 (150 fL)
- Target lines rotated about center in steps of 7.5 min arc of visual angle in opposite direction in each eye (see Fig. 1); separate measurements taken for extorsion (from observer's viewpoint, target rotated counterclockwise from horizontal in left eye, clockwise in right) and intorsion (clockwise rotation in left eye, counterclockwise in right)
- Target length: 2, 5, or 9 deg
- One eye viewed target directly, other eye viewed through **Dove prism**; fixation on center of target lines; eye movements monitored by binocular contact lens recording technique; darkened room

Experimental Procedure

- Independent variables: number of target lines, target size, amount of rotational misalignment
- Dependent variable: magnitude of target intorsion or extorsion that could be tolerated without destroying percept of horizontal lines (i.e., without producing double vision)
- Observer's task: indicate whether line or lines in display appeared horizontal (fused) or tilted (double)
- Between 20 and 30 trials per data point
- 2 observers

Experimental Results

- Maximum rotational misalignment of right-eye and left-eye images that can be tolerated without producing double vision decreases as target size increases; that is, small targets can be rotated more than large targets before double vision occurs.
- Greater rotational misalignment can be tolerated for a 50-line display pattern than for a single-line display.
- For small, complex displays, cyclofusional range is as high as ~16 deg; for small, simple displays, cyclofusional range is only 4-6 deg.
- No compensatory cyclofusional eye movements were observed; perceptual fusion of the rotationally disparate retinal images was due to central visual processes.
- These results suggest that whether a binocular target is seen as single or double depends on the amount of **horizontal** or **vertical retinal image disparity** introduced by rotational misalignment (CRef. 5.908), rather than on the angular rotational displacement. (For a given angular rotation, the magnitude of vertical or horizontal image disparity introduced increases with target length.)

Variability

Standard errors are too small to be accurately represented in the figure.

Repeatability/Comparison with Other Studies

For comparison, Fig. 2 plots results of a very limited study (Ref. 4) in which the rotational misalignment of stereoscopic half-images was reduced until observers reported good registration. Targets were aerial photographs of natural scenes viewed in a stereoscopic device with a 20-deg field of view. Figure 2 plots, for 16 observers, the mean rotational misalignment at which the half-fields appeared to be in good registration; error bars show ± 1 standard deviation.

Constraints

- Even when rotational misalignment of half-fields is low enough to permit perception of a single "fused" target, the target may not appear identical to the target in a display with no misalignment. Using displays similar to the single-line targets employed here, Ref. 2 demonstrated that observers can discriminate rotationally misaligned targets from targets that are not misaligned when rotational misalignment is considerably smaller (~1.5 deg) than the upper limit for a fused appearance found in this study.
- On a reading task, observers with normal eye balance can tolerate rotational misalignment near the fusion limit for ~2 hr with no more visual fatigue than would characterize other exacting visual tasks; however, some blurring, eye tearing, **accommodation** disturbances, and queasiness are experienced. When a slightly smaller rotational misalignment is

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

combined with vertical misalignment of half-images, observers show a possible slight decline in the upper fusion limit over an 8-hr session, but not a troublesome degree of fatigue (Ref. 1).

• With a comfort-in-use criterion of tolerance, rather than a diplopia criterion, a smaller orientation difference is tolerated with a complex background or scene than with a simple target (Ref. 5).

Key References

1. Crook, M.N., Bishop, H.P., & Raben, M.W. (1962). *The misalignment of stereoscopic materials as a factor in visual fatigue: Rotary misalignment* (US Navy Contract 494-17). Washington, DC: Office of Naval Research.

2. Gold, T., & Hyman, A. (1970). *Visual requirements study for head-up displays* (Janair Report No. 680712). Washington, DC: Office of Naval Research. (DTIC No. AD707128).

3. Kaufman, L., & Arditi, A. (1976). The fusion illusion. *Vision Research, 16,* 535-543.

*4. Kertesz, A.E. (1973). Disparity detection within Panum's fusional area. *Vision Research, 13,* 1537-1543.

5. Kraft, C.L. (1975). *Rotational tolerance in the alignment of stereo-photographic transparencies* (Document No. D180-19057-1). Seattle, WA: Boeing Co.

Cross References

1.956 Eye torsion: effects of angular disparity in binocular display patterns;

1.957 Factors affecting countertorsion of the eyes;

5.908 Retinal disparity due to image rotation in one eye

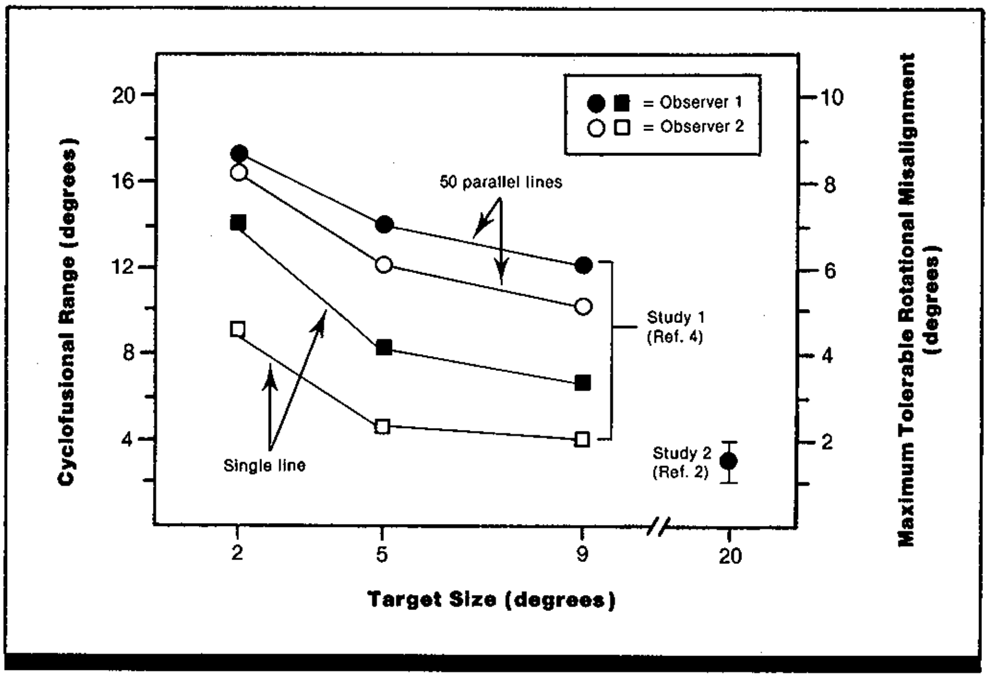


Figure 2. Tolerance for rotational misalignment as a function of stimulus size and type of display. Cyclofusional range is the sum of the maximum tolerable misalignment (in degrees) for intorsional and extorsional misalignments. Study 1 is the experiment described here. Study 2 is a very limited experiment using somewhat larger targets whose results are shown for comparison. (From Ref. 4)

5.914 Filter Separation and Free Stereoscopic Display Methods

Method	Principles	Special Considerations
Anaglyph (Fig. 1)	Printed half-images superimposed in complementary hues and viewed through filters of complementary hue over the two eyes. Each eye sees the print hue that is complementary to its filter as black, while the half-field printed in the same hue as the filter is not seen.	Printing inks and filters vary considerably in their spectra. Experimentation with both is necessary to ensure good separation of images and minimize crosstalk between eyes. Although anaglyphs are printed in color, note that only achromatic information can be conveyed. **Convergence** is at plane of printed page. Several viewers may observe anaglyphs simultaneously. Examples of anaglyphs may be found in Ref. 2.
Cross-polarization (Fig. 2)	Half-fields covered with orthogonally oriented polarizing filters and viewed through another set of orthogonally oriented polarizing filters mounted at the eyes. Each eye sees image polarized by half-field filter at orientation of the eye filter.	Half-images must be optically superimposed with half-silvered mirror to achieve desired convergence at optical distance of both half-fields. The half-image passing through mirror must be presented left-right reversed. To avoid crosstalk between eyes, luminance of displays must be relatively low.
Stereoscopic shadow-caster (Fig. 3)	Orthogonally polarized point sources, separated laterally by the interpupillary distance, cast shadows of solid objects on silvered or rear-projection screen. Observer views screen through orthogonally oriented polarizing filters to separate images of shadows in each eye.	Magnification is given by ratio of point-source-to-object distance and object-to-screen distance. **Lateral retinal disparity** may be changed by varying the separation of the point sources. Motion parallax (CRef. 5.902) is eliminated. Mathematical analysis can be found in Ref. 3.
Free stereoscopy (Fig. 4)	Observer crosses (crossed method) or uncrosses (uncrossed method) eyes to achieve binocular registration without aid of other devices.	Method alters natural relationship between accommodation and convergence. Older observers have less difficulty with uncrossed-eyes method, while younger observers tend to prefer crossed-eyes method.

Key Terms

Anaglyph; depth perception; filter-separation stereoscopy; free stereoscopy; polarized display; shadow caster; stereogram; stereoscopic display; three-dimensional displays; vectograph

General Description

Filter separation and free stereoscopic methods are alternatives to the use of **stereoscopes** to produce stereoscopic displays. The table shows schematic diagrams of several types of filter separation and free stereoscopic techniques, principles of their operation, and special considerations in their use. Note that free stereoscopy requires only the half-fields of a stereogram and an observer with good oculomotor control, but no filters, instruments, or other special devices. As a demonstration of the crossed-eyes method of free stereoscopy, gradually move a fixated pencil tip from between the half-fields of a stereogram toward the bridge of the nose while attending to the half-fields in peripheral vision, until three field images appear. The central image is a pseudoscopic view of the stereogram, as shown in Fig. 4a.

Applications

Stereoscopic displays and testing, stereoscopic displays for audiences, quick evaluation of stereograms.

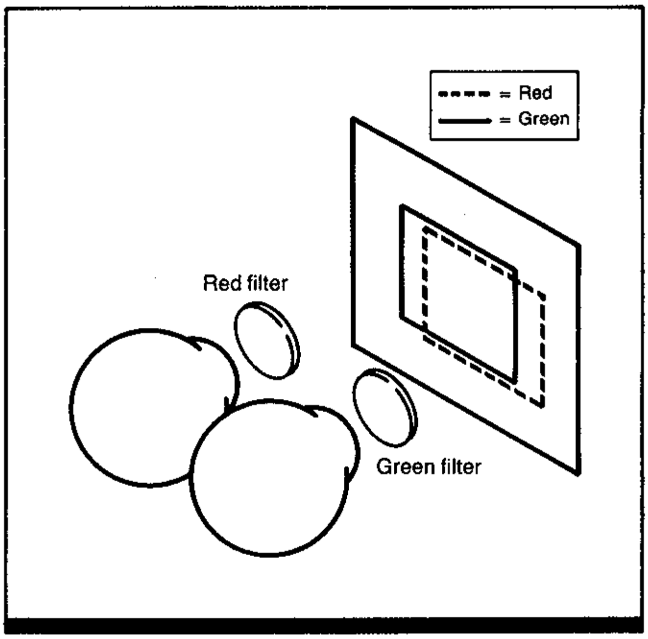


Figure 1. The anaglyph method. Colored images are separated by chromatic filters.

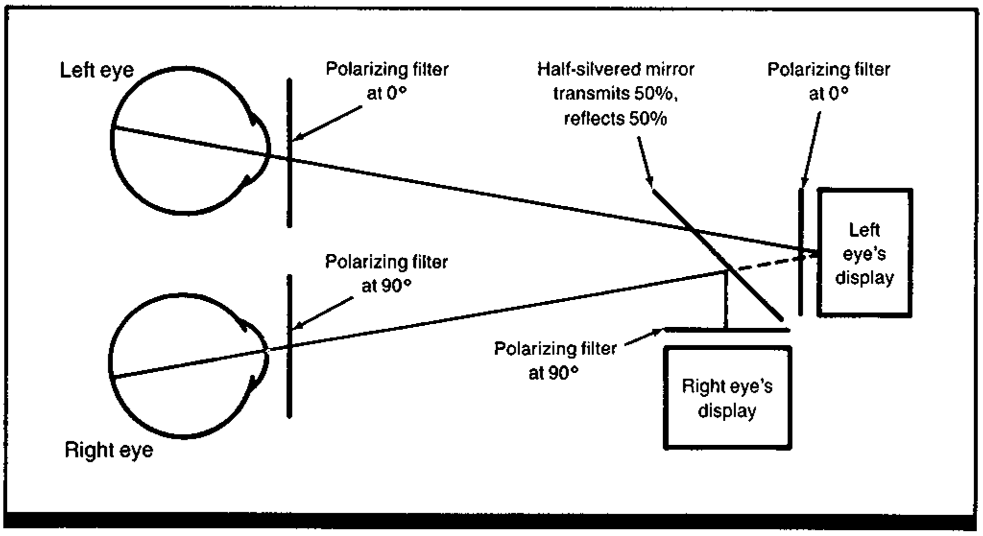


Figure 2. The crossed-polarization method. Typical arrangement shows optical superposition of half-fields with half-silvered mirror bisecting planes of the displays. Left eye's image passes through mirror, while right eye's image is reflected. Half-images are separated by polarizing filters at displays and over observer's eyes.

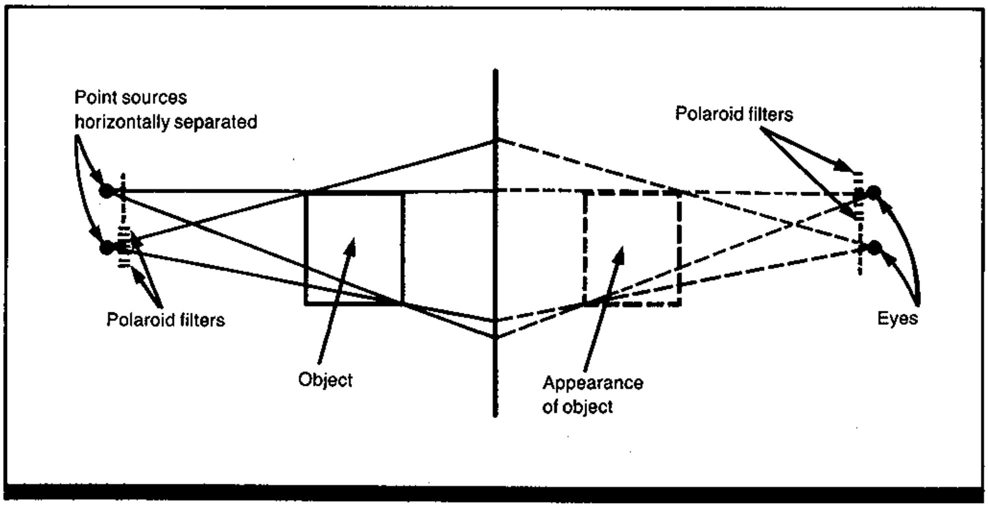


Figure 3. The stereoscopic shadow-caster. Polarized shadows of object are projected from laterally separated points on rear projection screen, and separated by polarizing filters at the eyes. (From Ref. 1)

Constraints

- Extraneous views of apparatus should be masked.
- There are many variations of the techniques shown in Figs. 1-3, e.g., the vectograph technique in which stereographic material may be printed on single photographic cross-polarized slides, or as anaglyphs.
- Apparent depth in all binocular displays depends on many cues other than **stereopsis.**

Key References

1. Gregory, R. L. (1964). Stereoscopic shadow images. *Nature, 203,* 1407-1408.

2. Julesz, B. (1971). *Foundations of cyclopean perception.* Chicago: University of Chicago Press.

3. Lee, D. N. (1969). Theory of the stereoscopic shadowcaster: An instrument for the study of binocular kinetic space perception. *Vision Research, 9,* 145-156.

4. Valyus, N. A. (1966). *Stereoscopy.* London: Focal Press.

Cross References

1.812 Binocular displays;

5.902 Motion parallax;

Handbook of perception and human performance, Ch. 23, Sects. 4.1, 4.2

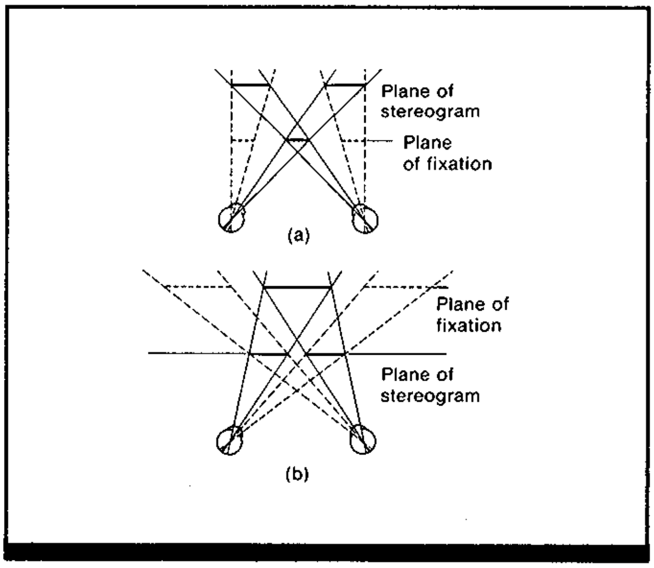


Figure 4. Free stereoscopy. Convergence to a plane closer (a) or more distant (b) than the plane of the stereogram brings the half-fields into binocular registration. The dashed lines shown on the fixation plane indicate the uniocular half-fields that flank the binocularly superimposed view. (From *Handbook of perception and human performance*)

5.915 Random-Dot Stereoscopic Displays

Key Terms

Cyclopean vision; depth perception; random-dot stereograms; stereoscopic display; three-dimensional displays; visual noise

General Description

Random-dot stereoscopy is a method for presenting depth information that neither eye alone can see, but that is visible with **binocular** viewing. In their simplest form, the two half-fields of a random-dot stereogram are identical, random-dot patterns, except that local patterns of dots in one eye are displaced laterally relative to the location of the same patterns of dots in the other eye. Such disparate zones give rise to apparent depth relative to non-disparate zones, and the pattern takes on a three-dimensional shape. Each eye alone sees only a noise pattern, and the shape exists only in the correlation of the spatial distributions of the two patterns. Figure 1a is a random-dot stereogram, depicting a square that seems to float above the page. The stereogram may be viewed in depth with free stereoscopy (CRef. 5.914), or with the aid of a **stereoscope**. The construction of the stereogram is shown in Fig. 1b. Three different placements of black and white random dots are required: dots that are placed identically in the two eyes (nondisparate dots), dots that are laterally displaced in the two eyes, but otherwise identical (disparate dots), and dots that fill the gaps in each half-image brought about by the introduction of the horizontal disparity. These stereograms mimic the situation in which a camouflaged object on the ground may be detected with telestereoscopic photographic techniques (Ref. 1).

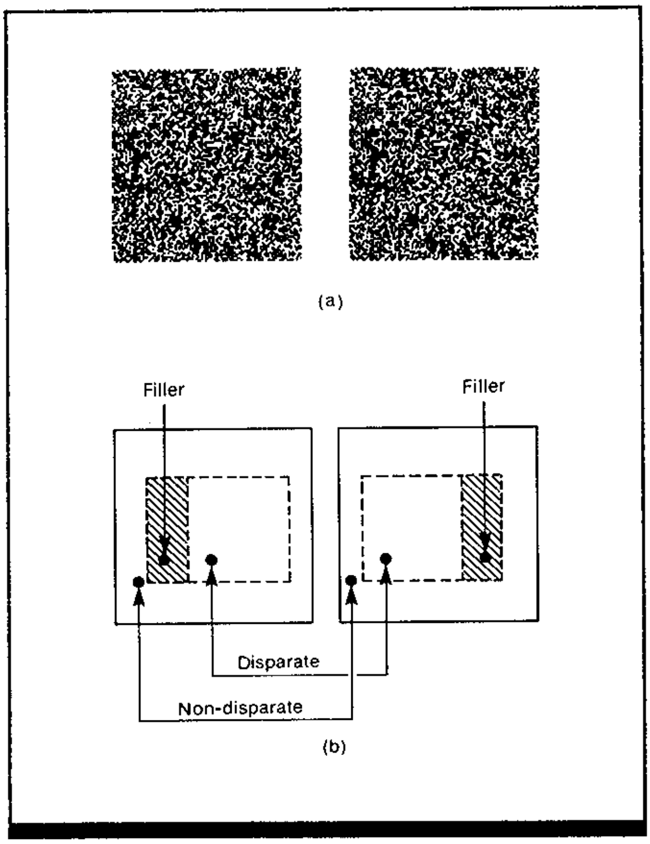


Figure 1. (a) A random-dot stereogram that, when viewed in a stereoscope or with (uncrossed) free stereoscopy, appears as a square floating above the plane of the page. With crossed eyes, the square is seen below the page through a square hole in the page. (From Ref. 3) (b) Schematic diagram illustrating the generation of (a). (From *Handbook of perception and human performance*)

Applications

Stereoacuity testing, displays containing spatial noise ("snow"), detection of camouflaged objects.

Methods

- Random-dot stereograms are most easily generated by computer
- Any type of spatial noise pattern or pixel element may be substituted for the random dots
- Motion may be depicted cinematically in dynamic random-dot stereograms by varying disparity and correlation zone from frame to frame
- The threshold percentage of correlated dots required to detect the shape in a random-dot stereogram provides a test of global stereoscopic discrimination (Ref. 2)

Constraints

- Moving random-dot stereogram images are subject to depth effects resulting from unequal luminance or time delay of the half-images (CRef. 5.933).
- Contrary to common belief, random-dot stereograms are not devoid of **monocular** form information; rather, they contain binocular forms that do not exist monocularly.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Aschenbrenner, C. M. (1954). Problems in getting information in and out of air photographs. *Photogrammatic Engineering, 20,* 398-401.

2. Julesz, B. (1971). *Foundations of cyclopean perception.* Chicago: University of Chicago Press.

3. Julesz, B. (1977). Recent results with dynamic random-dot stereograms. In S. Benton (Ed.), *Three dimensional imaging. Proceedings of the Society of Photo-Optical Instrumentation Engineers, 120,* 30-35.

Cross References

5.914 Filter separation and free stereoscopic display methods;

5.933 Illusory depth with interocular differences in luminance or onset delay (Pulfrich and Mach-Dvorak effects);

Handbook of perception and human performance, Ch. 23, Sect. 4.4

5.916 Perceived Depth as a Function of Lateral Retinal Image Disparity

Key Terms

Depth perception; distance vision; eye movements; retinal image disparity; three-dimensional displays

General Description

When the eyes are free to move, the perceived depth of a target roughly matches that which would be predicted from the **lateral retinal image disparity** of the target. When eye movements are restricted, however, perceived depth is veridical only for disparities up to 30-50 min arc of visual angle; targets with larger disparities are seen in less apparent depth than parallax geometry predicts.

Applications

Stereoscopic, autostereoscopic, and volumetric display designs, especially those in which depth must be accurately portrayed.

Methods

Test Conditions

- White background screen, luminance 12.73 cd/m² (4 mL); viewing distance to screen 250 cm, changed under some conditions to effective fixation distance of 24 cm by placing + 13-diopter prisms and − 3-diopter lenses in front of observer's eyes
- Eye movement condition: circular black target probe 1.5 cm in diameter, variable physical distance from observer; observer instructed to move eyes between probe and screen
- Flash condition (restricted eye movement): fixation on 0.5-cm diameter spot with vertical **nonius lines** on screen; stereoscopic vertical bar target 1.2 deg high, 0.12 deg wide; luminance 127.3 cd/m²; 80-msec exposure time; multiple exposures as requested by observer (typically 10-15); disparity varied from 7-210 min arc **convergent disparity**: image separation by cross-polarization technique
- Matching condition (restricted eye movement): same as flash condition except circular probe (described above) used as matching target

Experimental Procedure

- Method of adjustment under observer's control (eye movement and matching conditions); magnitude estimation (flash condition)
- Independent variables: target disparity (real or simulated distance from target to screen); effective fixation distance
- Dependent variables: distance to which observer adjusted probe target (eye movement and matching conditions); estimated distance of target bar (flashing condition)
- Observer's task: eye movement condition: adjust movable probe target to specified proportion (0.1-0.9) of distance to screen as instructed by experimenter; flash condition: estimate distance to target bar as a proportion of distance to screen; matching condition: adjust position of probe target to match apparent depth of target bar
- 4 observers, at least 2 practiced
- Three trials per data point

Experimental Results

- When observers move their eyes, the magnitude of perceived target depth increases monotonically as a function of retinal disparity throughout the distance range tested.
- Observers almost always overestimate depth when setting a target to a specified distance. This overestimation is greater at larger than at smaller viewing distances.
- When eye movements are restricted (observers maintain fixation on a single point), perceived depth increases with disparity up to ~40 min arc and then decreases.
- Depth judgments made under the matching condition closely parallel magnitude estimates of depth made under the flash condition.

Variability

Consistent results within and between subjects, but no specific variability estimates provided.

Repeatability/Comparison with Other Studies

Findings in matching condition are similar to those of Ref. 6, in which both convergent and divergent disparities were used. Magnitude estimates of depth in line stereograms (with free eye movements) have been found to be related linearly to disparity over the range of 0-33 min arc (Ref. 4). Reference 5 found perceived depth (with free eye movements) near the fovea to grow monotonically with disparity only up to ~20 min arc (CRef. 5.930).

Constraints

- In some individuals, stereoscopic vision may be lacking or may function in an anomalous way.
- A number of target-related factors are known to influence stereoscopic function and depth perception (CRef. 5.918).

Key References

1. Foley, J. M. (1967). Disparity increase with convergence for constant perceptual criteria. *Perception & Psychophysics, 2*, 605-608.

2. Foley, J. M. (1980). Binocular distance perception. *Psychological Review, 87*, 411-433.

*3. Foley, J. M., & Richards, W. (1972). Effects of voluntary eye movement and convergence on the binocular appreciation of depth. *Perception & Psychophysics, 11*, 423-427.

4. Lawson, R. B., & Gulick, W. L. (1967). Stereopsis and anomalous contour. *Vision Research, 7*, 271-297.

5. Ogle, K. N. (1952). On the limits of stereoscopic vision. *Journal of Experimental Psychology, 44*, 253-259.

6. Richards, W. (1971). Anomalous stereoscopic depth perception. *Journal of the Optical Society of America, 61*, 410-414.

Cross References

5.905 Lateral retinal image disparity;

5.918 Factors affecting stereoacuity;

5.930 Limits of stereoscoptic depth perception;

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

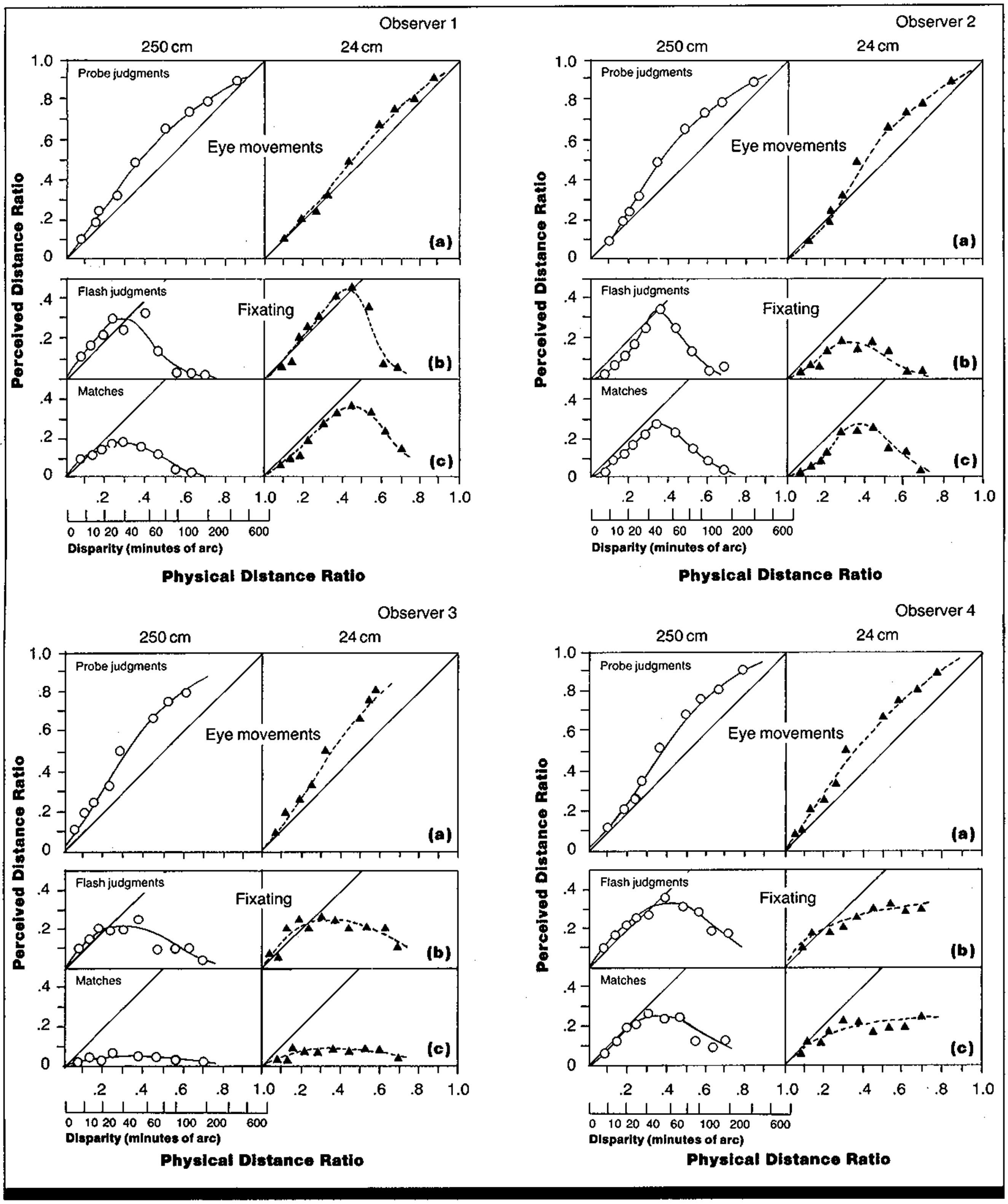


Figure 1. Perceived depth as a function of physical distance and retinal image disparity. Results are shown for two viewing distances under three different experimental procedures: (a) observers moved their eyes and adjusted a probe target to a specified distance; (b) observers fixated screen and estimated depth of a flashed target; (c) observers fixated screen and adjusted depth of a probe to match depth of a flashed target. Perceived distance ratio = judged distance of target or probe from screen divided by optical distance of target or probe from screen; physical distance ratio = actual distance of target or probe from screen divided by optical distance from observer to screen. (From Ref. 3)

5.917 Stereoacuity Tests

Key Terms

Armed Forces vision tester; biopter vision test; depth perception; frisby stereo test; Howard-Dolman apparatus; randot test; stereoacuity test; three-dimensional displays; titmus stereo test; TNO test; Verhoeff stereopter

General Description

Stereoacuity is the smallest resolvable difference in depth between two targets, generally expressed in terms of **visual angle**. Two types of stereoacuity tests are used: (1) real test objects are placed at different distances from an observer and (2) a separate two-dimensional image is shown to each eye, resulting in a binocular impression of depth.

Tests Using Real (Three-Dimensional) Targets

In some three-dimensional tests, two or more targets are placed at preset distances and observers must judge which target appears nearer or farther. The smallest angular discriminable distance between targets defines stereoacuity. In other tests, a moveable target is adjusted until it appears to be the same distance from observer as a fixed target. Stereoacuity is measured as the angular distance from the fixed target within which a significant percentage of adjustments falls within a given number of trials.

Tests Using Two-Dimensional Targets

In two-dimensional tests, pattern elements in a binocular display are presented with an imposed **lateral retinal image disparity** so that they appear closer or farther away than the rest of the pattern. In some tests, targets are presented by stereoscope to achieve optical separation or left- and right-eye images. In others, left- and right-eye images are overprinted on a single plate using Polaroid (vectographic) or anaglyphic techniques, and the plate is viewed through special spectacles that segregate the images so that each eye sees only the appropriate view (CRef. 5.914). Targets may be conventional drawings, photographs, or random-element patterns.

Comparison of Stereoacuity Tests

- No significant difference is found between stereoacuity measured using three-dimensional targets and stereoacuity determined with two-dimensional stereoscopic techniques (Ref. 1).
- Two-dimensional stereoacuity tests may be less cumbersome to administer than three-dimensional tests. Two-dimensional tests employing vectographic or anaglyphic plates are convenient and portable and do not require use of a stereoscope.
- Tests using random-element target patterns effectively eliminate monocular depth cues and ensure that observer responds solely to retinal disparity information.

Constraints

- Monocular depth cues, such as relative size, interposition (overlapping), figure-ground relationships, and perspective, are not always adequately controlled in stereoacuity tests and may lead to false-positive results.
- Stereoacuity scores may be lowered in testing situations where monocular depth cues compete with retinal disparity.
- Precision of stereoacuity scores depends on size of the disparity interval between successive targets of a test series as well as the smallest disparity available in the given test.
- With some tests, poor visual acuity may lead to low test scores.
- There are large individual differences in stereoscopic vision; stereoacuity is affected by practice.

Key References

1. Berry, R. N. (1948). Quantitative relations among vernier, real depth, and stereoscopic depth acuities. *Journal of Experimental Psychology, 38*, 708-721.

Cross References

5.905 Lateral retinal image disparity;

5.914 Filter separation and free stereoscopic display methods;

5.915 Randon-dot stereoscopic displays;

5.918 Factors affecting stereoacuity

Table 1. Some commonly used tests of stereoacuity.

Tests using two-dimensional targets

Test	Method of Target Presentation	Disparity Range Tested (sec arc)	Observation Distance (cm)	Type of Target Pattern	Comments
Depth perception test of the Armed Forces vision tester	Stereoscope (haploscope, major amblyscope)	Graded plates: >41, 41-15	800	Line drawn geometric forms	• Allows preliminary check for esotropia, exotropia, hypertropia, and suppression • Low scores may be caused by conflict between size and disparity
Biopter vision test	Biopter stereoscope	Screening plate: unspecified; Graded plates: 400-24	0 diopter (actual optical distance undetermined)	Line drawn figures, geometric forms	
Titmus stereo test	Vectograph plates	Screening plate: 3000; Graded plates: 800-40	40	Photograph, geometric forms, animal figures	• Often unreliable in differentiating observers with amblyopia and heterotropia • May give false positive
Random Dot E test	Vectograph plates	Graded plates: 504-50	50-500	Random dot patterns	• Disparity range obtained by varying observation distance
Randot tests	Vectograph plates	Screening plate: 600; Graded plates: 400-20	40	Random dot patterns	
Frisby stereo test	Vectograph plates	Graded plates: 495-85	40	Random texture patterns	• No special spectacles required • Good visual acuity required
TNO test	Anaglyphic plates	Screening plate: 1980; Graded plates: 480-15	40	Random dot pattern	• Includes a suppression test • Test may present difficulties to the color blind

Tests using three-dimensional targets

Description of Apparatus	Test	Disparity Range Tested (sec arc)	Observation Distance (cm)	Comments
Verhoeff Stereopter	Small box containing 3 wires of different thicknesses and variable depth, viewed through an aperture against a transilluminated background	132-10	100	• Passing score is 45 sec arc • Low score may be caused by conflict between size and disparity • False positive can result from uncorrected myopia
Howard-Dolman Apparatus	Open box containing two black rods, one fixed and one adjustable, viewed through an aperture	Continuous to 0 deg (1 cm separation of rods = 3.5 sec arc)	600	• Positioning of movable rod within an arbitrary distance of fixed rod in 75% of 20 trials considered success • Passing score is 11 sec arc • Low scores may be caused by poor eye-hand coordination

5.918 Factors Affecting Stereoacuity

Key Terms

Adjacency; contrast; depth discrimination; exposure duration; interstimulus onset asynchrony; light adaptation; luminance; motion in depth; retinal illuminance; retinal image disparity; retinal location; size perception; spatial orientation; stereoacuity; three-dimensional displays; viewing distance; visual field location

General Description

Stereoacuity is the visual resolution of small differences in depth or distance by means of binocular **retinal disparity** information. Stereoacuity typically is measured by having observers adjust two targets to the same distance, or state which of several targets is nearer. The stereoacuity limit, or smallest detectable lateral disparity, is defined as the variability in observers' equidistance settings or as the retinal disparity at which they reach some criterion percentage of correct responses in identifying the relative depths of targets. The table lists some factors known to influence stereoacuity, indicates the nature of the effect, summarizes empirical studies in the area and cites entries or sources where more information can be found.

Factor	Effect on Stereoacuity	Source
Illumination level	Maximal at illumination levels of ∿3 cd/m² and above Decreases with decreasing illumination for lower light levels	CRef. 5.919
Retinal location (lateral distance from point of fixation)	Maximal at **fovea** Decreases sharply with increasing distance from foveal center Declines by >50% for visual angles 2 deg into periphery, even more sharply for angles ≥6 deg	CRef. 5.920
Relative disparity	Maximal at plane of fixation Declines as relative disparity increases Decreases by 50% or more for relative disparities as small as 1-5 min arc	CRef. 5.921
Target/background contrast	Unaffected by changes in contrast above level required for target visibility	Ref. 5
Presence of depth reference	Detection of step displacement of single line degraded by factor of 10 when no depth reference target is present	Ref. 8
Configuration of reference contours	Almost twice as great with lateral depth reference targets as with vertically aligned reference	Ref. 8
Lateral separation of adjacent contours	Reduced by fourfold or more in presence of flanking contours at distance of about 2.5 min arc Declines less for smaller lateral separations Declines linearly with increasing distance for separations greater than ∿9 min arc	CRef. 5.922
Viewing distance	Unaffected by viewing distance when all depth cues except lateral retinal image disparity are elimininated	Ref. 5
Field of view	Increases as field size increases	Ref. 1 CRef. 5.923
Fixation conditions	Greater when fixation alternates from target to depth reference than when fixation maintained on reference Advantage due to alternating fixation increases with increasing angular separation of target and reference	Ref. 4
Length of target	Declines slowly as length decreases from 2.5 to ∿0.60 deg, then more rapidly with further decreases to ∿0.30 deg	Ref. 2
Width of target	Greatest at thickness of ∿2.4 min	Ref. 3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Factor	Effect on Stereoacuity	Source
Orientation in frontal plane	Greatest for vertical orientations Declines in proportion to cosine of angle of inclination for tilts away from vertical	CRef. 5.924
Lateral motion	Unaffected by lateral target motions $\leq$2.5 deg/sec Higher velocities not adequately studied, decline probable with very rapid motion	CRef. 5.923, 5.925
Motion in depth	Declines with motion in depth >1 deg/sec	Ref. 7
Spatial frequency	Conflicting results obtained; if stereoacuity varies with spatial frequency of target, effect probably small	Ref. 9
Exposure duration	Constant at durations >3-4 sec and <0.006 sec From 1 sec to 0.006 sec, decreases fourfold, approximately in proportion to −⅓ power of exposure	Ref. 8 CRef. 5.926
Target/comparison onset asynchrony	Declines fourfold when target and comparison presented sequentially with no overlap in time	Ref. 8
Right/left image onset asynchrony	Declines slowly with increasing onset asynchrony until critical delay is reached beyond which stereoscopic depth cannot be maintained Critical delay increases slowly from ∿100 to ∿250 msec with increase in exposure time	Ref. 6
Unequal retinal illuminances	Unaffected, provided target detail visible in each half-image Under certain conditions, special perceptual effects obtained that do not affect stereoacuity (**Pulfrich Effect**, slant effect)	CRef. 5.933

Applications

Stereoscopic, autostereoscopic, and volumetric displays.

Constraints

- Interactions may occur among the various factors affecting stereoacuity, but such interactions have not generally been studied.

Key References

1. Laglands, H. M. S. (1926). Experiments in binocular vision. *Transactions of the Optical Society* (London), *28*, 45-82.

2. Matsubayashi, A. (1938). Forschung über die Tiefenwahrnehmung. V. *Acta Societatis Ophthalmologicae Japonicae, 42*, 2-21 (German abstract, 1).

3. Matsubayashi, A. (1938). Forschung über die Tiefenwahrnehmung. VI. *Acta Societatis Ophthalmologicae Japonicae, 42*, 230-241 (German abstract, 15).

4. Ogle, K. N. (1956). Stereoscopic acuity and the role of convergence. *Journal of the Optical Society of America, 46*, 269-273.

5. Ogle, K. N. (1962). Spatial localization through binocular vision. In H. Davson (Ed.), *The eye* (Vol. 4, pp. 271-324). New York: Academic Press.

6. Ogle, K. N. (1963). Stereoscopic depth perception and exposure delay between images to the two eyes. *Journal of the Optical Society of America, 53*, 1296-1304.

7. Regan, D. M., & Beverley, K. I. (1973). This dissociation of ways movements from movements in depth: Psychophysics. *Vision Research, 13*, 2403-2415.

8. Westheimer, G. (1979). Cooperative neural processes involved in stereoscopic acuity. *Experimental Brain Research, 36*, 585-597.

9. Westheimer, G., & McKee, S. P. (1979). What prior uniocular processing is necessary for stereopsis? *Investigative Ophthalmology, 18*, 614-621.

Cross References

5.905 Lateral retinal image disparity;

5.919 Stereoacuity: effect of luminance;

5.920 Stereoacuity: effect of target location in the visual field;

5.921 Stereoacuity: effect of relative disparity;

5.922 Stereoacuity: effect of adjacent contours;

5.923 Stereoacuity: effect of field of view;

5.924 Stereoacuity: effect of target orientation;

5.925 Stereoacuity: effect of lateral target motion;

5.926 Stereoacuity: effect of exposure duration;

5.931 Stereoscopic depth perception: limiting differences in left and right half-images;

5.933 Illusory depth with interocular difference in luminance or onset delay (Pulfrich and Mach-Dvorak effects)

5.919 Stereoacuity: Effect of Luminance

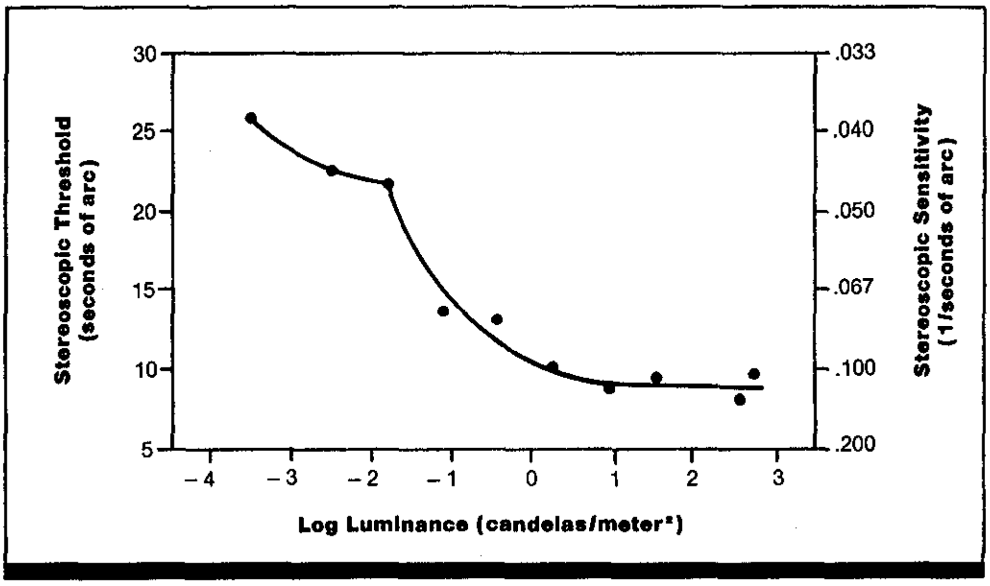


Figure 1. Stereoacuity as a function of luminance. (From Ref. 3)

Key Terms

Depth discrimination; light adaptation; retinal image disparity; stereoacuity; three-dimensional displays

General Description

Ability to detect **retinal image disparity** (depth) of a thin line target decreases as the level of illumination decreases.

Applications

Stereoscopic, autostereoscopic, and volumetric displays.

Methods

Test Conditions

- Three dark vertical lines 20 min arc of visual angle wide, 2 deg long, and 4.1 deg apart, serving as fixation guides
- Dark vertical target line, 20 min arc wide, 19 deg long, appearing to left of central fixation line at variable depth
- Bright background field, size unspecified (probably >20-deg diameter), varied in intensity using **neutral density filters**
- Background field and stimulus lines displayed using **Wheatstone mirror stereoscope**
- Viewing distance 35.6 cm; **accommodation** aided by 2.8-diopter convex lens; dark room

Experimental Procedure

- Method of adjustment under observer's control
- Observer dark-adapted 25 min prior to experiment, readapted for 2 min after each change of background illumination level
- Independent variable: intensity of background field; intensity levels presented in order of increasing luminance
- Dependent variable: smallest detectable disparity of target line (stereoscopic threshold), defined as average deviation of settings at each background intensity level
- Observer's task: adjust variable target line to appear to lie in plane of fixation (no depth), with each setting beginning at randomly selected disparity
- 20 trials per background intensity level; three series per observer
- 2 highly practiced observers

Experimental Results

- Stereoscopic acuity improves with increasing luminance up to ~3 cd/m^2, then levels off.
- The discontinuity in the curve at a luminance of 0.016 cd/m^2 represents the point of shift from rod-governed or **scotopic** vision (upper segment of curve) to **cone**-governed or **photopic** vision (low segment of curve).
- Solid curves are derived from an empirical formula (Ref. 2) describing **monocular** visibility of thin lines on backgrounds of varying luminance; this implies that stereoacuity threshold is related to prior monocular visibility. The formula used to fit the data is a better presentation (HCS):

$$\alpha = b\{1 + [1/(KI)^{1/2}]\}^2$$

where b and K are constants whose values are not reported, I is luminance, and α is the measured threshold. Method of fitting not described.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

Considerable variability reported, although no specific estimates are provided.

Repeatability/Comparison with Other Studies

The scotopic region of the reported curve has been fully replicated (Ref. 1).

Constraints

- A number of factors (such as target orientation, distance between target elements, etc.) are known to influence stereoacuity and should be taken into account in applying these results under different viewing conditions (CRef. 5.918).
- There are large individual differences in stereoscopic vision; stereoacuity is affected by practice.

Key References

1. Berry, R. N., Riggs, L. A., & Duncan, C. P. (1950).The relation of vernier and depth discriminations to field brightness. *Journal of Experimental Psychology, 40*, 349-354.

2. Hecht, S., & Mintz, E. U. (1939). The visibility of single lines at various illuminations and the retinal basis of visual resolution. *Journal of General Psychology, 22*,593-612.

*3. Mueller, C. G., & Lloyd, V. V. (1948). Stereoscopic acuity for various levels of illumination. *Proceedings of the National Academy of Sciences, 34*, 223-227.

Cross References

5.905 Lateral retinal image disparity;

5.918 Factors affecting stereoacuity

5.920 Stereoacuity: Effect of Target Location in the Visual Field

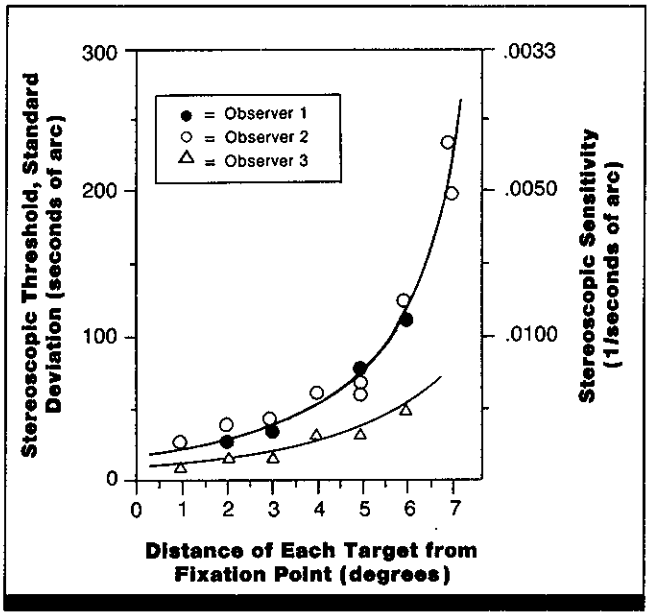


Figure 1. Disparity difference thresholds as a function of distance from fixation for two targets placed symmetrically to each side of the fixation point (Study 1). (From Ref. 1)

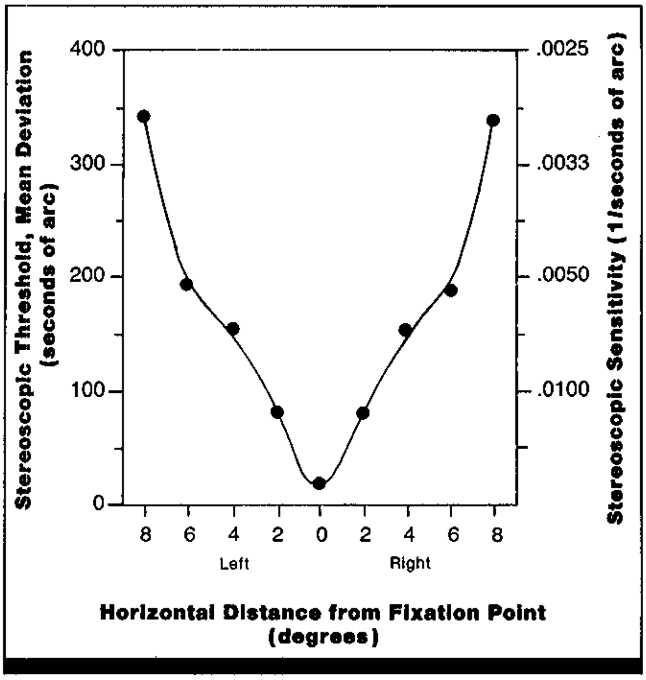


Figure 2. Disparity difference thresholds for two targets with constant lateral separation as a function of distance from midpoint of targets to fixation point (Study 2). (From Ref. 2)

Key Terms

Depth discrimination; retinal image disparity; retinal location; stereoacuity; three-dimensional displays; visual field location

General Description

Stereoacuity, or the ability to discriminate relative depth (**lateral retinal image disparity**), is greatest for targets in the center of the visual field (those that fall on the retinal **fovea**) and decreases with distance from the center. This is true when the targets whose depths are compared are both on the same side of the fixation point as well as when one target is to the right and the other an equal distance to the left of the fixation point.

Applications

Stereoscopic, autostereoscopic, and volumetric display designs.

Methods

Test Conditions

Study 1 (Ref. 1)

- Central fixation point; two flanking point light sources placed symmetrically on either side of fixation point
- Disparity of flanking targets varied by changing magnification of right eye's image of targets; distance of targets from fixation varied from 1-7 deg of visual angle
- Target lights exposed for ~2 sec per trial, during which time fixation point was extinguished
- Viewing distance 3 m; totally dark room

Study 2 (Ref. 2)

- Central fixation with light 60 sec diameter, 63.66 cd/m^2 (20 mL)
- Two targets with lights 60 sec diameter, set to match fixation point in brightness; lateral target separation ~1 deg; both targets displaced to left or right of fixation, 0-7 deg from midpoint of targets to fixation point
- Targets and fixation point presented via **haploscope**; viewing distance 100 cm; dark room

Experimental Procedure

Study 1

- Method of constant stimuli
- Two-alternative forced-choice paradigm; randomized presentation of disparities
- Independent variable: angular distance from each target to fixation; retinal disparity of targets
- Dependent variable: stereoscopic (disparity difference) threshold, defined as standard deviation of estimated psychometric function (corresponding to ~68% correct detection of depth difference)
- Observer's task: judge whether two target lights appeared to be at same or different distances
- 3 observers, at least 2 experienced

Study 2

- Method of average error
- Independent variables: angular distance from midpoint of target lights to fixation point; retinal disparity of targets
- Dependent variable: stereoscopic (disparity difference) threshold, defined as mean deviation (in seconds of arc) of equidistance settings
- Observer's task: judge when target lights appeared equidistant
- 3 observers, probably experienced

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Stereoacuity decreases as target distance from fixation increases.
- Study 1 finds a more rapid decrease for eccentricities greater than ~5 deg.
- Study 2 shows a discontinuity at 4-6 deg that is probably attributable to a change in luminosity caused by a change in the relative contributions of **rods** and **cones** with retinal location.
- Despite differences in the two stimulus configurations, the studies of Figs. 1 and 2 are in agreement.

Variability

Although stereoacuity generally varies widely among individuals, changes in stereoacuity with eccentricity are very similar for individuals in these studies.

Repeatability/Comparison with Other Studies

A decline in stereoacuity with distance from fixation appears as a secondary effect in many other studies.

Constraints

- In some individuals, stereoscopic vision may be lacking or may function in an anomalous way.
- Stereoacuity is strongly affected by practice.
- A number of factors (such as target orientation and luminance, etc.) influence stereoacuity and should be considered in applying these results under different viewing conditions (CRef. 5.918).

Key References

*1. Ogle, K. N. (1950). *Researches in binocular vision.* Philadelphia: Saunders.

*2. Rawlings, S. C., & Shipley, T. (1969). Stereoscopic acuity and horizontal angular distance from fixation. *Journal of the Optical Society of America, 59,* 991-993.

Cross References

5.905 Lateral retinal image disparity;

5.918 Factors affecting stereoacuity;

Handbook of perception and human performance, Ch. 23, Sect. 5.1

5.921 Stereoacuity: Effect of Relative Disparity

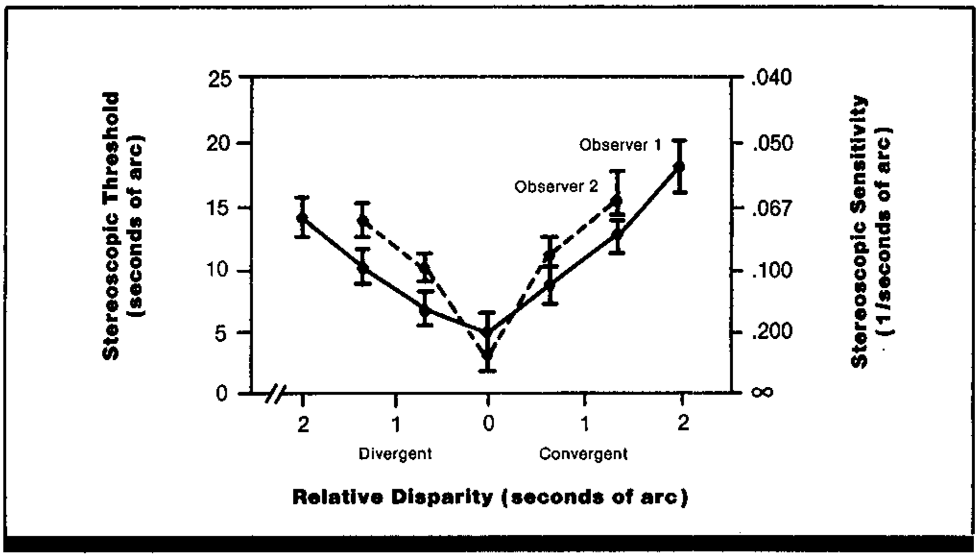


Figure 1. Stereoacuity as a function of target disparity relative to the fixation plane. (From Ref. 2)

Key Terms

Depth discrimination; retinal image disparity; stereoacuity; three-dimensional displays

General Description

The ability to resolve small depth displacements of a thin target line is reduced if the line has **lateral retinal image disparity** relative to reference lines in the plane of fixation. This decline in stereoacuity increases sharply with relative disparity. Stereoacuity is not affected when the target and reference lines appear at the same depth.

Applications

For displays requiring discrimination of apparent depth of a point or points in the field of vision, observer's judgment of perceptual depth may be biased by the presence of neighboring points set at disparities different from point of fixation, i.e., at different apparent depths.

Methods

Test Conditions

- Three white vertical lines, <0.5 min arc of visual angle wide, 15 min arc long, 10 min arc apart, displayed on CRT; luminance 32 cd/m^2 viewed against dark background in darkened room
- Central line served as target stimulus and disparity was varied; flanking lines had constant zero disparity and provided a stable fixation plane reference
- Observation distance 2.5 m; stereoscopic separation through cross-polarization technique (CRef. 5.914)
- Trial structure: 500-msec presentation of three-line stimulus with central line at 0, 1, or 2 min arc **convergent or divergent disparity** relative to flanking lines, followed by 200-msec blank interval, followed by 500-msec presentation of stimulus configuration with central line further displaced in depth by test amount; seven disparity test steps at each relative disparity, three convergent, three divergent, and one zero disparity, magnitudes varying for different relative disparities (typical range: seven equal steps spanning 0.8 min arc around relative disparity)

Experimental Procedure

- Method of constant stimuli
- Independent variables: disparity of test step, relative disparity; presentation order randomized
- Dependent variable: smallest detectable depth difference of target line (stereoscopic threshold), defined as the disparity difference associated with 75% correct response probability at each relative disparity as determined by probit analysis of responses
- Observer's task: judge whether the position of the target line after depth displacement during trial was "nearer" or "farther" than its position at beginning of trial
- At least 300 trials per data point
- 2 practiced observers screened for "good" stereopsis

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Resolution of disparity difference is greatest at plane of fixation and declines sharply as relative disparity increases. Stereothreshold is more than doubled for relative disparities as little as 1 min arc.
- A control experiment showed that these results are not due to absolute disparity of the target, but to relative disparity between the target and flanking lines. When flanking lines had equal (nonzero) disparity with the target, threshold was the same as when all three lines had zero disparity.

Variability

No information on variability was given.

Constraints

- The experiment was performed in a dark room with little reference to the plane of fixation other than the flanking lines. Displays which have more visual structure may yield a diminished effect.
- Only reference lines in the fixation plane were used; results may be different for relative disparities between test lines and reference lines at nonzero disparities.
- A number of other factors (such as target luminance and orientation, etc.) are known to influence stereoacuity and should be considered when applying these results under different viewing conditions (CRef. 5.918).
- There are large individual differences in stereoscopic vision.
- Stereoacuity is affected by practice.

Key References

1. Blakemore, C. (1970). The range and scope of binocular depth discrimination in man. *Journal of Physiology, 211*, 599-622.

*2. Westheimer, G. (1979). Cooperative neural processes involved in stereoscopic acuity. *Experimental Brain Research, 36*, 585-597.

Cross References

5.905 Lateral retinal image disparity;

5.914 Filter separation and free stereoscopic display methods;

5.918 Factors affecting stereoacuity;

5.922 Stereoacuity: effect of adjacent contours

5.922 Stereoacuity: Effect of Adjacent Contours

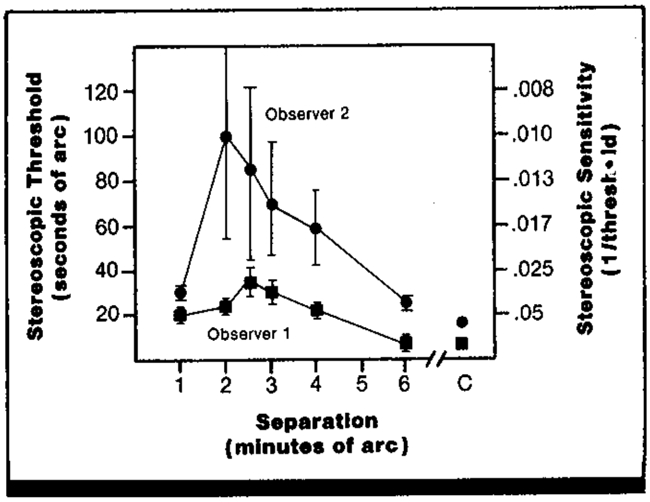


Figure 1. Smallest detectable displacement in depth of a test line as a function of distance from test line to flanking lines (Study 1). Point plotted at *C* is detection threshold when no flanking lines are present. (From Ref. 1)

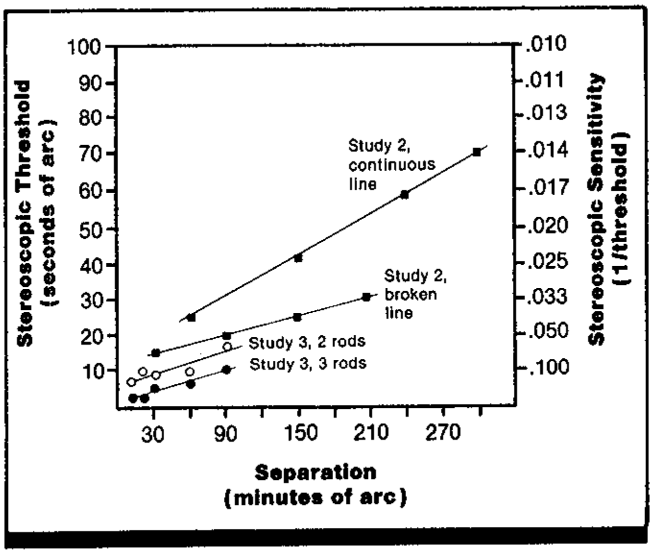


Figure 2. Smallest detectable displacement in depth of a test target as a function of distance of test target from a reference target. (From Ref. 2)

Key Terms

Adjacency; depth discrimination; spatial induction; spatial interactions; three-dimensional displays; visual masking

General Description

The ability to detect small displacements of a target in depth (stereoacuity) is generally greatest when the target is close to other contours that serve as a depth reference. When the distance between the target and reference contours is in the range of ~5-300 min arc of visual angle, stereoacuity declines with increasing separation of target and reference. While nearby contours generally facilitate depth localization, interference has been found for very small separations with some target configurations. Flanking contours interfere with stereoacuity when they are within 2-4 min arc of a test line, but not at smaller or wider separations.

Applications

Stereoscopic and autostereoscopic displays; design of sighting rectiles.

Methods

See Table 1.

Experimental Results

- Sensitivity to displacement of a target in depth is generally enhanced by the presence of adjacent contours.
- When the distance between target and adjacent contours is greater than ~6 min arc, stereoacuity declines monotonically as separation distance increases (Fig. 2).
- Stereoacuity is greater, and declines at a slightly slower rate with separation distance when two, rather than one, adjacent reference contours are present.
- When the distance between target and adjacent contours is small (1-6 min arc), the presence of contours on both sides of a target can interfere with depth localization of the target (Fig. 1). Interference is greatest at separations of 2.0-2.5 min arc. Stereoacuity is not affected if only one flanking line is present, or if the flanks are not in the plane of fixation.

Variability

Error bars in Fig. 1 show ± 1 standard error for data of Study 1. In Study 2, an analysis of variance showed significant effects of target-to-reference distance ($p < 0.01$); significant intersubject differences were also found. No information on variability was available for Study 3.

Repeatability/Comparison with Other Studies

Reference 5 reported stereoacuity to be at least ten times worse when observers had to detect depth changes of a target line appearing alone than when a second stationary line was also present to provide a depth reference.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- A number of factors (such as target luminance and orientation, etc.) influence stereoacuity and should be considered when applying these results under different viewing conditions (CRef. 5.918).
- Stereoacuity is strongly affected by practice.
- There are large individual differences in stereoscopic vision.

Key References

*1. Butler, T. W., & Westheimer, G. (1978). Interference with stereoscopic acuity: Spatial, temporal, and disparity tuning. *Vision Research, 18*, 1387-1392.

2. Graham, C. H. (Ed.). (1965). *Vision and visual perception.* New York: Wiley.

*3. Graham, C. H., Riggs, L. A., Mueller, C. G., & Solomon, R. L. (1949). Precision of stereoscopic settings as influenced by distance of target from a fiducial line. *The Journal of Psychology, 27*, 203-207.

*4. Matsubayashi, A. (1937). Forschung Über die Tiefenwahrnehmung. II. *Acta Societatis Ophthalmological Japiocal, 41*, 2055-2074.

5. Westheimer, G. (1979). Cooperative neural process involved in stereoscopic acuity. *Experimental Brain Research, 36*, 585-597.

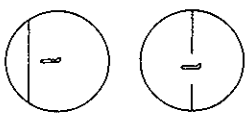
Cross References

5.914 Filter separation and free stereoscopic display methods;

5.917 Stereoacuity tests;

5.918 Factors affecting steroacuity

Table 1. Details of experimental methods.

Target Configuration	Test Conditions	Experimental Procedure
Study 1 (Ref. 1)		
	• Two target lines 10 min arc long, 30 sec arc wide, 3 min arc gap between; flanking lines 6 min arc long, 30 sec arc wide • Top target line varied in depth; all other lines in fixation plane; distance between targets and flanking lines varied • Lines 170 cd/m^2 viewed against dark background; 200-msec exposure per trial • Presentation via 2 oscilloscopes using cross-polarization technique of stereoscopic image separation (CRef 5.914)	• Method of constant stimuli • Two-alternative forced-choice model • Independent variables: disparity of upper target line, distance between targets and flanking lines • Dependent variable: smallest detectable difference, defined as disparity difference between 50 and 75% correct response frequencies • Observer's task: judge whether upper target line appeared behind or in front of lower target • Feedback provided • At least 300 trials per point • 2 well-practiced observers
Study 2 (Ref. 3)		
	• 22 deg diameter background field; field luminance 63.66 cd/m^2 (20mL) • One-line or two-line reticle with airplane target varied • For left reticle, distance from target to line varied; for right retical, distance from target to bottom of upper line varied • Conventional **stereoscope** used for presentation	• Method of adjustment • Independent variable: distance from target to reticle line • Dependent variable: stereoscopic threshold, defined as average deviation of observer's "equality" settings • Observer's task: adjust disparity of target until it appeared to lie in same plane as reticle • Thirty settings per point • 5 experienced observers
Study 3 (Ref. 4)		
	• For 2-rod target, 1 rod stationary, other variable in depth; for 3-rod target, outer rods stationary, center rod variable in depth • Three-dimensional Howard-Dolman-type apparatus (CRef. 5.917) • No other details or target or viewing conditions given	• Two-rod test: method of limits; 3-rod test: method of constant stimuli • Independent variables: disparity of variable rod, distance between stationary and variable rods • Dependent variable: threshold difference angle for stereoscopic vision • No other procedural details given

5.923 Stereoacuity: Effect of Field of View

Key Terms

Depth discrimination; retinal image disparity; size perception; stereoacuity; three-dimensional displays.

General Description

Stereoacuity (the ability to detect small displacements of a target in depth) declines as field size decreases.

Applications

Stereoscopic and autostereoscopic displays, especially those with a limited field of view. This decline occurs whether the target is stationary or moving.

Methods

Test Conditions

Study 1 (Ref. 1)

- Standard rod was black, 4.79 mm in diameter, oriented vertically in upper half of visual field and 100 cm from observer's eyes; similar comparison rod in lower half of visual field; observer could adjust distance to comparison rod; standard and comparison rods were laterally separated; standard rod moved back and forth in the frontal plane at one of five velocities (6.96, 10.05, 15.42, 20.42, or 39.40 deg/sec)
- Observer viewed area that included lower end of upper rod (standard) and upper end of lower rod (comparison); upper and lower boundaries of viewing area separated by 2.7 deg (screens forming boundaries were 21 cm from subject); left and right boundaries of viewing area separated by 2.3-20.4 deg
- Background formed by light box 250 cm from subject, illumination of 2 cd/m^2; darkened room
- **Binocular** viewing through 2.5-mm diameter artificial pupils

Study 2 (Ref. 2)

- Three vertical rods viewed through 12.7 x 35.6 cm (5 x 14 in.) window in a dark gray box; each rod subtended 0.06 deg; rods separated by 0.78 deg
- Box subtended 3.8 x 4.8 deg; window subtended 1.4 x 3.8 deg
- Two outer rods were stationary and located 559 cm from observer; middle rod was movable and was set at various positions closer or farther than the outer rods
- Observer viewed box and rods through pair of circular holes in screen 15.2 cm from eyes; holes adjusted to yield 3.8, 7.5, or 45 deg, or unrestricted field of view
- Ambient fluorescent illumination produced a background luminance of 3.4 cd/m^2 (1 fL); illumination of screen controlling field of view matched to wall behind box containing rods (~2 cd/m^2)
- Other laboratory equipment visible in larger fields of view

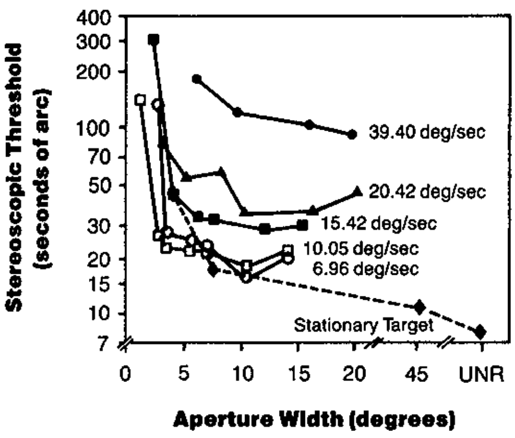


Figure 1. Stereoscopic threshold (on log scale) as a function of horizontal width of viewing aperture (field of view). "UNR" indicates an unrestricted field of view. Standard target moved at velocity shown next to each curve; comparison target was always stationary. Solid curves are from Study 1; dashed curve is from Study 2. (Adapted from Refs. 1, 2)

Experimental Procedure

Study1

- Method of adjustment
- Independent variables: width of field of view, target velocity
- Dependent variable: stereoscopic threshold, defined as the mean variable error in equidistance settings
- Observer's task: fixate the upper end of comparison (lower) rod and adjust it until it appeared equidistant with the moving upper (standard) rod
- 2 observers with better than 20/20 visual acuity and with extensive practice

Study 2

- Method of constant stimuli
- Independent variable: size of angular field of view
- Dependent variable: stereoscopic threshold, defined as disparity between rods at equidistance setting (setting at which comparison rod judged more distant on 50% of trials)
- Observer's task: judge comparison rod as nearer or farther than the two test rods
- 8 laboratory staff members as observers

Experimental Results

- Stereoacuity declines (stereoscopic threshold increases) as aperture size or as peripheral field of view decreases for both moving and stationary targets.
- Decline in stereoacuity is most marked with most restricted field of view.
- At all field sizes, stereoacuity declines as target velocity increases (and thus exposure time decreases).
- Decline in stereoacuity with decrease in field of view is most marked for observers with the poorest stereoacuity under unrestricted viewing (Study 2).

Variability

Standard deviation of equidistance settings increases with decrease in field of view (Study 2).

Constraints

- Field size was confounded with viewing time in Study 1.
- Many factors (such as target luminance and orientation) affect stereoacuity and must be considered in applying these results under different viewing conditions (CRef. 5.918).
- In some individuals, stereoscopic vision may be poor or lacking, or may function in an anomalous way.
- Stereoacuity is strongly affected by practice.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Lit, A., & Vicars, W. M. (1970). Stereoacuity for oscillating targets exposed through apertures of various horizontal extents. *Perception & Psychophysics, 8,* 348-352.

*2. Luria, S. M. (1969). Stereoscopic and resolution acuity with various fields of view. *Science, 164,* 452-453.

Cross References

5.918 Factors affecting stereoacuity;

5.925 Stereoacuity: effect of lateral target motion

5.924 Stereoacuity: Effect of Target Orientation

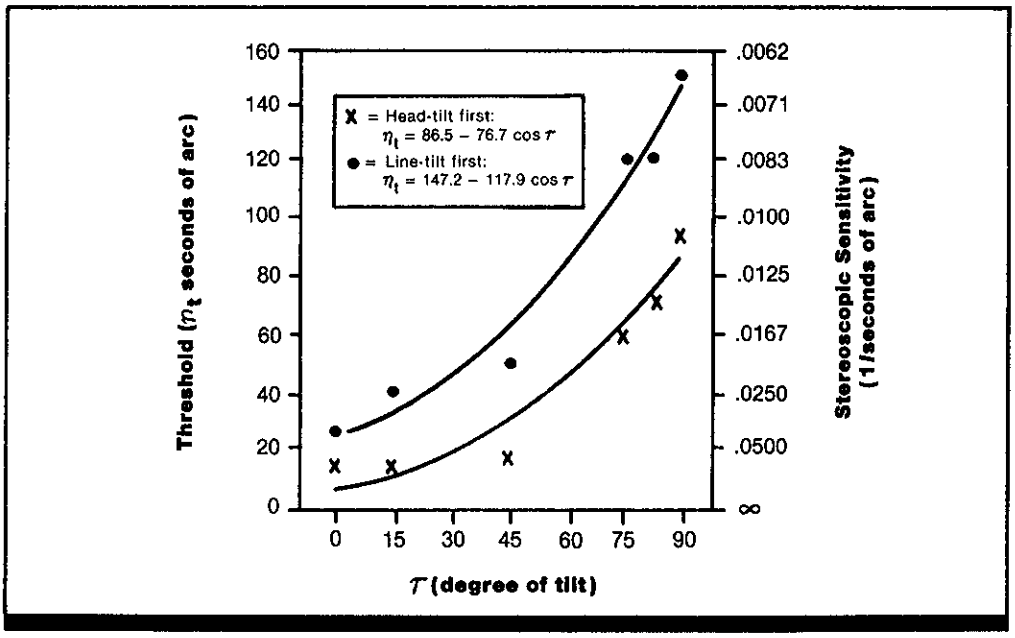


Figure 1. Stereoacuity for different target orientations. (From Ref. 2)

Key Terms

Depth discrimination; retinal image disparity; spatial orientation; stereoacuity; three-dimensional displays

General Description

The smallest difference in **retinal image disparity** required for the perception of depth between two thin lines increases as the orientation of the lines in the frontal plane departs from the vertical. Stereoscopic thresholds are lowest (sensitivity is greatest) when lines are upright; thresholds increase slowly for angles <45 deg from the vertical, then rise sharply as the lines approach the horizontal. **Stereoacuity** declines slightly less when the head is tilted and the lines remain upright than when the lines themselves are tilted.

Applications

Displays requiring depth judgments must take account of different stereoscopic sensitivities for elements at nonvertical orientations, especially those at inclination angles >45 deg.

Methods

Test Conditions

- Two luminous lines produced by masking of electroluminescent panels, each line 0.8 mm wide and 41.5 mm long, constant lateral separation of 65 mm; luminance 0.003 cd/m^2
- Both lines adjustable in depth; at equidistant setting, lines 2 m from observer; no fixation point provided; head constrained by bite bar; eye movements unrestricted; dark room
- Line-tilt condition: lines rotate together about axis located at horizontal and vertical midpoint of line configuration; head-tilt condition: lines remain vertical, observer's head rotated about same axis
- Six different tilt values at 0-90 deg from vertical; depth between test lines varied, nine different steps for each tilt (range: 0 to ±50 mm for vertical orientations, 0 to +150 mm for horizontal orientations)

Experimental Procedure

- Method of constant stimuli
- Independent variables: degree of tilt and depth between target lines, random presentation order; line-tilt condition first or head-tilt condition first, trials blocked by condition
- Dependent variable: smallest detectable depth difference of target lines, defined as difference between depth values associated with 50% and 75% correct response probabilities at each tilt
- Observer's task: judge whether right line appeared nearer or farther than left line; 10-sec limit for judgment
- 18 trials per data point
- 6 observers screened for "adequate" stereopsis and trained briefly on task

Experimental Results

- Minimum detectable depth difference increases as target orientation departs from the vertical. This increase in stereothreshold is proportional to the cosine of the angle of tilt and can be described by:

$$\text{threshold disparity} = a - b\cos\theta \qquad (1)$$

where θ = angular tilt in degrees from the vertical; a and b are empirically determined constants, with a = disparity threshold for horizontal lines and $(a - b)$ = threshold for vertical lines. Data functions in Figure 1 were generated by least-squares fit of Eq. 1, averaged over observers. Data for line-tilt and head-tilt conditions are pooled. Coefficients of determination (r^2, square of product-moment correlations) = 0.98 for line-tilt-first group and 0.94 for head-tilt-first group, indicating satisfactory fit to the data.

- Mean stereoscopic threshold is slightly lower with head tilt than with line tilt (60.1 versus 73.9 sec arc of visual angle, averaged over observers and degree of tilt).
- Mean stereoscopic thresholds are lower for observer group administered head-tilt condition first than for observer group receiving line-tilt condition first.

Variability

Standard errors of estimate for fits to Eq. 1 are 7.31 for line-tilt-first group and 7.48 for group given head-tilt condition first; no other information on variability reported.

Repeatability/Comparison with Other Studies

Other studies (Refs. 1, 3) have also found a cosine function to fit results of similar experiments.

Constraints

- Results obtained with thin lines have not been empirically generalized to other visual features such as edges or more complex forms. In application to complex two-dimensional targets, cosine relationship should be considered as a guideline only.
- Computed values for a and b of Eq. 1 given here hold only for the viewing conditions described and should not be applied, except qualitatively, when these conditions differ.
- A number of factors (such as target luminance, distance between target elements, etc.) influence stereoacuity and should be considered when applying these results under different viewing conditions (CRef. 5.918).
- There are large individual differences in stereoscopic vision.
- Stereoacuity is affected by practice.

Key References

1. Blake, R., Camisa, J., & Antonetti, O. (1976). Binocular depth discrimination depends on orientation. *Perception & Psychophysics, 20*, 113-118.

*2. Ebenholtz, S. M., & Walchli, R. M. (1965). Stereoscopic thresholds as a function of head- and object-orientation. *Vision Research, 5*, 455-461.

3. Ogle, K. N. (1955). Stereopsis and vertical disparity. *Archives of Ophthalmology, 53*, 495-504.

Cross References

5.905 Lateral retinal image disparity;

5.918 Factors affecting stereoacuity

5.925 Stereoacuity: Effect of Lateral Target Motion

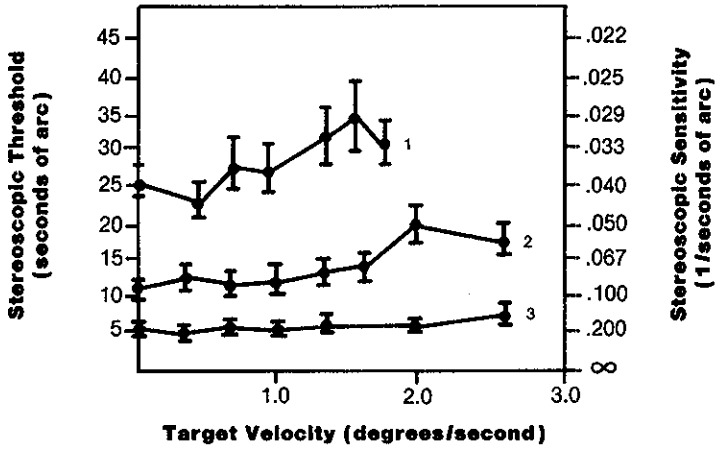


Figure 1. Stereoscopic threshold as a function of target velocity for three observers. (From Ref. 1)

Key Terms

Depth discrimination; retinal image disparity; stereoacuity; three-dimensional displays

General Description

The threshold for detecting a relative depth difference between two briefly presented thin lines remains unaffected if either or both of the lines are moving laterally with velocities up to 2.5 deg/sec.

Applications

Stereoscopic, autostereoscopic, and volumetric displays

Methods

Test Conditions

- Two white vertical lines displayed on CRT, each 15.5 min arc of visual angle long and 1 min arc wide, separated vertically by 3 min arc; luminance 64 cd/m^2; dark background; viewing distance 2.5 m; stereoscopic presentation using cross-polarization method of image separation (CRef. 5.914)
- Upper line possessed **convergent** or **divergent lateral retinal image disparity** of 8, 16, or 24 min arc relative to lower line; lines presented simultaneously for 190 msec, both moving laterally with velocity of 0-2.5 deg/sec; lines had same motion in both eyes and did not move in depth
- Fixation plane indicated by four corner dots describing a square 30 min arc in side length, invisible during trials; central foveal presentation

Experimental Procedure

- Method of constant stimuli; feedback provided
- Independent variables: horizontal target velocity, disparity of upper line relative to lower line
- Dependent variable: minimum disparity for correct detection of depth at each target velocity, defined as half the distance between the values corresponding to 25% and 75% correct judgments as determined by probit analysis of observer's responses
- Observer's task; judge upper line as nearer or farther than lower line
- ~300 trials per data point
- 3 highly practiced observers

Experimental Results

- Stereoacuity is unaffected by target motions up to about 2.5 deg/sec.
- Stereoacuity remains unaffected if lower line is stationary while only upper line moves.

Variability

Standard error bars are derived from probit analysis of responses.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Only relatively low velocities were studied. Higher lateral velocities probably lead to a decline of stereoacuity, but the velocity at which this occurs may depend on the spatial distribution of display.
- Results apply only to laterally moving stimuli that remain stationary in depth.
- A number of factors (such as target luminance, orientation of target elements, etc.) are known to influence stereoacuity and should be considered when applying these results under different viewing conditions (CRef. 5.918).
- Stereoacuity is affected by practice.
- The 3 observers in this study varied greatly in stereoacuity, with depth thresholds for stationary (0 velocity) targets of approximately 5, 11, and 27 min arc. Large variability in stereoacuity among people with normal visual acuity is the rule.

Key References

*1. Westheimer, G., & McKee, S.P. (1978). Stereoscopic acuity for moving retinal images. *Journal of the Optical Society of America, 68*, 450-455.

Cross References

5.905 Lateral retinal image disparity;

5.914 Filter separation and free stereoscopic display methods;

5.918 Factors affecting stereoacuity

5.926 Stereoacuity: Effect of Exposure Duration

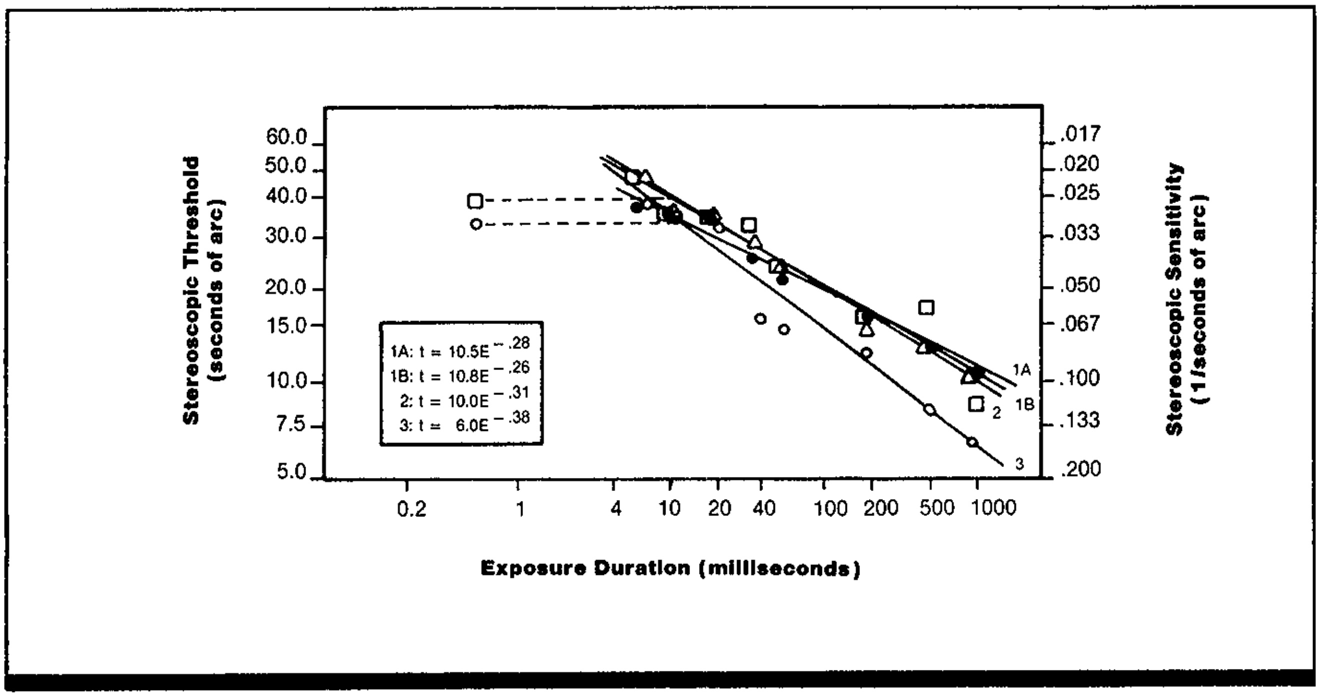


Figure 1. Stereoacuity as a function of exposure duration for 3 observers. Data points at shortest duration are for targets presented via electronic flash tube and show average threshold for targets of four (Observer 3) or five (Observer 1A) different luminances. For Observers 1B, 2, and 3, reference line was 3.5 mm nearer than fixation; for Observer 1A, reference point was in fixation plane. (From Ref. 2)

Key Terms

Depth discrimination; exposure duration; retinal image disparity; stereoacuity; three-dimensional displays

General Description

Ability to detect depth between targets (to discriminate **lateral retinal image disparities**) is reduced as target duration decreases.

Applications

Stereoscopic, autosteroscopic, and volumetric displays.

Methods

Test Conditions

- Three vertical lines 3.5 deg long, including fixation line with fixation point, reference line 0.5 deg to left and adjustable in disparity, and test line 0.5 deg to right; viewing distance 50 cm
- Targets set against bright white background with luminance of 101.86 cd/m^2; luminance of test line 510 cd/m^2; reference and fixation lines silhouetted against background, luminance not specified
- Test target presentation duration varied between 0.2 and 1000 msec, using mechanical photographic shutter, except targets of 0.2-msec duration presented by electronic flash at unspecified target luminance

Experimental Procedure

- Method of constant stimuli, two-alternative forced-choice procedure
- Independent variable: duration of target presentation
- Dependent variable: minimum discriminable disparity between test and reference targets, defined as standard deviation of probability density function underlying cumulative normal distribution fitted to obtained psychometric function
- Observer's task: report whether test target is "nearer" or "farther" than reference
- 100 trials per data point
- 3 observers, 1 practiced and 2 unpracticed

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- As target duration decreases from 1000 to 5 msec, disparity difference threshold increases from 10 to 40 sec arc (fourfold increase).
- Data appear well-fit by a function of the form

$$t = t_0 E^{-a}$$

where t_0 = threshold for a 1-sec exposure, E = exposure time, and a = a constant. Method of fitting not specified.
- Similarity in thresholds for 5- and 0.2-msec exposures suggests a leveling off of threshold at ~40-50 sec arc at durations <5 msec.

Variability

Good consistency within and between subjects, but no specific estimates are provided.

Repeatability/Comparison with Other Studies

Findings are similar, though not directly comparable, to those reported in Refs. 1 and 3.

Constraints

- Findings have not been extended to targets at **scotopic** (night vision) luminance levels.
- A lower limiting threshold value can be expected for durations >1 sec equal to the stereoacuity threshold for targets presented continuously.
- A number of factors (target luminance and orientation, etc.) are known to influence stereoacuity and should be taken into account in applying these results under different viewing conditions (CRef. 5.918).
- There are large individual differences in stereoscopic vision.
- Stereoacuity is affected by practice.

Key References

1. Foley, J. M., & Tyler, C. W. (1976). Effect of stimulus duration on stereo and vernier displacement thresholds. *Perception & Psychophysics, 20*, 125-128.

*2. Ogle, K. N., & Weil, M. A. (1958). Stereoscopic vision and the duration of the stimulus. *Archives of Ophthalmology, 59*, 4-17.

3. Shortess, G. K., & Krauskopf, J. (1961). Role of involuntary eye movements in stereoscopic acuity. *Journal of the Optical Society of America, 51*, 555-559.

Cross References

5.905 Lateral retinal image disparity;

5.918 Factors affecting stereoacuity

5.927 Stereoacuity: Effect of Vertical Disparity

Key Terms

Binocular image registration; depth discrimination; double vision; retinal location; stereoacuity; three-dimensional displays; vertical misalignment; vertical retinal image disparity; visual field location

General Description

Ability to discriminate small differences in depth (due to changes in **lateral retinal image disparity**) persists even with vertical target disparities of up to 25 min arc of visual angle which produce double vision (diplopia). Both stereoacuity and the upper vertical disparity limit beyond which stereopsis ceases to function decrease as lateral retinal disparity increases and as target distance from fixation increases.

Applications

Stereoscopic and autostereoscopic displays with significant vertical misalignment of the half-fields.

Methods

Test Conditions

- A small illuminated fixation point and point source test light viewed through apertures and seen against a distant white background; vertical disparity of test light variable by optical and mechanical means
- 50-cm viewing distance; test light flashed for 200 msec
- Five equally spaced disparities within an informally determined range for each observer
- Target dot: 0.5 deg or 4 deg to one side of fixation dot

Experimental Procedure

- Method of constant stimuli
- Independent variables: vertical disparity of half-images of test light, target distance from fixation
- Dependent variable: stereoacuity reciprocal of threshold in min arc, with threshold defined as the estimated standard deviation of disparities to which observer is equally likely to respond "nearer" and "farther"
- Observer's task: judge if test light is nearer or farther than fixation point
- 2 observers, one inexperienced (observer 1) and one experienced (observer 2)

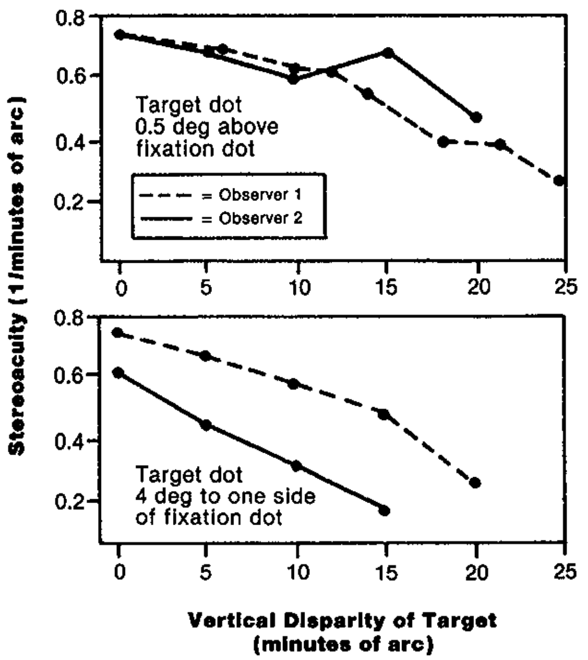


Figure 1. Reduction of stereoacuity with increasing vertical disparity. (From Ref. 2)

Experimental Results

- Stereoacuity decreases with increased vertical disparity for both observers.
- Stereoacuity deteriorates faster with increased distance from fixation, shown by greater slope of functions at 4 deg than at 0.5 deg from fixation.
- Analysis of responses shows direction of depth correctly identified for up to 25 min arc vertical disparity when target was 0.5 deg above fixation point.
- The upper vertical disparity limit (not shown on graph) decreases with lateral disparity and target distance from fixation.

Variability

No information on variability was given.

Constraints

- In some individuals, stereoscopic vision may be poor or lacking or may function in an anomalous way.
- A number of factors (target luminance and orientation, etc.) are known to influence stereoacuity and should be considered when applying these results (CRef. 5.918).
- Stereoacuity is strongly affected by practice.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Ogle, K. N. (1950). *Researches in binocular vision*. Philadelphia: Saunders.

*2. Ogle, K. N. (1955). Stereopsis and vertical disparity. *Archives of Ophthalmology, 53*, 495-504.

Cross References

5.906 Vertical retinal image disparity;

5.918 Factors affecting stereoacuity;

5.920 Stereoacuity: effect of target location in the visual field;

5.921 Stereoacuity: effect of relative disparity;

5.928 Response time and accuracy of depth judgments: effect of vertical disparity

5.928 Response Time and Accuracy of Depth Judgments: Effect of Vertical Disparity

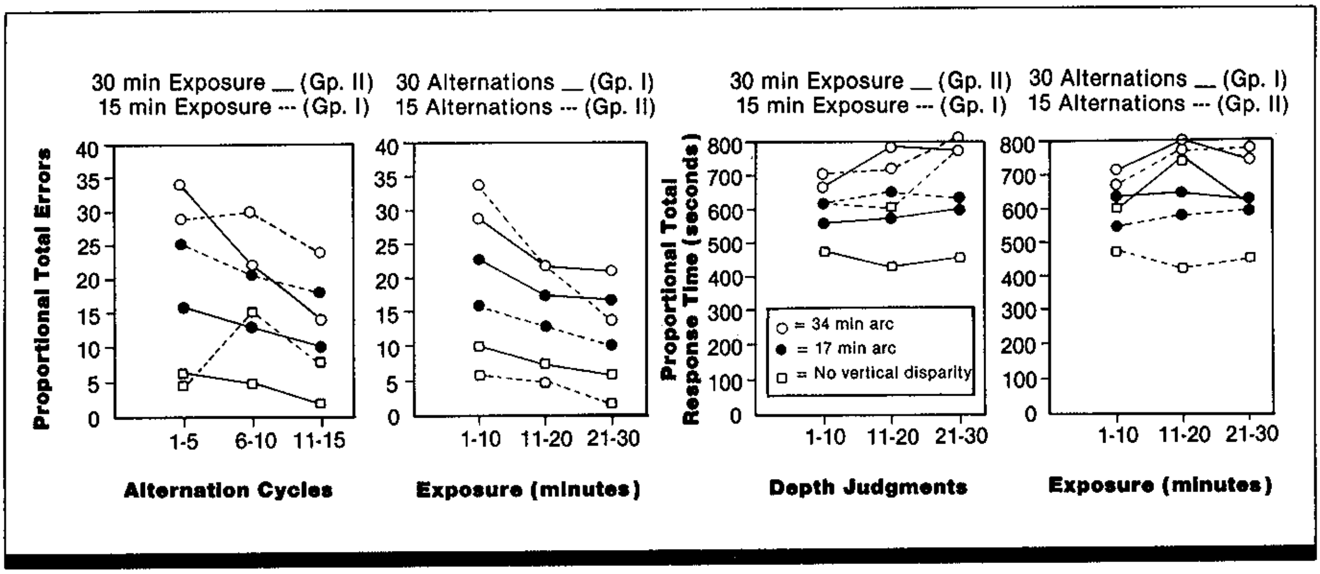


Figure 1. Relative accuracy and latency (response time) of depth judgments in the presence of vertical retinal image disparity. Vertical misalignment alternated from 0 disparity to 0, 17, or 34 min disparity, either once or twice per minute, for 15 or 30 min exposure periods. (From Ref. 1)

Key Terms

Binocular image registration; depth perception; reaction time; stereoacuity; three-dimensional displays; vertical misalignment; vertical retinal image disparity

General Description

Vertical misalignment of target images in the two eyes (vertical retinal image disparity) decreases the accuracy of stereoscopic depth judgments and increases the time required to make such judgments, especially when the eyes must frequently readjust to the vertical disparities.

Applications

Stereoscopic and autostereoscopic display designs, especially those with unstable vertical alignment between the two half-fields.

Methods

Test Conditions

- Modified Howard-Dolman apparatus with black opaque diamonds mounted on glass plates replacing rods (CRef. 5.917); two diamonds 24.8 min of visual angle high, 18 min wide, separated by 36 min arc laterally; horizontal disparity (convergent or divergent) of diamonds 11 sec arc
- 6.1-m (20-ft) viewing distance; targets viewed through rectangular aperture 42 min arc high by 107 min arc wide; white translucent Lucite background illuminated to 185 cd/m²; small fixation cross provided
- Plano lens on right eye; plano lens on left eye interchanged with either 0.5 diopter, 1 diopter, or plano lens every 30 or 60 sec, so that every 30 or 60 sec, half-fields changed state from 0 vertical disparity to either 17 or 34 min vertical disparity, or disparity remained unchanged

Experimental Procedure

- Two-alternative forced-choice paradigm; trials blocked by disparity condition; one depth judgment per interval of prism alternation (two per full cycle)
- Independent variables: degree of vertical disparity, number of prism alternation cycles, exposure interval
- Dependent variables: number of errors in depth judgment and response time per block of alternation cycles, errors and response time per 10-min block of exposure
- Observer's task: indicate whether the left or the right diamond target appeared in front
- No feedback given
- 18 observers exposed to one vertical disparity alternation cycle per min (Group I), 18 observers exposed to 0.5 alternation cycle per min (Group II); all had normal or corrected-to-normal **visual acuity**, and normal lateral and vertical phoria (CRef. 1.809)

Experimental Results

- Number of errors and response time increase with increasing vertical disparity. (Since Group I had twice the number of vertical disparity alternation cycles per 30-min period as Group 2, data from the final 15 cycles are discarded for that group when errors are analyzed as a function of number of alternation cycles).
- Accuracy of depth judgments, but not response time, improves as the number of vertical disparity alternations increases and as exposure time increases; however, accuracy also improves when there is no vertical disparity, so the improvement cannot be attributed to adaptation to vertical disparities.
- Alternation rate (one versus two vertical disparity alternations per minute) does not influence performance.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Stereoacuity decreases with increasing vertical disparity when compensatory eye movements are not allowed (CRef. 5.927), but adaptation (motor readjustment) also occurs, given sufficient time, to vertical disparity of up to ~1 deg (CRef. 5.912). The latter result suggests that rate of alternation should affect performance in the present study; this did not happen, according to the authors, due to the relative insensitivity of the measures used.

Constraints

- Reference 2 found that adaptation to vertical misalignment took place after 2-16 min, so alternation rate may affect performance when slower rates are used.
- The difference in response times between Groups I and II for the 0 disparity condition suggests that the groups were not adequately matched in baseline performance.
- No data comparing performance on plano lens intervals with prism intervals are given; if alternation rates were too fast for adaptation to occur, performance would be better in the plano intervals.
- In some individuals, stereoscopic vision may be lacking or may function in an anomalous way.
- Stereoacuity is strongly affected by practice.
- A number of factors (such as target orientation, illumination level, etc.) influence stereoacuity and should be considered in applying these results under different viewing conditions (CRef. 5.918).

Key References

*1. Harker, G. S., & Henderson, A. C. (1956). Effect of vertical misalignment of optical images on depth judgments. *Journal of the Optical Society of America, 46,* 841-845.

2. Ogle, K. N., & Prangen, A. deH. (1953). Observations on vertical divergences and hyperphorias. *Archives of Ophthalmology, 49,* 313-334.

Cross References

1.809 Phoria;

5.906 Vertical retinal image disparity;

5.912 Tolerance for vertical disparity;

5.917 Stereoacuity tests;

5.918 Factors affecting stereoacuity;

5.927 Stereoacuity: effect of vertical disparity

5.929 Relations Among Real Depth Acuity, Stereoacuity, and Vernier Acuity

Key Terms

Depth discrimination; pattern resolution; retinal image disparity; stereoacuity; three-dimensional displays; vernier acuity

General Description

Measurement of **stereoacuity** with a **stereoscope** and with real three-dimensional depth targets gives equivalent results. Hence, although there are other cues to depth, stereopsis (sensation of three-dimensionality arising from **lateral retinal image disparity**) gives the first resolution. **Vernier acuity**, another measure of visual spatial resolution with typical values of the same order as stereoacuity, is better than the latter when the separation of the vernier test contours (and the vertical separation of stereoscopic contours) is less than ~2 min arc of visual angle. At separations >2 min, stereoacuity is better.

Methods

Test Conditions

- Two vertical rods (2.4 min diameter) subtending 107 sec, placed one above the other; bottom rod physically moved laterally or in depth for vernier alignment and real depth tasks, respectively; retinal disparity of bottom rod altered, using a stereoscope for stereoscopic task
- Optical distance to rods 4.62 m in all conditions
- Viewed through 1-deg 23-min × 20-min aperture against white background

Experimental Procedure

- Method of constant stimuli with five positions of the bottom (variable) rod
- Independent variable: vertical angular separation between upper and lower rods
- Dependent variable: depth threshold or vernier threshold, defined as half the disparity (or vernier displacement) corresponding to a graphically estimated ±25% deviation from chance (50%) performance
- Observer's task: for real depth and stereoscopic conditions, report whether lower rod is in back or front of upper rod; for vernier condition, report whether lower rod is to left or right of upper rod
- Each data point is derived from >200 trials
- 3 practiced observers

Experimental Results

- Vernier discrimination is maximal and better than stereoscopic and real depth discrimination for rod separation less than ~45 sec arc.
- For separations greater than ~40 sec arc, vernier thresholds are progressively higher than the corresponding real and stereoscopic depth thresholds (i.e., vernier acuity is less than real and stereoscopic depth acuity).
- Stereoscopic and real depth thresholds are similar to one another and are similarly affected by vertical separation of rods, with optimal separation at ~310 sec arc.

Variability

Within-subject variability not given; between-subject variability low by visual inspection of Fig. 1.

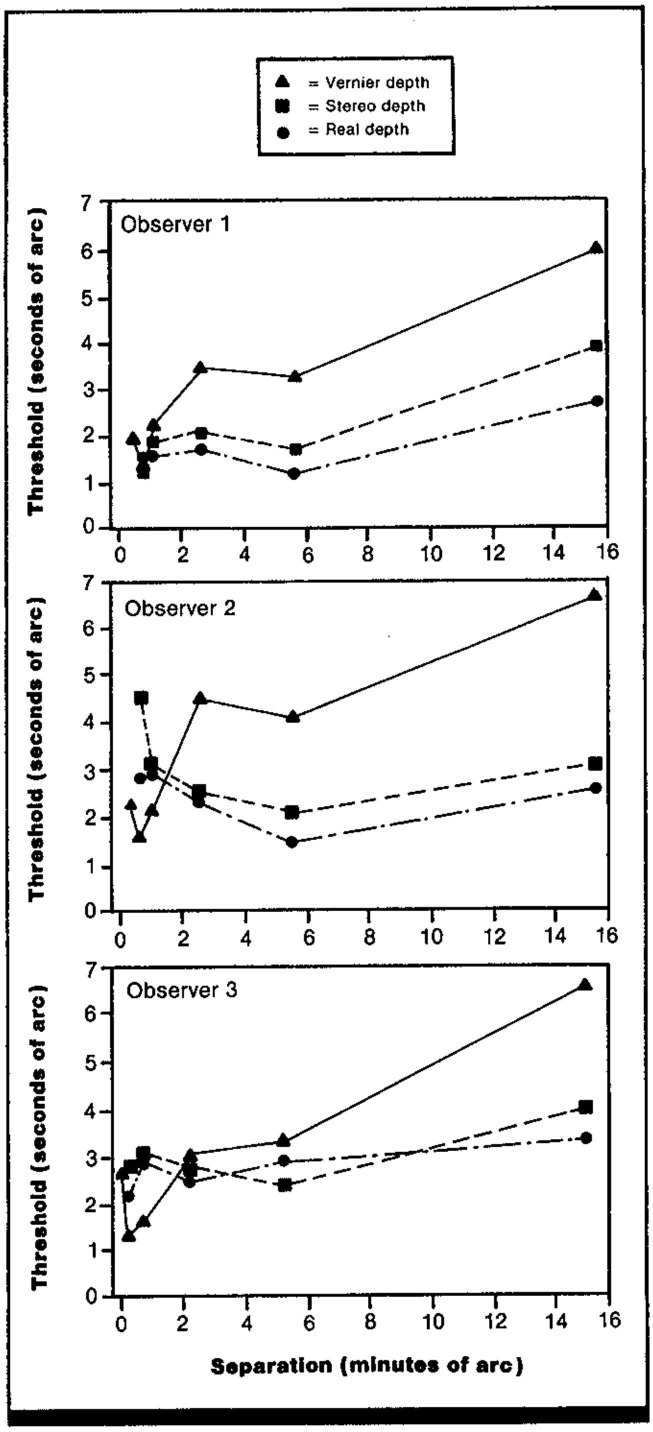


Figure 1. Stereoscopic depth, real depth, and vernier depth thresholds as a function of vertical separation between target lines. Data are shown for three observers. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Many factors influence both stereoacuity and vernier acuity and should be considered when applying these results under different viewing conditions (CRefs. 1.603, 5.918).

• Stereoacuity (and hence real depth acuity) is generally known to be strongly affected by practice.

• There are individual differences in both visual acuity and stereoacuity; stereoscopic vision may be lacking or may function in an anomalous way in some individuals.

Key References

*1. Berry, R. N. (1948). Quantitative relations among vernier, real depth, and stereoscopic depth acuities. *Journal of Experimental Psychology, 38,* 708-721.

2. Graham, C. H. (1965). Visual space perception. In C. H. Graham (Ed.), *Vision and visual perception*. New York: Wiley.

Cross References

1.603 Factors affecting visual acuity;

5.918 Factors affecting stereoacuity

5.930 Limits of Stereoscopic Depth Perception

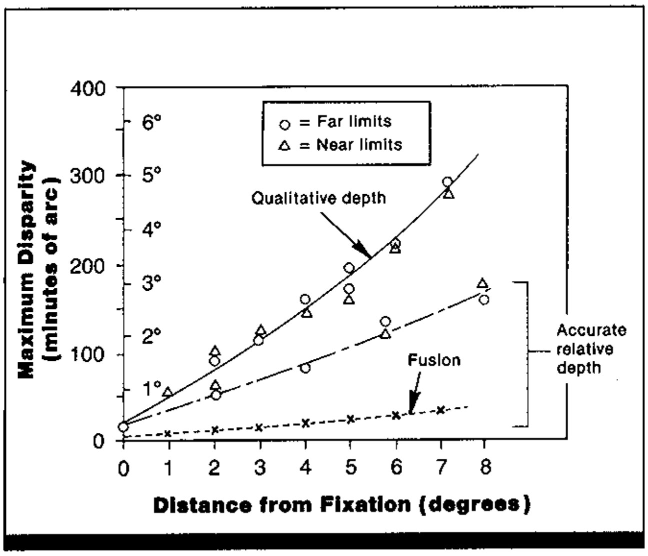


Figure 1. Maximum retinal image disparity that gives rise to different types of stereoscopic depth for targets at varying lateral distances from fixation. Disparity limits are shown for: (1) fusion of left and right retinal images; (2) accurate judgment of relative depth; (3) accurate qualitative depth judgment of target as nearer or farther than fixation point. Data are shown for one trained observer. (From Ref. 1)

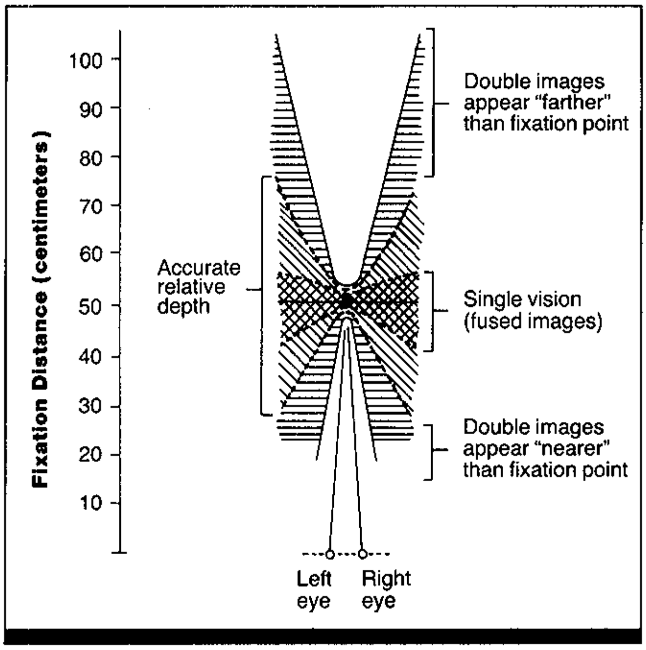


Figure 2. Regions in space corresponding to disparity limits plotted in Fig. 1 for fixation distance of 50 cm in the plane defined by the optical nodes of the eye and the fixation point. No depth occurs in the unshaded regions. (Adapted from Ref. 1)

Key Terms

Binocular fusion; depth perception; double vision; retinal image disparity; single vision; three-dimensional displays

General Description

As the **lateral retinal image disparity** (CRef. 5.905) of a target increases, the experience of stereoscopic depth perception changes, until at relatively large disparities, stereoscopic vision breaks down altogether.

When retinal image disparity is small, the perceived depth of a target varies linearly with lateral retinal image disparity. Observers are able to discriminate both the direction of depth of an object (nearer or farther than fixation) and the relative depth between objects. (This is sometimes known as patent stereopsis.) At disparities less than ~20 min arc of visual angle, the target appears single (left and right eye images are fused); at slightly larger disparities, the target appears double (diplopic), but this does not interfere with its accurate localization in depth.

As disparity continues to increase, perceived depth no longer varies in a regular way; however, observers are still able to discriminate whether a target is nearer or farther than the point being fixated (qualitative stereopsis). Finally, at very large disparities, stereoscopic depth perception is no longer possible.

The upper disparity limit for image fusion, accurate relative depth, and qualitative depth perception increases with increasing angular distance from the fixation point. Because the changes with distance from fixation are large, the disparity limits of these functions may overlap; however, each type of stereoscopic depth perception operates within a specifiable region of the third dimension (Fig. 2).

Methods

Test Conditions

- Illuminated fixation spot 0.25 mm diameter
- Vertical target line 2 deg high, produced by projection of needle onto plate glass viewed through rotatable half-silvered mirrors so virtual image appears at variable depths; target disparity continuously variable
- Viewing distance 50 cm; observer's head held rigid in headrest and chin cup; semi-darkened room
- Luminance of targets, background not reported

Experimental Procedure

- Method of adjustment, method of constant stimuli
- Independent variables: retinal disparity, angular distance of target from fixation point
- Dependent variables: maximum disparity at which observer reported (1) single vision (fusion) (2) impression of increasing or decreasing (relative) depth (3) impression of correction direction (near or far) of depth
- Observer's task: report when limiting disparity reached for each of the dependent variables
- 2 observers, one untrained, one highly trained

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Maximum disparity limits for single vision (fusion), relative (quantitatively accurate) depth, and "qualitative" depth increase monotonically with distance from fixation up to 7 deg peripheral angle.
- As disparity increases from zero, fusion is lost first, then accurate relative depth, then qualitative depth.
- For peripheral angles less than ~5-7 deg, the regions of the third dimension in which each type of stereoscopic vision is operative can be determined to a close approximation by the following formula:

$$\Delta D = \pm \delta D^2/(i \pm \delta D)$$

where ΔD is the distance from the plane of fixation to a given point on the limiting boundary for the specific type of stereoscopic vision, δ is the limiting disparity in radians for this type of stereoscopic vision, D is the distance from the observer's eyes to the fixation point, and i is the interpupillary distance. (By convention, δ is taken as positive for points further than fixation and negative for points closer than fixation.)

Figure 2 plots the limiting boundaries in three-dimensional space for fusion, accurate relative depth, and qualitative depth at peripheral angles <7 deg to the left and right of fixation from a viewing distance of 50 cm.

Variability

Considerable variability reported, but no specific estimates are provided.

Repeatability/Comparison with Other Studies

In Ref. 3, perceived depth was found to be related monotonically to disparity for disparities in excess of those producing accurate relative depth in the present study; however, apparent depth in this region *decreases* with increasing disparity.

Constraints

- Disparity limits for stereoscopic depth and singleness of vision vary widely across observers and individual studies (CRef. 5.911).
- Target-related factors known to influence stereoacuity may also influence limits for stereoscopic depth and singleness of vision (CRef. 5.918).
- Fusion limits are generally larger for more complex targets.

Key References

*1. Ogle, K.N. (1952). Disparity limits of stereopsis. *Archives of Ophthalmology, 48*, 50-60.

2. Ogle, K.N. (1962). Spatial localization through binocular vision. In H. Davson (Ed.), *The eye* (Vol. 4). New York: Academic Press.

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Cross References

5.905 Lateral retinal image disparity;

5.911 Limits of single vision;

5.916 Perceived depth as a function of lateral retinal image disparity;

5.918 Factors affecting stereoacuity

5.931 Stereoscopic Depth Perception: Limiting Differences in Left and Right Half-Images

Dimension of Interocular Difference	Probable Limit for Stereopsis	Phenomenological Effects	Source
Luminance	Contrast detection threshold with lower luminance	With moving targets, target's apparent position in depth is distorted and depends on speed and horizontal component of motion	Ref. 3 CRef. 5.933
Adaptation level	Absolute detection threshold of **light-adapted** eye	Similar to effects with interocular luminance difference, but adaptation produces less depth distortion	Ref. 3 CRef. 5.933
Contrast	Contrast detection threshold or slightly above for lower contrast eye	Distortion of tilt about a vertical axis reported by some but denied by others	Ref. 1
Half-image onset asynchrony	Stimulus energy (luminance x time) for brief-image presentation; maximum **monocular** visual persistence for longer presentations (~80 msec)	With moving targets, target's apparent position in depth depends on speed and horizontal component of motion	Ref. 2 CRef. 5.933
Size and shape	Ability to maintain vertical registration of half-images; vertical magnification differences of at least 20% can be tolerated; even greater horizontal magnification differences can be tolerated	Distortions of tilt about a vertical axis	CRef. 5.909
Image quality (blur and spatial filtering)	Ability to identify correspondent contours in the two eyes. **Stereoacuity** deteriorates more with high-pass than low-pass filtering	None reported	Ref. 4

Key Terms

Aniseikonia; binocular image registration; depth perception; interocular contrast difference; interocular focus difference; interocular luminance difference; interocular onset asynchrony; interocular shape difference; interocular size difference; retinal image disparity; three-dimensional displays

General Description

The left and right half-images (left and right eye views) in a stereoscopic display may differ markedly along some dimensions without destroying stereoscopic depth, although the magnitude of apparent depth and/or ability to detect the presence of depth may be radically altered. The table lists a number of such half-image differences, the probable limiting factors that determine at which level of difference stereopsis would be destroyed, the associated phenomenological effects, and sources of additional information.

Applications

Stereoscopic displays.

Constraints

- Stereoacuity generally declines continuously with any difference between the half-images.
- Qualitative stereopsis, yielding direction but not magnitude of depth, may be present for any targets capable of eliciting vergence eye movements (CRefs. 1.950, 1.952).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blakemore, C. (1970). A new kind of stereoscopic vision. *Vision Research, 10,* 1181-1199.

2. Engel, G. R. (1970). An investigation of visual responses to brief stereoscopic stimuli. *Quarterly Journal of Experimental Psychology, 22,* 148-160.

3. Rogers, B. J., & Anstis, S. M. (1972). Intensity versus adaptation and the Pulfrich stereophenomenon. *Vision Research, 12,* 909-928.

4. Westheimer, G., & McKee, S. P. (1980). Stereoscopic acuity with defocused and spatially filtered retinal images. *Journal of the Optical Society of America, 70,* 772-778.

Cross References

1.950 Factors affecting vergence eye movements;

1.952 Vergence eye movements: eliciting target characteristics;

5.909 Binocular differences in image size and shape (aniseikonia);

5.933 Illusory depth with interocular differences in luminance or onset delay (Pulfrich and Mach-Dvorak effects)

5.932 Depth Perception with Unequal Numbers of Contours in the Two Eyes

Key Terms

Depth perception; Panum's limiting case; retinal image disparity; three-dimensional displays

General Description

Unequal numbers of contour elements in the two eyes may give rise to apparent depth. When one eye views a fixation line and a second line, and the other eye views only the fixation line, two lines are seen and are perceived as being displaced in depth relative to one another. Three lines or points (two presented to one eye and one to the other) represent the minimum stimulus condition for the production of stereopsis; this is known as Panum's limiting case.

Figure 1a shows the basic stereograms which produce the effect; the top views in Fig. 1b show the physical arrangement of objects which might produce depth perception in this sort. In both cases, f_L and f_R are foveally fixated, and line g is behind f, and falls on the line of sight of f in one eye. The visual system presumes that one eye's view of g is occluded by f, and veridical depth (depth true to the physical situation) is perceived.

Fixation to the other object in depth may be achieved without affecting relative apparent depth between the two objects. For example, one may align g_L with f_R **binocularly** in the stereogram on the left in Fig. 1a making (f_R, g_L) the fixation object. In this case, f_R will be the monocular element, and the right eye's view of g on the fixation plane will be presumed to be occluded by the closer object f. However, the phenomenon also occurs with stereograms that are impossible to realize in physical space, such as a fixation dot in both eyes and a single line in one eye (impossible because the dot is too small to occlude the line). Panum's limiting case occurs not only with three contour elements, but in a variety of cases in which there is an extra contour element in one eye.

Generally, observers report apparent depth that is consistent with the **lateral retinal image disparity** between the closest binocular element and the **monocular** element. Hence, apparent depth grows with increasing lateral separation between the nearest binocular element and the monocular element. This is what would be expected if the binocular element corresponds to an object in space that occludes the monocular element in one eye (Ref. 1). However, occasionally, depth locations inconsistent with possible physical arrangements are also reported, especially depth reversals. Reference 2 describes a theory which accounts for perceived depth in Panum's case and the reversals on the basis of slight fixation disparities. This theory, however, predicts a slightly smaller amount of apparent depth than has been reported.

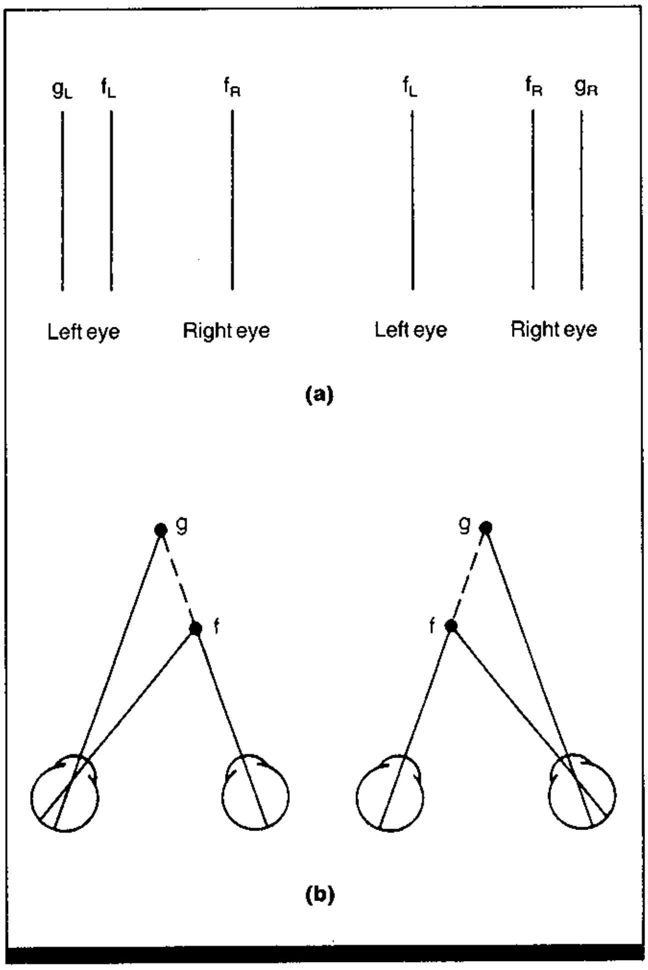

Figure 1. (a) Panum's limiting case stereograms and (b) top views of physical arrangements consistent with the stereograms in (a). (From *Handbook of perception and human performance*)

Applications

Stereoscopic and autostereoscopic displays in which information may be simultaneously presented both binocularly and monocularly.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• The use of Panum's limiting case for presentation of depth information is not reliable due to wide variability in resultant apparent depth within and between individuals.
• Reversals in apparent depth due to Panum's case have been reported only with stereoscopic presentation, and not with objects arranged in physical space where one eye's view of an object is occluded.
• Where monocular elements exist due to occlusion by an exit pupil (CRef. 1.209), there are other cues to relative depth, and apparent depth will generally be valid.

Key References

1. Gettys, C. F., & Harker, G. S. (1967). Some observations and measurements of the Panum phenomenon. *Perception & Psychophysics, 2*, 387-395.

2. Kaufman, L. (1978). *An explanation of Panum's limiting case.* Unpublished manuscript, New York University, New York.

Cross References

1.209 Visual optics;

5.905 Lateral retinal image disparity;

5.916 Perceived depth as a function of lateral retinal image disparity;

Handbook of perception and human performance, Ch. 23, Sect. 3.3

5.933 Illusory Depth with Interocular Differences in Luminance or Onset Delay (Pulfrich and Mach-Dvorak Effects)

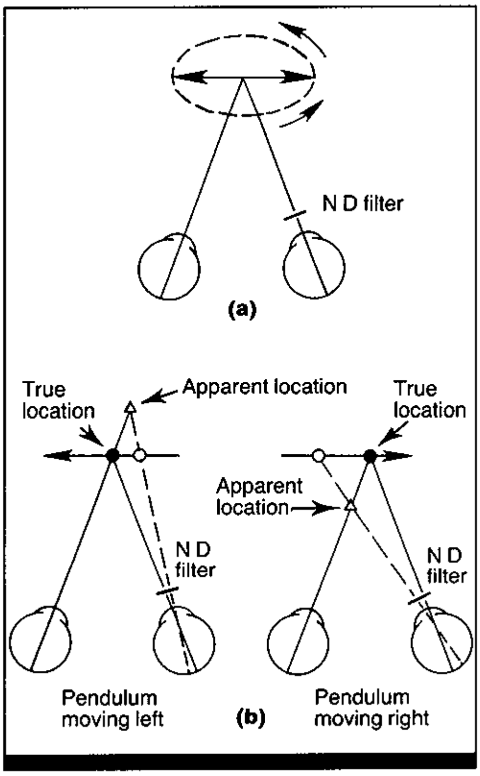

Figure 1. Top view of pendulum motion showing Pulfrich effect and illustrating how delay to filtered eye can produce perception of depth. (From *Handbook of perception and human performance*)

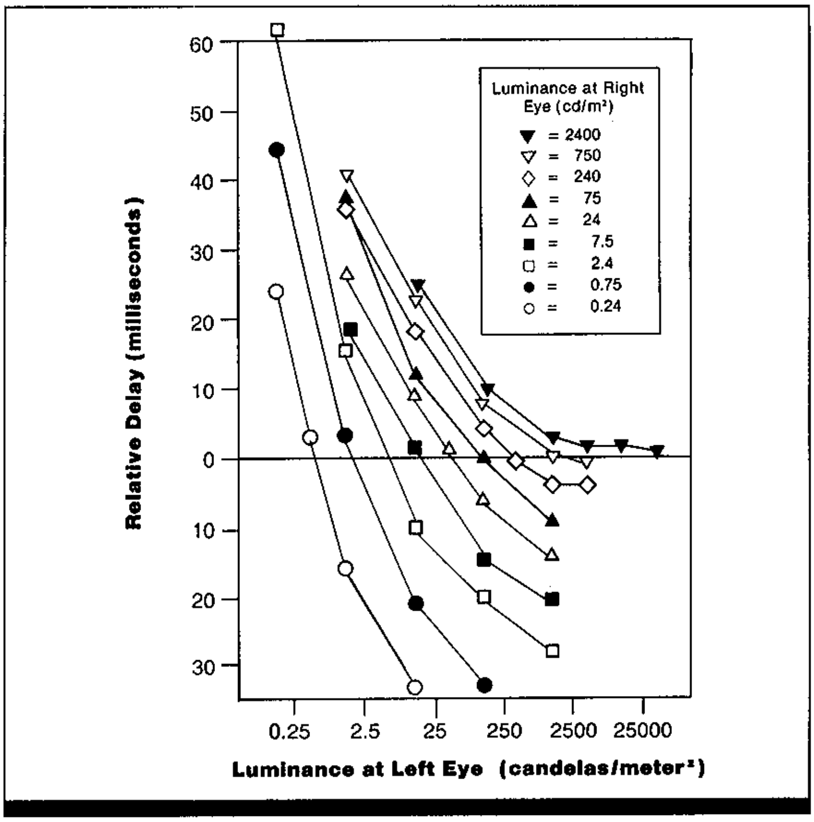

Figure 2. Relative delay between the eyes as a function of left and right eye luminance. Measurements are for 1 observer. Display was vertical rod oscillating horizontally, viewed through a 2-mm artificial pupil in a mirror stereoscope. A neutral density filter was placed over one eye, producing a stereoscopic depth effect (see Fig. 1 and text). The target to the second eye was then physically delayed by an amount just necessary to null the perceived depth. The physical delay required to eliminate the perception of depth provides a measure of the relative physiological delay produced by the luminance-attenuating filter. (From Ref. 4)

Key Terms

Depth perception; interocular delay; interocular luminance difference; Mach-Dvorak effect; motion in depth; Pulfrich effect; retinal image disparity; three-dimensional displays

General Description

A target moving laterally will also appear to be moving in depth when either the retinal illuminance of one eye is lowered or one eye's view is delayed in time, relative to the other eye's view.

The stereoscopic effect produced with a moving object by dimming one eye's field is known as the *Pulfrich effect* and is illustrated in Fig. 1a. When a **neutral density** (luminance attenuating) filter is placed over one eye, a pendulum moving back and forth in a plane parallel to the observer (solid line) will seem to rotate elliptically in depth (dotted line), appearing alternately in front of and behind the true plane of target motion.

The physiological action of the filter is to delay the perception arising from the eye it covers (here, the right eye). Thus, as shown in Fig. 1b, at any given instant during the leftward or rightward motion of the targets, the position at which the right eye sees it (open circles) lags the true location, at which it is seen by the left eye (filled circles). This produces an effective **lateral retinal image disparity**, which causes the object to appear to be at the location indicated by the triangle. With the filter over the right eye, the target path appears closer than its true path when it is moving to the right, and farther away when it is moving to the left. At the extremes of its left-right motion, when target velocity is zero, delay produces no disparity and the object appears at its true distance.

An identical perception of elliptical motion in depth can be produced by physically delaying the target image to one eye, rather than filtering one eye's view. When produced in

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

this way, the phenomenon is known as the Mach-Dvorak effect.

The maximum perceived depth (greatest apparent displacement of the target from its true path on the fronto-parallel plane) varies with the luminance difference and the time delay between the eyes, as well as with general illumination level. The effects of these and other factors on the phenomenon are given in Table 1.

The effective retinal image disparity produced by delaying or dimming one eye's view can be calculated from the relative temporal delay between the eyes and the velocity function of the target over time. Relative temporal delay produced by luminance attenuation of one eye's view is shown in Fig. 2 for various luminance differences and general illumination levels. Perceived displacement in depth can be determined from effective retinal disparity, subject to certain constraints (CRefs. 5.916, 5.925).

It is possible that there is a slower response of the retina to dimmer light so that the filtered eye's messages to the brain are slower than the response of the eye which has greater retinal illumination. This notion is favored by the fact that the effect is enhanced in dim conditions and destroyed by high luminance levels (where both retinas would respond at essentially the same time). The filter of one eye thus has the effect of delaying presentation of the target to the brain.

Applications

Stereoscopic and autostereoscopic displays.

Constraints

- If the difference in retinal illuminances of the two eyes is very large, the view of the dimmer eye will be suppressed and the effect will not be seen.
- If the time delay between left and right images is very large, the target will no longer be perceived as simultaneously viewed by both eyes and the effect will not appear.
- At very high luminance levels, if the eye is not adapted to the target luminance, relative temporal delay between right and left eyes may depart from the values shown in Fig. 2. Amount of perceived depth and direction of target rotation may be altered accordingly (Ref. 4).
- The path shown in Fig. 1a is only approximately an ellipse (CRef. 5.916).

Key References

1. Fit, A. (1949). The magnitude of the Pulfrich stereophenomenon as a function of binocular differences of intensity at various levels of illumination. *American Journal of Psychology, 62*, 159-181.

2. Harker, G. S. (1973). The Mach-Dvorak phenomenon and binocular fusion of moving stimuli. *Vision Research, 13*, 1041-1058.

3. Morgan, M. (1980). Analogue models of motion perception. *Philosophical Transactions of the Royal Society of London, 290(B)*, 117-135.

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Cross References

5.905 Lateral retinal image disparity;

5.916 Perceived depth as a function of lateral retinal image disparity;

5.919 Stereoacuity: effect of luminance;

5.925 Stereoacuity: effect of lateral target motion;

Handbook of perception and human performance, Ch. 23, Sect. 3.3

Table 1. Factors influencing depth effects due to unequal luminance or time delay of stereoscopic half-fields.

Factor	Influence on Depth Effects
Half-field affected	Perceived rotation is clockwise (as seen from above) if left half-field is dimmer or is time-delayed; counterclockwise if right half-field is dimmer or delayed
Amount of luminance difference or time delay	Amount of perceived depth displacement increases as time delay or luminance difference increases Rate of this depth increase rises as general level of illumination decreases For very large half-field luminance differences, amount of perceived depth displacement may reach asymptote, with no further displacement as luminance difference increases
Illumination level	For given time delay or luminance difference between left and right half-fields, perceived depth increases as general illumination level decreases
Type of filter	Effect is obtained with colored filters as well as neutral density filters
Method of display	Effect has been demonstrated using stroboscopic, as well as continuous, target motion Related effects have been observed with visual noise displays in which one eye's view is dimmed or delayed
Target lightness	Effect obtained when targets to left and right eyes differ in lightness (one target is white, one black), but not in shape
Target Shape	Effect obtained when targets to left and right eyes differ in shape but not in lightness
Visual field	Effect does not occur if only the target is visible
Fixation	Effects obtained regardless of point of fixation, and with eyes fixed or moving

5.934 Color Stereopsis

Key Terms

Color stereopsis; depth illusion; depth perception; three-dimensional displays

General Description

Color stereopsis is the apparent difference in depth between two objects of different color lying in the same plane. Color stereopsis, or chromostereopsis, may result from differential dispersion of colored light due to chromatic aberration of the eye. The apparent depth separation between differently colored visual stimuli varies as a function of the decentration distance of light as it enters the pupil. It also varies as a function of the optical power of prisms placed in front of the eyes. The direction of decentration (nasal or temporal), or whether the prisms are converging or diverging, determines which color will be seen in front of the other.

Applications

Color displays (e.g., flight simulation displays) requiring depth judgments must take into account color as a depth cue. This is especially true for displays which include very narrow beams or highly saturated colors.

Methods

Test Conditions

- Two patches, red and blue, cut from stiff, finely textured paper; saturated colors
- Color patches mounted in viewing box with careful lighting to avoid reflection; no other depth cues
- Controlled decentration of artificial pupils; decentered pupils replaced with converging or diverging prisms
- Observer's head adjusted so that eyes were symmetric with respect to a line passing midway between the objects, perpendicular to plane of observation; chin rest; 115-cm viewing distance; 1 deg visual angle of patches

Experimental Procedure

- Independent variables: degree of separation of artificial pupils, power of prism, direction of prism base
- Dependent variable: apparent depth difference of color patches
- Observer's task: align test patch or pointer to appear in the same plane as comparison patch
- 1 observer

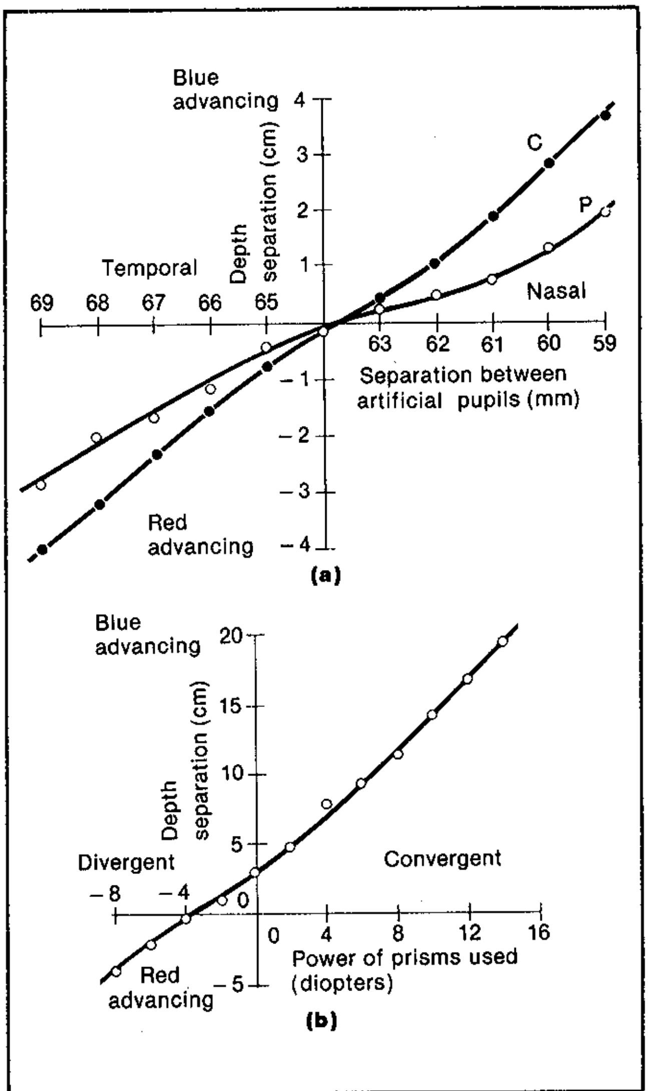

Figure 1. (a) Apparent depth difference between red and blue color patches as seen through decentered pupils, and measured by alignment of color patches (C) or pointers (P). (b) Depth difference in positions of red and blue patches seen through prisms and measured by alignment of patches. (From Ref. 2)

Experimental Results

- Apparent depth separation of blue and red patches increases with decentration of artificial pupils and increases with increasing optic power of prisms.
- Blue advances with nasal decentration and convergent prisms.
- Red advances with temporal decentration and divergent prisms.

Repeatability/Comparison with Other Studies

Other studies (Refs. 3, 4) have found similar results.

Constraints

- It is difficult to measure the exact difference in color (red or blue) that will be imaged as farther away because both chromatic aberration (CRef. 1.212) and **spherical aberration** (CRef. 1.211) must be accounted for.
- Pupil size affects which color will appear in front of the other. With a small pupil, red appears closer than blue or green, but with a large pupil, blue or green appears closer than red.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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*2. Kishto, B. N. (1965). The colour stereoscope effect. *Vision Research, 5*, 313-329.

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5. Sundet, J. M. (1972). The effect of pupil size variations on the color stereoscopic phenomenon. *Vision Research, 12*, 1027-1032.

6. Vos, J. J. (1960). Some new aspects of color stereoscopy. *Journal of the Optical Society of America, 50*, 785-790.

Cross References

1.211 Spherical aberration;

1.212 Axial chromatic aberration

5.935 Duration Thresholds for Stereoscopic Targets at Different Visual Field Locations

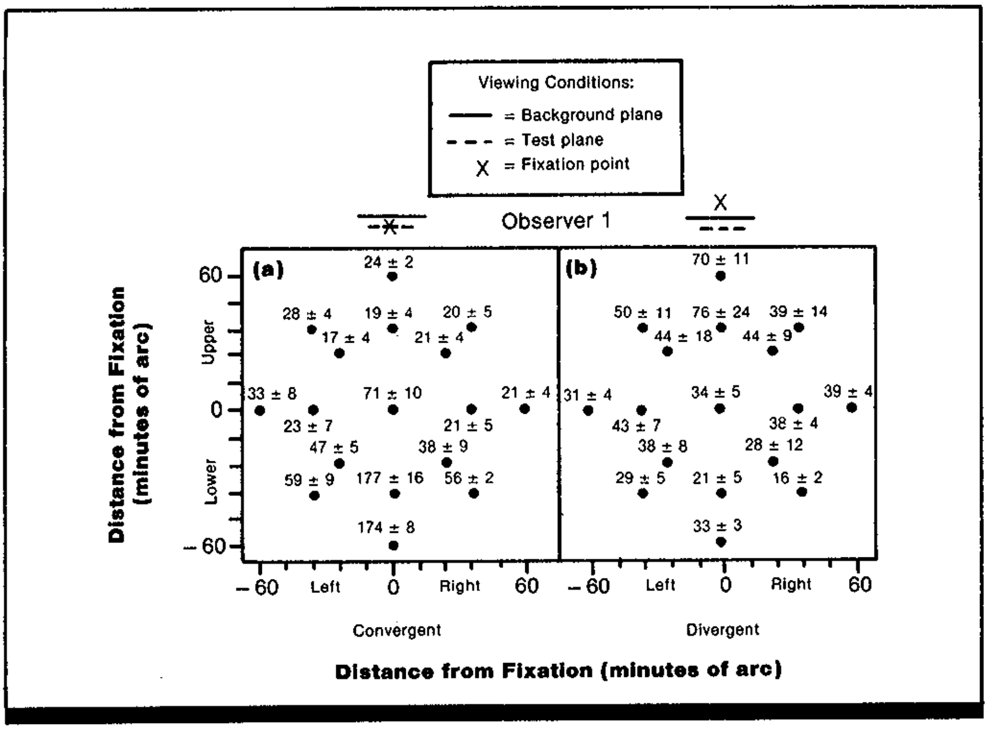

Figure 1. Threshold duration (means and standard deviations in msec) for detecting a test target centered at the points shown (for one typical observer). The fixation marker is at the center of gaze (0,0), and the abscissa and ordinate designate distance from fixation in 12 min arc units. *(a)* = fixation marker with 6 min convergent disparity. *(b)* = fixation marker with 6 min divergent disparity. (From Ref. 1)

Key Terms

Depth perception; exposure duration; retinal image disparity; retinal location; three-dimensional displays; visual field location

General Description

Targets presented in the upper half of the visual field are detected at consistently shorter durations than those in the lower half of the visual field for depths farther than fixation. Targets in the lower visual field are detected at shorter durations for depths closer than fixation. No such difference is found for left versus right visual fields.

Applications

Stereoscopic and autostereoscopic displays.

Methods

Test Conditions

- Subject fixated marker, then test square at different depth than surround; for a specified time, viewing time increased at next trial by 10 msec if square not detected; decreased by 10 msec if detected
- Computer-generated dynamic visual noise (like "snow" on a television screen) consisting of dots illuminated at random in a 50 x 50 array; dot size 6 min arc of visual angle
- Stereo images presented at 100-Hz frame rate with 12.5% dot density per frame; correlated area consisted of background with 0 min **lateral retinal image disparity** and small target square (e.g., 24 x 24 min) with 6 or 12 min disparity relative to background; semi-luminous marker (slightly brighter than other dots) presented in center of array with no disparity or 6 min convergent or 6 min divergent disparity
- To obtain data in Fig. 2, target square presented in four positions with *x* and *y* coordinates from center fixation point of (36, 36), (36, −36), (−36, 36) and (−36, −36) min arc

Experimental Procedure

- Staircase procedure
- Independent variables: distance of target from fixation, relative disparity of target (convergent versus divergent)
- Dependent variable: detection duration threshold, measured as duration at which target detected on 50% of trials
- Observer's task: indicate whether or not test square detected
- 3 observers

Experimental Results

- The center of the visual field has poorer temporal resolution (longer duration thresholds) than the rest of the visual field for divergent disparities (Fig. 1).
- All 3 observers showed consistent and substantial threshold differences between upper and lower halves of the field (Fig. 2); performance was better (detection quicker) in the upper field for convergent disparity.
- No differences were found in duration thresholds for left versus right halves of the visual field (Fig. 2).

Variability

Standard errors are presented in Fig. 1. No reliability data were offered for results shown in Fig. 2.

Repeatability/Comparison with Other Studies

The lack of a left-right half-field difference is contrary to previous reports (Refs. 2, 3). This may be due to task differences, with previous studies requiring identification of the briefly presented geometric figures, and the current study requiring only detection of the presence of an object in the visual field.

Constraints

- The large differences in threshold between the center of the **fovea** and the rest of the visual field (at least for divergent disparities) and between the upper and lower half-fields can be demonstrated only with dynamic random-dot stereograms that are devoid of all **monocular** cues to depth (CRef. 5.901).
- The slightest monocular cue leads to much-improved perception times and abolishes any threshold differences.

Key References

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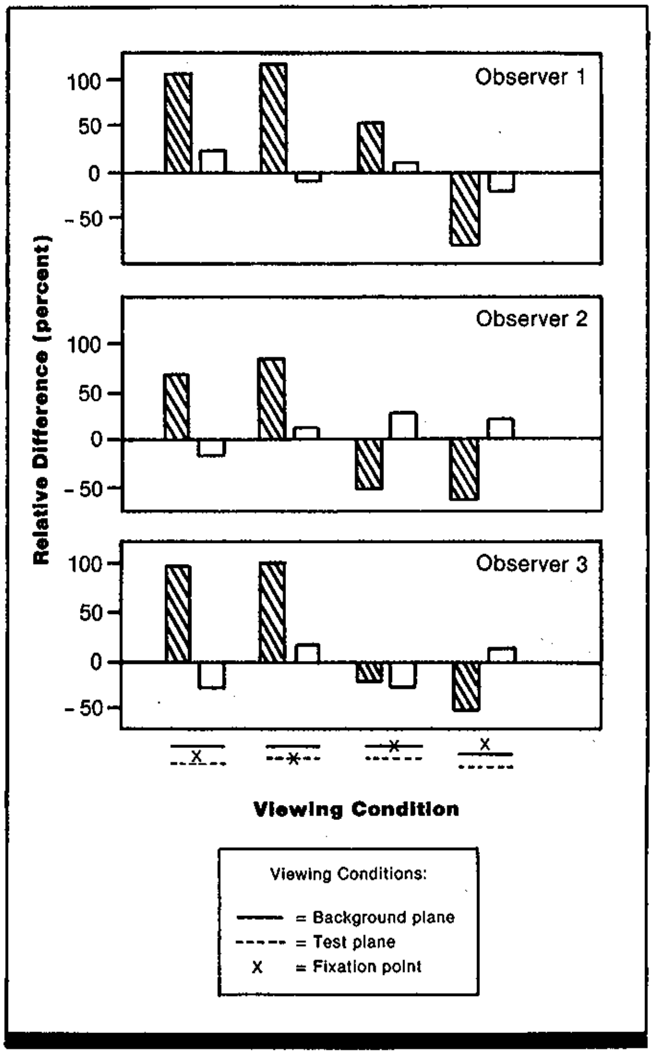

Figure 2. Percent relative difference between mean duration threshold of lower and upper hemifields (shaded bar) and left and right hemifield (unfilled bar) under four different viewing conditions for three typical observers. (From Ref. 1)

Cross References

5.901 Monocular distance cues;

5.920 Stereoacuity: effect of target location in the visual field;

5.926 Stereoacuity: effect of exposure duration;

Handbook of perception and human performance, Ch. 23, Sects. 4.4, 5.11

5.936 Binocular Displacement

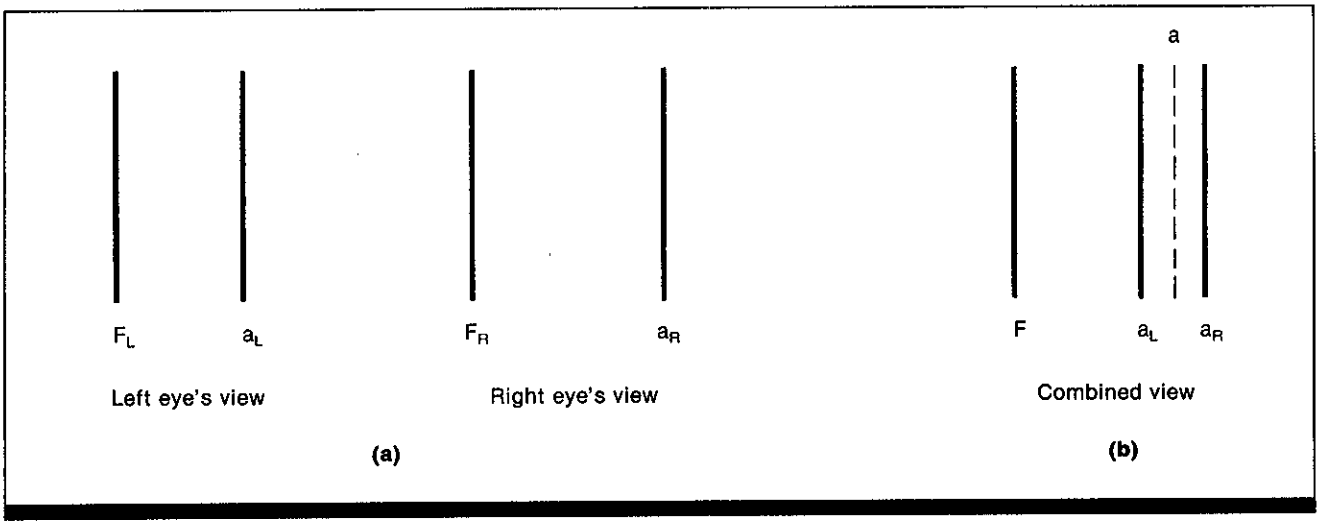

Figure 1. Stereogram which may produce displacement. (See text for details.)

Key Terms

Binocular displacement; binocular fusion; binocular image registration; three-dimensional displays

General Description

Observers report the location of an object or contour with **lateral retinal image disparity** in the two eyes to be midway between the locations seen by each eye. This phenomenon, known as displacement, is illustrated in Fig. 1. Figure 1a is a stereogram consisting of a fixed line F (with images F_L and F_R in the left and right eyes, respectively) and an apparently more distant line a (a_L, a_R) imaged with **divergent disparity**. Figure 1b shows the half-fields of this stereogram superimposed and registered as they would be seen in a stereoscope. The dashed line indicates the apparent location of line a in the stereoscopic view, if displacement occurs.

Figure 2 illustrates an explanation for displacement. If an observer has a slight **fixation disparity**, attempted fixation of F may result in actual fixation on a plane slightly more distant than the plane of F. When this occurs, the resulting disparity of F on the actual plane of fixation may be so small as to go unnoticed by the observer. If the observer's eyes were actually converged to the plane of F, the half-images of a would appear at the locations a_L and a_R indicated by the open circles. Instead, the observer's eyes are converged to the more distant plane where the half-images of a_L and a_R are close enough to appear single at depth a at a point midway between the locations of a_L and a_R on the plan of F.

Another theoretical account (Ref. 3) views displacement as the phenomenological correlate of "sensory fusion" between disparate half-images.

Applications

Stereoscopic and autostereoscopic presentations where judgment of the vertical and/or horizontal locations of points or targets is critical.

Constraints

- Displacement is not reported by all observers and it is rarely, if ever, reported for depictions of natural scenes or when viewing true or volumetric three-dimensional space.
- The theory described above does not account for displacement with vertical disparities which, though rare, have also been reported.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

1.808 Convergence angle;

1.809 Phoria;

1.912 Fixation stability: magnitude of horizontal drift;

5.905 Lateral retinal image disparity;

5.911 Limits of single vision;

5.915 Random-dot stereoscopic displays

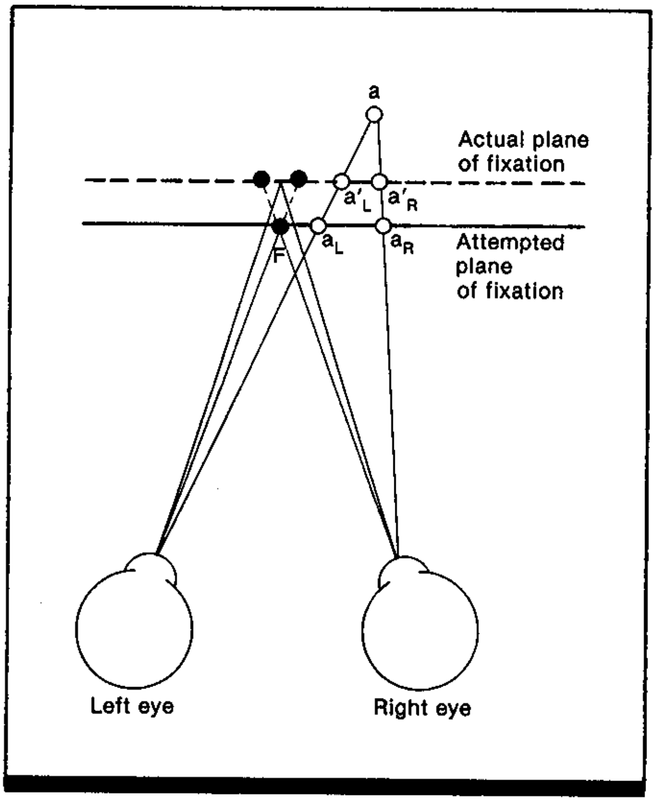

Figure 2. Top view of three-dimensional situation corresponding to stereogram of Fig. 1, illustrating Ogle's (Ref. 2) theory of displacement as due to fixation disparity.

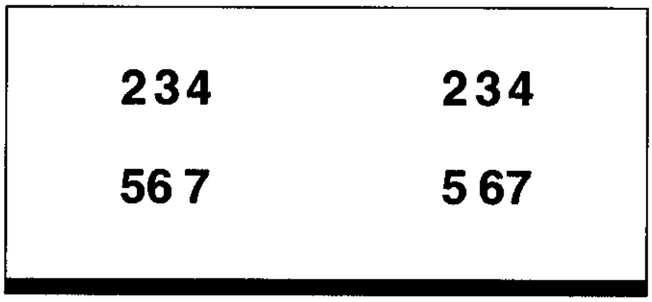

Figure 3. Another example of displacement. When viewed in a stereoscope or through free stereoscopy (by converging or diverging the eyes to bring the half-fields into register), the number "6" appears to lie directly under the numeral "3", even though its half-images are actually placed on either side of the "3" in the separate half-fields. (From Ref. 1)

5.937 Hysteresis Effects in Stereoscopic Vision

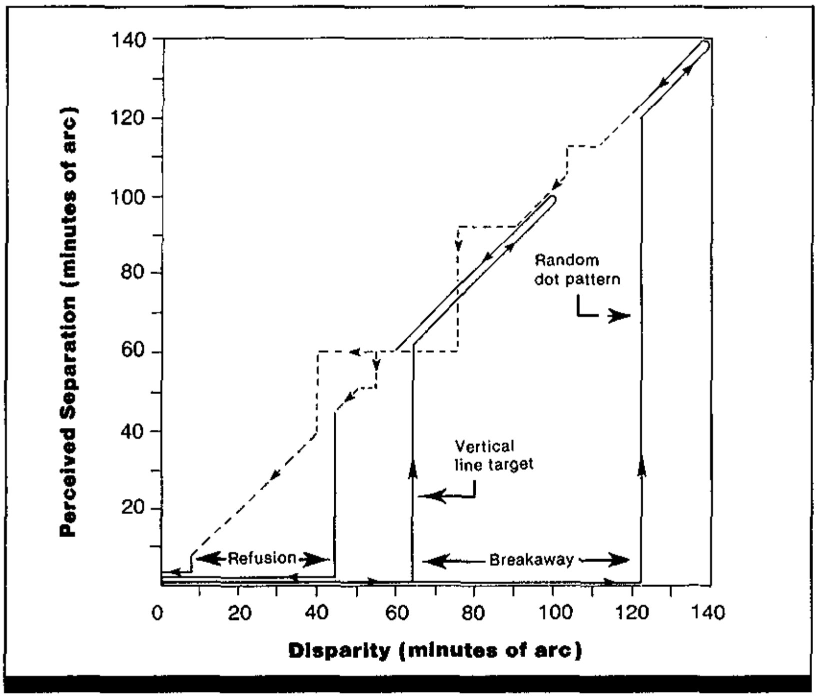

Figure 1. Horizontal disparity hysteresis loops for line and random-dot patterns (stabilized vision) (Study 1). Arrows indicate the direction in which horizontal separation between left and right images is changed. Breakaway is the point at which double images are first seen as image separation in the eyes is increased; re-fusion is the point at which the pattern first appears single as image separation is decreased. Dotted lines indicate region of transient fusion between target line and fiducial marks also present in visual field (line targets) or between small groups of picture elements that have high correlation between left and right images (random-dot patterns). (From Ref. 3)

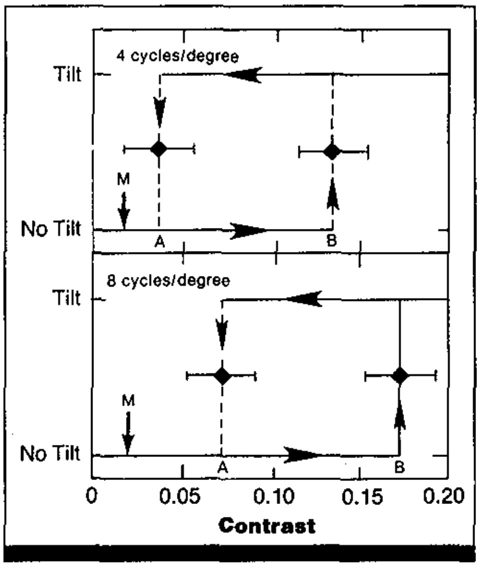

Figure 2. Contrast hysteresis loops for stereoscopic bar patterns of two spatial frequencies (one cycle = two bar widths) (Study 2). Arrows indicate the direction of contrast change in the eye whose contrast is varied. Filled circles are mean contrast for transition from tilt to no tilt (*A*) and from no tilt to tilt (*B*). *M* shows the monocular contrast thresholds measured under the same conditions. (From Ref. 5)

Key Terms

Binocular fusion; contrast; double vision; retinal image disparity; single vision; three-dimensional displays; visual hysteresis

General Description

If the left and right half-images of a stereoscopic target are placed in registration in the two eyes and are then slowly pulled apart, horizontal image separation (**lateral retinal image disparity**) of as much as 2 deg of visual angle can be tolerated before fusion breaks down and double images are seen. If image separation is then decreased, disparity must be reduced substantially below the point at which fusion was first lost for fusion to be regained and the target again to appear single. Similar hysteresis effects are found for vertical separations of left and right half-images; however, both the disparity at which fusion is lost and the decrease in disparity required for re-fusion are lower than with horizontal image separation. The magnitude of the effect and the disparity of the transition points from fusion to double images varies with target pattern type.

Hysteresis effects in stereoscopic vision are also found for contrast. When a bar pattern viewed by one eye has slightly different bar width than the pattern viewed by the other eye, the combined view appears as a pattern rotated in depth about the vertical axis due to the retinal image disparity introduced by the differential bar width. When pattern contrast in one eye is reduced, the perception of tilt disappears and the pattern appears flat. The contrast at which the pattern changes in appearance from tilted to flat as contrast is decreased is significantly less than the contrast at which the perceived pattern shifts from flat to tilted as contrast is increased from low to high. The effect is greatest for patterns whose **spatial frequency** falls between 2 and 8 cycles/deg.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Stereoscopic displays in which some misalignment of half-field or contrast disparity must be tolerated.

Methods

Test Conditions

Study 1 (Ref. 3)

• Normal vision or **stabilized vision** using contact lens technique; **binocular** viewing
• Target line 60 min arc of visual angle long, 13 min arc wide, viewed against white surround; vertical orientation for horizontal disparity measurements, horizontal orientation for vertical disparity measurements; contrast set high enough to prevent fragmentation or disappearance of line under stabilized conditions
• **Random-dot pattern** subtending 3.43 deg, with central 1.37-deg square appearing in front of pattern plane (8 min arc disparity); pattern picture elements ~2 min arc square
• Targets in each eye moved slowly and symmetrically apart until target no longer appeared single, then moved toward each other until fusion regained; cycle repeated several times

Study 2 (Ref. 5)

• Vertical **sine-wave gratings** (bar patterns) displayed via CRT; mean luminance 30 cd/m^2; stereoscopic separation using cross-polarization technique (CRef. 5.914)
• Bar patterns in each eye 4.5 × 3.0 deg; viewing distance 118 cm
• Spatial frequency of bar pattern slightly different in each eye (usual ratio = 1.22), creating perception of unitary pattern tilted about vertical axis; mean spatial frequency (both eyes) of 0.5-11.0 cycles/deg
• Pattern contrast held constant in one eye (usually 0.5); contrast in other eye varied
• Target contrast in one eye increased from high contrast until pattern appeared flat, or increased from zero until pattern appeared tilted

Experimental Procedure

Study 1

• Independent variables: degree of image separation (retinal disparity) of targets in left and right eyes; type of pattern
• Dependent variable: appearance of target images as fused or double
• Observer's task: report when target first appeared double (increasing target separation) or first appeared fused (decreasing target separation)
• 4 experienced observers; results for 1 observer shown in Fig. 1

Study 2

• Independent variables: mean spatial frequency of bar pattern, pattern contrast in variable eye
• Dependent variable: appearance of bar pattern as tilted or not tilted
• Observer's task: signal contrast level at which grating pattern first appeared tilted from frontoparallel plane (ascending contrast) or first appeared untilted (descending contrast)
• 5 observers, 3 naive; results for 1 experienced observer shown in Fig. 2

Experimental Results

• When fused target images are slowly pulled apart in the two eyes, single vision can be maintained for target disparities as large as ~1-2 deg.
• If target separation proceeds too rapidly, the target is briefly covered, or this upper limit is exceeded, fusion breaks down and the target appears double. Once fusion has been broken, left and right image disparity must be decreased by 30-90% (to a value substantially lower than that at which fusion was previously maintained) for fusion to be regained.
• The maximum disparity at which targets appear fused is much greater for random-dot patterns than for simple line patterns, and the disparity required for re-fusion is substantially lower.
• Hysteresis effects in normal (unstabilized) vision are similar to those in stabilized vision, but both transition points (fusion loss and re-fusion) occur at somewhat higher image disparities.
• Similar hysteresis effects are observed for vertically disparate targets, but less disparity can be tolerated without destroying fusion, and, once fusion is lost, disparity must be reduced to a lower value to regain singleness of vision.
• When the eyes view bar patterns of slightly different bar width, and pattern contrast in one eye is varied, the contrast at which the combined pattern just appears tilted in depth is lower when contrast is decreased from a high value than when contrast is increased from a low value ($p < 0.005$).
• This contrast-dependent hysteresis is strongest at spatial frequencies between 2-8 cycles/deg and vanishes at significantly higher and lower spatial frequencies.
• Follow-up measurements show that increasing the contrast level of the eye with fixed contrast also increases the level of the transition points that define the hysteresis loop.

Variability

Study 1: standard deviations were 10-25% for most conditions (1 observer). Study 2: error bars in Fig. 2 show ~1 standard deviation for transition points for 1 observer; results for other observers were similar.

Repeatability/Comparison with Other Studies

• Similar hysteresis effects have been found for the vergence eye movement system (Ref. 4).
• Other studies (Refs. 1, 2) using somewhat different targets and techniques have found much smaller hysteresis effects in the disparity limits for double vision.

Constraints

• Factors that affect the strength of perceived tilt with stereoscopic gratings of slightly different spatial frequencies can also be expected to affect the contrast-dependent hysteresis described here. Contrast hysteresis is strongest when the conditions for perceived tilt are optimal.
• Factors that influence the disparity limits for stereopsis (such as amount of pattern detail) are likely to affect disparity-dependent hysteresis as well.

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Cross References

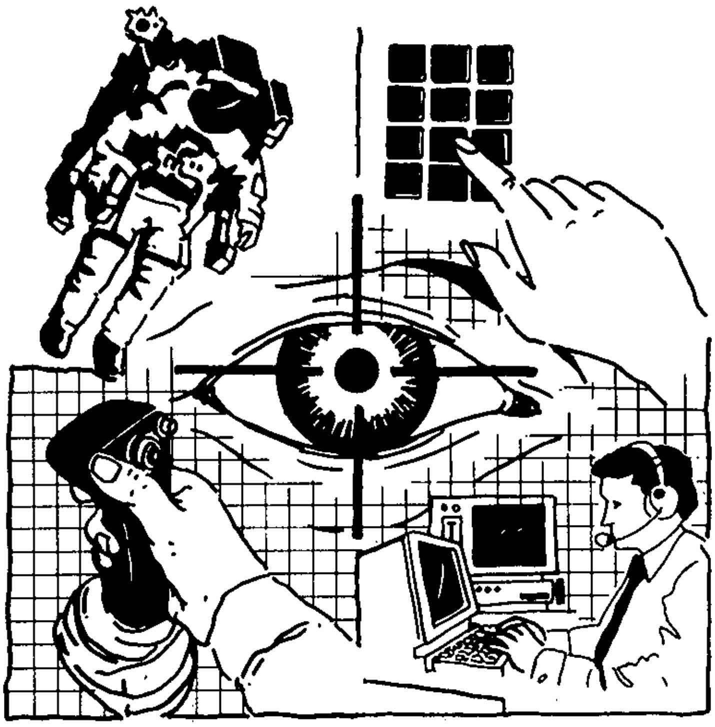
5.905 Lateral retinal image disparity;

5.911 Limits of single vision;

5.914 Filter separation and free stereoscopic display methods

Notes

Section 5.10 Comparisons and Interactions among the Senses



5.1001 Characteristics of the Senses

Key Terms

Acuity; dynamic range; reaction time; sensory modality; spectral resolution

General Description

Humans are tool users; much of their activity requires machines. Working together as systems, people and machines perform a series of acts or tasks to attain a desired goal. People are system components, and their characteristics must be taken into account in configuring efficient systems, because one system requirement is sensing the situation, both of the system and of the environment. An appreciable part of designing systems, then, is applying what is known about the characteristics of human senses. The volume of literature on human senses is vast and growing, and includes much data that have implications for system design. A data summary of the characteristics of human senses, such as that of Table 1, is useful as a starting point in system design. The table column headings list the types of senses, i.e., the sense modalities, while the row titles are characteristics or parameters of each modality. By using the tabled data, along with basic equations and curves relating stimulus and response, a first try or cut can be made in the iterative process or designing systems and allocating functions to people and machines.

Constraints

- The various cells in the table are not independent, i.e., the effect of one parameter depends upon the value of one or more other parameters. This interaction is sometimes large and must be taken into account. For example, the 1 min arc listed for visual acuity is a nominal value; for low contrast, low luminance, nonstandard test patterns, some spectral distributions, or short presentation times, or under conditions of vibration, visual resolution may be much poorer. The table must be only a starting point in system design or system evaluation.
- The effects of parameter values and changes in these values are often quite different for different people; system design must allow for individual differences in sensory capabilities.

Key References

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Cross References

1.103 Range of light intensities confronting the eye;

1.110 Luminous efficiency (spectral sensitivity);

1.602 Measurement of visual acuity;

1.632 Contrast sensitivity: effect of luminance level (foveal vision);

1.704 Chromaticity discrimination;

2.103 Measurement of sound amplitude;

2.302 Auditory sensitivity in quiet: effect of frequency;

2.401 Intensity discrimination of random noise and "square-wave" noise;

3.109 Vibrotactile stimulation: detectability of intensity differences;

3.115 Tactile localization and two-point discrimination;

3.207 Threshold for linear acceleration;

3.208 Threshold for angular acceleration;

5.1002 Comparison of perceptual capabilities across sensory modalities;

9.101 Reaction time tasks and variability

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Characteristics of the senses. (From Ref. 14)

Parameter	Vision	Audition	Touch	Taste and Smell	Vestibular
Sufficient stimulus	Light-radiated electromagnetic energy in the visible spectrum	Sound-vibratory energy, usually airborne	Tissue displacement by physical means	Particles of matter in solution (liquid or aerosol)	Accelerative forces
Spectral range	Wavelengths from ~400 to ~700 nm (violet to red)	20-20,000 Hz	>0 to <400 pulses per second	Taste: salt, sweet sour, bitter Smell: fragrant, acid, burnt, and caprylic	Linear and rotational accelerations
Spectral resolution	120-160 steps in wavelength (hue) varying from 1-20 nm (CRef. 1.704)	~3 Hz for 20-1000 Hz; 0.3% above 1000 Hz	~10 percent change in number of pulses per second		
Dynamic range	~90 dB (useful range); for **rods** = .000032-.0127 cd/m²; for **cones** = .0127-31830 cd/m² (CRef. 1.103)	~140 dB (where 0 db = 0.0002 dyne/cm²) (CRef. 2.103)	~30 dB (0.01-10 mm displacement)	Taste: ~50 dB (0.00003 to 3% concentration of quinine sulphate) Smell: 100 dB	Absolute threshold is ~0.2 deg/sec/sec (CRefs. 3.207, 3.208)
Amplitude resolution ($\Delta I/I$)*	Contrast = .015 (CRef. 1.632)	0.5 dB (1000 Hz at 20 dB or above) (CRef. 2.401)	~0.15 (CRef. 3.109)	Taste: ~0.20 Smell: 0.10-50 dB	~0.10 change in acceleration
Acuity	1 min of visual angle (CRef. 1.602)	Temporal acuity (clicks) ~0.001 sec (CRef. Sect. 2.5)	Two-point acuity ranges from 0.1 mm (tongue) to 50 mm (back) (CRef. 3.115)		
Response rate for successive stimuli	~0.1 sec (CRef. Sect. 1.5)	~0.01 sec (tone bursts) (CRef. Sect. 2.5)	Touches sensed as discrete to 20/sec	Taste: ~30 sec Smell: ~20-60 sec	~1-2 sec; **nystagmus** may persist to 2 min after rapid changes in rotation
Reaction time for simple muscular movement	~0.22 sec (CRef. 9.101)	~0.19 sec (CRef. 9.101)	~0.15 sec (for finger motion, if finger is the one stimulated) (CRef. 9.101)	(CRef. 9.101)	(CRef. 9.101)
Best operating range	500-600 nm (green-yellow) at 34.26-68.52 cd/m² (CRef. 1.110)	300-6000 cps at 40-80 dB (CRef. 2.302)		Taste: 0.1-10% concentration	~1 *g* acceleration directed head to foot
Indications for use	1. Spatial orientation required 2. Spatial scanning or search required 3. Simultaneous comparisons required 4. Multidimensional material presented 5. High ambient noise levels (Ref. 4)	1. Warning or emergency signals 2. Interruption of attention required 3. Small temporal relations important 4. Poor ambient lighting 5. High vibration or *g* forces present (Ref. 4)	1. Conditions unfavorable for both vision and audition 2. Visual and auditory senses (Ref. 4) 3. Detection of fine surface irregularities	1. Parameter to be sensed has characteristic smell or taste (i. e., burning insulation)	1. Gross sensing of acceleration information
References	Refs. 1, 3, 12, 13	Refs. 6, 7, 9, 10	Refs. 2, 5	Ref. 8	Ref. 11

*I = intensity level; ΔI = smallest detectable change in intensity from I.

5.1002 Comparison of Perceptual Capabilities Across Sensory Modalities

Table 1. Optimal sensory modality for some perceptual tasks.

Perceptual Task	Optimal Modality	Source
Egocentric localization (localization in space, using body as frame of reference)	Vision	Ref. 5
Shape	Vision	Ref. 1
Size		
Linear extent	Vision, touch	Ref. 2
Two dimensions	Vision or touch, depending on which touch receptor is stimulated: the tongue may be as accurate as the visual sense, but fingers will produce inferior performance	Refs. 3, 13
Spatial acuity	Vision	Ref. 9
Temporal pattern		
Recognition	Audition, but vision better than touch	Ref. 6
Reproduction	Audition, but touch better than vision	Ref. 6
Temporal rate	Audition, especially with rapid presentation	Ref. 11
Texture	Vision generally best, but when information is redundant, touch may be as accurate	Refs. 8, 12
Time intervals	Audition	Ref. 7
Vertical orientation of body	Vision, but vestibular sense is adequate when no visual cues are available	Ref. 10

Key Terms

Body orientation; pattern recognition; shape; size perception; spatial acuity; spatial localization; temporal acuity

General Description

More than one of the sensory modalities (e.g., vision, audition, touch, proprioception, and the vestibular sense) can generally perform a given perceptual task, but often one is better suited for that task than the others. Vision, for example, is the optimal modality for detecting spatial relations, and audition is best suited for judging temporal relations. Table 1 lists some general perceptual tasks, notes the modalities most appropriate for each, and lists sources for additional information. Table 2 lists some common perceptual situations and indicates whether information is best presented visually or auditorily.

Constraints

- The tables indicate only whether a given modality is *relatively* better or worse for a given task compared to the other modalities, not whether the various modalities are categorically "good" or "bad" for that task.
- Variability within and among individuals may be significant.

Table 2. Guidelines for presenting information via auditory versus visual modality. (Adapted from Ref. 4)

If:	Use:
Information to be communicated is simple	Audition
Information to be communicated is complex	Vision
Information will be referred to later	Vision
Information will not be referred to later	Audition
Information calls for immediate action	Audition
No immediate action is required	Vision
Person receiving information is moving	Audition
Person receiving information is stationary	Vision
Visual system is overloaded	Audition
Auditory system is overloaded	Vision
Work environment is noisy	Vision
Lighting is too bright, dark, or variable	Audition

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.1001 Characteristics of the senses;

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

9.101 Reaction time tasks and variability;

Handbook of perception and human performance, Ch. 25, Sect. 2

5.1003 Visual Detection in the Presence of Auditory Stimulation

Key Terms

Accessory stimulation; intersensory facilitation; target detection

General Description

Sensitivity to a visual stimulus may be influenced by the presence of an accessory auditory stimulus (an auditory stimulus that is presented in close temporal proximity to the primary visual stimulus, but which does not require any response). The presence of the accessory auditory stimulus may either increase or decrease sensitivity to the primary visual stimulus, depending on the characteristics of the two stimuli. Table 1 lists some of these characteristics, describes their effect on visual sensitivity, and indicates sources of more information.

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Cross References

5.1004 Auditory detection in the presence of visual stimulation;

5.1005 Tactual detection and discrimination in the presence of accessory stimulation;

5.1014 Speeding of choice reaction time by intersensory accessory stimulation

Factor	Experimental Study	Results	Comments	Source
Wavelength of the primary visual stimulus	Research conducted in the Soviet Union; experimental details unavailable. In most studies, several intensities of auditory stimulus are coupled with lights of various wavelengths. Visual thresholds are then determined for each light-tone combination	Accessory auditory stimulation increases sensitivity to blue-green light and reduces sensitivity to orange-red light, but does not affect sensitivity to yellow or spectral red and violet. A steady increase in the auditory stimulus from 25-95 dB SPL results in a steady increase of sensitivity to green light and a steady decrease of sensitivity to orange light	Instrumentation, methodology, and statistical treatment of the data may be inadequate	Ref. 3
Location of the primary visual stimulus in the field of view	Research conducted in the Soviet Union; experimental details unavailable	Sensitivity in both peripheral and central regions of the eye is affected by accessory auditory stimulation, but in opposite directions. Sensitivity to white light in the central visual field is heightened by moderately intensive auditory stimuli, while peripheral sensitivity declines. Exposure to ultrasonic frequencies (e.g., 32,800 Hz) has been reported to increase peripheral sensitivity	Instrumentation, methodology, and statistical treatment of the data may be inadequate	Ref. 3

Factor	Experimental Study	Results	Comments	Source
Relationship between the ear stimulated and the side of the visual field stimulated	The effects of auditory stimuli on visual sensitivity of the two halves of the visual field of each eye were tested in **dark-adapted** subjects using the descending method of limits. Tones of 80 dB SPL were presented **monaurally** either to the contralateral (opposite) or ipsilateral (same) ear as both **foveal** and peripheral points of light in either the left or right visual field of each eye	Tones increase sensitivity to a peripheral visual stimulus when presented to the ear contralateral to the visual field stimulated. Tones presented to the ear ipsilateral to the visual field stimulated have no facilitating effect. The center of the visual field is influenced equally by monaural tones to either ear	Previous research (Ref. 4) showed that accessory auditory stimuli must be >50 dB SPL to be effective	Ref. 5
Intensity and pitch of the accessory auditory stimulus	Both peripheral and foveal thresholds of dark-adapted subjects were tested in the presences of 5 levels of pitch (100, 400, 1000, 3000, and 9000 Hz) and three levels of loudness	The 3000 Hz sound heightens foveal sensitivity, and both the 1000- and 3000-Hz sounds heighten peripheral sensitivity. The facilitating effect of higher pitch on peripheral vision becomes stronger as loudness decreases. In contrast, there is a tendency for the facilitating effect on foveal vision to become stronger as loudness increases	Strong individual differences are found	Refs. 2, 4
Duration of the accessory stimulus	Using a forced-choice method, 6 trained observers performed a visual **signal detection** task under four acoustic conditions. In visual signal detection task, observer viewed binocularly from a distance of one meter a flat-textured circular patch of illuminated white glass, 17 cm in diameter and luminance of 2141 cd/m^2. Peripheral photopic stimuli were screened from view. Stimulus duration was 10 msec, presented once every 90 msec for 500 msec. **White noise** at 75 dB SPL was presented through earphones to both ears at once. Noise was either ten bursts per sec flutter or continuous, and occurred either continuously over the trial or only during the observation intervals	For both steady white noise and auditory flutter, visual performance is facilitated by noise presented only during observation intervals; noise continuously present has no effect	In another study (Ref. 1), a continuously presented tone of 70 dB SPL had an inhibitory effect on the visual threshold that reached its maximum 10-12 sec after the sound was introduced	Ref. 7

5.1004 Auditory Detection in the Presence of Visual Stimulation

Key Terms

Accessory stimulation; intersensory facilitation

General Description

In general, listeners perform better on an auditory detection task when an accessory visual stimulus is present. (An accessory stimulus in one that occurs in temporal proximity to the primary stimulus but bears no meaningful relationship to it and requires no response.) This phenomenon was first observed when it was noted that partly deaf individuals frequently can hear better in the light than in the dark (Ref. 2). Several characteristics of the visual as well as the auditory stimulus influence the degree to which the accessory visual stimulus improves auditory thresholds. The table lists these characteristics, describes their effects, and gives sources of further information.

Key References

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Cross References

5.1003 Visual detection in the presence of auditory stimulation;

5.1005 Tactual detection and discrimination in the presence of accessory stimulation;

5.1014 Speeding of choice reaction time by intersensory accessory stimulation;

Handbook of perception and human performance, Ch. 25, Sect. 1.2

Factor	Experimental Study	Results	Comments	Source
Interval between visual stimulus and auditory stimulus	A 1000-Hz tone was presented to 11 subjects for 165 msec at each of five intensities (bracketing each subject's auditory threshold). Each tone was paired with a flash of light presented at one of five intervals from 2.0 sec before the tone to 0.5 sec after the tone	A light presented from 1.0 sec before the tone to 0.5 sec after the tone facilitated auditory detection, with maximum facilitation occurring when the light was present 0.5 sec before the tone	The light presented before the tone acted as a ready signal to alert the subjects that a tone would follow. The results may not apply to situations with unrelated visual and auditory signals	Ref. 1
Hue of the accessory visual stimulus	A sequence of pure tones of four different frequencies lasting 1.5 sec (alternated with 3 sec of silence) were presented. Tones were paired with one of four colored lights (yellow, red, green, and blue). Using the method of limits, two series of ten thresholds were obtained for 5 subjects for each of the 16 color-tone combinations, plus two series of ten thresholds obtained for tones not paired with colored lights	Auditory sensitivity tended to increase with yellow visual stimulus; with other colors, auditory sensitivity tended to decrease at the higher frequencies, but not at the lower frequencies	A Soviet study reported that auditory sensitivity increased with green light, but decreased with red light. In the study reported here, the brightness of the color patch may partially account for the results. In addition, substantial individual differences occurred	Refs. 2, 4

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Factor	Experimental Study	Results	Comments	Source
Pitch of the auditory stimulus	For five frequencies of pulsed tones presented through headphones, auditory thresholds were obtained for 20 practiced subjects under three visual conditions: normal ambient lighting (baseline condition), darkness, and pulsed lighting	Auditory sensitivity was better in darkness, but only at the highest frequency (6000 Hz). Thus the inhibitory effect of concurrent visual stimulation depended on sound frequency. No effects occurred in the middle (1000-2000 Hz) or lower (250-500 Hz) frequency ranges		Ref. 5
Relationship between the ear stimulated and the side of the visual field stimulated	Using the method of limits, auditory thresholds for **monaurally** presented clicks were measured both in darkness and in the presence of a 200-msec light. The light was presented to the right visual field of the left eye 100 msec before the tone. Subjects included 5 men and 2 women	The sensitivity of the left ear increased when the visual stimulus was presented to the right visual field of the left eye; the light did not influence the auditory threshold of the right ear	The accessory stimulation was presented only to the left eye	Ref. 3
Intensity of light and personality type	Auditory thresholds of 30 practiced subjects were determined by the descending method of limits under ten intensities of light projected on a screen (patterned condition) or onto eyecups (homogeneous condition). Ten subjects were designated as introverts, 10 as extroverts, and 10 as ambiverts on the basis of scores on the Eysenck Personality Inventory	Auditory sensitivity increased under weak and decreased under strong intensities of light for introverts, increased under all intensities for extroverts, and increased under weak and medium intensities for ambiverts		Refs. 6, 7

5.1005 Tactual Detection and Discrimination in the Presence of Accessory Stimulation

Table 1. Effects of accessory stimulation on some aspects of tactual sensitivity.

Tactual Sensation	Accessory Stimulus Modality	Effect	Source
Pressure	Audition	Auditory stimulus of weak intensity lowers pressure threshold; more intense stimulus raises threshold	Ref. 2
Vibration and texture	Audition	"Rough" auditory accessory stimulus facilitates tactual perception	Ref. 4
Weight	Temperature	Cold and hot weights feel heavier than weights at room temperature	Ref. 1
Tactual discrimination	Vision	Discrimination is slightly better (by 2%) in the light than in the dark	Ref. 3

Key Terms

Intersensory facilitation; pressure sensitivity; tactile detection; tactile discrimination; texture perception; weight perception

General Description

Sensitivity to a tactual stimulus may be influenced by the presence of an accessory stimulus in a different modality (a stimulus that is presented in close temporal proximity to the primary tactual stimulus but which does not require any response).

Only a few studies (none recent) have investigated the effect of an accessory stimulus on tactual thresholds or tactual discrimination, and none have systematically investigated factors such as intensity or duration of the accessory stimulus. The available studies are summarized in Table 1.

Constraints

- The information presented here should be interpreted with caution. Testing variables, such as ambient noise level, and subject variables, such as fatigue, were often uncontrolled.

Key References

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Cross References

5.1003 Visual detection in the presence of auditory stimulation;

5.1004 Auditory detection in the presence of visual stimulation;

Handbook of perception and human performance, Ch. 25, Sect. 1.2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

5.1006 Tactile Versus Auditory Localization of Sound

Key Terms

Intersensory comparison; sound localization

General Description

The source of acoustic clicks can be localized either by hearing or by the tactile sense when electronically generated stimuli are presented to the ears or index fingertips, respectively. Auditory localization is more precise than tactile localization by a small but significant amount. Both intensity and time difference cues are important in auditory sound localization, but intensity differences alone produce more accurate localization than time differences alone for the type of stimuli used here. Tactile localization depends almost entirely on intensity differences. For both modalities, sound localization is most precise when both intensity and time difference cues are provided.

Applications

Evaluation of the capability of individuals with a hearing disability to localize sound-emitting sources by tactile sensing. Design of communication systems for people with sight and/or hearing disabilities or for environments where normal hearing is disrupted.

Methods

Test Conditions

- Stimuli were electronically generated clicks of varying amplitude, duration, and time of onset; auditory stimuli presented binaurally through earphones; tactile stimuli presented through pair of Goodman V-47 vibrators to left and right index fingertips
- Base intensity levels of 60 and 40 dB sensation level (SL) at 0 deg azimuth for auditory and tactile stimuli, respectively; identical waveform for both auditory and tactile stimuli; intensity differences of 0.00, 2.49, 4.28, 5.82, 7.40, 8.60, and 8.66 dB sensation level (SL), and time differences of 0.000, 0.132, 0.260, 0.379, 0.486, 0.578, and 0.653 msec, respectively, between left and right clicks; differences generated 13 apparent sound-source locations varying from 0 to 90 deg left or right of subject in 15-deg increments; time differences of 1, 2, 4, and 6 msec were also used (data not shown)
- Three conditions were: intensity and time cues presented together, intensity cues alone with 0-sec time difference between clicks, time cues alone with 0-dB intensity difference between clicks
- Scale with 1-deg units from 90 deg left to 90 deg right painted on 182.88-cm (72-in.) diameter semicircular board with dim red lights on circumference at 15-deg increments to provide knowledge of results; 33-in. luminous pointer at center of semicircular scale rotated by subjects to indicate perceived location of sound source
- Randomized combinations of the three cue conditions and 13 stimulus locations; each combination presented once per session
- Subjects were in darkened, enclosed chamber 2.29 m in diameter and 2.13 m high

Experimental Procedure

- Within-subjects design with latin square counterbalancing of presentation order
- Independent variable: intensity difference and/or time difference between left and right clicks
- Dependent variable: perceived location of stimulus
- Subject's task: rotate pointer to perceived source of stimulus; feedback provided only for condition with both intensity and time differences
- Tactile and auditory localization sessions presented on alternate days; four sessions for each modality
- Subjects: 4 psychology graduate students

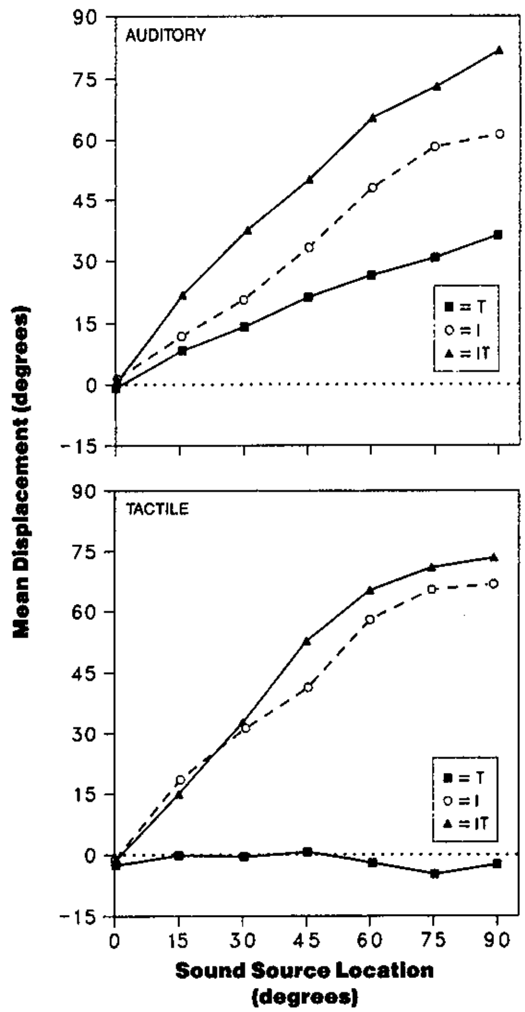

Figure 1. Auditory and tactile localization of acoustic clicks. Graph shows the mean displacement from straight ahead (0 deg) of a pointer adjusted to apparent source location as a function of the actual source location. Localization cues provided: intensity differences (I), time difference (T), or both intensity and time differences (IT) between stimuli to right and left ears or right and left index fingertips. (From Ref. 3)

Experimental Results

- Auditory localization depends on both binaural intensity differences and binaural time differences; tactile localization depends almost completely on intensity differences (only time differences of 4 msec or longer have an effect).
- For audition, intensity cues alone produce significantly greater error in localization than the intensity-time cue combination ($p < 0.01$), and time differences alone produce

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more error than intensity alone ($p < 0.01$). Time differences of >2 msec yield a perception of two separate clicks and no localization occurs.

- For tactile localization, intensity differences alone result in less precise localization than the intensity-time combination ($p < 0.01$).
- Average error for auditory localization (8.0 deg) was significantly less than for tactile localization (10.3 deg) ($p < 0.01$).

Variability

An analysis of variance was performed to assess the significance of the independent variables and interactions.

Repeatability/Comparison with Other Studies

Other studies have reported good tactile localization for a variety of auditory stimuli (Refs. 1, 2, 3). One study (Ref. 1) found time to be an effective cue for tactile localization.

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Cross References

6.504 Identification of vibrotactile patterns: effect of exposure duration and intensity;

Handbook of perception and human performance, Ch. 31, Sect. 3.2

5.1007 Spatial Localization in the Presence of Intersensory Conflict

Modalities	Procedure	Results	Comments	References
Vision and proprioception	18 college-aged women viewed their right hand through a prism that displaced visual field 14 deg and pushed a button with the unseen left hand to indicate where the seen hand was felt to be located, or, with eyes closed, where the hand was felt to be located	When the hand is viewed through the prism, the hand is felt to be located near the seen (displaced) position; that is, visual bias of proprioception $V(P)$ occurs	Although this study did not test whether proprioception biases vision, other studies have found a $P(V)$ effect ranging from 16-40% (Ref. 4)	Ref. 2
Vision and audition	48 undergraduate women judged the location of a 2-sec, 1-kHz pure tone from a hidden speaker displaced 10, 20, or 30 deg left or right of a visible light; head fixed, eyes either straight ahead or directed toward the visual stimulus	Significant visual bias of audition, $V(A)$, occurs at all three displacement levels; effects are larger when eyes are fixed straight ahead	Results are comparable to those found with meaningful stimuli (Ref. 4)	Ref. 1
Proprioception and audition	With eyes covered, 24 college students heard clicks through a speaker placed at one of five positions from 10 deg left to 10 deg right of straight ahead. Subjects pointed with their right hand toward one of four locations: 1) a sound displaced ~11 deg from straight ahead, 2) the previously determined location of their unseen left hand finger, 3) the felt position of the left hand finger touching the speaker producing the sound, or 4) the heard location of the sound produced by the touched speaker. The latter two were the discrepancy conditions	The felt position of the finger biases the heard position of the sound by ~41%, while the sound biases the felt finger location by ~18%	Because the pointing response is proprioceptive, the authors suggest that a different response mode might change the results	Ref. 4

Key Terms

Intersensory bias; intersensory conflict; sensory dominance; spatial localization; ventriloquism effect; visual capture

General Description

In the real world, information from our different senses is usually consistent. When normally redundant spatial modalities are placed in conflict experimentally, information from one modality usually dominates the overall perception; that is, the perceived location of an object in the nondominant modality is shifted toward the perceived location in the dominant modality. Such biases affect egocentric localization (judgments of the spatial position of an object with respect to the body) in several ways.

- When a discrepancy is created between the visual location of an object or limb and the proprioceptive (or felt) location, a visual bias of proprioception, or $V(P)$, occurs which amounts to 60-70% of the total visual-proprioceptive discrepancy; that is, the object feels as if it is located fairly close to its apparent visual position. This is termed visual

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capture. There is also proprioceptive bias of vision, $P(V)$, of 16-40% in which the seen position is shifted toward the felt position.

- When visual information and auditory information are discrepant, only visual bias of audition, or $V(A)$, occurs; the shift in perceived location is called the ventriloquism effect and amounts to 40-80% of the total visual-auditory discrepancy.
- Although discrepant **proprioceptive** and auditory information results in two kinds of bias, the proprioceptive bias of audition, $P(A)$, is much stronger than the auditory bias of proprioception, $A(P)$. The proprioceptive bias leads to a perceptual shift amounting to 50-80% of the total discrepancy and the auditory bias to only 1-18%.

The accompanying table summarizes several studies investigating the effects of intersensory conflict on egocentric localization.

Applications

Environments with intersensory distortion, such as underwater or microgravity (space) environments.

Repeatability/Comparison with Other Studies

Visual information strongly dominates tactual information when subjects are asked to judge the shape of an object (Ref. 5). Also, visual information dominates proprioceptive information when subjects must set a bar so that it feels physically horizontal (Ref. 3; CRef. 5.1011).

Constraints

- Which sense will dominate in a specific situation depends on a variety of factors that may not have been tested.
- The various combinations of cues in these studies are not necessarily equivalent in their effect on the subject's assumption about whether the two discrepant cues represent the same spatial event (Ref. 7).

Key References

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Cross References

2.814 Effect of static head position on localization;

2.815 Effect of visual and proprioceptive cues on localization;

5.1008 Spatial localization in the presence of visual-proprioceptive conflict: effect of amount of intersensory discrepancy;

5.1011 Orientation perception in the presence of visual-proprioceptive conflict

5.1008 Spatial Localization in the Presence of Visual-Proprioceptive Conflict: Effect of Amount of Intersensory Discrepancy

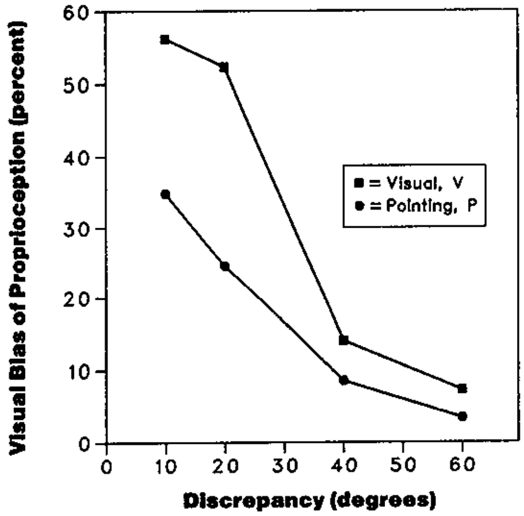

Figure 1. Visual bias of proprioception, *V(P)*, as a function of the difference in visual and actual (proprioceptive) target locations. Ordinate shows the amount by which the felt position of the target shifted toward the seen position as a percentage of the total visual-proprioceptive discrepancy. Apparent target position was indicated by pointing *(P)* or by identifying visual scale marker corresponding to apparent position *(V)*, as indicated in legend. (From Ref. 4)

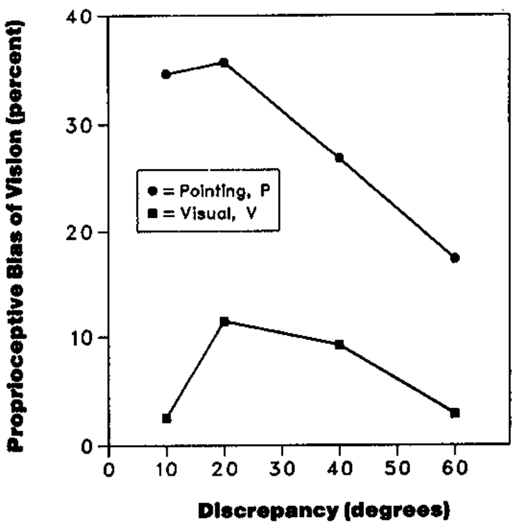

Figure 2. Proprioceptive bias of vision, *P(V)*, as a function of the difference in visual and actual (proprioceptive) target locations. Ordinate shows the amount by which the apparent visual position of the target shifted toward the felt position as a percentage of the total visual-proprioceptive discrepancy. Apparent target position was indicated by pointing *(P)* or by identifying visual scale marker corresponding to apparent position *(V)*, as indicated in legend. (From Ref. 4)

Key Terms

Intersensory bias; intersensory conflict; sensory dominance; spatial localization; visual capture

General Description

When subjects are given discrepant visual and proprioceptive information about the spatial location of a target, the information from one sense modality may influence the perception in the other modality. This is known as intersensory bias. Visual bias of **proprioception**, or *V(P)*, means that visual information dominates proprioceptive information (that is, the felt position of a target is altered in the direction of its perceived visual location), while proprioceptive bias of vision, or *P(V)* indicates that proprioception dominates vision.

Increasing intersensory discrepancies produce decreasing magnitudes of intersensory bias when measured as a percentage of the total discrepancy. That is, as the information from one sense becomes more discrepant from the information from the second sense, the influence of the former on the latter decreases.

Applications

Environments with visual or proprioceptive distortion, such as underwater or microgravity environments.

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Methods

Test Conditions

- Subject seated facing horizontal, transparent plexiglas surface with 1.5 mm stripes at 1 deg intervals radiating from point under subject's nose; target (white plexiglas square, 3.7 cm per side) set at end of adjustable rod under surface; target set at one of three azimuth positions at a constant distance from bridge of subject's nose.
- Subject's vision blocked except for 3.8-cm diameter eyepiece centered on right eye that restricted field of view to 30 deg
- Adjustable mirror arrangement could displace apparent (visual) azimuth location of target from 10-60 deg to left of actual position
- Guide string stretching from handgrip bar under chin to center of target, along which observer moved hand to target for proprioceptive exposure
- For each trial, 3-sec visual and/or proprioceptive exposure to target followed by either pointing or visual judgment after 3-sec delay with target removed

Experimental Procedure

- 12 randomly ordered trials (four for each of three target positions) for each condition, including visual-control condition (visual stimulus only), proprioceptive-control condition (proprioceptive stimulus only), visual-conflict condition (proprioceptive plus visual information, with subject instructed to respond to visual position of the finger), and proprioceptive-conflict condition (proprioceptive plus visual information, with subject instructed to respond to felt position of the finger)
- Independent variables: azimuth location of target, amount of discrepancy between visual and proprioceptive information, modality of response
- Dependent variable: perceptual bias, defined as perceived target displacement from its real position as a percentage of total distance between felt (real) and optically displaced target locations
- Subject's task: indicate perceived position of target by pointing (proprioceptive-response condition) or by reading code character from calibrated horizontal tape (visual-response condition)
- 120 practiced undergraduates of both sexes, ranging in age from 15 to 52 (mean of 22.9 years)

Experimental Results

- When considered in terms of the perceived separation between the visual stimulus and the proprioceptive stimulus, the ability of subjects to distinguish between proprioceptive and visual locations increases monotonically with the amount of visual-proprioceptive discrepancy (i.e., the sum of percent $V(P)$ and percent $P(V)$ decreases within increasing discrepancy).
- Visual bias of proprioception, $V(P)$, declines significantly with increasing visual-proprioceptive discrepancy ($p<0.01$) (Fig. 1). Proprioceptive bias of vision, $P(V)$, is not significantly related to amount of discrepancy (Fig. 2).
- Use of a visual response to indicate perceived location produces a stronger $V(P)$ than a proprioceptive response ($p<0.01$), while use of a proprioceptive response produces a stronger $P(V)$ than a visual response ($p<0.01$).
- The absolute amount of visual bias of proprioception (in deg) remains roughly constant as the discrepancy between the seen and felt positions of the target increases. The absolute proprioceptive bias of vision is roughly constant when the response is visual, but increases when the response is proprioceptive (i.e., pointing).

Variability

Neither within- nor between-subject variability was reported; however, several potential subjects were discarded due to high variability in their control task performance.

The effect of the independent variables and interactions was determined by an analysis of variance followed by Scheffe comparisons.

Repeatability/Comparison with Other Studies

Earlier studies (e.g., Ref. 2) found less proprioceptive bias of vision and more visual bias of proprioception. However, in the previous studies (1) limb movement was passive (experimenter placed the limb), and (2) usually the target was present during the subject's response; these differences in methods may be enough to produce the differences in results.

Intersensory-bias effects have also been found for discrepant visual and auditory sources in which sound is perceived as coming from a direction other than the true direction in the presence of a discrepant visual stimulus (the ventriloquism effect) (Refs. 1, 3).

Constraints

- Results may not be generalizable to situations where stimuli alternately come from widely disparate directions.
- Results may vary depending on the instructions given.
- Greater $V(P)$ results if limb placement is passive rather than active (Ref. 5).
- Results may differ if target remains present during response, thus removing memory requirements.

Key References

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Cross References

2.814 Effect of static head position on localization;

5.1007 Spatial localization in the presence of intersensory conflict;

5.1011 Orientation perception in the presence of visual-proprioceptive conflict;

Handbook of perception and human performance, Ch. 25, Sect. 2.5

5.1009 Spatial Localization in the Presence of Intersensory Conflict: Effect of Cognitive and Response Factors

Key Terms

Intersensory conflict; spatial localization; ventriloquism effect; visual capture

General Description

In the real world, the different senses usually provide consistent information about the spatial location of objects. When normally redundant sensory modalities are placed in conflict by experimental means, the information from one modality may influence the perception in another modality. This is known as intersensory bias. For example, when the finger is viewed through prisms that laterally displace the visual field, visual and **proprioceptive** information regarding the location of the finger is discrepant. Generally, vision biases proprioception, that is, the felt position of the finger will tend to match its seen position; however, proprioceptive bias of vision also occurs, although it is not generally as great. Intersensory bias is usually measured in terms of shift in apparent spatial position toward the position registered via a given modality as a percentage of the total intersensory discrepancy. For example, total visual bias of proprioception is the amount by which the felt position of the finger is shifted toward the seen position as a percentage of the total visual-proprioceptive discrepancy (optically produced visual shift from true or proprioceptive position).

The magnitude of intersensory bias is affected by three major cognitive factors and two major response factors. Important cognitive factors are (1) the degree to which subjects are aware that inputs to the two senses are discrepant; (2) the degree to which the inputs appear to be linked or unified (i.e., appear to relate to a single object in space); and (3) the modality to which attention is directed. Response factors are (1) the degree to which the response is related to one of the modalities; and (2) the timing of the response with respect to the stimulus. The table summarizes the results of several studies investigating these factors.

Key References

1. Jack, C. E., & Thurlow, W. R. (1973). Effects of degree of visual association and angle of displacement on the "ventriloquism" effect. *Perceptual and Motor Skills, 37*, 967-979.

2. Miller, E. A. (1972). Interaction of vision and touch in conflict and non-conflict form perception tasks. *Journal of Experimental Psychology, 96*, 114-123.

3. Radeau, M., & Bertelson, P. (1977). Adaptation to auditory-visual discordance and ventriloquism in semirealistic situations. *Perception & Psychophysics, 22*, 137-146.

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6. Warren, D. H., & Schmitt, T. L. (1978). On the plasticity of visual-proprioceptive bias effects. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 302-310.

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8. Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin, 88*, 638-667.

Cross References

5.1007 Spatial localization in the presence of intersensory conflict;

5.1008 Spatial localization in the presence of visual-proprioceptive conflict: effect of amount of intersensory discrepancy;

5.1011 Orientation perception in the presence of visual-proprioceptive conflict;

Handbook of perception and human performance, Ch. 25, Sect. 2.5

Factor	Procedure	Results	Comments	Source
Subject's knowledge about discrepancy of inputs	In visual-proprioceptive condition, subjects viewed left finger through prisms that displaced the visual field and pointed to felt position of finger with unseen right forefinger. In visual-auditory condition, subjects listened to sound from a speaker that was viewed through displacing prisms and pointed with an unseen finger to the location of the sound. Subjects in the cognitive condition were shown that visual information might be unreliable because of the effects of the prism; subjects in the control condition were told nothing about the prism effects	Visual bias of proprioception is only slightly lower for cognitive condition subjects than for control subjects (81% versus 90%), but visual bias of audition is greatly reduced (42% versus 81%) in the cognitive condition	The results suggest that proprioception and audition may provide qualitatively different information for spatial perception. Alternatively, the effect may vary with the compellingness of the situation or with how much of the subject's own body can be seen (Ref. 8)	Ref. 4

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Factor	Procedure	Results	Comments	Source
Compellingness (subject's assumption that discrepant sensory modalities are providing information about a single external object or event)	Subjects heard a voice while watching either a videotape of the speaker's face or a light whose brightness was modulated by the voice; video and audio portions of presentation were synchronized, but displaced spatially from one another by 20 deg. Subjects had to indicate whether or not the auditory and visual stimuli appeared fused (i.e., the sound appeared to come from the same place as the visual image)	The physically separated voice amd face appeared to be fused ∿78% of the time, while the flashing light and voice appeared fused only ∿49% of the time	Several other studies have shown that increased compellingness is associated with increased intersensory bias	Ref. 3
Attention	Subjects viewed hand through displacing prisms and pointed with unseen hand to felt or seen position of viewed hand. Subjects' attention was drawn to either visual or proprioceptive information by interspersing visual-proprioceptive conflict trials with nonconflict ("context") trials in which subjects pointed to a visual target only (visual context condition) or to a proprioceptive target only (proprioceptive context condition)	In the visual context condition, visual bias of proprioception was large and proprioceptive bias of vision was small (i.e., hand tended to be felt as located where it was seen). In the proprioceptive context condition, however, proprioceptive bias of vision was much larger than visual bias of proprioception (hand tended to be seen as located where it was felt)	Verbal instructions to subjects to focus attention on either visual or proprioceptive information were ineffective in altering intersensory bias; subjects directed attention to proprioceptive information and inhibited attention to visual information only when forced to do so by the nature of the task	Refs. 6, 8
Response modality	3 sec after receiving discrepant visual and proprioceptive information concerning the location of their left index finger, subjects either were shown a numbered scale from which they called off the number located where they remembered their fingers had been seen or felt, or pointed with their right hand to where the left index finger had been located	The modality that is also the response modality plays a greater role in the intersensory bias, both by biasing the other modality more and by being biased less itself. Thus the group responding using the visual scale shows a visual bias of proprioception of 91%, significantly larger than the 71% of the group using the pointing response; the average proprioceptive bias of vision is 35% for the pointing group, but −3% for the visual group	To determine an absolute measure of the strength of intersensory bias, a response that is not dependent on either of the experimental modalities should be used, for example, magnitude estimation	Ref. 5 CRef. 5.1008
Timing of the response	After viewing the finger under visual displacement conditions, subjects closed their eyes and retracted the finger from position. After a delay of 0, 10, 20, 40 or 60 sec, subjects pointed to the remembered location of the finger	As response delay increased, proprioceptive bias of vision increases and visual bias of proprioception decreases (although only the decrease for proprioceptive bias of vision is significant)	The increased role of proprioception may be because (a) removal of the fingers provides increased proprioceptive information, or (b) proprioceptive information is relatively more memorable than visual information. Other studies using short delays (<15 sec) have found no difference in the amount of visual and proprioceptive bias with and without response delay (summarized in Ref. 8)	Ref. 8

5.1010 Cross-Modal Versus Intra-Modal Perception of Distance and Location

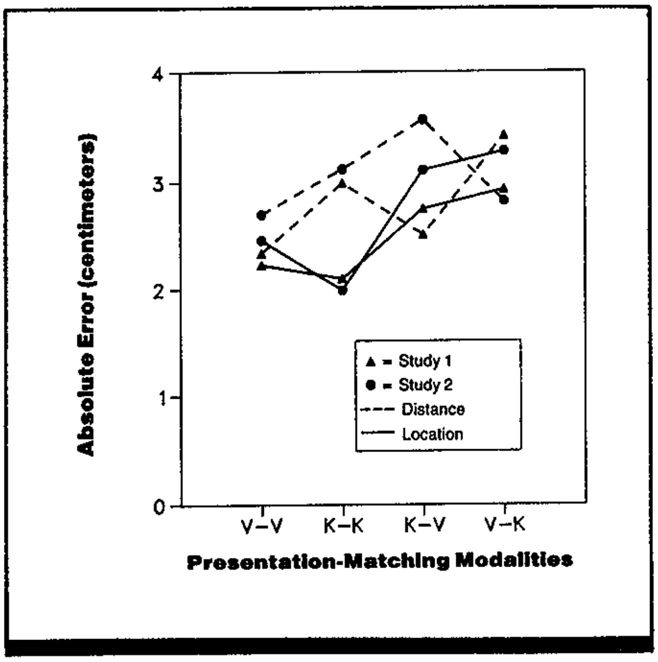

Figure 1. Absolute error for four conditions of intra- or cross-modal matching judgments. V = visual; K = kinesthetic. (From Ref. 3)

Key Terms

Active movement; distance vision; intersensory perception; passive movement; spatial localization

General Description

Judgment of the location of a stimulus moved to a target position is more accurate when the target movement is presented in the same sensory modality (vision or **kinesthesia**) as that used to produce a perceptually equivalent match (intra-modal matching) than when observed and matching movements are in different modalities (cross-modal matching). However, judgments of target distance (extent of movement) do not differ for intra- and cross-modal matches. If the kinesthetic movement is imposed on the arm (passive movement), rather than self-produced (active movement), cross-modal judgment of target distance is more accurate and has less directional bias.

Applications

Designs for which operators must judge distance or location by vision or touch.

Methods

Test Conditions

- Visual target was luminous rod (exposed as its covering slide was moved) in an otherwise dark room as it was moved along a track; after stopping at target position for 2 sec, slide was returned to starting point
- For visual matching, slide or pointer moved by experimenter under direction of subject to match distance traveled by visual target or its end location
- For kinesthetic judgments, target slider grasped and moved by subject until it contacted a mechanical stop; for kinesthetic matches, subject moved slider over perceptually equivalent distance or to equivalent end location; eyes covered during all kinesthetic presentations or judgments
- Two different starting positions and three target distances were used for each modality
- In Study 1, target moved 10, 20 or 30 cm; in Study 2: 10, 30, or 50 cm
- Two trials per condition (Study 1); four trials per condition (Study 2)

Experimental Procedure

- Method of adjustment
- Independent variables: modality of target presentation, modality of perceptual match, type of match (distance or location)
- Dependent variable: matching error, defined as difference between position or distance of target and matched location or distance
- Subject's task: move hand slider or instruct experimenter in movement of visual target so that distance traveled or end location achieved matches distance or end location of previously presented visual or kinesthetic target
- 20 subjects, 10 per condition (Study 1); 72 subjects, 9 per condition (Study 2)

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- When subjects match the final location (end position) of a previously presented reference target by moving a matching target to the same apparent location, accuracy is greater when both reference target and matching target are presented in the same modality, either visually or kinesthetically (intra-modal matching) than when reference and matching targets are presented in different modalities (cross-modal matching).
- There is no difference in the accuracy of intra-modal and cross-modal matches when subjects match the distance traversed by a moving target.

Repeatability/Comparison with Other Studies

Comparable results for judging target location are reported in Ref. 1. Reference 2 shows that when kinesthetic movement is passive, subjects tend to underestimate distance.

Key References

1. Connolly, K., & Jones, B. (1970). A developmental study of afferent-reafferent integration. *British Journal of Psychology, 61,* 259-266.

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*3. Salmoni, A. W., & Sullivan, S. J. (1976). The intersensory integration of vision and kinesthesis for distance and location cues. *Journal of Human Movement Studies, 2,* 225-232.

Cross References

3.311 Perception of arm position: effect of active versus passive movement;

3.312 Perception of arm position: effect of active versus passive movement and practice;

9.204 Blind positioning: effects of prior target exposure;

Handbook of perception and human performance, Ch. 13, Sect. 2.2

5.1011 Orientation Perception in the Presence of Visual-Proprioceptive Conflict

Key Terms

Intersensory bias; intersensory conflict; sensory dominance; spatial orientation; visual capture

General Description

Subjects are able to accurately adjust the position of a bar to horizontal using only **proprioceptive** (and no visual) information. When visual and proprioceptive inputs are discrepant, vision generally dominates proprioception. When subjects view a bar through prisms which tilt the visual field 15 deg, visual information is completely dominant (i.e., subjects told to set the bar until it feels horizontal set it approximately to match the distorted visual horizontal rather than true horizontal). As the degree of optical distortion increases, subjects report awareness of a conflict between what is seen and what is felt, yet are unable to make objectively accurate settings. Typically, for intermediate levels of optical tilt (30-75 deg), the bar is between actual (felt) and apparent (optical) horizontals.

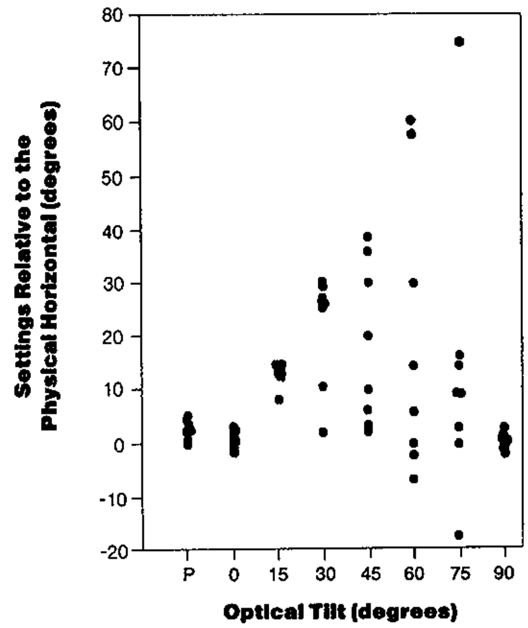

Figure 1. Effect of optical tilt on the felt horizontal. Deviation of setting from the physical horizontal is shown as a function of the amount of optical tilt. Each data point shows the results for one subject. P (proprioception) represents the control condition with no visual input. (From Ref. 2)

Methods

Test Conditions

- Wooden bar 61 cm (24 in.) long, 9 cm deep, and 1.9 cm thick; bar mounted 3.9 cm in front of wooden screen 45.7 cm^2; subject moved fingertips of right hand over middle 15.9 cm of bar marked by tape
- Bar pivoted at center with slant controlled by 6:1 ratio gear operated by subject's left hand; left side upward for half of subjects, right side upward for other half
- Bar viewed through eyepiece containing two **Dove prisms** adjustable by experimenter to produce optical slant of 0-90 deg from horizontal; circular visual field mask limiting view to central taped portion of bar
- Some subjects both saw and felt the bar; other subjects only felt the bar
- Ten settings per subject, 5 for each bar starting position (Fig. 1 shows only first settings made by each subject)

Experimental Procedure

- Method of adjustment under subject's control; between-subjects design
- Independent variables: degree (0-90) of optical tilt of bar relative to physical horizontal; proprioceptive and visual information or proprioceptive information only; starting position of bar (15 deg either side of horizontal)
- Dependent variable: position of bar at which it was felt to be horizontal
- Subject's task: set bar to feel physically horizontal
- 64 subjects, 16-18 years old

Experimental Results

- The most accurate settings of a bar to horizontal are made by control subjects who use proprioceptive information only (i.e., cannot see the bar) and by subjects whose visual fields are tilted by 0 deg and 90 deg. The performance of all other groups is significantly worse.
- Subjects tend to rely on visual information (reporting that the bar feels horizontal when it looks horizontal) for visual distortions up to 30 deg.
- For distortions of 30-75 deg, compromise settings, where the bar is placed between physical and visual horizontal positions, are common.
- Subjects do not become increasingly accurate over trials.

Variability

An analysis of variance applied to a square-root transformation of the data showed some vision vs. vision and/or vision vs. proprioception between-group differences to be significant ($p<0.01$). Performance was highly variable across subjects.

Repeatability/Comparison with Other Studies

Results are consistent with data concerning visual capture, whereby the felt location of a limb changes as a result of visual field displacement (Ref. 1; CRef. 5.1007). Most **perceptual adaptation** studies find that mislocation induced by visual distortion is reduced with practice (CRef. *Handbook*); lack of improvement in accuracy over trials in the present study is probably due to task differences, such as absence of feedback (Refs. 1, 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Results may depend on active limb movement (Ref. 1).

Key References

1. Hay, J. C., Pick, H. L., Jr., & Ikeda, K. (1965). Visual capture produced by prism spectacles. *Psychonomic Science*, *2*, 215-216.

*2. Over, R. (1966). An experimentally induced conflict between vision and proprioception. *British Journal of Psychology*, *57*, 335-341.

Cross References

5.1007 Spatial localization in the presence of intersensory conflict;

5.1008 Spatial localization in the presence of visual-proprioceptive conflict: effect of amount of intersensory discrepancy;

5.1009 Spatial localization in the presence of intersensory conflict: effect of cognitive and response factors;

5.1010 Cross-modal versus intramodal perception of distance and location;

Handbook of perception and human performance, Ch. 25, Sect. 2.2

5.1012 Speeding of Reaction Time by Bisensory Stimulation

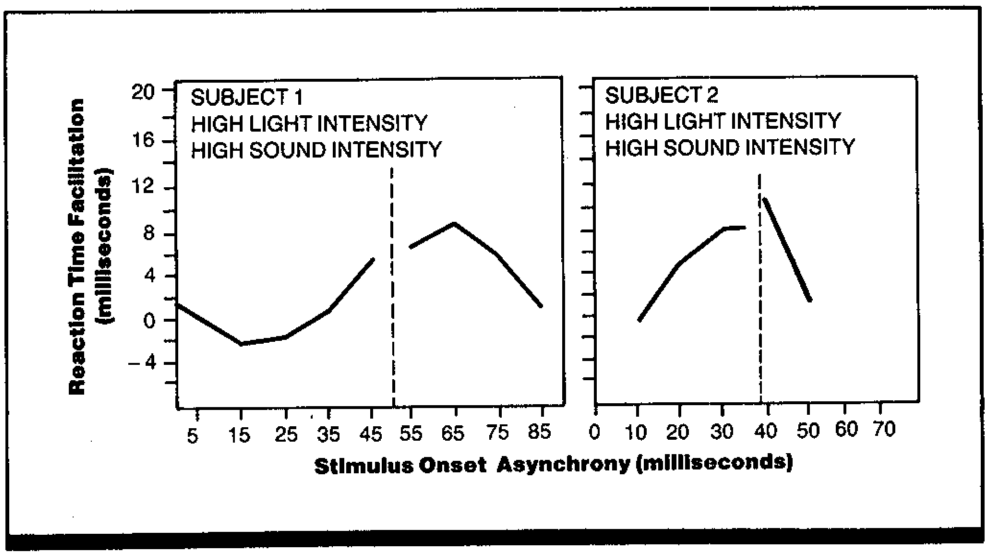

Figure 1. Facilitation of reaction time as a function of interstimulus-onset asynchrony for combined visual and auditory stimuli. Both light and sound were of high intensity. Dashed line represents difference between mean RT to light alone and mean RT to sound alone. Facilitation is measured as the difference between RT to the combined (light + sound) stimulus and the RT to the light alone (for asynchronies to the right of the dashed line) or to the sound alone (for asynchronies to the left of the dashed line). (Negative values indicate inhibition.) (From Ref. 2)

Key Terms

Intersensory facilitation; multimodal perception; reaction time

General Description

Typically, **reaction time** (RT) to visual stimuli is longer than RT to auditory stimuli; presenting visual and auditory stimuli simultaneously as a single, multisensory event does not reduce the RT below that to either stimulus alone (i.e., no facilitation occurs). However, by manipulating the interval between the onset of the light and the onset of sound (interstimulus-onset asynchrony), facilitation is achieved, and is greatest when interstimulus-onset asynchrony equals the difference in RTs to the visual and auditory stimuli alone.

Stimulus intensity affects the degree of facilitation; decreasing the auditory signal diminishes facilitation slightly, while decreasing the visual signal produces a substantial decrement.

Methods

Test Conditions

- Subject seated in soundproof, dimly lit, lightproof room with head in headrest
- Visual stimulus: 50 msec flash of circular target 1 deg, 10 min of visual angle in diameter, 50 cm from subject; two luminances: 10,278 cd/m^2 (3000 fL) or filtered down two log units
- Auditory stimulus: 50 msec noise burst presented via headphone; two amplitudes for each subject: 95, 75 dB above threshold for Subject 1; 85, 65 dB above threshold for Subject 2
- Onset of visual stimulus preceded onset of auditory stimulus by 0, 5, 15, 25, 35, 45, 55, 65, 75, or 85 msec
- Trial structure: 1000 Hz warning tone 1 sec in duration delivered by loudspeaker, followed by 2, 2.25, or 2.5 sec silent period, randomly assigned, followed by presentation of stimuli at one value of interstimulus-onset asynchrony; one trial every 13 sec

Experimental Procedure

- Independent variables: interstimulus-onset asynchrony; stimulus intensity
- Dependent variables: RT to stimulus (visual stimulus alone, auditory stimulus alone, or paired stimuli)
- Subject's task: press button as soon as stimulus is detected
- 2 subjects

Experimental Results

- Facilitation with combined auditory and visual stimuli is a U-shaped function of interstimulus-onset asynchrony. Maximum facilitation is found at the asynchrony equal to the difference in RTs to the visual and auditory stimuli when presented alone.
- RTs are as much as 10 msec shorter with the combined stimulus presentation (visual stimulus preceding auditory stimulus by 30-50 msec) than with either modality alone.
- Decreasing the intensity of the sound by 2 log units has only a minor influence on RT facilitation.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Decreasing the intensity of the light stimulus by 2 log units substantially increases RTs to the light and sound stimuli.
• Subject's subjective impression is that light and sound were presented simultaneously for all values of interstimulus onset asynchrony.

Variability

Within-subject standard deviations range from 4.2-11.1 msec, and were smallest when facilitation was greatest.

Constraints

• Many factors affect reaction time and must be considered in applying these results under different conditions (CRef. 9.108).

Key References

1. Gielen, S. C. A. M., Schmidt, R. A., & van den Heuvel, P. J. M. (1983). On the nature of intersensory facilitation of reaction time. *Perception & Psychophysics, 34,* 161-168.

*2. Hershenson, M. (1962). Reaction time as a measure of intersensory facilitation. *Journal of Experimental Psychology, 63,* 289-293.

3. Hilgard, E. R. (1933). Reinforcement and inhibition of eyelid reflexes. *Journal of General Psychology, 8,* 85-113.

Cross References

5.1014 Speeding of choice reaction time by intersensory accessory stimulation;

5.1015 Speeding of reaction time by intersensory warning signals;

9.108 Factors affecting simple reaction time;

11.420 Response time with redundant information;

Handbook of perception and human performance, Ch. 25, Sect. 1.3

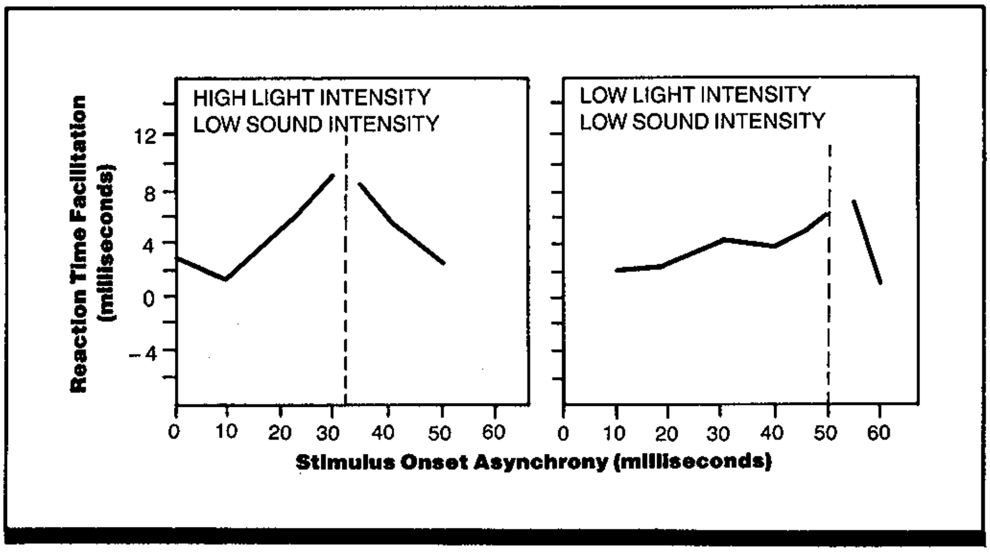

Figure 2. Facilitation of reaction time as a function of interstimulus-onset asynchrony for combined visual and auditory stimuli. Intensities of light and sound varied as indicated. Dashed line represents difference between mean RT to light alone and mean RT to sound alone. Facilitation measured as for Figure 1. (From Ref. 2)

5.1013 Visual Prepotency in a Choice Reaction Time Task

Table 1. Mean reaction times (in msec) for visual, auditory, and bisensory stimuli. (From Ref. 1)

	Simple RT		Choice RT		Bisensory RT		Number of Responses on Bisensory Trials		
Condition	Tone	Light	Tone	Light	Tone	Light	Tone	Light	Total
1	179 (7.2)	197 (7.9)	297 (8.3)	299 (9.0)		303	1	49	50
2	191 (8.9)	203 (8.6)	297 (8.4)	284 (7.2)	200	296	13	97	110
3	190 (6.7)	205 (8.1)	318 (11.0)	298 (9.3)	297	282	3	47	50
4	189 (8.4)	195 (8.1)	358 (11.0)	348 (9.3)	389 (18.4)	330 (12.2)	24	36	60

Note: Subjects presented with light, tone, or both and pressed one of two response keys to indicate stimulus detected. On simple RT trials, subjects knew whether stimulus would be tone or light; on choice RT trials, subjects did not know which stimulus to expect; on bisensory trials both stimuli occurred simultaneously but subject responded to only one. Distribution of responses between "light" and "tone" response keys is given in righthand columns. Standard errors of the mean are shown in parentheses when reported.

Key Terms

Choice reaction time; sensory dominance

General Description

In a simple reaction time (RT) task in which subjects must respond as quickly as possible to a tone or a light and know which stimulus to expect on each trial, RTs are slightly shorter to the tone than to the light (although the differences are not always statistically significant). In a **choice reaction time** task where subjects do not know whether a tone or a light will be presented and must press one of two keys indicating which stimulus occurred, RT is much longer than when the subject knows beforehand which stimulus to expect.

When both a tone and a light are presented simultaneously (bisensory trials), responses are made consistently to the visual rather than to the auditory stimulus. After the stimulus presentation, subjects often report being unaware that the tone was present. Such apparent prepotency of vision over audition occurs when the relative intensities of the visual and auditory stimuli are varied, whether subjects are deceived or informed about the occurrences of the bisensory stimuli, and when instructions explicitly state that responses should be made to the tone when both stimuli occur.

Methods

Test Conditions

Condition 1

- Subjects seated in dimly illuminated room, 45 cm in front of a 30-cm^2 panel containing 5-cm speaker and 6-W incandescent light source
- Stimuli were 4000-Hz, 65-dB SPL tone and light from incandescent source matched to tone for subjective intensity by each subject
- Two keys operated by index fingers, right key was designated tone key and left designated light key for half of subjects; left key was tone key and right key was light key for other half
- Trials consisted of tone, light, or both presented simultaneously (bisensory trials)
- Intertrial interval of 15 sec; warning signal for trials was a verbal "ready"
- 30 simple RT trials, in which subject was told ahead of time which stimulus (tone or light) would occur: 30 choice RT trials, in which subject not told which stimulus would occur; 5 bisensory trials (except 6 for condition 4) in which light and tone presented together; bisensory trials intermixed with choice RT trials
- Subjects unaware that bisensory trials (light and tone simultaneously) would occur, explained as "accidents" if noticed by subject

Condition 2

- Same as Condition 1, except tone loudness adjusted until subjectively twice as intense as the light, which was 538 lux (50 fc)

Condition 3

- Same as Condition 1, except room illumination normal, no warning signal for trials, subjects informed that bisensory trials would occur and instructed to press key to indicate which signal recognized first

Condition 4

- Same as Condition 3, except subjects instructed to press tone key if light and tone presented simultaneously

Experimental Procedure (all conditions)

- Independent variables: task type (simple or choice RT); stimulus modality (tone, light, or both)
- Dependent variables: RT, subject's indication of whether response was correct or incorrect for bisensory trials, report of awareness of bisensory trials
- Subject's task: press tone key or light key, as soon as corresponding stimulus was detected; for choice RT task, report whether he or she had pressed correct key
- 10 subjects for Condition 1, 3, 4; 22 subjects for Condition 2; all college students; each given four practice trials

Experimental Results

- For simple reaction time (RT) tasks, responses are made more quickly to tone than to light presentations, although the difference was significant only for Condition 1 ($p < 0.05$).
- Choice RTs are much slower than simple RTs, with no consistent difference between visual and auditory stimuli.
- Keypresses were made to the light on 49 of 50 bisensory trials presented in Condition 1; with the single tone response made was considered by the subject to be incorrect (Table 1).
- Of 270 bisensory trials across all conditions, 230 responses were made to the visual (light) stimulus.
- Of the "tone" responses on bisensory trials, almost all

(37 of 40) occurred either when instructions were to respond to the tone in cases of conflict (Condition 4) or when the tone was subjectively twice as intense as the light (Condition 2).

- Of the 270 bisensory trials across all conditions, subjects reported being completely unaware of the presence of the tone on 47 trials.

Variability

Standard errors of the mean are shown in Table 1; the range over conditions was 6.7 -18.4.

Repeatability/Comparison with Other Studies

Many studies have found slightly lower RTs to auditory than to visual stimuli. When an auditory warning signal (a stimulus to which no response in required) accompanies a visual stimulus in a visual choice RT task, RTs are reduced; but no consistent effect is found when a visual warning signal is paired with an auditory stimulus (Ref. 2, CRef. 5.1014).

Constraints

- Greatly reduced reaction times ("tone" keypresses) on bisensory trials were found in Condition 2, suggesting a relation between tone intensity and bisensory RTs when the "tone" response was made. Several subjects volunteered the information that the tone was aversively loud when adjusted to twice the subjective intensity of the light. Such an aversive component may account for the reduction in RTs for the tone.
- Many factors affect reaction time and should be considered in applying these results under other conditions (CRef. 9.108).

Key References

*1. Colavita, F. B. (1974). Human sensory dominance. *Perception & Psychophysics, 16,* 409-412.

2. Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review, 83,* 157-171.

Cross References

5.1012 Speeding reaction time by bisensory stimulation;

5.1014 Speeding of choice reaction time by intersensory accessory stimulation;

5.1015 Speeding of reaction time by intersensory warning signals;

9.108 Factors affecting simple reaction time;

11.420 Response time with redundant information

5.1014 Speeding of Choice Reaction Time by Intersensory Accessory Stimulation

Key Terms

Accessory stimulation; choice reaction time; intersensory facilitation

General Description

In a **choice reaction time** (RT) task in which subjects must indicate as quickly as possible whether a visual stimulus appears to the left or the right of center, subjects respond more quickly when the visual stimulus is accompanied by an auditory accessory stimulus (an "irrelevant" stimulus requiring no response) than when the visual stimulus is presented alone. The auditory accessory stimulus reduces RT to the visual stimulus when it precedes or follows the visual stimulus by as much as 100 msec. However, the presence of a visual accessory stimulus has no effect on choice RT to either a visual stimulus or an auditory stimulus.

Methods

Test Conditions

- Visual RT stimulus: X on left or right half of screen
- Visual accessory stimulus: 50 msec flash of light in center of screen
- Auditory RT stimulus: 500 Hz tone in left or right ear via earphones
- Auditory accessory stimulus: 50 msec burst of white noise
- Two response keys, corresponding to left and right choices
- Accessory signal presented on 80% of trials; accessory signal preceded or followed RT stimulus by 0-100 msec
- Conditions: visual accessory stimulus and visual RT stimulus; visual accessory stimulus and auditory RT stimulus; auditory accessory stimulus and visual RT stimulus

Experimental Procedure

- Independent variables: auditory or visual RT task, auditory or visual accessory stimulus, interval between accessory stimulus and RT stimulus
- Dependent variables: RT, error rate
- Subject's task: indicate as quickly as possible by pressing left or right key whether stimulus was presented to left ear or right ear or left or right of screen
- No information given on subjects

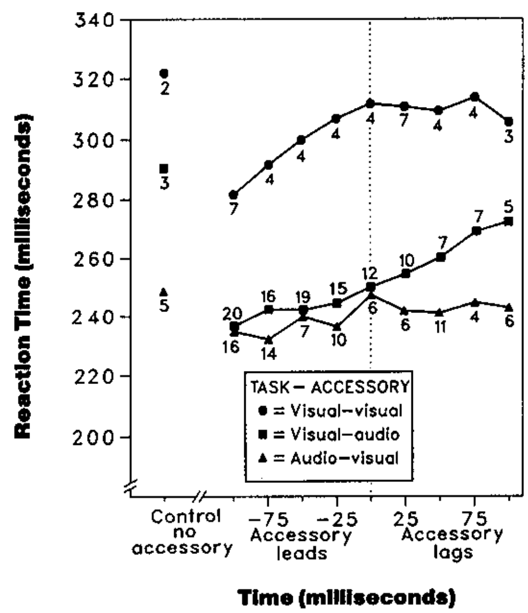

Figure 1. Choice reaction time with accessory stimulation. Subjects pressed one of two response keys to indicate whether a visual or auditory stimulus (task stimulus) was presented on the left or right. Task stimulus was accompanied by an accessory stimulus presented before or after the RT task stimulus at the interval shown on the horizontal axis. Number of errors in left-right categorizations are shown for each data point. (From Ref. 3)

Experimental Results

- Reaction time (RT) to indicate whether a visual stimulus is to the left or the right decreases when an auditory accessory stimulus is presented within 100-msec before or after the visual stimulus. When the visual stimulus and auditory accessory occur simultaneously, RT to the visual stimulus is ~40 msec less than RT with no accessory stimulus.
- Although RT to a visual stimulus decreases when an auditory accessory signal is present, errors in judging whether the visual stimulus is on the left or the right increase.
- A visual accessory signal is much less effective than an auditory accessory in reducing RT to a visual stimulus.
- When a visual accessory stimulus is presented simultaneously with either a visual or an auditory RT stimulus, reaction time to the test stimulus is not changed significantly.

Variability

No information on variability was reported.

Repeatability/Comparison with Other Studies

Reference 1 found facilitation when a visual stimulus was followed 20-120 msec later by an auditory accessory stimulus. Reference 2 found a decrease in RT when a visual accessory followed an auditory RT stimulus by <40 msec, although no facilitation was observed for greater delays. Similarly, it has been reported that choice RTs for a visual stimulus are more influenced by attention allocation probes (events indicating stimulus modality) than are choice RTs for auditory or proprioceptive stimuli (Ref. 3).

When visual and auditory signals are simultaneous and the task is to respond to the modality of presentation, subjects usually respond to the visual signal and are often unaware of auditory stimulation (Ref. 3; CRef. 5.1013).

Simple reaction time is faster for combined auditory and visual stimuli than for a stimulus of either modality alone (CRef. 5.1012).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Many factors influence reaction time and should be considered in applying these results under different conditions (CRef. 9.108).

Key References

1. Morrell, L. K. (1968). Cross-modality effects upon choice reaction time. *Psychonomic Science, 11*, 129-130.

2. Morrell, L. K., (1968). Temporal characteristics of sensory interaction in choice reaction times. *Journal of Experimental Psychology, 77*, 14-18.

*3. Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review, 83*, 157-171.

Cross References

5.1012 Speeding of reaction time by bisensory stimulation;

5.1013 Visual prepotency in a choice reaction time task;

5.1015 Speeding of reaction time by intersensory warning signals;

9.108 Factors affecting simple reaction time;

9.114 Choice reaction time: effect of warning interval on error;

11.420 Response time with redundant information;

Handbook of perception and human performance, Ch. 24, Sect. 1.2

5.1015 Speeding of Reaction Time by Intersensory Warning Signals

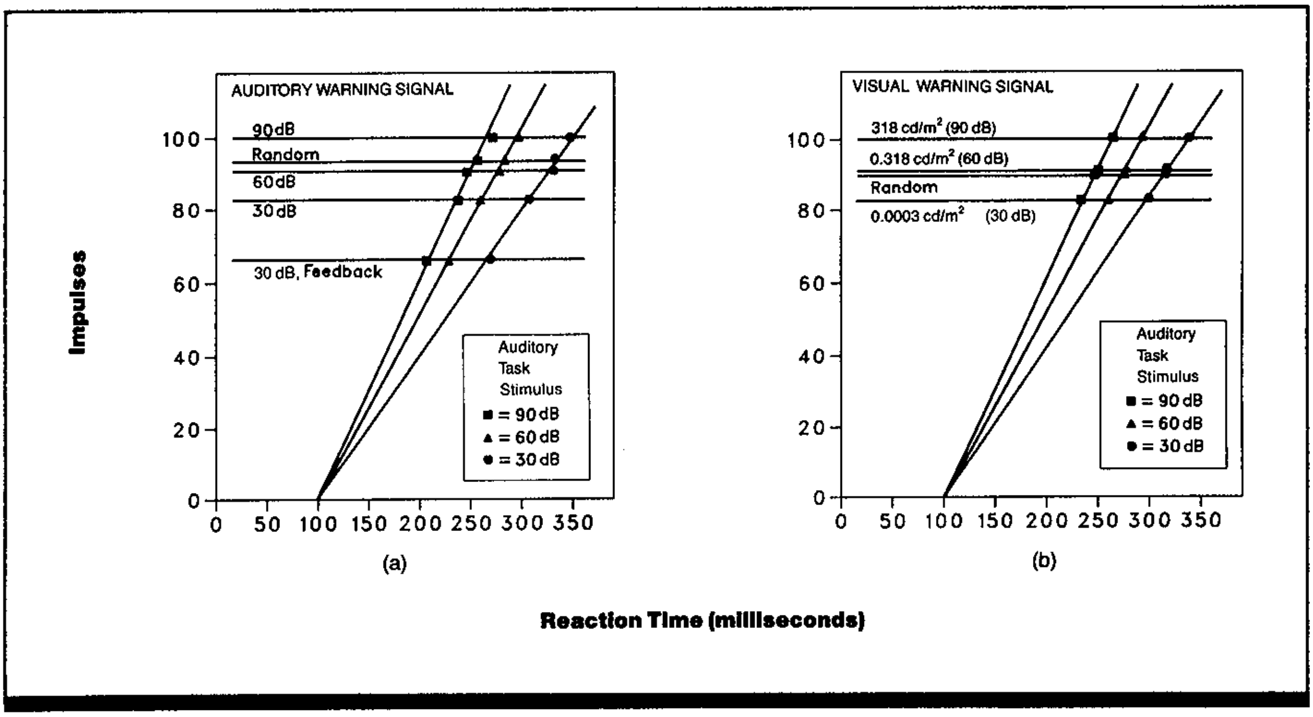

Figure 1. Effect of warning signal intensity on reaction time to an auditory task stimulus. Number of impulses reflects signal intensity, with 90-dB signals assigned an arbitrary value of 100 impulse units. (See text for complete description of data treatment.) (a) Auditory warning signal presented at 30, 60, or 90 dB SPL as shown by horizontal lines, or with three intensity levels randomly intermixed; for feedback condition, subjects informed of their response times after each trial. Auditory task stimulus presented at one of three randomly intermixed intensity levels, as shown. (b) Corresponding data for visual warning signals. 100 msec (origin of fit lines) is assumed to be the minimum value beyond which RT cannot be reduced (consisting of RT components not under the influence of stimulus intensity). (From Ref. 2)

Key Terms

Intersensory facilitation; reaction time; stimulus intensity; warning signal

General Description

The effect of an auditory or visual warning (or ready) signal on reaction time (RT) to an auditory stimulus depends on the intensities of the warning signal and the auditory task stimulus (the stimulus to which a response must be made). Increasing the intensity of the warning signal lengthens RTs to the auditory task stimulus. Increasing the intensity of the task stimulus shortens RT. RTs are shortest when the lowest intensity warning signal and the highest intensity task stimulus are used. These effects are seen when the warning signal is visual and the task stimulus is auditory as well as when both stimuli are auditory.

Methods

Test Conditions

- Subjects seated in totally dark chamber; responses made on telegraph key on chair arm
- 1000-Hz tones generated by audio oscillator, delivered via headphones, used as task stimulus (1.5-sec duration) and warning signal (0.5-sec duration); three intensities (30-90 dB SPL)
- White light used as visual warning signal, delivered through 38.1 × 38.1-cm (15 × 15-in.) eye-level Plexiglas window, 91.4 cm in front of subject; three intensities [0.0003-318 cd/m^2 (0.0001-100 mL)] corresponding in subjective magnitude to tones of 30-90 dB SPL
- Warning signal presented 1, 2, or 3 sec before task stimulus; intervals presented in irregular order over trials
- RT performance either reported or not reported to subjects
- Five 45-min auditory warning sessions: warning intensity constant for four sessions (one with feedback), random for one session; four visual warning sessions: warning intensity constant for three sessions, random for one session; 90 trials per session
- Task stimulus intensity randomized over trials; warning intensity order counterbalanced over sessions

Experimental Procedure

- Method of constant stimuli, simple reaction time (RT)
- Independent variables: warning signal modality; task stimulus intensity; feedback
- Dependent variable: reaction time
- Subject's task: respond as quickly as possible when task stimulus detected by making a keypress
- Subjects: 32 soldiers (16 in each warning signal modality condition)

Experimental Results

• For plotting in Fig. 1, data were transformed as follows: the mean RT for each warning signal condition was calculated and then 100 msec was subtracted from each value to remove an assumed irreducible minimum RT; the resulting value for the 90-dB condition was arbitrarily assigned an index value of 100 impulses and the vertical positions of the other warning signal conditions were calculated as a proportion of the 90-dB index value. (The conversion to impulse units is based on an assumption of the decision theory model that a response is initiated when the number of neural impulses generated by the stimulus reaches some criterion value.) Linear functions were fit to each set of data points originating at 100 msec (presumed irreducible minimum RT) by the method of least squares.
• Mean RT systematically decreases as the intensity of the auditory task stimulus increases ($p<0.001$).
• Mean RT increases as the intensity of an auditory warning signal increases ($p<0.001$).
• Mean RT increases as the intensity of a visual warning signal increases ($p<0.025$).
• With both auditory and visual warning signals, mean RTs were shortest when the lowest intensity warning signal was paired with the highest intensity auditory task stimulus.
• Feedback in the auditory warning-auditory task signal condition facilitated (decreased) RT.
• A significant interaction is found between auditory warning signal intensity and task stimulus intensity ($p<0.025$). This finding is consistent with a decision-theory interpretation of the data wherein task stimulus intensity determines the slope of the input function, while the warning signal influences the value of the detection criterion, as if the warning signal intensity set a criterion against which the task stimulus is measured.

Variability

An analysis of variance was conducted to evaluate the significance of the independent variables and interactions. No specific information about between-subject variability or within-subject variability was provided, although it has been reported (Ref. 2) that individual differences in RTs are often substantial.

Repeatability/Comparison with Other Studies

In a choice reaction time task, the presence of an auditory accessory stimulus improves RT to a visual stimulus, but a visual accessory stimulus has no consistent effect on either visual or auditory RT performance (CRef. 5.1014).

Constraints

• An analysis of variance showed that the interaction of auditory task signal intensity conditions with visual warning signal intensity conditions was not statistically significant although the effect of a visual warning signal was, by itself, significant ($p<0.025$). This result may be inconsistent with an input function model (Ref. 2).
• Reported mean reaction times (RTs) to auditory task stimuli (234-304 msec) are somewhat longer than are typically reported (110-150 msec), suggesting that RTs may have been increased, perhaps as a function of uncertainty associated with random-length intervals between warning and task stimuli (CRefs. 9.108, *Handbook*).
• Many factors affect reaction time and must be considered in applying these results under different conditions (CRef. 9.108).

Key References

1. Grice, G. R., & Hunter, J. J. (1964). Stimulus intensity effects depend upon the type of experimental design. *Psychological Review, 71*, 247-256.

*2. Kohfeld, D. L. (1969). Effects of the intensity of auditory and visual ready signals on simple reaction time. *Journal of Experimental Psychology, 82*, 88-95.

3. Murray, H. G., & Kohfeld, D. L. (1965). Role of adaptation level in stimulus intensity dynamism. *Psychonomic Science, 3*, 439-440.

Cross References

5.1012 Speeding of reaction time by bisensory stimulation;

5.1014 Speeding of choice reaction time by intersensory accessory stimulation;

9.101 Reaction time tasks and variability;

9.108 Factors affecting simple reaction time;

9.114 Choice reaction time: effect of warning interval on error;

Handbook of perception and human performance, Ch. 25, Sects. 1.1, 1.3

5.1016 Intermodal and Cross-Modal Spatial Pattern Recognition

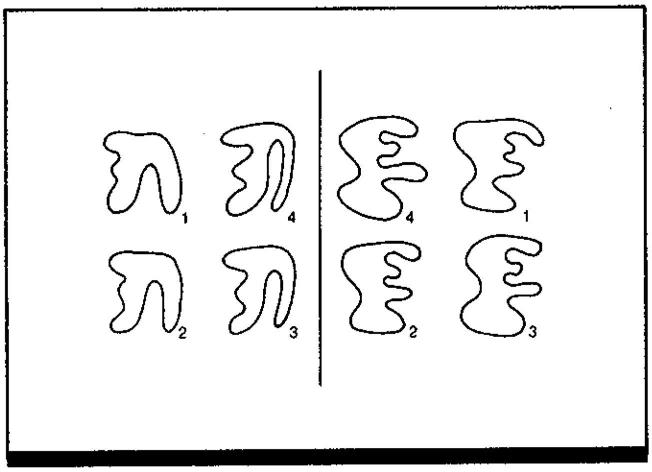

Figure 1. Two of the visual arrays used for the pattern recognition task. Pattern 4 was always the standard. Patterns 1-3 represent the least similar to most similar (but not identical) comparison patterns. (From Ref. 1)

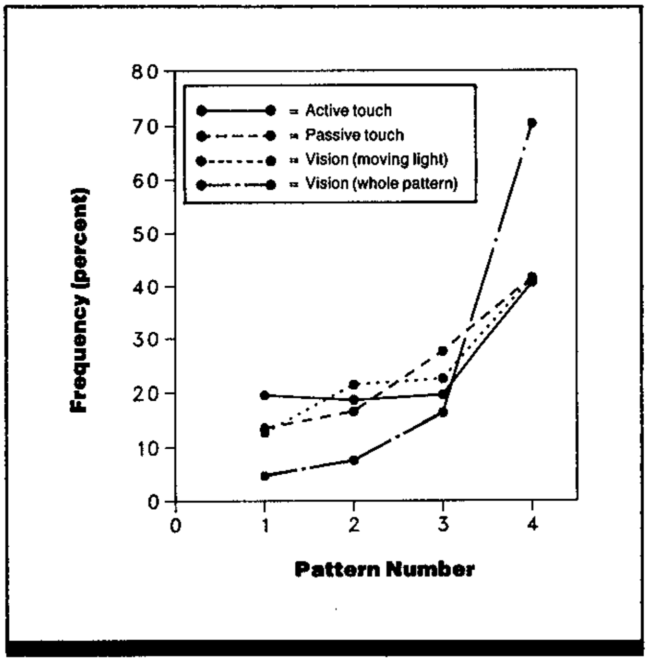

Figure 2. Frequency with which subjects selected a visual pattern as identical to the standard presented, under four different modes of pattern presentation. Pattern 4, the standard, indicates correct matches. Patterns 1, 2, and 3 were increasingly similar to the standard. (From Ref. 1)

Key Terms

Active touch; haptic form perception; passive touch; pattern recognition; visual form perception

General Description

Visual pattern recognition is the same for patterns presented haptically (by active or passive touch) or visually (by viewing a moving light tracing the pattern). Visual pattern recognition is superior for patterns seen in their entirety.

Methods

Test Conditions

- Ten standard patterns composed of curved, closed grooves 1.8 cm wide; each standard was a member of an array with three comparison (similar, but not identical) patterns (sample pattern array shown in Fig. 1)
- Subjects inspected the standards by passive touch (right hand of subject moved by the experimenter around pattern groove), active touch (subject moved hand-held stylus fitted into pattern groove), or visually by observing a light moved along the groove or by observing the entire pattern illuminated for 5 sec
- Following inspection of the standard pattern, the comparison array was available for visual inspection; one comparison pattern was always identical to the standard, and the other three were different
- Ten trials per condition

Experimental Procedure

- Independent variable: method of inspecting standard pattern
- Dependent variable: recognition accuracy, as measured by frequency of correct pattern choice
- Observer's task: visually identify previously inspected standard pattern from an array of four comparison patterns
- 40 observers, 20 male and 20 female college students

Experimental Results

- Patterns inspected by active touch, passive touch, or visual observation of a moving light that traces the pattern can be recognized with equal accuracy in a static array of comparison patterns presented visually.
- Visual pattern recognition for patterns visually inspected in their entirety is superior to visual pattern recognition for patterns presented by touch or by visual tracing ($p < 0.002$).

Variability

Mann-Whitney U tests on choice scores were used to compare the performance of subjects in the four conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Many studies of tactual form perception indicate that active inspection is superior to passive inspection (Ref. 2).

Key References

*1. Bairstow, P. J., & Laszlo, J. I. (1978). Perception of movement patterns. Recognition from visual arrays of distorted patterns. *Quarterly Journal of Experimental Psychology, 30*, 311-317.

2. Gibson, J. J. (1962). Observations on active touch. *Psychological Review, 69*, 477-491.

Cross References

Handbook of perception and human performance, Ch. 13, Sect. 2.2

5.1017 Discrimination and Reproduction of Temporal Patterns: Comparison of Audition, Vision, and Touch

Table 1. Discrimination and reproduction of temporal patterns as a function of presentation modality and training. (From Ref. 1)

	% Correct Responses			
	Before Training		After Training	
	Discrimination	Reproduction	Discrimination	Reproduction
Auditory	84.7	66.9	86.8	76.5
Visual	74.6	31.8	77.7	70.2
Tactual	70.1	47.1	74.3	76.1

Key Terms

Auditory pattern perception; rhythm; temporal pattern reproduction; temporal perception; touch; training; visual pattern perception

General Description

Subjects are more accurate in discriminating and reproducing temporal patterns when the patterns are presented by audition than when they are presented by vision or touch. Practice improves pattern reproduction performance, but does not affect pattern discrimination performance.

Methods

Test Conditions

- Temporal (rhythmic) patterns were presented in auditory, visual, and tactile modalities; stimuli were presented via loudspeaker, neon flash tube, and vibrator device, respectively; no description of patterns given
- For the discrimination task, the subject was presented with two patterns and indicated if they were the same or different; for the reproduction task, subject reproduced pattern by beating in air with a baton connected to an electrical circuit for recording purposes
- Training consisted of two half-hour practice periods on each of five days, with feedback; patterns other than those used in testing were presented

Experimental Procedure

- Independent variables: modality of pattern presentation
- Dependent variables: for discrimination, number of correct determinations; for reproduction, number of patterns correctly reproduced (subject's reproduction of pattern judged as correct if response contained the correct number of impulses and if each was within 25% of its correct temporal position)
- Subject's task: for discrimination, state whether pair of patterns was the same or different; for reproduction, reproduce pattern in air with baton
- 14 undergraduates and laboratory workers

Experimental Results

- The discrimination of temporal patterns is most accurate with auditory presentation of the patterns, of intermediate accuracy with visual presentation, and least accurate with tactile presentation.
- Reproduction of temporal patterns is most accurate when presentation is auditory and least accurate when presentation is visual.
- Training significantly improves reproduction accuracy and greatly reduces differences due to presentation modality.
- Training has little effect on discrimination performance, regardless of presentation modality.

Variability

Variability not reported for subjects used in the experiment reported. However, in an identical study in which subjects were given no training, standard deviations ranged from 5.1-7.4% on discrimination tasks and 9.1-11.4% on reproduction tasks.

Repeatability/Comparison with Other Studies

Performance of the subjects before training was virtually identical to the performance of 21 subjects who were tested in an identical experiment without training.

Constraints

The manner of presentation of stimuli to the three modalities is not equivalent, and the outcome may reflect this rather than inherent modality differences. However, other studies support the superiority of audition for perception of temporally distributed patterns.

Key References

*1. Gault, R. H., & Goodfellow, L. D. (1938). An empirical comparison of audition, vision, and touch in the discrimination of temporal patterns and ability to reproduce them. *The Journal of General Psychology, 18*, 41-47.

Cross References

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

5.1019 Duration perception with auditory, visual, and bisensory stimuli;

5.1020 Perception of temporal rate: auditory-visual interactions;

5.1021 Detection of auditory-visual asynchrony

5.1018 Temporal Pattern Recognition with Unimodal Versus Multimodal Presentation

Table 1. Average number of elements presented before correct identification of pattern. (From Ref. 2)

	Presentation Rate (elements/sec)			
Presentation Modality	**1**	**2**	**4**	**Average for All Rates**
Auditory	25	36	131	64
Tactile	26	40	133	66
Visual	24	38	255	104
Auditory-Tactile	27	41	135	68
Auditory-Visual	24	32	91	49
Tactile-Visual	23	44	145	71
Auditory-Tactile-Visual	23	31	128	61

Key Terms

Intersensory facilitation; pattern recognition; stimulus redundancy

General Description

When a temporal pattern is presented one element at a time, increasing the presentation rate significantly increases the number of elements that must be repeated before the pattern can be identified. At slow rates (1-2 elements/sec) recognition speed is roughly the same regardless of the presentation modality or whether the pattern is presented in one modality alone or in two or three modalities simultaneously. At higher rates (4 elements/sec), however, combined auditory-visual (AV) presentation produces faster recognition than either the auditory (A) or visual (V) presentation alone. The fact that the multimodal presentation results in faster pattern recognition indicates an additive interaction between the modalities.

Methods

Test Conditions

- Auditory stimuli: two 65 dB SPL tones presented by loudspeakers 1.89 m (6 ft) apart, 1.22 m from subject; first tone of 1200 Hz; second tone of 3000 Hz
- Tactual stimuli: two vibrators, one held in each hand, hands 0.305 m apart; first vibrator powered by 12-V, 60-Hz source; second vibrator by 6-V, 30-Hz source
- Visual stimuli: two panel lights 2.54 cm in diameter, 0.305 m apart, located at eye-level 1.22 m from subject; one red light, one green light; luminance 0.857 cd/m^2
- 10 different temporal patterns of eight dichotomous elements, based on left-right location (e.g., LLRLLRLR); presentation rates of 1, 2, or 4 elements/sec; pattern cycled until it was identified or until 560 elements had been presented
- Pattern presentation modes: pattern presented in one modality only, two modalities simultaneously, or three modalities simultaneously

Experimental Procedure

- Order of presentation of both stimulus pattern and stimulus modality was counterbalanced
- Independent variables: modality (or modalities) of presentation, rate of presentation
- Dependent variable: number of elements presented before pattern could be identified
- Subject's task: verbally replicate correct pattern sequence.
- Each data point in table is mean for 28 subjects
- 120 paid college undergraduates

Experimental Results

- As the presentation rate for temporal patterns increases, so does the number of pattern elements that must be presented for correct identification ($p < 0.05$). This trend holds regardless of whether the pattern is presented through vision, touch, hearing, or a combination of two or three of these modalities.
- Combined auditory visual presentation produces fastest recognition ($p < 0.05$); the auditory-tactile combination is intermediate; and recognition is slowest with combined tactile-visual presentation.

Variability

Analysis of variance was used to determine significance of modality and presentation rate. No specific values for within-subject or between-subject variability were given.

Repeatability/Comparison with Other Studies

Results agree with the findings of Ref. 1 regarding fast and slow presentation of elements, the rate of learning for different modalities, and the fashion in which patterns are learned.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- There is no simple way of predicting performance with multimodal presentation from performance with presentation via a single modality.
- The relative capability of each modality in recognizing temporal patterns may differ with different stimulus parameters.

Key References

1. Garner, W. R., & Gottwald, R. L. (1968). The perception of patterns. *Quarterly Journal of Experimental Psychology, 20,* 97-100.

*2. Handel, S., & Buffardi, L. (1969). Using several modalities to perceive one temporal pattern. *Quarterly Journal of Experimental Psychology, 21,* 256-266.

Cross References

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1020 Perception of temporal rate: auditory-visual interactions;

5.1021 Detection of auditory-visual asynchrony;

6.505 Identification of vibrotactile patterns: temporal resolution

5.1019 Duration Perception with Auditory, Visual, and Bisensory Stimuli

Key Terms

Attention; intersensory conflict; multimodal perception; sensory dominance; temporal perception

General Description

At durations of 1-2 sec, auditory stimuli are perceived to last longer than visual stimuli of comparable intensity or salience. The judged duration of an auditory-visual stimulus compound, therefore, involves conflicting perceptions. Resolution of this conflict depends on the situation, with reports of resolution in favor of the stimulus with the longer perceived duration (Ref. 4), in favor of the more salient (intense) stimulus (Ref. 1), and in favor of the stimulus on which attention is focused (Ref. 2). The accompanying table summarizes the results of several studies in this area.

Constraints

- Perceived duration for short intervals varies with processing complexity (Ref. 3).
- The variables that determine the nature of sensory dominance are not well understood.
- The observed effects may not be robust; that is, they may not appear in situations involving higher levels of overall perceptual stimulation.

Key References

1. Goldstone, S., Boardman, W. K., & Lhamon, W. T. (1959). Intersensory comparisons of temporal judgments. *Journal of Experimental Psychology, 57*, 243-248.

2. Lhamon, W. T., & Goldstone, S. (1974). Studies of auditory-visual differences in human time judgment: 2. More transmitted information with sounds than lights. *Perceptual and Motor Skills, 39*, 295-307.

3. Thomas, E. A. C., & Cantor, N. (1976). Simultaneous time and size perception. *Perception & Psychophysics, 19*, 353-360.

4. Walker, J. T., & Scott, K. J. (1981). Auditory-visual conflicts in the perceived duration of lights, tones, and gaps. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1327-1339.

Cross References

2.502 Detection of gaps in continuous noise;

2.503 Discrimination of event duration;

2.504 Perceived event duration: effect of complexity and familiarity;

4.301 Information theory;

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

5.1020 Perception of temporal rate: auditory-visual interactions

Table 1. Temporal duration judgments for auditory, visual, and bisensory (combined auditory-visual) stimuli.

Test Conditions	Procedure and Task	Results	Source
Bisensory compounds, sound and light in separate spatial locations			
• 725-Hz pure tone, 53 dB (weak) or 78 dB SPL (strong), via headphones; 1-deg circular light patch, 10.6 (weak) or 13.7 (strong) cd/m^2 (4 or 6 fc) • Sound and light presented simultaneously, with no stimulus focus during first half of trials, focus on either sound or light during second half of trials	• Modified method of limits • Subjects judged whether stimulus duration on each trial was more or less than 1 sec (no standard interval provided for comparison) • 40 college students	• With a bisensory stimulus comprised of strong tone and weak light, a 0.50-sec stimulus was judged equal to 1 sec; this is approximately equal to the results obtained when a 70 dB SPL tone is presented alone • With a bisensory stimulus comprised of strong light and weak tone, a 0.99-sec stimulus was judged equal to 1 sec; this is approximately equal to the results obtained when a light of 13.7 cd/m^2 is presented alone • Thus, under bisenory stimulation, the more intense stimulus modality dominates duration judgments. An auditory "second" is much shorter than a visual second • Instructions to focus on either sound or light do not change judgment biases toward the more intense stimulus	Ref. 1

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Test Conditions	Procedure and Task	Results	Source
• 1000-Hz tone, 68 dB SPL via headphones; 1.3-deg light patch of 14-21 cd/m^2 • On each trial, a 1-sec standard interval was followed by a test interval that varied in duration from 0.55-1.45 sec • In bisensory condition, subjects told to attend to both tone and light, or told to focus on either light or tone • Trials contained only tone, only light, or both tone and light	• Modified method of constant stimuli • Subject judged the duration of the variable interval as longer or shorter than the standard interval using a 9-category scale • 40 adult men and women, 20 in no-focus and 20 in focus condition	• Information transmission (CRef. 4.301) is greater for an auditory stimulus than for a visual stimulus on single modality temporal judgments • Auditory-visual bisensory stimuli yield intermediate levels of information transmission; however, instructions to focus on either vision or audition for bisensory stimuli yielded transmission close to that for the attended modality alone	Ref. 2
Bisensory compounds, sound and light in same spatial location			
• 600-Hz tone, 75 (strong) or 50 (weak) dB(A), via loudspeaker; 15 x 20 mm, 29.88 cd/m^2 (90 mL), in center of speaker enclosure; speaker 1.4 m from subject • 0.5-, 1.0-, 1.5-sec intervals • Filled intervals; light, tone, or both presented for given interval; gaps: tone and light presented continuously except during test intervals, which consisted of a gap in the tone, the light, or both simultaneously	• Subject reproduced with a button press the perceived duration of the stimulus or the gap in the stimulus • A total of 60 college students across all conditions	• The perceived duration of a tone of 1.0 or 1.5 sec is longer by ~5-10% than the perceived duration of a light of equal length. Only with 0.5 sec durations and a weak tone intensity is the light perceived as longer in duration than the tone • When a light and tone are presented simultaneously, the perceived duration of the bisensory stimulus is close to that of a tone alone • A gap in an otherwise continuous tone appears longer than a gap in a continuous light, and the perceived duration of a gap in a bisensory stimulus is close to the perceived duration of a gap in a tone alone • The bias toward the auditory stimulus in bisensory compounds is not reduced when judgments to both light and tone are made sequentially to focus attention on the separate stimulus components	Ref. 4

5.1020 Perception of Temporal Rate: Auditory-Visual Interactions

Key Terms

Amplitude modulation; cross-modal judgment; flicker perception; flutter; intersensory bias; sensory dominance; temporal perception

General Description

People have a very difficult time accurately matching the flicker rate of a visual stimulus to the flutter rate of an auditory stimulus for sub-fusion stimuli (that is, stimuli presented at rates below that at which the stimulus appears fused or steady rather than oscillating). At frequencies >2 or 3 Hz, auditory stimuli drive visual stimuli; changes in the rate of auditory flutter produce perceived changes in rate of visual flicker even when flicker rate has remained constant. Visual stimuli do not drive auditory stimuli. The accompanying table summarizes several studies investigating auditory-visual interactions in judgments of temporal rate.

Repeatability/Comparison with Other Studies

Reference 4 found that auditory flutter "drives" perceived flicker rate; however there is no auditory driving of visual evoked potentials to flickering stimuli, even when flutter and flicker rates are set so that the subject experiences the perception of auditory driving. Auditory driving also has no effect on visual flicker thresholds.

Applications

Tasks that involve decisions based on perceived rate of visual flicker should be avoided, especially in situations that are noisy or that include repetitive sounds.

Constraints

- The precise nature of the auditory driving phenomenon is not well understood, and the phenomenon appears to vary somewhat with the particular type of matching task, viewing conditions, and size and color of the visual stimulus.
- Many factors affect the perception of flicker (CRef. 1.501).

Key References

*1. Gebhard, J. W., & Mowbray, G. H. (1959). On discriminating the rate of visual flicker and auditory flutter. *American Journal of Psychology, 75*, 521-529.

*2. Knox, G. W. (1945). Investigations of flicker and fusion. IV. The effect of auditory flicker on the pronouncedness of visual flicker. *Journal of General Psychology, 33*, 145-154.

*3. Myers, A. K., Cotton, B., & Hilp, H. A. (1981). Matching the rate of concurrent tone bursts and light flashes as a function of flash surround luminance. *Perception & Psychophysics, 30*, 33-38.

4. Regan, D., & Spekreijse, H. (1977). Auditory-visual interactions and the correspondence between auditory space and perceived visual space. *Perception, 6*, 133-138.

*5. Shipley, T. (1964). Auditory flutter-driving of visual flicker. *Science, 145*, 1328-1330.

Cross References

1.501 Factors affecting sensitivity to flicker;

2.501 Sensitivity to amplitude modulation of broadband noise;

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1019 Duration perception with auditory, visual, and bisensory stimuli;

5.1021 Detection of auditory-visual asynchrony

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Auditory-visual interactions in the perception of temporal rate below the fusion threshold.

Test Conditions and Procedure	Task	Results	Source
• Visual flicker of 16 or 24 Hz; intensity of stimulus adjusted so that **critical flicker frequency** was 48 Hz; viewing through artificial pupil; 5 min of **dark adaptation** before each session • Auditory flutter of 15, 18, 21, 24, 27, or 30 Hz • 3 subjects	Adjust visual flicker in presence of flutter to have same frequency of flicker it had before the flutter was added	• All flutter rates make flicker appear "coarser," hence flicker rate is set higher with flutter than without • Adjustment of flicker is an inverse linear function of flutter rate • Attention to sound increases bias; attention to light decreases it	Ref. 2
• Visual stimulus: 25 deg, 20.8 cd/m^2, 10-msec flash, flickering at 2-10 Hz, viewed by right eye • Auditory stimulus: 1 msec, 31.5-octave band click at 69 dB SPL presented to right ear; variable flutter frequency • Method of adjustment • 2 observers	Starting with flicker and flutter in synchrony, adjust flutter to point at which flicker and flutter seem to be asynchronous	• Apparent rate of flicker increases or decreases as flutter rate increases or decreases • About 4 Hz, auditory driving of flicker is more pronounced when flutter rate is higher than flicker rate • Around 10 Hz, intersensory matches become extremely variable	Ref. 5
• Visual stimulus: 1 deg circle of white light, 33.2 cd/m^2 (100 mL); **foveal, binocular** viewing; 70 deg, 16.6 cd/m^2 surround; flicker rates of 5-40 Hz • Auditory stimulus: 35-dB SPL **white noise**; flutter rates of 5-40 Hz • Method of adjustment • 3 trained observers	Adjust the rate of flicker to match a standard rate of flutter or adjust the rate of flutter to match a standard rate of flicker	• **Difference thresholds** for cross-modality matches are up to 10 times larger than those for within-modality matches • Matching flutter to a standard flicker is consistently more difficult than matching flicker to flutter	Ref. 1
• Visual stimulus: 0.75 deg light emitting diode (LED), either 650 nm, 340 cd/m^2, or 568 nm, 240 cd/m^2; centered on a 22.3-deg, 215-cd/m^2 white surround or dark surround; flicker rates of 4, 7, or 10 Hz, **binocular** viewing • Auditory stimuli: 1500 Hz, 87-dB SPL tone, flutter rates of 4, 7, or 10 Hz • Method of adjustment • 24 trials • College students	Starting from asynchronous rates, adjust flicker or flutter to point of synchrony	• When flutter is adjusted to match a fixed flicker, the flutter must be set to a higher rate than the flicker to appear equal; the bias is enhanced when the surround of the visual stimulus is dark • When flicker is adjusted to match a fixed flutter, the flicker must be set to a higher rate to appear equal; the bias is enhanced when the surround of the visual stimulus is light rather than dark	Ref. 3

5.1021 Detection of Auditory-Visual Asynchrony

Table 1. Degree of asynchrony between visual and auditory presentations at threshold. (From Ref. 1)

Stimulus	Condition	Mean Detected Asynchrony (msec)
Man speaking	Auditory delay	257.9
	Auditory advance	131.1
Hammer hitting peg	Auditory delay	187.5
	Auditory advance	74.8

Key Terms

Intersensory conflict; temporal perception

General Description

With audiovisual displays such as films, asynchrony between auditory and visual patterns is more easily detected when the auditory component precedes rather than lags the visual component (Table 1). This effect occurs both when the film is of a person speaking and when the film presents a hammer hitting a peg, but is greater for the nonverbal pattern. No differences in detection of asynchrony are found for auditory presentation to the left ear, right ear, or both.

Methods

Test Conditions

- Stimulus was videotape of man reading or hammer hitting peg
- Visual portion presented on Sony CRT (22.86 cm diagonal) 1 m from subject
- Auditory portion presented via headphones to left, right, or both ears
- Auditory signal advanced or delayed relative to visual display by up to 500 msec at constant rate of 51 msec/sec

Experimental Procedure

- Method of adjustment, under subject's control
- Independent variables: film content (hammer peg or man speaking), ear(s) to which auditory component directed (left, right, both), direction of asynchrony (auditory advance or delay, native language of subject (Spanish or English)
- Dependent variable: minimum detectable asynchrony (msec)
- Subject's task: beginning with a synchronous display, increase asynchrony until just detectable
- 28 subjects, males and females, ages 18-60, 18 native English speakers, 10 native Spanish speakers

Experimental Results

- Asynchrony is significantly easier to detect ($p < 0.001$) when the sound precedes rather than follows the associated visual pattern.
- Asynchrony is more easily detected under an auditory advance (sound preceding) condition ($p < 0.001$) regardless of the subject's native language, for presentation to one or both ears, and for both types of film (hammering and person speaking).
- Asynchrony is more readily detectable in the film of a hammer hitting a peg than in the film of a man speaking ($p < 0.002$).
- Differences between English-speaking and Spanish-speaking subjects, between males and females, and between ear of auditory presentation are no greater than can be expected on chance basis.

Repeatability/Comparison with Other Studies

Related research (Ref. 4; CRef. 8.303) has shown that visual perception of lip movement can strongly influence speech perception. Apparent simultaneity of stimulation delivered to right and left brain hemispheres for right-handed subjects has been found to require that presentation to the right hemisphere precede delivery to the left by 3-4 msec (Ref. 3).

Key References

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Cross References

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

5.1019 Duration perception with auditory, visual, and bisensory stimuli;

5.1020 Perception of temporal rate: auditory-visual interactions;

8.303 Effects of visual cues on speech intelligibility

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Notes

5.1022 Order Perception with Heteromodal Stimulus Sequences

Key Terms

Heteromodal perception; temporal perception

General Description

When heteromodal stimulus sequences composed of auditory (*A*), tactile (*T*), and visual (*V*) elements are presented in varied orders, correct order perception depends largely on the length of the interval between stimulus onsets. Performance is better when (a) there are fewer stimuli in a sequence; (b) presentations are discrete rather than continuously cycled; (c) sequences are repeated rather than presented once; and (d) only the first stimulus must be identified.

Methods

Test Conditions

- Auditory stimulus (*A*) was click delivered via earphone (right ear) consisting of 0.1-msec octave-band (700-1400 Hz) rectangular pulse ~30 dB SL; visual stimulus (*V*) was a light flash through a 10-cm-diameter yellow diffuser, 50 cm in front of subject, 20-µsec duration at half-amplitude, 40-µsec at base, ~60 dB above luminance threshold; tactile stimulus (*T*) was vibration to right index fingertip, 1.25 gm at peak amplitude (approximately 2.24 micron displacement), voltage increased from 0 to peak in 7.5 msec, stimulus level ~15 dB above threshold
- Auditory stimulus magnitude set to equal magnitude of visual stimulus
- Studies 1-3 presented six possible sequences of heteromodal stimuli (e.g., ATV, AVT); in Studies 1 and 2, sequences presented only once per trial; in Study 3, sequences comprising each trial presented as many times as subject wished; in Study 4, two sequences were used with each sequence cycled continuously for as long as subject desired
- 15, 45, or 150 msec between onset of each stimulus element in sequence in Studies 1-3, 45- or 150-msec between stimulus onsets in Study 4

Experimental Procedure

- Independent variables: interval between onsets of stimuli in each sequence; continuous or discrete presentations; single or multiple presentations
- Dependent variable: percentage of correct identifications; *d'*, a measure of the subject's sensitivity (CRef. 10.1001), was also calculated to allow comparisons between conditions in which chance performance varies because of different numbers of possible responses
- Subject's task: Study 1: identify which stimulus (A, V, or T) was presented first; Studies 2-4: identify which of the six (Studies 2, 3) or two (Study 4) possible sequences was presented on each trial
- No information about subjects given

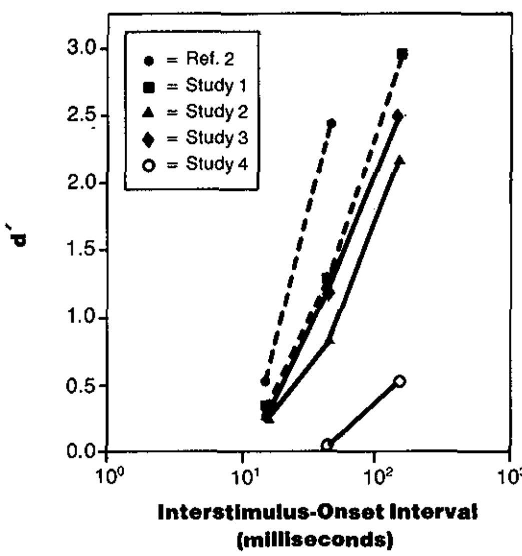

Figure 1. Identification of heteromodal pattern sequences as a function of interval between the onsets of successive pattern elements. In Study 1, subjects had to identify which stimulus element of the pattern (auditory, visual, or tactile) appeared first; for the other studies, subjects had to identify which of several possible patterns was presented. Patterns were presented once per trial (Study 2), as many times per trial as the subject desired (Study 3), or cycled continuously (Study 4). The interstimulus-onset interval corresponding to a *d'* value of 1.0 represents the threshold value. (From Ref. 1)

Experimental Results

- When the task is to identify the first stimulus of a three-element sequence and element onsets are separated by 15 msec, performance is not much better than chance. When elements are separated by 45 msec, identifications are roughly 70% correct. With 150-msec intervals, performance is nearly perfect (Study 1, Fig. 1).
- When subjects are required to identify which of six patterns occurs and each pattern is presented once, performance is slightly better than chance with 15-msec intervals between stimulus elements. Performance improves when elements are presented 45 msec apart, and is roughly 80% correct with a 150-msec interval (Study 2, Fig. 1).
- When subjects are required to identify which pattern occurs and each pattern is repeated as many times as the subject requires, performance improves over the single presentation case (Study 3, Fig. 1).
- When patterns cycle continuously (Study 4, Fig. 1) and stimulus elements are separated by 45 msec, subjects report perceiving three distinct sensory streams. The visual stream is almost fused as a continuous light, and with 45-msec intervals, performance is no better than chance. At separations of 150 msec, performance is slightly better than chance (~65% correct).

Variability

Variability among subjects ranged between 6 and 20%.

Repeatability/Comparison with Other Studies

Figure 1 shows data from Ref. 2, a study similar to Study 1 in which subjects were required to identify which of two stimuli (auditory or visual) occurred first in a sequence; identification performance is above chance with 15-msec interstimulus intervals, and at very high levels with 45-msec intervals. This performance is better than performance with three stimuli in Study 1. The threshold for reporting the first

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member of two-element sequences of auditory rather than heteromodal stimuli is about the same as for heteromodal sequences (interstimulus onset interval for threshold identification [$d' = 1.0$] estimated at 20 msec). This 20-msec interstimulus onset interval level, however, is better than has been found for three-element heteromodal patterns (CRef. 6.407).

When patterns are presented only once, sets of three tones are correctly identified ($d' = 1.0$) with less than 10-msec separation compared to 55-msec separations for three heteromodal stimuli.

For continuously cycling pattern sequences, thresholds generally range from 100-700 msec, depending on sound similarity.

Key References

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2. Hirsh, I. J., & Sherrick, C. E. (1961). Perceived order in different sense modalities. *Journal of Experimental Psychology, 62*, 423-432.

Cross References

5.1017 Discrimination and reproduction of temporal patterns: comparison of audition, vision, and touch;

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

5.1020 Perception of temporal rate: auditory-visual interactions;

6.407 Auditory perception of sequence;

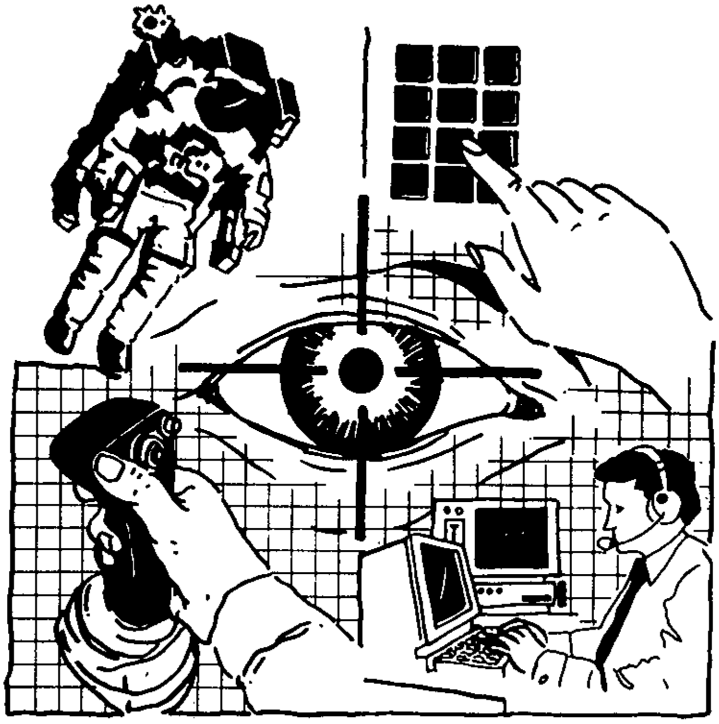
6.408 Auditory perception of sequence: effect of interstimulus onset interval;

10.1001 Techniques for body self-rotation without surface contact in micro-gravitational environments

Handbook of perception and human performance, Ch. 32, Sect. 4.2

Notes

Section 5.11 Adaptation of Space Perception



5.1101 Adaptation of Space Perception

General Description

When confronted with an artificially induced discrepancy between or within sensory modalities, human observers can undergo a semipermanent change in their perception and/or perceptual-motor behavior that serves to eliminate or reduce this intersensory conflict. Thus, for example, viewing the hand through a light-displacing **wedge prism** causes the limb to appear to be located off to one side of its true position and leads to errors in pointing at visual targets. However, after a relatively short period of active interaction with the environment, such as reaching for visible objects, the discrepancy between seen and felt position of the hand is no longer experienced and observers are once again able to point accurately at objects. This compensatory process is referred to as **adaptation**.

Although the majority of studies described here will involve the somewhat-contrived condition of wearing goggles containing lenses or prisms, there are some real-life situations with intersensory discordance. Examples are the underwater environment, as viewed through a face mask (CRefs. 5.1124, 5.1125, 5.1126), looking through the windscreen of an airplane, the hyper- and microgravitational environments experienced by the pilot or astronaut, and the visual-vestibular situations created by flight simulators and helmet-mounted displays.

In experimental environments, the most commonly used device for producing perceptual rearrangement is the wedge prism, mentioned above. Typically attached to goggles worn by the observer, the wedge prism causes a variety of effects, including displacement of the visual field (typically by ~11 deg), apparent bowing of edges that are perpendicular to the direction of displacement, and a color fringe at each of these edges (CRef. 5.1102).

Other optical devices for experimentally rearranging visual space include: (a) mirrors (displacement, up-down reversal, inversion); (b) Dove prisms (right-left reversal, inversion, tilt); (c) **telestereoscope** (modification of the apparent depth of solid objects); (d) **meridional-size lens** (apparent tilt of the visual field away from or toward the observer); (e) combination of spherical lens and wedge prism (lengthening or shortening of perceived distance); (f) wedge prisms (one over each eye) with bases in opposite directions (apparent slant in depth toward or away from the observer); and (g) convex mirror (distortion of apparent size without concomitant change in perceived distance (CRef. 5.1102).

When attached to goggles worn by the observer all of these optical media caused instability or illusory movement of the visual field (loss of **visual position constancy**) during head movements (CRef. 5.1120).

Auditory space may be rearranged by means of a "pseudophone," a device that either functionally reverses the location of the two ears, causing a right-left reversal of auditory space, or rotates the auditory field laterally, analogous to prismatic displacement (CRef. 5.1127).

Methods

In studies of adaptation to perceptual rearrangement, the basic paradigm involves a *preexposure period, exposure period,* and *postexposure period.* During the pre- and postexposure periods, the observer is tested with normal perception (no distorting devices), but receives no feedback concerning accuracy of performance. Interposed between these two phases is an *exposure period,* during which the observer is exposed to some sort of perceptual distortion. During the exposure, the observer interacts with the rearranged environment and receives feedback about his actions. This interaction can be either "constrained" (activity is restricted, e.g., subject sits at a table with head restrained) or "unconstrained" (observer is free to move about the environment at will) (CRef. 5.1103). Adaptation is most frequently measured in terms of the *difference* between pre- and postexposure responses on some perceptual or perceptual-motor task, such as target pointing. If adaptation has occurred, the observer will show a compensatory shift in the response, referred to as a **negative aftereffect** since it is measured after the distorting devices are removed (CRef. 5.1103).

Adaptation to Prismatic Displacement

If prism adaptation is to occur, the prismatic displacement must remain constant over a period of time (CRef. 5.1104). Exposure to a visual field that changes from time to time in the amount and/or direction of its optical displacement (a situation referred to as "sensory disarrangement") fails to result in a systematic adaptive shift in vision or in visuomotor performance; eye-hand coordination does become less precise, as revealed by an increase in variable error.

Prism adaptation is usually enhanced when the observer is allowed to move the limbs or entire body in an active manner and is diminished when the observer is immobile or passively moved (CRef. 5.1104). There is some controversy about the early claim that active interaction with the environment on the part of the observer is *necessary* for the occurrence of prism adaptation. More recent studies have demonstrated that both passive and immobile subjects are capable of a certain amount of adaptation, if they are provided with salient information about the perceptual rearrangement. Of particular importance in exposure conditions involving observation of the limbs is that the observer receives clearcut information about the prism-induced discrepancy between vision and proprioception and/or errorcorrective feedback (CRefs. 5.1104, 5.1105, 5.1108).

Adaptation to prismatic displacement takes place quite rapidly (especially if error-corrective feedback is provided), although this adaptation rarely reaches the theoretical maximum specified by the strength of the prism, i.e., is never complete. Adaptation dissipates when prism exposure is ended—quickly if the observer is able to move about and look at his or her body, more slowly if the observer sits quietly in the dark (CRefs. 5.1104, 5.1106, 5.1111).

There is evidence that prism adaptation is facilitated by

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spacing (vs. massing) of prism exposure trials, although other evidence contradicts this claim (CRef. 5.1106). Prism-adaptive changes in eye-hand coordination show partial (approximately 50%) transfer from the hand viewed during prism exposure to the hand that was not viewed while prisms were worn (CRefs. 5.1106, 5.1109). Prism adaptation is also influenced by delay of feedback: when exposure is *concurrent* (i.e., the prismatically displaced hand is viewed continuously), even extremely short delays of visual feedback (e.g., 0.3 sec) will preclude all adaptation; with *terminal* exposure (i.e., the prismatically displaced hand is seen only at the end of each reaching movement), adaptation is possible with delays of as much as 8 sec, although it is substantially less than that found with no delay(CRefs. 5.1107, 5.1108).

As with learning in general, prism adaptation is subject to **conditioning** to the various stimuli present in the adapting situation (CRef. 5.1110). The most common example of this is the "situational effect," in which observers who return to the laboratory to be tested on prism adaptation for a second (or greater) time reveal a certain amount of adaptive shift even before they are allowed to interact with the prism-displaced visual field. Thus, it appears that the situation in which they had previously been adapted is capable of eliciting a partial adaptive response. An alternative interpretation—that observers remain partially adapted between testing sessions—seems extremely unlikely, given all of the experience with normal vision that they will have had during this period. Prism adaptation acquired in one stimulus situation will be manifested, usually with some decrement in a somewhat different stimulus situation, an example of "stimulus generalization." Similarly, adaptation as measured by means of one response will be revealed by other responses—a case of "response generalization" (CRef. 5.1109).

There is some evidence, albeit conflicting, that repeated sessions of prism adaptation, separated by periods of normal vision, will cause the observer to become better able to adapt in future sessions—an effect analogous to so-called "learning sets" (CRef. 5.1110).

Prism adaptation is manifested in a variety of ways (CRef. 5.1112). The major end product of genuine prism adaptation is a change in the apparent position of various body parts relative to one another; vision itself is relatively impervious to change (CRef. 5.1112). Thus, for example, when the observer is provided with continuous exposure to the prism-displaced arm and hand, the resulting adaptation of eye-hand coordination is almost entirely based on a change in where the limb appears to be located, rather than an alteration in external spatial position assumed by the visual system to correspond to a given retinal locus. In some situations (e.g., with terminal exposure), there may actually be a visual shift in the apparent location of a target. But, even here, it appears that the change is proprioceptive—a modification of the apparent position of the eyes relative to the head (CRef. 5.1107).

It has been demonstrated that, unless precautions are taken, prism-induced changes in apparent eye position may be due merely to the eyes having been held off to one side (asymmetrical **convergence**) during prism exposure, and have thus been subject to a preservative tendency to remain turned to that side (referred to as "eye muscle potentiation").

Adaptation to Distortion of Visual Orientation

Even with quite prolonged exposure, adult human beings are probably incapable of coming to see an optically right-left reversed or up-down inverted visual field as normal. However, they can adapt their visuomotor coordination to such environments and can successfully perform a number of complex tasks, such as skiing and cycling, while wearing the distorting device (CRef. 5.1114). On the other hand, exposure to moderate (<30-40 deg) optical tilt of the visual field results in at least partial adaptation: the apparent tilt declines during the exposure period and an objectively vertical line appears tilted in the opposite direction (a negative aftereffect) when the inducing prisms have been removed (CRefs. 5.1115, 5.1116, 5.1117, 5.1118, 5.1119). Optical tilt adaptation reaches asymptote (at 20-30% of the theoretical maximum) in ~1 hr of active exposure (e.g., walking about in a normal indoor setting); complete post-exposure decay of the adaptation with eyes shut requires only ~15 min. The magnitude of tilt adaptation is a linear function of the degree of optical tilt to which the subject is exposed (CRefs. 5.1115, 5.1116, 5.1117, 5.1119). The rate of adaptation to optical tilt can be increased by gradually incrementing the amount of tilt, rather than presenting the entire tilt at once (CRef. 5.1118). It would appear that the underlying basis for optical tilt adaptation is a recalibration of the correspondence between external points in space and retinal loci assumed by the visual system—a true visual change.

A direct comparison of optical tilt adaptation and adaptation to prismatic displacement has revealed that the two processes are qualitatively different and independent of each other (CRef. 5.1119).

Adaptation to the Loss of Visual Position Constancy

With head movements, most of the various types of visual rearrangement result in a loss of visual position constancy (CRef. 5.1120). The most dramatic example of this visual instability occurs when the observer is wearing right-left and/or up-down reversing goggles; head movements in the dimension (horizontal or vertical) of the visual transposition cause the visual field to appear to move in the same direction and by twice the angle of head rotation. Another means of disrupting visual position constancy is to cause a point of light (in an otherwise dark environment) to move in a manner that is incompatible with the direction and speed of head movement. Most studies have revealed quite substantial adaptation to the loss of visual position constancy, with rapid spontaneous decay of the adaptation occurring as soon as the eyes are closed (CRef. 5.1120).

Adaptation to Distortions of Depth, Distance, and Size

Human observers are capable of at least partial adaptation to distortion of visual depth, distance, and size (CRefs. 5.1121, 5.1122). For example, when observers view a scene through a telestereoscope (which optically changes the effective distance between the two eyes, thereby altering the apparent separation in depth of objects at different distances), they show adaptation to the distorted depth amounting to ~20% of the theoretical maximum (CRef. 5.1121). Partial adaptation has also been reported for distortion of depth produced by the meridional size lens, the distortion of distance caused by the combination of spherical lens, and wedge prism (CRef. 5.112), and the decrease in apparent size caused by viewing objects in a convex mirror (CRef. 5.1122).

Adaptation to Distortions of Form

Straight edges perpendicular to the direction of displacement produced by wedge prisms appear curved when viewed through the prisms. After prolonged, active viewing of the straight edges, the apparent curvature is somewhat lessened, and the edges appear curved in the opposite direction when the prisms are removed. This appears to be a case of true visual adaptation (CRef. 5.1123). Somewhat more substantial adaptation to apparent curvature occurs when the wedge prisms, instead of being mounted in goggles worn by the subject, are attached to contact lenses and controlled by the observer's eyes (CRef. 5.1123).

Adaptation to Auditory Rearrangement

Exposure to the rearrangement of auditory space by means of a pseudophone leads to partial adaptation when sounds are *displaced* relative to their objective location, but not when the auditory field is transposed (sound sources on one side of the head are heard on the other side) (CRef. 5.1127). Changes in auditory localization can also occur as the result of exposure to prism-induced *visual* displacement if the resulting prism adaptation includes a change in the felt relation of head to shoulders (CRef. 5.1113).

Adaptation to Underwater Optical Distortions

Looking through a face mask underwater causes objects to seem larger and farther away, edges appear bowed, and the visual field to appear unstable with head motion (CRefs. 5.1124, 5.1125, 5.1126). Active interaction with this environment (e.g., swimming about, reaching for and picking up objects), causes partial adaptation to these distortions and an after-effect upon leaving the water (CRefs. 5.1125, 5.1126). It is interesting that expert divers experience less initial distortion and less severe aftereffects than do novices (CRefs. 5.1125, 5.1126). Although divers do not appear to adapt completely to the underwater distortions, they have proven capable of making "intellectual" corrections for the increase in apparent distance if they are provided with verbal feedback about the accuracy of their estimates.

Constraints

• Numerous factors influence adaptation to perceptual rearrangement, many of which have not yet been examined systematically (CRefs. 5.1104, 5.1108, 5.1109, 5.1110).

• Substantial individual differences are found in adaptability to given forms of perceptual rearrangement. Some observers adapt very little and others completely. Little is known about the correlates of these differences.

• Adaptation occurs only when some form of information is obtained by the observer about the nature of the perceptual rearrangement. The best and most efficient means of obtaining this information is to allow the observer to interact *actively* with the environment: passive movement is effective only when it is combined with very salient information about the nature of the distortion and displacement.

• How the observer is exposed to the altered environment will affect both the amount and type of adaptation obtained. Terminal prism exposure, for example, produces primarily visual adaptation, while concurrent (continuous) exposure procedures produce proprioceptive adaptation. Error-corrective feedback from target-pointing errors produces more adaptation than does simple visual feedback from viewing the moving hand with no target present.

• Even under optimal conditions, adaptation to perceptual rearrangement is usually insufficient to resolve completely the intersensory discrepancy. Nevertheless, conscious and "intellectual" correction strategies, together with sensory capture (dominance of one sense when senses yield discrepant information), may allow the observer's behavior to return to normal (CRef. 5.1110).

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Cross References

5.1102 Visual effects of various optical devices;

5.1103 Methods for inducing and measuring adaptation to prismatic displacement of the visual field;

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1105 Adaptation to prismatic displacement of the visual field: effect of training;

5.1106 Recovery from adaptation to prismatic displacement of the visual field: effects of practice;

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

5.1111 Recovery from adaptation to prismatic displacement of the visual field: effects of prior prism exposure;

5.1112 Effects of adaptation to prismatic displacement of the visual field;

5.1113 Prismatic displacement of the visual field: visual and auditory judgments of straight ahead;

5.1114 Perceptual effects of inversion and left-right reversal of the visual field;

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

5.1117 Adaptation to visual tilt: effect of rotation magnitude;

5.1118 Adaptation to visual tilt: effect of constant versus incremental tilt;

5.1119 Adaptation to tilt and displacement: acquisition rate, magnitude, and decay time;

5.1120 Factors affecting adaptation to loss of visual position constancy;

5.1121 Adaptation to distortions of depth and distance;

5.1122 Adaptation to distortions of size;

5.1123 Factors affecting adaptation to visual distortions of form;

5.1124 Effect of underwater environments on perception;

5.1125 Underwater visual adaptation: effect of experience;

5.1126 Adaptation after prolonged exposure to an underwater environment;

5.1127 Adaptation to rearrangement of auditory space

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Notes

5.1102 Visual Effects of Various Optical Devices

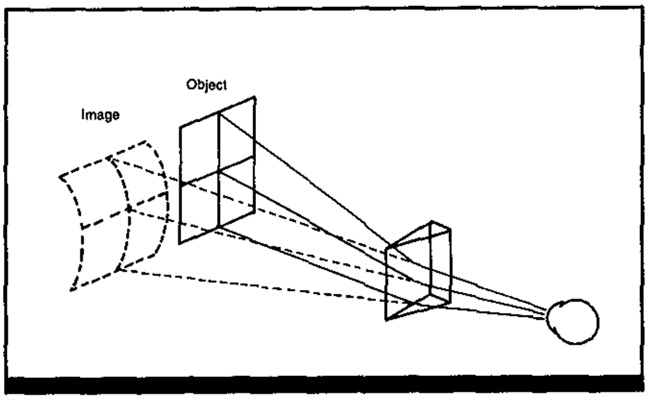

Figure 1. Wedge prism displaces image laterally. Light rays from some parts of the object are bent more than others, depending on thickness of the prism and angle of incidence of the light. This causes compression of the image on the base side and expansion on the apex size, as well as curvature of vertical lines, particularly toward the apex. (From Experiments with goggles, I. Kohler. Copyright © 1962 by Scientific American, Inc. All rights reserved.)

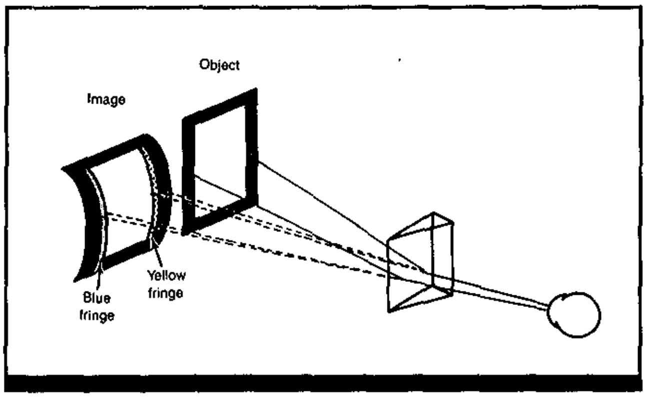

Figure 2. Prism bends short wavelengths of light more than long wavelengths. If prism base is to right, blue rays, being bent most, fall as blue fringe along left-hand border of light-colored object; similarly, yellow-red fringe of color appears along right-hand border. Opposite effects are obtained when prism base is to left. (From Experiments with goggles, I. Kohler. Copyright © 1962 by Scientific American, Inc. All rights reserved.)

Key Terms

Dove prism; image distortion; image inversion; image reversal; meridional-size lens; mirror; spherical lens; telestereoscope; visual field displacement; visual tilt; wedge prism

General Description

Optical devices, such as prisms and lenses, induce various distortions in the appearance of objects. Given adequate exposure, observers wearing these devices generally are able to adapt to the distortions. The accompanying table list devices commonly used in studying such perceptual **adaptation**, describes their perceptual and behavioral effects, and cites sources of more information.

Constraints

- Most of the perceptual and behavioral effects described here are apparent only when the optical devices are first put on. With continued exposure, the effects generally decrease or disappear altogether as the observer undergoes adaptation to the distortions. Aftereffects—generally in a direction opposite to the original effect—may appear when the devices are removed.
- The perceptual and behavioral effects of wearing these optical devices vary with the nature of the task the observer performs while wearing the device as well as other factors, such as exposure duration and the strength of the optical device (CRefs. 5.1104, 5.1108, 5.1109, 5.1110, 5.115, 5.1120, 5.1123).
- Any light-transforming device, such as those described above, also usually reduces the field of view and may initially produce effects similar to those of vision-restricting tubes, especially disorientation, dizziness during rapid head movements, and difficulty maintaining body equilibrium during locomotion.

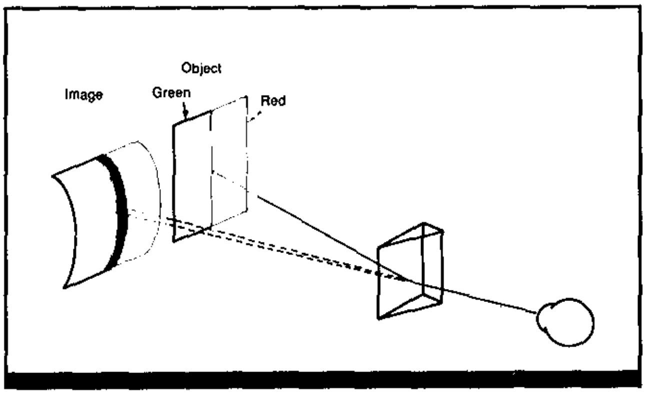

Figure 3. Differential bending of long and short wavelengths of light by wedge prisms causes different colors to be displaced relative to one another. When adjacent red and green areas are viewed through base-right prism (as shown) greater shift of green image leaves thin black void at color boundary. When prism is reversed, green overlaps red, producing thin white border between the two color areas. (From Experiments with goggles, I. Kohler. Copyright © 1962 by Scientific American, Inc. All rights reserved.)

- Dove prisms should be used only in parallel light to avoid serious chromatic aberration.
- Distortions produced by real-world devices, such as windscreens, are likely to be less regular and more variable than the effects described here.

Optical Device	Optical Effect	Initial Perceptual and Behavioral Effects	Sources
Wedge prism: base left or right, over one eye only or one over each eye with bases in same direction	(See Fig. 1)	Apparent curvature of vertical lines Apparent contraction and expansion of scene with lateral head movements, and seesaw motion with up-down head movements Misreaching for objects Apparent lateral displacement of visual field (noticeable only when misreaching occurs) Possible misperception of head, eye, or other body parts	Refs. 4, 5; CRefs. 5.1104, 5.1123
	(See Fig. 2)	Apparent color fringes on light colored objects	
	(See Fig. 3)	Lateral displacement of colored surfaces When prism is attached to or controlled by eye (e.g., mounted on contact lens) initially inaccurate eye movements (does not occur with prism goggles)	
Wedge prisms: one over each eye, bases in opposite directions	Images are displaced so that **lateral retinal image disparity** of objects or parts of objects is increased or decreased (See Fig. 4)	Alteration of apparent distance: with prism bases facing outward, a rod will appear bent away from observer, and flat surfaces will appear concave; base-in prisms will induce the opposite effects	Ref. 4
		Color stereo effects: surfaces of different colors appear to lie at different distances; if prism bases face outward, blue seems closest, red furthest, other colors in between; with prism bases inward, blue appears farthest and red nearest; there is no adaptation to this effect, even after 52 days of prism exposure	Ref. 4; CRefs. 1.212, 5.934
Mirror	Right-level reversal	Apparent reversal of right and left images misreaching for objects Loss of **visual position constancy**, i.e., as head moves, world appears to move rapidly in the same direction as head movement Possible misperception of felt position of head, eye, or other body part Disorientation Motion sickness	CRef. 5.1114
Inverting prism	(See Fig. 5)	Apparent inversion of up and down Misreaching for objects Disorientation Motion sickness	Ref. 10; CRef. 5.1114
Reversing and inverting prisms	(See Fig. 6)	Apparent reversal of right and left and inversion of up and down Misreaching for objects Loss of visual position constancy Extreme disorientation Motion sickness	Refs. 3, 7, 8, 9, 10 CRef. 5.1114
Prism producing tilt	(See Fig. 7)	Apparent tilt of visual field clockwise or counterclockwise Possible misperception of head, eye, or body orientation	CRef. 5.1116
Telestereoscope	(See Fig. 8)	Alteration of apparent depth: objects appear either more or less distant than actual position	Ref. 13; CRef. 5.1121
Meridional-size lens over one eye only	Magnification of visual image along meridian perpendicular to lens axis; magnification of the image in one eye only creates horizontal or vertical disparity between left and right retinal images, depending on lens orientation	Apparent slant in depth of the frontoparallel plane	Ref. 2; CRefs. 5.909, 5.1121

Optical Device	Optical Effect	Initial Perceptual and Behavioral Effects	Sources
Spherical lens and wedge prism combined	Alter **accommodation** and convergence	Alteration of apparent distance	Refs. 11, 12; CRef. 5.1121
Convex mirror	Refracts light waves so that they are bent inward, creating a smaller image	Reduction in apparent size of objects Possible increase in apparent object distance	Ref. 6; CRef. 5.1122
Tubes attached to head	Radical restriction in field of view; loss of peripheral vision; lack of overlap of successive fields of view (when turning head)	Reduction in apparent size of objects Apparent reduction in body size Disorientation Difficulty in maintaining equilibrium during walking Dizziness during rapid head movements	Ref. 1

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Cross References

1.212 Axial chromatic aberration;

5.909 Binocular differences in image size and shape (aniseikonia);

5.934 Color stereopsis;

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation of prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

5.1114 Perceptual effects of inversion and left-right reversal of the visual field;

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

5.1120 Factors affecting adaptation to loss of visual position constancy;

5.1121 Adaptation to distortions of depth and distance;

5.1122 Adaptation distortions of size;

5.1123 Factors affecting adaptation to visual distortions of form

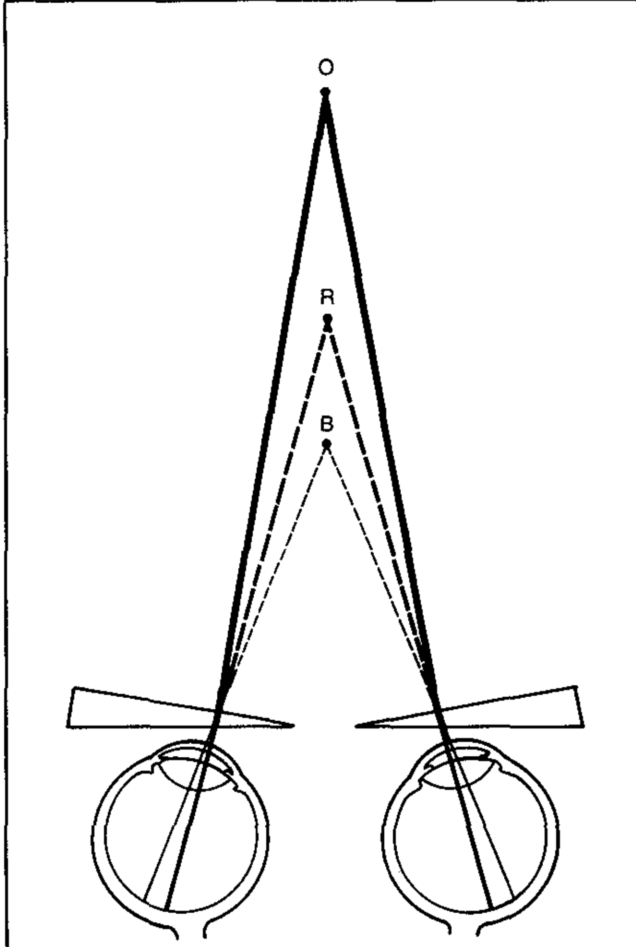

Figure 4. Light rays emanating from point O are refracted differently by wedge prisms depending on wavelength. Blue light is bent most; red, least. When prism bases are outward, blue light is deflected outward and appears located at point B; red light is bent less and appears more distant at point R. Relative distances of the color are reversed when prism bases face inward. (From Experiments with goggles, I. Kohler. Copyright © 1962 by Scientific American, Inc. All rights reserved.)

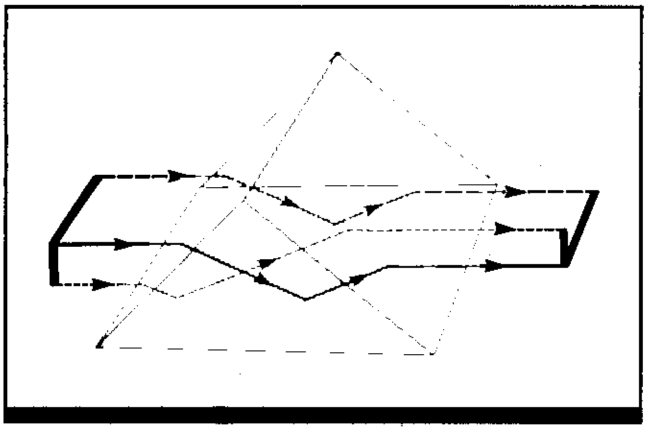

Figure 5. Image inversion with Dove prism. (From Ref. 10)

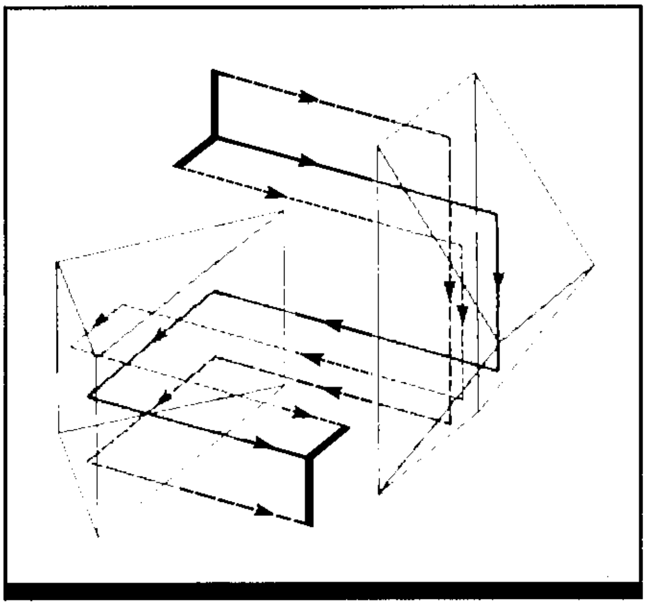

Figure 6. Two Dove prisms combined to produce inversion and reversal of the optical image (From Ref. 10)

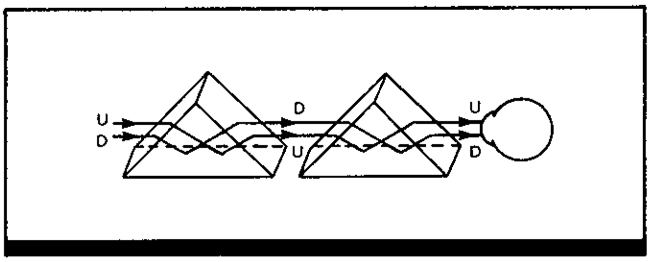

Figure 7. Two Dove prisms in tandem. To produce optical tilt, one of the prisms is rotated by the desired amount. The image rotation angle is two times the rotation angle of the prism. (From Ref. 14)

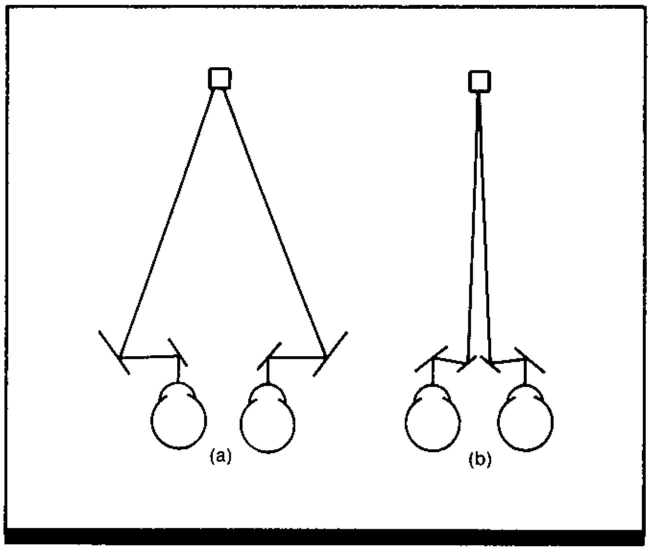

Figure 8. Schematic representation of the light paths from a target (cube) through a telestereoscope set to produce (a) enhancement of binocular retinal image disparity by increase in effective interpupillary distance; (b) reduction in disparity by decrease in effective interpupillary distance. (From Ref. 13)

5.1103 Methods for Inducing and Measuring Adaptation to Prismatic Displacement of the Visual Field

Key Terms

Active movement; altered visual direction; concurrent exposure; negative aftereffect; passive movement; prismatic displacement; reduction of effect; terminal exposure; visual field displacement; visuomotor coordination

General Description

Observers who wear prisms that laterally displace the visual field generally undergo rapid **adaptation** to the rearrangement; that is, they show semipermanent changes in perceptual or perceptual-motor responses that compensate for the optical displacement. When an observer first puts on displacing prisms, localization responses, such as target pointing and reaching, show errors in the direction of the displacement when the observer cannot see his or her hand. After a period of exposure to the prisms, the observer is able to point more accurately to a target, even when the hand cannot be seen. This increased accuracy is termed the *visuomotor reduction of effect*, and indicates that adaptation to the prisms has occurred. If the prisms are now removed, the observer will again point inaccurately with the unseen hand, but this time in a direction opposite that of the prism displacement (known as the *negative aftereffect*). (See Fig. 1)

Studies of adaptation to prismatic displacement generally assess adaptation by measuring one of these two effects.

Figures 2 and 3 illustrate equipment used to induce and measure adaptation to prismatic displacement. Several methodological variations are possible. Under *unconstrained exposure* conditions, the observer moves about freely in the environment; under *constrained exposure*, movements are restricted, and the observer, with head held in place, typically sits at a table and is able to view the hand through the distorting device.

Two variations of the constrained condition are frequently used. With *concurrent exposure*, the observer views the hand continuously while moving it about or pointing to a target, whereas with *terminal exposure* the hand or finger is visible only at the end of each movement or after it has reached the target.

In the apparatus shown in Fig. 4, an observer moves freely or is passively transported around the environment. Active movement (in which observers walk about or move the limbs or body themselves) readily induces perceptual adaptation. However, if observers interact with the environment in a passive manner (observer's limbs or body are moved by the experimenter) adaptation is usually substantially reduced, though not necessarily eliminated.

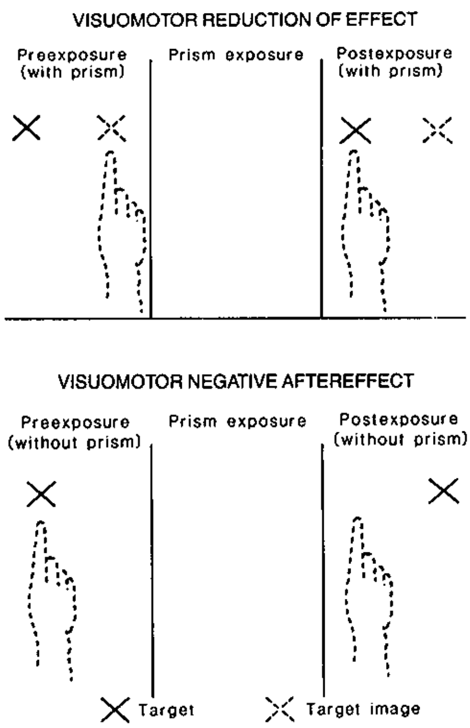

Figure 1. Schematic representation of the visuomotor reduction of effect and the visuomotor negative aftereffect. Reduction of effect: the observer, while wearing rightward displacing prisms and with the hand hidden from view, initially points to where the target appears to be located, missing it by approximately the amount of the prismatic displacement. After a period of prism exposure, during which the hand is viewed, the observer learns to point accurately at the target when the hand is again hidden, despite the target's still being prismatically displaced. Negative aftereffect: the observer, with normal vision, initially points at the target with approximate accuracy when the pointing hand is hidden. After a period of prism exposure, the prism is removed. The observer, pointing with unseen hand, now errs to the left of the target (i.e., in the direction opposite the prismatic displacement), thereby revealing the adaptation that occurred during prism exposure. (From Ref. 4)

Applications

Evaluation of adaptation to optical distortion of the visual scene introduced by viewing or display media (such as windscreens, goggles, heads-up display surfaces), to optical effects of corrective lenses, or to visual distortions caused by underwater viewing through a facemask.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

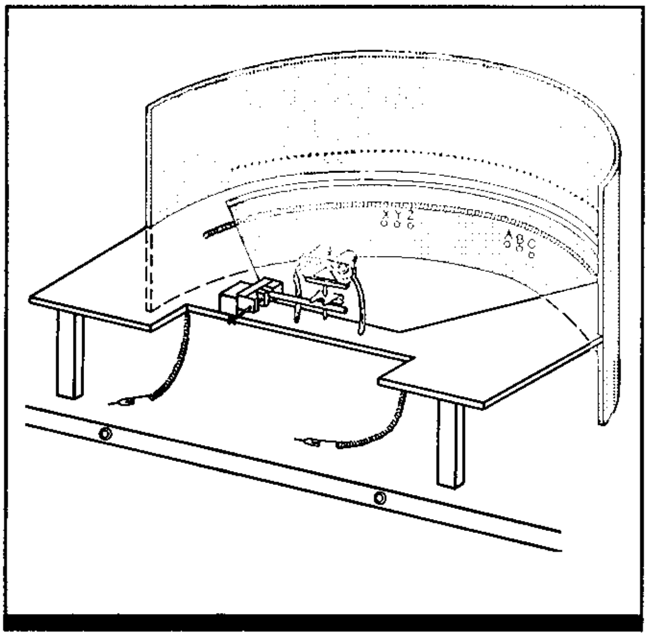

Figure 2. An apparatus used to induce and measure adaptation to prisms. Observer looks through mounted prism goggles and points to targets by reaching beneath the horizontal panel. A metal stylus worn on the index finger contacts a curved-position transducer attached to a digital voltmeter. The panel has an opening which can be covered or uncovered. When the cover is removed, the hand can be seen and prism-induced errors corrected. Trials conducted with the cover in place assess adaptation and the negative aftereffect. (From Ref. 3)

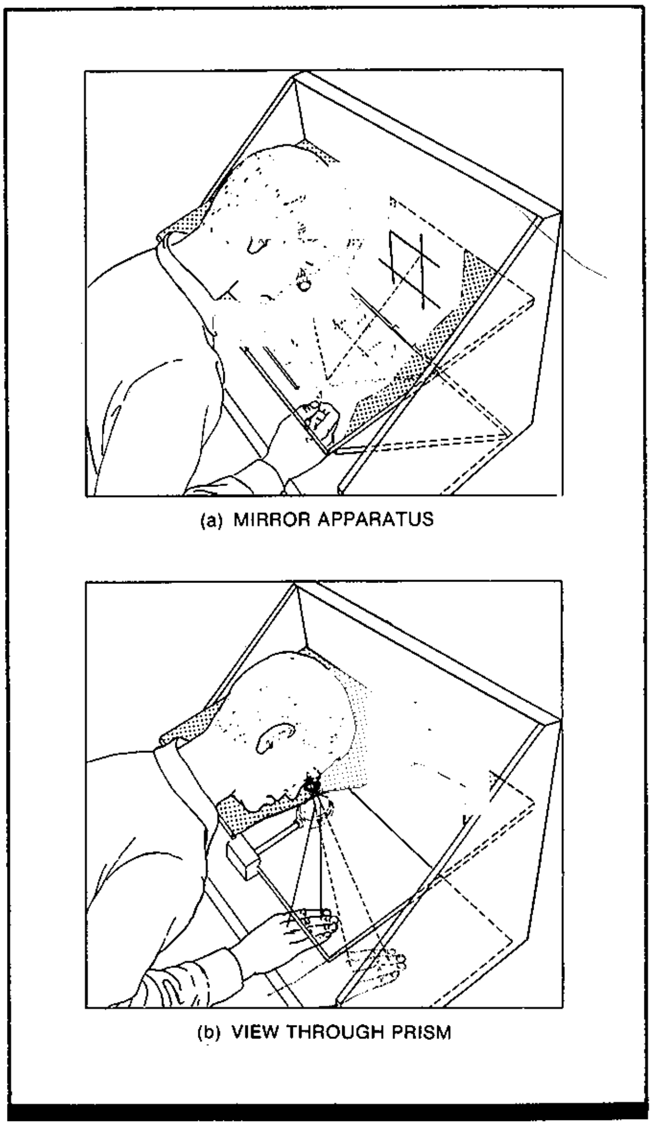

Figure 3. Another apparatus used to induce and measure prism adaptation. (a) During pre-exposure, observer points to apparent location of corners of a square seen in a mirror. The hand is beneath the mirror and cannot be seen. (b) Mirror is replaced by prism, and observer sees displaced image of the hand as it moves (actively or passively) against homogeneous background during this prism exposure period. Postexposure measures are taken with the apparatus as depicted in (a). (From Plasticity in sensory-motor systems, R. Held. Copyright © 1965 by Scientific American, Inc. All rights reserved.)

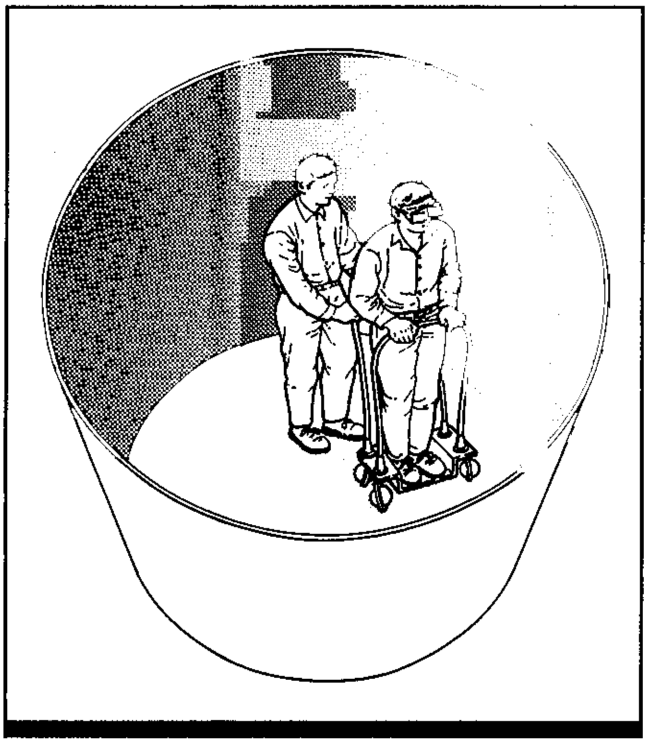

Figure 4. In this apparatus, an observer wearing prism goggles moves about inside a large drum whose inside surface is covered with an irregular pattern of small dots. Under passive movement conditions, the observer is transported around the inside of the drum on a cart. Under active movement conditions, the observer walks freely around the inside of the drum. (From Plasticity in sensory-motor systems, R. Held. Copyright © 1965 by Scientific American, Inc. All rights reserved.)

Constraints

- Pointing errors will occur during and after prism exposure only if the observer is unable to see the pointing hand as well as the target, or if reaching must be done quickly. If both hand and target are visible and pointing is not too rapid, the observer can easily correct the pointing response to match the target as the reach is made.
- Many different factors may influence adaptation to prismatic displacement (CRefs. 5.1104, 5.1110).
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.

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Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

Handbook of perception and human performance, Ch. 24, Sect. 2.1

Notes

5.1104 Adaptation to Prismatic Displacement of the Visual Field: Effect of Exposure Conditions

Key Terms

Active movement; altered visual direction; concurrent exposure; exposure duration; incremental exposure; massed practice; passive movement; prismatic displacement; spaced practice; terminal exposure; visual field displacement

General Description

Looking through a wedge prism displaces objects in the visual scene to one side. If an observer whose hand is hidden from view points at a target while wearing prisms, the pointing will be similarly displaced. However, if the observer has a chance to see and move the hand while wearing prisms, he or she can quickly learn to point accurately, even when the hand is once more hidden from view. This increase in target-pointing accuracy with continuing prism exposure (termed the reduction of effect) is an indication that the observer has adapted to the prismatic displacement. When the prisms are now removed, the observer will again point to one side of the target, but in a direction opposite the displacement initially induced by the prisms. This response is called a negative aftereffect. The magnitude of prism adaptation as measured by these two effects generally falls short of the theoretical maximum (total amount of prism displacement).

After the displacing prisms are removed, the observer gradually recovers from the adaptation until perceptual and motor responses again match those that prevailed before prism exposure. When this recovery is accomplished through interaction with the normal (undistorted) visual environment, it is referred to as *unlearning*. When the observer sits immobile in a darkened room after prism removal, adaptation is said to undergo spontaneous *decay*.

A number of exposure conditions influence the ease with which adaptation is acquired, the magnitude of the adaptation, and subsequent recovery. The table lists some of these factors, describes their effect on prism adaptation, and cites entries or outside sources of more information.

Applications

Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Constraints

- Adaptation to prism-induced displacement of the visual field is also affected by response requirements (CRef. 5.1109), feedback conditions (CRef. 5.1108), and cognitive/learning factors (CRef. 5.1110).
- Interactions may occur among the various factors affecting adaptation to prismatic displacement, but such interactions have generally not been studied.
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.

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Cross References

5.1103 Methods for inducing and measuring adaptation to prismatic displacement of the visual field;

5.1105 Adaptation to prismatic displacement of the visual field: effect of training;

5.1106 Recovery from adaptation to prismatic displacement of the visual field: effects of practice;

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects

Factor	Effect on Perceptual Adaptation	Source
Stability of perceptual rearrangement	Adaptation does not occur if prismatic displacement changes constantly and randomly; however, if it changes in a consistent direction, in small steps, substantial adaptation occurs	Refs. 1, 3, 5, 11
Provision to observer of salient information regarding prismatic distortion	Necessary for adaptation to occur	
Observer's awareness of prismatic distortion	Adaptation can occur without observer's conscious awareness of the distortion	
Modality of information regarding prism distortion	Visual information leads to higher level of adaptation than does verbal or kinesthetic information	Refs. 15, 18
"Assumption of unity" of multisensory cues	Observer's belief that different sensory modalities (e.g., vision and proprioception) are providing information about identical objects increases the magnitude of adaptation	Ref. 17
Incremental exposure (prism displacement increased in small steps) versus constant exposure (observer exposed to largest displacement magnitude from the beginning)	No difference between the two methods in total amount of adaptation on final trials	Ref. 12
Concurrent (continuous) exposure versus terminal exposure (view of finger or hand at final position only) during adaptation	Adaptation decays more rapidly with concurrent than with terminal exposure	Refs. 4, 8, 16
Presence versus absence of target during adaptation	Adaptation is greater with target present; no difference in rate of decay for two conditions in 15-min post-exposure period	CRefs. 5.1105, 5.1108
Active versus **passive movement**	Active movement facilitates, but is not necessary for, adaptation	Refs. 2, 6, 7
Exposure time	Prism adaptation increases as a negatively accelerated function of exposure time or number of exposure trials	CRef. 5.1105
Time since prism removal	Both negative aftereffects and the reduction of effect decay as a negatively accelerated function of postexposure time in the dark	Refs. 6, 8, 9, 14
Massed versus **spaced practice**	Some studies have shown that spaced practice facilitates adaptation; other studies have not reported this effect	CRef. 5.1106
Visual versus non-visual target in post-adaptation period	Larger negative aftereffect with visual target	Ref. 10
Exposure to normal visual environment versus no visual experience (observer sits in dark room after prisms removed)	Normal visual experience leads to more rapid and/or complete return to preadaptation state	Refs. 9, 13, 19

5.1105 Adaptation to Prismatic Displacement of the Visual Field: Effect of Training

Key Terms

Altered visual direction; exposure duration; prismatic displacement; target acquisition; visual field displacement

General Description

Observers wearing prisms that cause lateral displacement of the visual field can adapt to the distorted view if they can see their hands move. **Adaptation** is greater, however, when observers point to a target than when they just view their outstretched fingers. The magnitude of adaptation rises as the number of exposures increases over the first 30-40 trials, then levels off.

Applications

- Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses

Methods

Test Conditions

- For exposure trials, observer wore goggles containing 20-diopter wedge prisms that displaced visual field 11.3 deg leftward in both eyes; head stabilized by bite-plate; goggles without prisms worn in control condition
- Observer wore luminous rubber finger while wearing prisms
- Observer told that goggles displaced visual field to left
- 19.7 x 0.48 cm (7 3/4 x 3/16 in) target covered with luminous tape, visible only in target-pointing condition; vertical target position varied over trials; viewing distance 51.4 cm; dark room
- For each exposure trial (which lasted 4 sec), observer moved finger toward and away from own body to recorded beat of metronome set for 1 beat/2 sec; finger curled around far side of board to point at target; finger visible during pointing; arm under board and could not be seen
- For pre- and postexposure trials, observer pointed at target while not wearing prism goggles; view of finger was blocked

Experimental Procedure

- Independent variables: presence or absence of target, number of exposure trials
- Dependent variable: magnitude of adaptation, measured as the difference between observer's mean pre- and postexposure pointing accuracy
- Observer's task: for target-pointing condition, point at target with finger (arm under table when pointing); look at prismatically displaced finger and note error in pointing; attempt to correct any error on next trial. For no-target condition, put finger in pointing position; view prismatically displaced finger for 1 sec; randomly vary finger position from trial to trial; observer could not see arm. For no-prism (control) condition, look at nondisplaced finger for 1 sec; randomly vary finger position from trial to trial; observer could not see arm
- 95 trials in each condition with a four-trial series of measurements to test adaptation (without distorting goggles) conducted seven times between fifth and ninety-fifth exposure trials; each observer run in all three conditions; at least 1 week between conditions
- 12 observers, male and female undergraduates

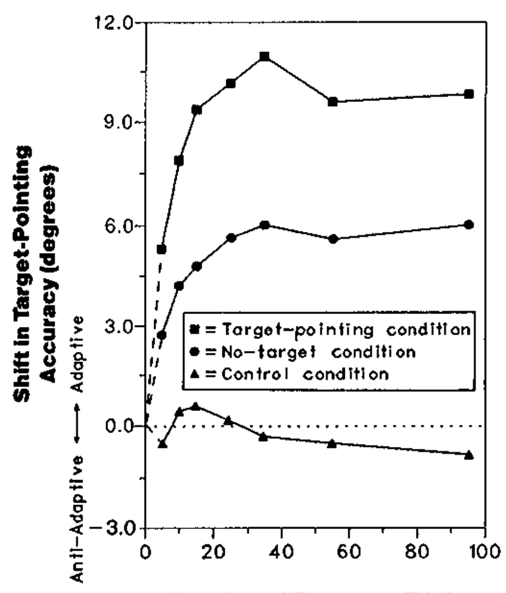

Figure 1. Magnitude of adaptation (in degrees of visual angle) as a function of number of exposure trials, with and without target present. The vertical axis indicates to what extent observers point to one side of a straight-ahead target after wearing prisms that displace the visual field to the left. Values >0 indicate adaptive shifts (rightward pointing reflecting compensation for apparent displacement of target), and values <0, anti-adaptive (leftward) shifts. (From Ref. 3)

Experimental Results

- Adaptation to prism displacement is significantly greater when observers view their fingers pointing at a target than when they see only their fingers and no target is present.
- In target-pointing condition, adaptation peaks at 86% of total possible adaptation (total possible is 7.6 cm for 20 naive observers, as determined by the distance between mean observer placement of target straight ahead while wearing prism goggles and while wearing clear-glass goggles); adaptation peaks at 53% for no-target condition.
- Adaptation rises sharply as a negatively accelerated function of number of exposure trials over the first 30-40 trials, and then levels off.
- There was no spontaneous decay of adaptation after 10 post-exposure minutes in the dark.

Variability

An analysis of variance was performed to test the significance of the results. No other information on variability was given.

Repeatability/Comparison with Other Studies

The sharply rising, negatively accelerated displacement adaptation curve is similar to the findings of many other studies.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Pointing errors will occur during and after prism exposure only if the observer is unable to see the pointing hand as well as the target, or if reaching must be done quickly. If both hand and target are visible and pointing is not too rapid, the observer can easily correct the pointing response to match the target as the reach is made.
- A number of factors such as prism exposure conditions (CRef. 5.1104), response requirements (CRef. 5.1109), feedback conditions (CRef. 5.1108) and cognitive/learning factors (CRef. 5.1110) affect adaptation to prismatic displacement and should be considered in applying these results under different conditions.

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Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

Handbook of perception and human performance, Ch. 24, Sect. 2.2

5.1106 Recovery from Adaptation to Prismatic Displacement of the Visual Field: Effect of Practice

Key Terms

Altered visual direction; intermanual transfer; massed practice; prismatic displacement; spaced practice; visual field displacement

General Description

Observers wearing prisms that laterally displace the visual field show greater **adaptation** to this alteration when they are exposed to the prismatic displacement for several short periods separated by dark intervals than when they are exposed to the displacement for one continuous period of equivalent length. When only one arm is viewed in motion during prism exposure but the other arm is used for a target-pointing task after prisms are removed, observers show pointing errors in a direction compensatory for the optical displacement, even though pointing with the unexposed arm. Such intermanual transfer of adaptation is significantly greater if practice is spaced rather than massed.

Applications

• Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Methods

Test Conditions

• Observer moved one arm in time with metronome (90 beats/min); observer wore 20-diopter prism over right eye, that displaced visual field laterally 11.3 deg; left eye occluded; head stabilized by biteboard
• Group 1 viewed arm continuously for ten 30-sec intervals alternating with 30-sec intervals of darkness with no arm movement (spaced practice) for a total exposure time of 5 min and total session time of 9.5 min
• Group 2 viewed arm continuously for 5 min; no rest intervals (massed practice)
• Group 3 viewed arm continuously for 9.5 min; no rest intervals (massed practice)
• Within each practice condition, observers were divided into one transfer group (test arm opposite of practice arm) and one nontransfer group (test arm same as practice arm)
• Though not indicated, presumably observers sat in dark without moving arms throughout postexposure period, except during test trials

Experimental Procedure

• Independent variables: type of practice (massed versus spaced), same or opposite test arm; time since prism removal
• Dependent variable: amount of adaptation, defined as the difference between mean pre-exposure and post-exposure target-pointing accuracy
• Observer's task: point to target (without seeing hand) before and after wearing prisms
• 32 female undergraduates per group

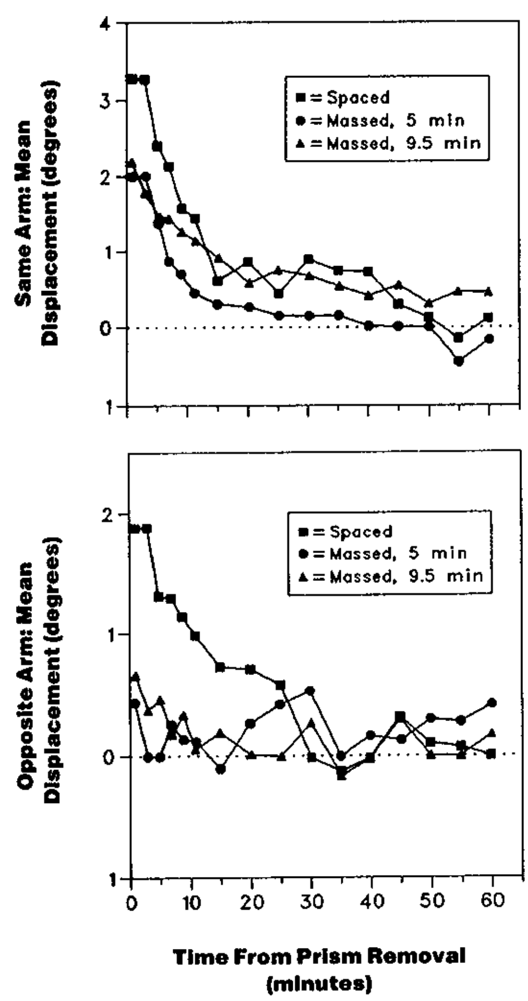

Figure 1. Decline of adaptation for transfer and nontransfer testing following spaced and massed practice during prism exposure. The vertical axis indicates the extent to which observers point to one side of a target after wearing prisms that laterally displace the visual fields. Values >0 indicate adaptive shifts (pointing that compensates for apparent displacement of target) and values <0, anti-adaptive shifts. Observers were tested with the same arm viewed during prism exposure or with the opposite arm (Ref. 3).

Experimental Results

• Adaptation to prism displacement (measured during the first minute after prism removal) is significant ($p < 0.01$) for all three nontransfer practice groups (test arm same as exposure arm), but it is significantly greater for the group with spaced practice than for the groups with massed practice ($p < 0.05$).
• Intermanual transfer of adaptation is significant for the spaced practice group, but not for the massed practice groups.

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• Adaptation declines as a negatively decelerated function of time since prism exposure; the level of adaptation remains higher for groups with spaced practice than for groups with massed practice during the first 7-20 minutes after prism removal.

Variability

t tests were performed to assess the significance of the results. No specific information on variability was given.

Repeatability/Comparison with Other Studies

The trend in the decline of prism adaptation with postexposure time reported here is consistent with the findings of other studies.

Intermanual transfer of adaptation generally has been found only with terminal exposure (discrete exposure trials equivalent to spaced practice); transfer is minimal or nonexistent with continuous exposure (massed practice) (Ref. 1). Intermanual transfer is facilitated when the head is free to move rather than restrained during prism exposure (Ref. 1).

Constraints

• Decay of adaptation is considerably slower if the observer points at a target rather than just viewing the finger during prism exposure (Ref. 5).

• Adaptation declines after prism removal whether the observer moves the adapted arm or just rests in the dark (Ref. 2).

• Pointing errors will occur during and after prism exposure only if the observer is unable to see the pointing hand as well as the target, or if reaching must be done quickly. If both hand and target are visible and pointing is not too rapid, the observer can easily correct the pointing response to match the target as the reach is made.

• A number of factors are known to influence the acquisition of adaptation to displacing prisms, and should be considered in applying these results.

• Adaptation to prism displacement of the visual field varies greatly from individual to individual.

Key References

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Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

Handbook of perception and human performance, Ch. 24, Sect. 2.2

5.1107 Adaptation to Prismatic Displacement of the Visual Field: Effect of Feedback Delay

Key Terms

Altered visual direction; exposure duration; feedback delay; prismatic displacement; target acquisition; visual feedback; visual field displacement

General Description

Observers who wear prisms that laterally displace the visual field adapt to the prismatic displacement, provided they receive immediate visual feedback regarding hand movements while wearing the prisms. When visual feedback is delayed by even 0.3 sec, no evidence of **adaptation** is obtained.

Applications

• Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Methods

Test Conditions

• Observer wore prisms that displaced visual field by 20 diopters (approximately 11 deg visual angle), left or right, in alternate sessions
• Observer held control stick and moved unseen hand from left to right and back at rate of 21 cycles/min to metronome beat; visual feedback obtained by watching oscilloscope trace that represented hand movements; two sessions with no delay of feedback, and ten sessions with delays of 0.3, 0.5, 0.9, 1.7, or 3.3 sec
• Separate test apparatus with two targets viewed binocularly in mirror apparatus that obscured hand
• Head stabilized by biteboard during prism exposure and testing

Experimental Procedure

• Independent variables: exposure time, delay versus no delay of feedback
• Dependent variables: level of adaptation, measured as mean difference between pre- and post-exposure target marking
• Observer's task: during exposure, move control stick left and right in time with metronome; during testing, mark position of two targets ten times each with right hand, hand unseen while marking
• Target-marking measurements taken before exposure and after 2, 6, 14, and 30 min of prism exposure at each session; prisms not worn during measurements
• 24 observers initially tested (no delay condition); 6 observers who showed approximately equal adaptation for leftward and rightward displacement were selected for the delayed feedback conditions

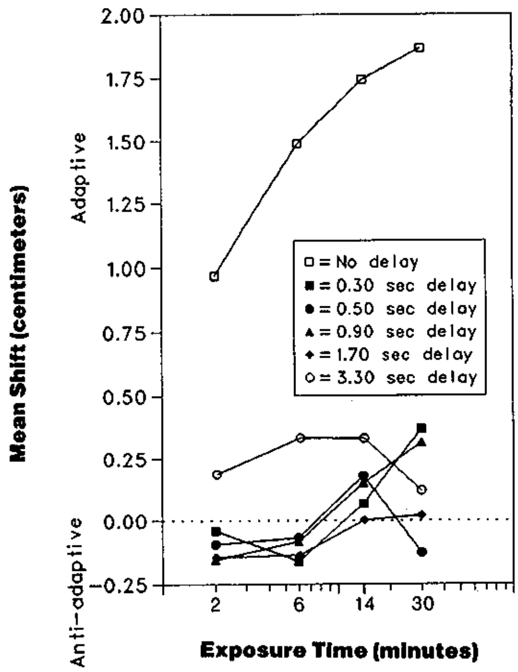

Figure 1. Magnitude of prismatic adaptation as a function of exposure time with delay and no delay of visual feedback. The vertical axis indicates the extent to which observers mark to one side of the target after wearing prisms that displace the visual field. Values >0 indicate adaptive shifts reflecting compensation for apparent visual displacement; values <0 indicate anti-adaptive shifts in target marking. (From Ref. 1)

Experimental Results

• Observers show no adaptation to prism-induced displacement of the visual field when visual feedback regarding the displacement is delayed; however, significant adaptation is obtained with immediate feedback at all exposure durations ($p<0.01$).
• The length of prism exposure has significant influence on adaptation to displacement ($p<0.001$).

Variability

Analysis of variance and *t* tests were performed to test the significance of independent variables and interactions.

Repeatability/Comparison with Other Studies

Significant adaptation has been found to occur with feedback delays as long as 8 sec when visual feedback is presented in brief, discrete exposure trials (terminal exposure) rather than continuously, as in the study presented here (Ref. 2).

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Constraints

- Pointing errors will occur during and after prism exposure only if the observer is unable to see the pointing hand as well as the target, or if reaching must be done quickly. If both hand and target are visible and pointing is not too rapid, the observer can easily correct the pointing response to match the target as the reach is made.
- Many factors influence adaptation to prismatic displacement of the visual field and should be considered in applying these results under different conditions (CRefs. 5.1104, 5.1108, 5.1109, 5.1110).
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.

Key References

*1. Held, R., Efstathiou, A., & Greene, M. (1966). Adaptation to displaced and delayed visual feedback from the hand. *Journal of Experimental Psychology, 72,* 887-891.

2. Rhoades, R.W. (1968). *The effect of a visual feedback delay on adaptation to distorted vision.* Unpublished manuscript, University of California Riverside, Riverside, CA.

Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field; effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual fields: cognitive/learning effects;

5.1112 Effects of adaptation to prismatic displacement of the visual field;

Handbook of perception and human performance, Ch. 24, Sect. 2.2

5.1108 Adaptation to Prismatic Displacement of the Visual Field: Effect of Feedback Conditions

Feedback Conditions	Consequences for Perceptual Adaptation	Source
Presence versus absence of error-corrective feedback (observer points at target while wearing prisms)	Error-corrective feedback facilitates adaptation; no difference between feedback vs. no feedback conditions in rate of decay (decline in adaptation as observer sits in dark room after prism removal)	Ref. 12 CRef. 5.1105
Type of error-corrective feedback:		
visual feedback	Adaptation occurs	Refs. 3, 11
tactile feedback	Adaptation occurs	Refs. 7, 8
verbal feedback	Adaptation occurs	Refs. 4, 5, 10
Delay of feedback information:		
concurrent (continuous) exposure (information about hand location conveyed by trace on oscilloscope screen)	No perceptual adaptation, even with as little as 300 msec delay	Ref. 6 CRef. 5.1107
terminal exposure (view of hand or other limb in terminal position only)	Some evidence for limited adaptation with delays of up to 8 sec, but results not conclusive	Ref. 9
Consistency of feedback versus constant change in feedback	Adaptation occurs only with consistent feedback information	Refs. 1, 2

Key Terms

Altered visual direction; error-corrective feedback; feedback delay; prismatic displacement; visual field displacement

General Description

Observers who wear prisms that laterally displace the visual field will show compensatory **adaptation** to the distortion if provided with salient information regarding the prismatic displacement. Visual and other feedback from moving the limbs or pointing at targets while wearing the prisms is one way in which such information can be obtained. The table lists various feedback conditions that can influence adaptation to prismatic displacement, describes their effects, and cites entries or outside sources of more information.

Applications

• Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Constraints

• The presence of error-corrective feedback is nearly always confounded with practice of the same response (e.g., target pointing) that is used to measure adaptation: this may lead to overestimation of the amount of adaptation that has occurred.

• Many factors, such as exposure conditions (CRef. 5.1104), response conditions (CRef. 5.1109), and cognitive/learning factors (CRef. 5.1110), also influence adaptation to prismatic displacement.

• Adaptation to prism displacement of the visual field varies greatly from individual to individual.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1105 Adaptation to prismatic displacement of the visual field: effect of training;

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects

5.1109 Adaptation to Prismatic Displacement of the Visual Field: Effect of Response Conditions

Response Condition	Effect on Adaptation	Source
Post-exposure change in direction of arm movement used in pointing at target	No decrement in adaptation	Refs. 6, 12
Change from sagittal (thrusting) arm movements during exposure and transverse (lateral) arm movements after exposure	No decrement in adaptation	Ref. 4
Change from transverse arm movements during exposure to sagittal arm movements after exposure	Large decrement in adaptation	Ref. 4
Change from rapid ballistic-type target-pointing response during exposure to slow zeroing-in target-pointing response after exposure	No decrement in adaptation	Ref. 1
Change from slow zeroing-in target-pointing response during exposure to rapid, ballistic-type pointing after exposure	Large decrement in adaptation	Ref. 1
Pointing with one hand during exposure and with other hand during postexposure testing:		
Terminal exposure (hand seen in final position only during prism exposure)	Substantial **intermanual transfer,** with maximum 50% decrement in adaptation for unexposed versus exposed hand	Refs. 9, 10, 11
Concurrent exposure (hand viewed continuously during prism exposure)	No intermanual transfer of adaptation	Refs. 9,10, 11
Constrained head position during prism exposure	Little intermanual transfer	Ref. 5
Unconstrained head position during prism exposure	Some intermanual transfer	Ref. 5
Viewing one hand moving during exposure, pointing with other hand after exposure		
Spaced practice with prism displacement	Substantial intermanual transfer (59% of adaptation measured for hand viewed during exposure)	CRef. 5.1106
Massed practice with prism displacement	No intermanual transfer	CRef. 5.1106
Viewing pointing hand with one eye during exposure and with other eye after exposure	No decrement in measured adaptation; complete interocular transfer	Refs. 2, 3
Similarity of postexposure to exposure task	The greater the similarity of tasks, the greater the magnitude of prismatic adaptation effects	Refs. 7, 8

Key Terms

Altered visual direction; intermanual transfer; interocular transfer; prismatic displacement; visual field displacement

General Description

Observers who wear prisms that laterally displace the visual field generally adapt readily to the distortion. To measure such adaptation, observers typically undergo (1) a period of prism exposure during which they interact with the displaced environment by performing responses such as arm movement or target pointing; (2) postexposure testing following prism removal, during which accuracy of performance on the same or a different response is compared with accuracy before prism exposure to assess the effect of prism wearing. In general, the greater the similarity between the response made during prism exposure and the response made during postexposure testing, the greater the measured **adaptation** to the prism displacement. However, the degree of adaptation cannot be predicted entirely from the degree of similarity of the required responses. Qualitative differences in those responses also influence the amount of adaptation. The table lists some response differences that influence measured adaptation, indicates the nature of the effect, and cites sources of more information.

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Applications

• Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Constraints

• A number of factors, such as prism exposure conditions (CRef. 5.1104), feedback conditions (CRef. 5.1108), and cognitive/learning factors (CRef. 5.1110), affect adaptation to prismatic displacement and must be considered in applying these results.

• Adaptation to prism displacement of the visual field varies greatly from individual to individual.

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Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1106 Recovery from adaptation to prismatic displacement of the visual field: effects of practice;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects

5.1110 Adaptation to Prismatic Displacement of the Visual Field: Cognitive/Learning Effects

Key Terms

Altered visual direction; attention; conditioning; intersensory bias; learning set; motor learning; prismatic displacement; training; visual field displacement

General Description

When an observer wears prisms that laterally displace the visual field, a discrepancy is created between vision and other senses (such as proprioception) which can lead to errors in reaching for objects or pointing at targets. With adequate exposure to the displacing prisms, observers will adapt to the distortion and their responses will become more accurate. On a more immediate basis, intersensory bias (dominance of one sense when senses are in conflict) and unconscious or deliberate correction for the displacement lead to reduction in target-pointing errors. These cognitive effects do not represent true **adaptation**, since the effects disappear as soon as the prisms are removed. Generally, these factors are controlled in studies showing prism adaptation. **Conditioning** and learning also affect the observer's response to displacement of the visual field and influence the course and magnitude of adaptation. The table lists a number of cognitive and learning factors that affect the response to prismatic displacement, describes their effects, and cites entries or outside sources of more information.

Applications

- Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Constraints

- Many factors influence adaptation to displacement and may interact with these cognitive/learning effects in as yet untested ways (CRefs. 5.1104, 5.1108, 5.1109).
- Adaptation to prism displacement of the visual field varies greatly among individuals.

Key References

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Cross References

5.1007 Spatial localization in the presence of intersensory conflict;

5.1008 Spatial localization in the presence of visual-proprioceptive conflict: effect of amount of intersensory discrepancy;

5.1009 Spatial localization in the presence of intersensory conflict: effect of cognitive and response factors;

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1111 Recovery from adaptation to prismatic displacement of the visual field: effects of prior prism exposure

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Factor	Description	Source
Immediate correction	Observers spontaneously take account of qualitative coordinates of visual framework; when observers view well-structured field through prisms and cannot see own body, immediate apparent displacement will be only ~40% of actual optical displacement; corrective effect absent with unstructured field (e.g., viewing point of light in the dark)	Refs. 4, 16, 19, 24
Deliberate corrective responses	Observers wearing displacing prisms can point accurately to target on second trial by making deliberate correction after noting pointing error on first trial	Ref. 23
Intersensory bias	When displacing prisms first worn, discrepancy between visual and other senses may be decreased by sensory capture in which one sense dominates another (e.g., felt position of hand may change so that stationary hand is immediately felt to be located very close to where it is seen to be); active movement by observer decreases intersensory bias and promotes true adaptation	CRefs. 5,1007, 5,1008, 5.1009
Motor learning	When observers perform tasks such as target pointing while wearing prisms, they acquire a rule for correct pointing that becomes automatic with practice; this component of adaptation helps to decrease pointing errors while prisms are worn and contributes to postexposure aftereffects	Refs. 21, 22
Prismatic shaping	When prismatic displacement is incremented in very small steps so observer never makes a target-pointing error large enough to cause awareness of displacement, adaptation is still substantial	Ref. 7
Attentional determinants of adaptation	Adaptation to displacement seems to take place primarily in sensory modality that is not attended to; if observer must monitor visual information during exposure, adaptation is largely proprioceptive, and vice versa	Refs. 1, 18
Conditioning effects	Neutral stimuli, such as testing apparatus, testing room, etc., can become discriminative stimuli for adaptation; postexposure adaptation responses will be greater in their presence than in their absence; later exposure to these stimuli will elicit partial adaptive responses even before prisms are put on again and will reduce the magnitude of adaptation achieved on subsequent prism exposure	Refs. 6, 9, 14
Empty spectacle frames or goggles	When prisms are mounted in spectacles or goggles during prism exposure, larger **negative aftereffect** is found during postexposure testing when empty spectacle frames are worn than when they are not worn	Refs. 11, 12, 17, 20
Auditory tone	When tone is present during prism exposure, presence of tone after prisms are removed elicits adaptive response	Ref. 13
Gaze-contingency	Observers who wear split-half prism spectacles (only upper half of visual field displaced) experience negative aftereffect when eye movements are in upward, but not downward, direction	Ref. 10
Felt direction of gaze	Placing eyes in position they were felt to be in during prism exposure causes post-exposure adaptation aftereffect	Ref. 5
Prior experience with prism displacements in same direction	Repeated experience with prisms leads to an immediate adaptive shift on the first trial of subsequent adaptation sessions, but the total amount of adaptation acquired is no greater than when there is no previous exposure	Ref. 15
	Exposure to two successive displacements in same direction yields greater adaptation and slower postexposure recovery from adaptation than successive displacements in opposite directions	Ref. 15
Prior experience with prism displacements in opposite direction	Alternating exposure to opposite displacements leads to progressive reduction in errors (while prisms are worn) with successive displacements; perceptual adaptation increases with increase in spatial and temporal segregation of alternating trials	Ref. 2 CRef. 5.1111
	Adaptation is less and recovery from adaptation faster after two successive displacements in opposite directions than after successive displacements in same direction	

5.1111 Recovery from Adaptation to Prismatic Displacement of the Visual Field: Effects of Prior Prism Exposure

Key Terms

Altered visual direction; prismatic displacement; proactive inhibition; response recovery; visual field displacement

General Description

Observers who adapt first to one prism-induced lateral displacement of the visual field and then to an equal displacement in the opposite direction show greater recovery from the second adaptation during the first few minutes after prism removal than observers who adapt to only a single displacement. This effect is thought to occur because adaptive responses learned during the first displacement interfere with the performance of the more recently acquired adaptive responses to the second displacement (a phenomenon termed *proactive inhibition*).

Applications

Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

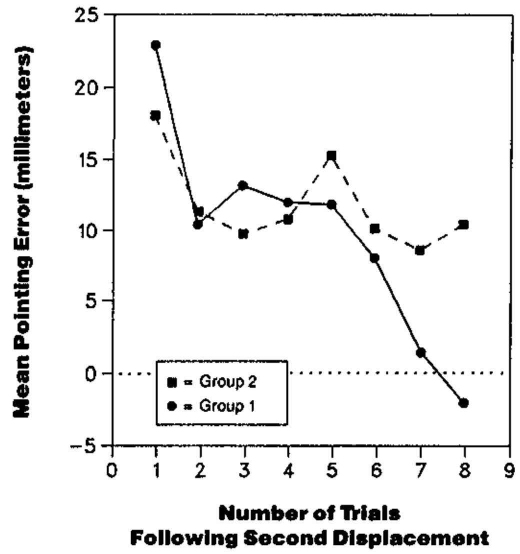

Figure 1. Decline in adaptation to prism displacement as a function of number of trials since prism removal. Group 1 observers were exposed to prism displacement in one direction followed by equal displacement in the opposite direction; Group 2 observers were exposed to one direction of displacement only. The vertical axis shows the mean error in pointing to the target center after the second prism displacement. Values >0 represent adaptive shifts in pointing (pointing that compensates for previous apparent displacement of target); values <0, anti-adaptive shifts. (From Ref. 1)

Methods

Test Conditions

- Target with 12-cm vertical and horizontal lines intersecting at midpoints; lines cross-hatched at 1-cm intervals; viewing distance 60 cm
- Target illuminated by 25-W lamp; training trials, continuous illumination; test trials and recovery trials, light extinguished just before pointing hand reached target; room dark except for target illumination
- Observer wore **Risley prisms** that displaced visual field by 16 diopters (~9 deg) left or right, or not at all; observer's head immobilized by chin and forehead rests

Experimental Procedure

- Independent variables: direction of prismatic displacement, number of different prism displacements
- Dependent variable: mean error in pointing at target
- Observer's task: touch center of target with pen
- Group 1: 12 preliminary practice trials with no prism displacement, 15 sequences of two training trials and one test trial with left or right displacement, followed by similar sequence of trials with displacement in other direction, practiced to criterion of three successive test trials within 1 cm of target; eight recovery trials with no displacement immediately following criterion at 1-min intervals for 7 min (data presented only for recovery trials)
- Group 2: same as Group 1, except observers exposed to only one displacement (either left or right), with practice to criterion given above
- 10 male psychology student observers

Experimental Results

- Observers exposed successively to two opposite prism displacements show significantly greater overall recovery from adaptation (as indicated by reduction in target-pointing errors) at 7 min after removal of the prisms than observers exposed to prism displacement in only one direction ($p < 0.01$).
- The trend of the recovery from adaptation does not differ significantly between the two groups.
- Direction of final prism displacement (left or right) has no effect on recovery from prism adaptation. Data for both displacement directions are pooled in the figure.
- In a second experiment reported in the same study, all observers were exposed to two successive prismatic displacements of the visual field — one group to displacements in the same direction, but of different magnitudes, and one group to displacements of equal magnitude, but in opposite the same direction, but of different magnitudes, and one group to displacements of equal magnitude, but in opposite directions. The group exposed to opposite displacements showed greater recovery from adaptation and a sharper decline in pointing errors over the first 7 min after removal of the prisms than did the group exposed to displacements in the same direction. These results further support the view that adaptive responses learned during the first displacement intrude upon and inhibit the performance of adaptive responses learned during the second and opposite displacement after prisms have been removed.

Variability

Analysis of variance performed to test significance of independent variables and interactions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Pointing errors will occur during and after prism exposure only if the observer is unable to see the pointing hand as well as the target, or if reaching must be done quickly. If both hand and target are visible and pointing is not too rapid, during reaching the observer can easily correct the pointing response to match the target.
- A number of factors, such as prism exposure conditions (CRef. 5.1104), response requirements (CRef. 5.1109), feedback conditions (CRef. 5.1108) and cognitive/learning factors (CRef. 5.1110), affect adaptation to prismatic displacement and should be considered in applying these results under different conditions.
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.

Key References

*1. Devane, J. R. (1968). Proaction in the recovery from practice under visual displacement. *Perceptual and Motor Skills, 27*, 411-416.

2. Lazar, G., & Van Laer, J. (1968). Adaptation to displaced vision after experience with lesser displacement. *Perceptual and Motor Skills, 26*, 579-582.

Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1106 Recovery from adaptation to prismatic displacement of the visual field: effects of practice;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

Handbook of perception and human performance, Ch. 24, Sect. 2.2

5.1112 Effects of Adaptation to Prismatic Displacement of the Visual Field

Key Terms

Altered proprioception; altered visual direction; altered visuomotor coordination; prismatic displacement; visual field displacement

General Description

When an observer wears prisms that laterally displace the visual field, perception and performance may be altered in various ways, depending on prism exposure conditions and the observer's task during prism wearing, the test used to measure **adaptation** to the distortion after prisms are removed, and the main locus of adaptation (i.e., the body part most affected by prism exposure). Adaptation to displacing prisms can lead to changes in proprioception (apparent position of various body parts), changes in vision, and changes in visuomotor coordination independent of vision and proprioception (motor learning). The table shows the potential end states of adaptation to prismatic displacement. For each body site or function where adaptation may occur, it lists the potential and actual effects of prism exposure and describes the test used to detect the adaptation.

Applications

Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

		Evidence of Adaptation	
Primary Adaptation Site	**Test[a]**	**Main Effects**	**Other Effects[b]**
Actual Effects			
Simple Sites			
Hand, arm (facilitated by continuous viewing of hand/arm during prism exposure)	Move adapted hand/arm a specified distance from other hand/arm	Limbs appear to be closer or further than when limb not adapted, depending on direction of prismatic displacement, and on which hand was viewed during adaptation	Misreaching with adapted hand only, at target in any sensory modality, as well as to straight ahead
Neck, head (facilitated by continuous viewing of environment)	Align head with trunk	Head misturned in direction of displacement	Misreaching, with any limb, at target in any modality; shift in apparent visual and auditory straight ahead in direction opposite to prismatic displacement (a straight-ahead target appears shifted in direction opposite to prism displacement)
Eyes	Place eyes in apparent straight ahead position	Eyes are misdirected toward same side as displacement	Misreaching, with any limb, at visual target; shift in apparent visual straight ahead in direction opposite to displacement

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Primary Adaptation Site	Test[a]	Evidence of Adaptation: Main Effects	Other Effects[b]
Potential Effects			
Simple Sites			
Retina	a) Indicate when visual target appears straight ahead b) Place eyes in apparent straight ahead position	a) Shift in apparent straight ahead b) No shift in apparent position of eyes	Misreaching, with any limb, at visual target
Complex Sites			
Head-Arm	a) Point head to hand b) Separate measures of apparent head position and apparent arm position	a) Head misturned in direction of displacement b) No shift in apparent arm or head position	Misreaching for visual or auditory target in direction opposite displacement
Eye-Arm	a) Direct eye to hand b) Separate measures of apparent arm position and apparent direction of gaze	a) Eyes misdirected toward same side as displacement b) No shift in apparent arm or eye position	Misreaching for visual target in direction opposite displacement
Assimilated, corrected response (motor learning)	a) Point at visual target b) Separate measures of adaptation of arm, head, eyes, head-arm, and eye-arm sites	a) Error in pointing in direction opposite displacement b) Algebraic sum of other shifts is less than target pointing error	No other manifestations

[a]Unless otherwise indicated, test occurs in the absence of vision
[b]Tests made after prisms removed

Constraints

Many factors affect adaptation to prismatic displacement (CRefs. 5.1104, 5.1108, 5.1109, 5.1110).

Key References

1. R. B. Welch (1986). Adaptation of space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception.* New York: Wiley.

Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation of prismatic displacement of the visual field: cognitive/learning effects

5.1113 Prismatic Displacement of the Visual Field: Visual and Auditory Judgments of Straight Ahead

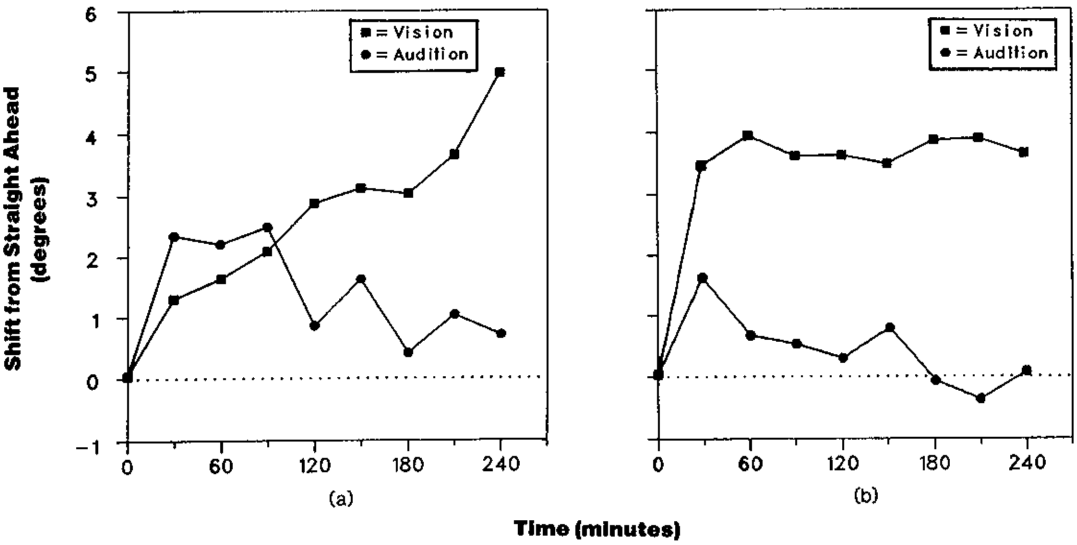

Figure 1. Mean shift in visual and auditory judgment of straight ahead as a function of duration of exposure to prism-induced lateral displacement of the visual field. (a) Attenuated auditory stimulation earmuffs; (b) normal auditory stimulation (no earmuffs). The vertical axis shows the extent to which a target judged straight ahead by observers was shifted from true straight ahead. Positive values indicate a shift in the same direction as prism displacement; negative values, shifts in the opposite direction. Only positive shifts are adaptive (compensatory) for visual judgments; all shifts are maladaptive for auditory judgments. (From Ref. 5)

Key Terms

Altered visual direction; bore sight; intersensory bias; prismatic displacement; sound localization; visual field displacement; visual localization

General Description

Observers wearing prisms that laterally displace the visual field initially make errors in straight-ahead judgments of auditory as well as visual targets. With continued prism exposure, there is an adaptive shift in the visual straight-ahead that compensates for the visual displacement and increases the accuracy of visual direction-finding judgments. A similar shift is seen in perceived auditory straight-ahead. However, this shift is maladaptive, since it increases errors in localizing auditory targets. After further prism exposure, the mean auditory shift decreases while the mean visual shift continues to grow. This represents increasingly accurate straight-ahead judgments for both auditory and visual targets. Maladaptive auditory shifts in direction-finding are greater when auditory stimulation is attenuated by earmuffs during prism exposure than when no earmuffs are worn.

Applications

- Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- All observers wore monocular prism goggles (16.4 diopter) that displaced visual field to left or right; left eye occluded
- One group of observers also wore sound-attenuating earmuffs; the other group wore no earmuffs
- Observers walked outdoors for 4 hr; before this exposure and at half-hour intervals within the 4 hr, observers were tested without prisms or earmuffs in a dark quiet room
- Visual test target: luminous line 2.54 × 0.15 cm (1 × 0.0625 in.); auditory test target: small pulsed white noise; both targets 0.91 m from observer; head stabilized by biteboard

Experimental Procedure

- Method of adjustment under observer's control
- Independent variables: earmuffs versus no earmuffs, exposure time, left versus right visual displacement
- Dependent variable: amount of adaptation, measured as difference between means of 10 pre- and post-exposure localization settings (mean shift in visual and auditory straight ahead)
- Observer's task: move visual or auditory stimulus until it appeared to be directly in front of him
- 16 male college student observers, 8 per group

Experimental Results

- For observers wearing earmuffs, visual and auditory shifts in apparent straight ahead are roughly equal at ~2 deg after 90 min of exposure to prisms that laterally displace the visual field; thereafter, the mean auditory shift decreases and, at 120 min, is significantly less than the visual shift; the visual and auditory shifts continue to separate until, after 4 hr, the auditory shift is <1 deg while the visual shift has reached 5 deg and appears to be still rising.
- For observers without earmuffs, the mean auditory shift in perceived straight ahead is significantly smaller than the visual shift after 30 min of prism exposure; thereafter, the auditory shift declines and is not significantly different from zero; visual adaptation increases rapidly, but plateaus at a lower level than for observers wearing earmuffs.
- Direction of visual displacement (left or right) has no influence on results for either group.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Several other studies have found the visual and auditory shifts caused by wearing displacing prisms to be approximately equal (Refs. 1, 2, 3, 4). However, in these studies, exposure may not have lasted as long as 4 hr.

Constraints

- The observer's movements while wearing prisms may alter the results. For example, if the observer's head is immobilized and one hand only is viewed, there will be no change in the felt position of the head and consequently no shift in the perceived location of auditory targets (Ref. 3).
- A number of factors such as prism exposure conditions (CRef. 5.1104), response requirements (CRef. 5.1109), feedback conditions (CRef. 5.1108) and cognitive/learning factors (CRef. 5.1110) affect adaptation to prismatic displacement and should be considered in applying these results under different conditions.
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.

Key References

1. Cohen, M. M. (1974). Changes in auditory localization following prismatic exposure under continuous and terminal visual feedback. *Perceptual and Motor Skills, 38,* 1202.

2. Freedman, S. J., & Gardos, G. (1965, June). *Compensation for auditory rearrangement and transfer to eye-hand coordination.* Paper presented at MIT Conference on Adaptation, Cambridge, MA.

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*5. Rekosh, J. H., & Freedman, S. J. (1967). Errors in auditory direction-finding after compensation for visual re-arrangement. *Perception & Psychophysics, 2,* 466-468.

Cross References

2.801 Sound localization;

2.814 Effect of static head position on localization;

2.815 Effect of visual and proprioceptive cues on localization;

5.1007 Spatial localization in the presence of intersensory conflict;

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

Handbook of perception and human performance, Ch. 24, Sect. 7.2

5.1114 Perceptual Effects of Inversion and Left-Right Reversal of the Visual Field

Perceptual Aspect or Effect	Description	Source
During Exposure to Distorting Devices		
Appearance of visual scene	Evidence conflicting; most studies find that visual scene never comes to appear upright or unreversed even with prolonged viewing through inverting and/or reversing devices	Refs. 6, 7, 8, 9, 10
	Exceptions reported:	
	(a) When observers wore left-right reversing goggles for 37 days, objects came to look normally oriented (observers in these studies were required to perform vigorous and complex tasks such as skiing and mountain climbing)	Ref. 4
	(b) With intensive training, observers who wore left-right reversing spectacles for half of each day came to see visual field as unreversed	Ref. 12
	(c) Observers wearing left-right reversing goggles or inverting goggles reported piecemeal adaptation; that is, some objects in the visual field appeared upright or unreversed, while other objects simultaneously seemed reversed or inverted	Refs. 2, 4
Stability of visual field	When inverting and/or reversing devices are first worn, visual field appears to move when head is moved; with continued exposure, visual stability returns; apparent movement of visual scene may cause nausea during early stages of exposure	Refs. 8, 9, 10
	Visual-motion-induced nausea does not occur in stroboscopic light	Ref. 5
Coordinated perceptual-motor activity	After initial period of extreme disorientation, observers are able to perform many complex tasks accurately when distorting devices are worn for long periods of time	Refs. 4, 8, 9, 10
Immediately After Removal of Distorting Devices		
Orientation aftereffects	Generally no visual negative aftereffects when inverting and/or reversing devices removed (i.e., visual scene appears upright and unreversed), although world may seem strange compared with appearance while devices worn	Refs. 8, 9, 10
	Exceptions (occur when the visual field comes to appear normal—unreversed or uninverted—while distorting goggles being worn):	
	(a) Visual aftereffects (normal scene temporarily appeared reversed) after removal of reversing goggles worn for 37 days	Ref. 4
	(b) Visual aftereffects (world temporarily appeared inverted) after removing inverting goggles worn for 9 days	Ref. 4
Visual motion aftereffects	Observers report visual field motion immediately after removing inverting and reversing goggles; motion-induced nausea may also result	Refs. 2, 4, 8, 9, 10

Key Terms

Motion sickness; visual field inversion

General Description

When observers first wear mirrors or prisms that reverse and/or invert the visual field, the distortion leads to disorientation, illusory motion of the visual field when the head is moved, nausea induced by the illusory visual motion, and visuomotor and locomotive difficulties. With prolonged exposure, observers can adjust to the visual rearrangement and eventually are able to perform accurately even complex tasks such as fencing and bike-riding. While the evidence is contradictory, most studies indicate that observers do not show true visual **adaptation** to the orientation distortion—the world never comes to appear truly upright or unreversed while the prisms are worn, and no **negative aftereffects** occur when the distorting devices are removed.

The table describes the effects of visual field inversion and reversal during and after exposure to the distorting devices and cites sources of more information.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Few studies have examined the quantitative aspects of adaptation to distortion of the up-down and right-left axes of visual space. Therefore, the effect of exposure duration, type of task performed while wearing the distorting device, and other factors on adaptation to visual field inversion and reversal have not yet been determined.

Key References

1. Gonshor, A., & Melvill Jones, G. (1980). Postural adaptation to prolonged optical reversal of vision in man. *Brain Research, 192,* 239-248.

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*9. Stratton, G. M. (1897). Upright vision and the retinal image. *Psychological Review, 4,* 182-187.

*10. Stratton, G. M. (1897). Vision without inversion of the retinal image. *Psychological Review, 4,* 341-360, 463-481.

11. Stratton, G. M. (1899). The spatial harmony of touch and sight. *Mind, 2,* 492-505.

12. Taylor, J. G. (1962). *The behavioral basis of perception.* New Haven: Yale University Press.

Cross References

5.1101 Adaptation of space perception;

5.1120 Factors affecting adaptation to loss of visual position constancy;

Handbook of perception and human performance, Ch. 24, Sect. 3.2

5.1115 Factors Affecting Adaptation to Visual Tilt

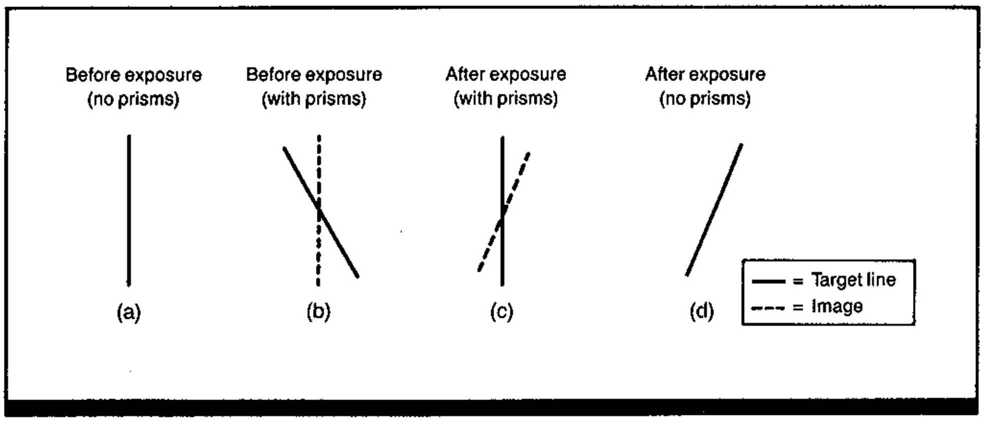

Figure 1. Observers' verticality settings before and after exposure to prisms producing rightward rotation of the visual image. Before prism exposure (a) observers can set a line accurately to the vertical. When prisms are first put on (b), verticality settings are rotated by approximately the magnitude of the optical tilt. After wearing the prisms for a while, observers become more accurate in setting the line to vertical in spite of the continued optical tilt (although compensation is usually not complete, as illustrated here). When prisms are once more removed, verticality settings are slanted in the direction of the previous optical tilt.

Key Terms

Active movement; altered visual orientation; constant tilt; exposure duration; incremental tilt; passive movement; prismatic rotation; tilt adaptation; visual field rotation

General Description

Observers wearing prisms which alter visual orientation (so that an upright image looks tilted) adjust rapidly to the distortion. Typically, before wearing prisms, observers in the dark can accurately set a luminous rod to a vertical orientation in the dark. When prisms are first put on, verticality settings show errors in a direction opposite the tilt. As prisms are worn, however, performance rapidly becomes accurate, provided observers can see their hands and other relevant body parts. After prisms are removed, the observer's verticality setting of the rod is slanted in the direction of the prism tilt (Fig. 1). This change in perception and perceptual-motor behavior to compensate for imposed slant is termed **adaptation.** Adaptation to tilt generally asymptotes at about 30% of the full prismatic distortion, after approximately 1 hr of prism exposure. The table lists some factors known to influence the acquisition of tilt adaptation, indicates the nature of the effects, summarizes empirical studies in the area, and cites entries or sources of more information.

Constraints

- Even when prisms are not worn, viewing a physically tilted edge for a few minutes will lead to a small but reliable reduction in its perceived tilt, and an objectively vertical edge viewed immediately after will appear tilted slightly in the opposite direction from the first edge. This "configurational effect" can become confounded with adaptation to prism-induced tilt, although the latter effect is much stronger.
- Adaptation to visual tilt varies greatly from individual to individual.
- Interactions may occur among the various factors affecting adaptation to tilt, but such interactions generally have not been studied.

Key References

1. Harris, C. S. (1974). Beware of the straight-ahead shift—a nonperceptual change in experiments on adaptation to displaced vision. *Perception*, 3, 461-476.

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6. Quinlan, D. (1970). Effects of sight of the body and active locomotion in perceptual adaptation. *Journal of Experimental Psychology, 86*, 91-96.

Cross References

5.1116 Adaptation to visual tilt: acquisition and decay;

5.1117 Adaptation to visual tilt: effect of rotation magnitude;

5.1118 Adaptation to visual tilt: effect of constant versus incremental tilt

Factor	Effect on Tilt Adaptation	Source
Active versus **passive movement** of observer	Active body and head movement facilitates tilt adaptation	Refs. 5,6
Familiarity of scene being viewed with prisms	Some adaptation to tilt occurs spontaneously when scene is familiar	Refs. 1, 2
Exposure time	Adaptation increases as a negatively accelerated function of exposure time	CRef. 5.1116
Amount of tilt	Magnitude of adaptation is a linear function of degree of tilt for tilts of 0-32 deg	CRef. 5.1117
Constant versus incremental tilt	Acquisition curve is steeper when observer exposed to tilt in small increments than when exposed to largest tilt from beginning; final magnitude of adaptation is the same	CRef. 5.1118
Viewing natural environment versus body parts only	Movement in natural environment facilitates tilt adaptation	Refs. 3, 4

5.1116 Adaptation to Visual Tilt: Acquisition and Decay

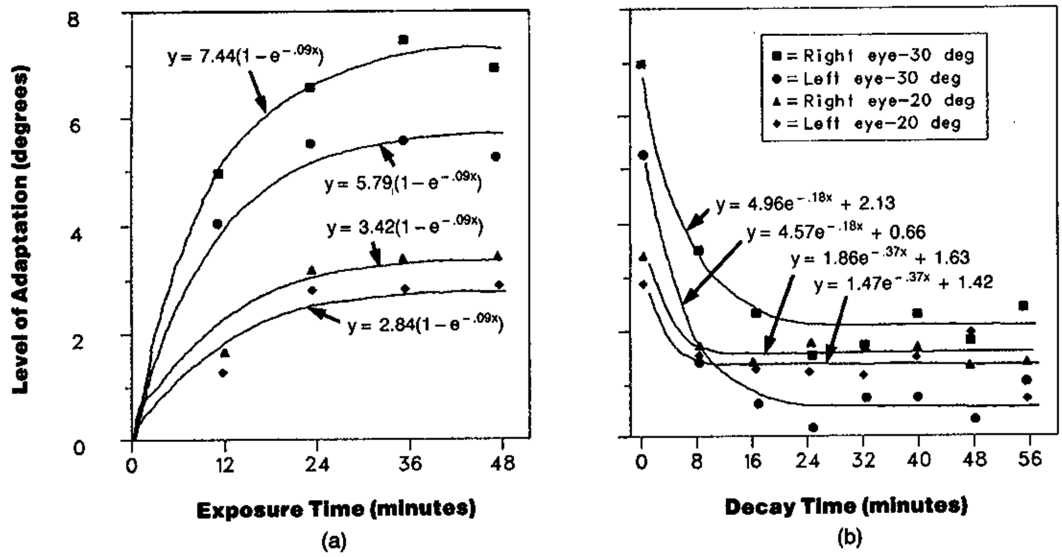

Figure 1. Mean level of adaptation to 30 and to 20 deg of optical tilt in the exposed (right) and unexposed (left) eye as a function of exposure time while prisms are worn, and decay time in the dark after prism removal. Adaptation is measured as the amount by which observers' postexposure verticality judgments depart from apparent vertical as measured before prism exposure. (From Ref. 2)

Key Terms

Altered visual orientation; interocular transfer; prismatic rotation; tilt adaptation; visual field rotation

General Description

Observers who wear prisms that tilt the visual field adapt rapidly to the distortion. Tilt **adaptation** reaches a peak after 12-15 min of prism exposure and is higher for 30-deg than for 20-deg tilt rotation. When prisms are removed, adaptation declines to a low level after 15 min in the dark. If only one eye is exposed to the rotating prisms, postexposure judgments of target verticality show adaptation effects regardless of which eye is tested—exposed or unexposed.

Applications

Environments subject to optical distortion.

Methods

Test Conditions

- Observer's right eye covered by **Dove prisms** mounted in tandem and affixed by headset; left eye occluded
- Prisms tilted visual field by 20 or 30 deg; visual field 10 deg in diameter
- During exposure period observer walked in hallway; observer wore black cloak that covered body and was instructed not to touch walls; after prism removal, observer sat in dark
- Test stimulus: luminous vertical line 30-cm long by 0.4-cm wide; viewing distance 121.92 cm; tests made without prisms in dark room

Experimental Procedure

- Independent variables: magnitude of tilt, duration of exposure, time since prism removal, test eye (exposed versus covered)
- Dependent variable: level of adaptation, defined as difference between mean pre-exposure and post-exposure verticality settings, determined separately for exposed and unexposed eyes
- Observer's task: set a luminous vertical line to upright position prior to, and at various times during and after adaptation
- 16 observers, undergraduates, males and females, 8 tested at each tilt magnitude

Experimental Results

- Adaptation to visual field rotation is significantly greater for 30-deg tilt (mean = 5.83 deg) than for 20-deg tilt (mean = 2.71 deg). (Mean scores are for both eyes combined.)
- Adaptation is greater in the exposed eye than in the unexposed eye, but the difference is significant only when the exposed eye is tested first.
- Magnitude of adaptation to tilt levels off after ~12-15 min of prism exposure.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Decay of adaptation is more rapid for 20-deg than for 30-deg tilt, i.e., for a smaller tilt. Decay reaches an asymptote after 8 min for 20-deg tilt, and after 16 min for 30-deg tilt.
• Decay is not complete for either tilt magnitude after 56 min in dark.
• The smoothed curves in Fig. 1a are negatively accelerated exponential growth functions of the form adaptation level $= a(1 - e^{-bt})$, where a is the estimated asymptote of adaptation and b estimates the rate at which adaptation approaches the asymptote as a function of exposure time t. Curves were fit by the method of least squares for both left (occluded) and right (exposed) eye.
• The smoothed curves in Fig. 1b are negatively decelerated exponential decay functions of the form adaptation level $= ae^{-bt} + c$, where $a + c$ is the adaptation level at the beginning of the decay period, b estimates the rate of decay per unit of time t, and c is the asymptote of decay. Curves were fit by method of least squares as in Fig. 1a. Standard error of estimate was 0.28 (for 10 parameters and 32 data points).

Variability

Two subjects (one in each tilt magnitude group) failed to show at least 1 deg of adaptation after 48 min of exposure and were replaced. One observer showed unusually large negative values (anti-adaptive shift) in left eye during tests of decay.

Repeatability/Comparison with Other Studies

Difference in adaptation level for the two eyes found in this study is probably an experimental artifact due to the order in which the eyes were tested. Other studies have shown complete **interocular transfer** of tilt adaptation (Ref. 1).

Constraints

• Adaptation will decay completely (performance will return to preadaptation levels) if the observer is re-exposed to normal conditions.
• Even when prisms are not worn, viewing a physically tilted edge for a few minutes will lead to a small but reliable reduction in its perceived tilt.
• Many factors influence adaptation to prism-induced tilt of the visual field and should be considered in applying these results under different conditions (CRef. 5.1115).
• Adaptation to visual tilt varies greatly from individual to individual.

Key References

1. Hajos, A., & Ritter, M. (1965). Experiments to the problem of interocular transfer. *Acta Psychologica, 24,* 81-90.

*2. Redding, G. (1975). Decay of visual adaptation to tilt and displacement. *Perception & Psychophysics, 17,* 203-208.

Cross References

5.1115 Factors affecting adaptation to visual tilt;

5.1117 Adaptation to visual tilt: effect of rotation magnitude;

Handbook of perception and human performance, Ch. 24, Sect 3.2

5.1117 Adaptation to Visual Tilt: Effect of Rotation Magnitude

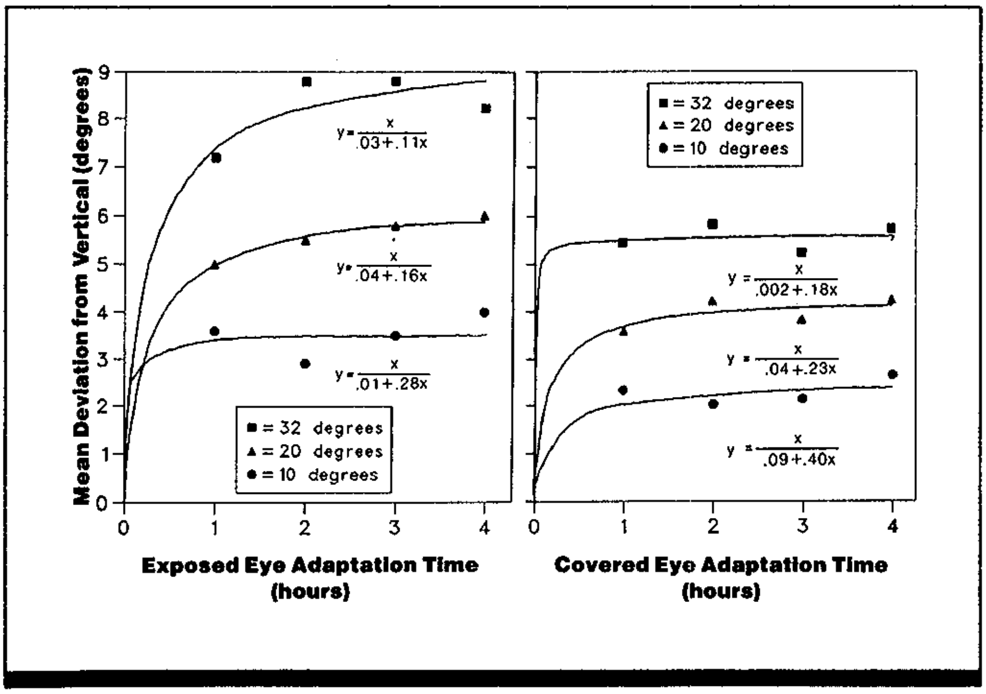

Figure 1. Magnitude of adaptation to optical tilt as a function of exposure time for the exposed and covered eye at three levels of induced tilt. Adaptation is measured as amount by which observers' verticality settings after prism exposure depart from apparent vertical as measured before prisms were worn (Ref. 1).

Key Terms

Altered visual orientation; exposure duration; interocular transfer; prismatic rotation; tilt adaptation; tilt magnitude; visual field rotation

General Description

When observers wear prisms that tilt the visual field by 10, 20, or 32 deg, amount of **adaptation** increases linearly with imposed magnitude of tilt. Asymptote of tilt adaptation is reached at 20-30% of the theoretical maximum. For adaptation periods >1 hr, exposure time does not significantly affect the magnitude of adaptation. When only one eye is exposed to the rotating prisms, post-exposure judgments of target verticality show adaptation regardless of which eye (exposed or unexposed) is tested, although effect is less for the unexposed eye.

Methods

Test Conditions

- Observer wore **Dove prisms** that tilted visual field by 10, 20, or 32-deg clockwise or counterclockwise; prisms mounted in tandem over right eye and secured by headgear; left eye occluded
- Observer walked in hallway and up and down stairs; played with puzzles, cards, and darts; and read
- Visual field 30 deg in diameter
- Total exposure time 4 hr
- Test stimulus: luminous line 30.48 × 0.64 cm (12 × 0.25 in) in dark room; prisms not worn during testing

Experimental Procedure

- Independent variables: magnitude of tilt, exposure time, test eye (covered versus exposed)
- Dependent variables: level of adaptation, defined as difference between mean pre-exposure and post-exposure verticality settings determined separately for each eye
- Observer's task: set a luminous line to appear vertical prior to, and (at 1-hr intervals) during, adaptation
- 4 verticality settings at each tilt magnitude for each direction of tilt; plotted points are averages for clockwise and counterclockwise tilt
- 24 female undergraduate observers, 4 tested at each combination of tilt magnitude and tilt direction

Experimental Results

- Level of tilt adaptation increases linearly with the magnitude of imposed tilt. Mean level of adaptation, averaged over exposure time, is 3.50, 5.59, and 8.24 deg, for tilts of 10, 20, and 32 deg, respectively, for the exposed eye and 2.26, 3.94, and 5.56 deg for the covered eye.
- The exposed eye shows significantly higher levels of adaptation than the covered eye ($p < 0.005$).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Beyond the first hour of exposure, adaptation level does not increase significantly with exposure time and reaches asymptotes well below the theoretical maximum. The smooth curves shown in Fig. 1 are hyperbolic functions fit to the data by the method of least squares. Standard errors of estimate for the fits are 0.58, 0.12, and 0.82 deg for the exposed eye and 0.38, 0.40, and 0.46 deg for the unexposed eye at 10, 20, and 32 deg, respectively. Other studies suggest that adaptation to tilt occurs rapidly at first, reaching asymptote at ~15 min, and increases very slowly thereafter.

Variability

Analysis of variance was performed to test the significance of the independent variables. No other information on variability was given.

Repeatability/Comparison with Other Studies

The level of adaptation found is comparable to that reported elsewhere (CRef. 5.1116). One study (Ref. 3) found complete adaptation to 20-deg tilt after 2 hr when preselected fast-adapting observers were used. Other studies (Ref. 2) have shown greater **interocular transfer** of adaptation than reported here. The author suggests that incomplete transfer in this experiment may have been due to the fact that the exposed eye was always tested first.

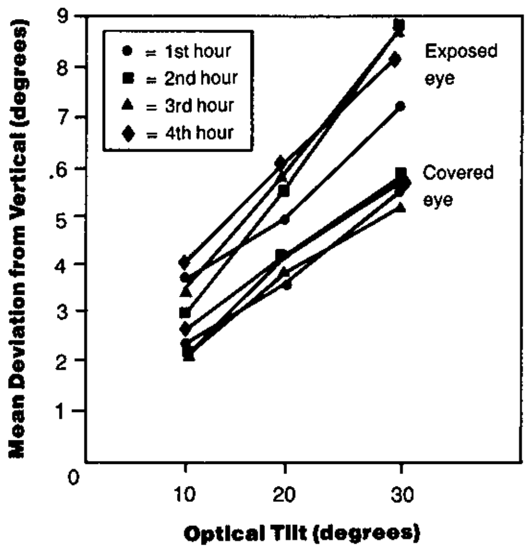

Figure 2. Magnitude of adaptation as a function of optical tilt for the exposed and covered eyes after 1-4 hr of prism exposure. Adaptation is measured as in Fig. 1 (Ref. 1).

Constraints

• A number of factors influence adaptation to prism-induced tilt and should be considered in applying these results under different conditions (CRef. 5.1115).

• Individuals vary greatly in their degree of adaptation to prism-induced tilt of the visual field.

• Even when prisms are not worn, viewing a physically tilted edge for a few minutes will lead to a small, but reliable, reduction in its perceived tilt, and an objectively vertical edge viewed immediately after will appear tilted slightly in the opposite direction from the first edge. This "configurational effect" can become confounded with adaptation to prism-induced tilt, although the latter effect is much stronger.

Key References

*1. Ebenholtz, S. (1966). Adaptation to a rotated visual field as a function of degree of optical tilt and exposure time. *Journal of Experimental Psychology, 72*, 629-634.

2. Hajos, A., & Ritter, M. (1965). Experiments to the problem of interocular transfer. *Acta Psychologica, 24*, 81-90.

3. Mikaelian, H. H., & Held, R. (1964). Two types of adaptation to an optically-rotated field. *American Journal of Psychology, 77*, 257-263.

4. Redding, G. (1975). Decay of visual adaptation to tilt and displacement. *Perception & Psychophysics, 17*, 203-208.

Cross References

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

Handbook of perception and human performance, Ch. 24, Sect. 3.2

5.1118 Adaptation to Visual Tilt: Effect of Constant Versus Incremental Tilt

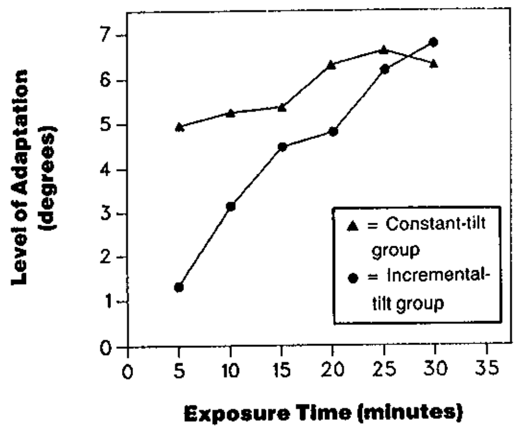

Figure 1. Magnitude of tilt adaptation as a function of time prisms were worn for group exposed to constant 30-deg tilt and group exposed to tilt incrementing from 5-30 deg at the rate of 5 deg/5 min. Vertical axis shows extent to which observers' verticality settings after prism exposure were displaced from the apparent vertical measured before prism exposure. Units on horizontal axis represent amount of tilt as well as exposure time for incremental-tilt group. (From Ref. 3)

Key Terms

Altered visual orientation; incremental exposure; prismatic rotation; tilt adaptation; visual field rotation

General Description

When observers wear prisms that optically tilt the visual field, the total amount of tilt **adaptation** is the same whether the prism tilt is constant at a given set magnitude or increases by 5-deg increments every 5 min until it reaches the set magnitude. However, the rate of adaptation is greater for variable than for constant prism tilt.

Methods

Test Conditions

- Observer wore two **Dove prisms** mounted over right eye; prisms tilted visual field by constant 30-deg clockwise or by tilts that increased from 5 to 30-deg clockwise at the rate of 5 deg per 5 min; left eye occluded
- Observer walked through hallway while wearing prisms; total exposure time 30 min
- No prisms worn during testing; head stabilized by forehead and chin rests

Experimental Procedure

- Independent variable: type of tilt (constant versus incremental); exposure time
- Dependent variable: amount of adaptation, defined as the difference between mean pre- and post-exposure settings of a line to vertical (settings taken every 5 min)
- Observer's task: set luminous line to appear vertical
- 2 judgments per observer at each exposure interval
- 16 observers; 8 per group

Experimental Results

- The level of adaptation achieved is the same for the constant-tilt group and the incremental-tilt group at the end of the total exposure period.
- The rate of adaptation is significantly greater for the incremental-tilt group than for the constant-tilt group.

Variability

No information on variability was given.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Repeatability/Comparison with Other Studies

Another study (Ref. 2) demonstrated that the highest levels of adaptation are reached in the shortest period of time when the rate of tilt increment is 1.4 deg/min. Similar effects on adaptation with incremental modification have been noted in studies of adaptation to displacement of the visual field (Ref. 5), and in studies of visual effects of head movements during vestibular stimulation (Ref. 4).

Constraints

- Many factors influence adaptation to prism-induced tilt of the visual field and should be considered in applying these results under different conditions (CRef. 5.1115).
- Even when prisms are not worn, viewing a physically tilted edge for a few minutes will lead to a small, but reliable, reduction in its perceived tilt, and an objectively vertical edge viewed immediately after will appear tilted slightly in the opposite direction from the first edge. This "configurational effect" can become confounded with adaptation to prism-induced tilt, although the latter effect is much stronger.
- Adaptation to visual tilt varies greatly from individual to individual.

Key References

1. Ebenholtz, S. M. (1973). Optimal input rates for tilt adaptation. *American Journal of Psychology, 86*, 193-200.

2. Ebenholtz, S., & Callan, J. (1980). Tilt adaptation as a feedback control process. *Journal of Experimental Psychology: Human Perception and Performance, 6*, 413-432.

*3. Ebenholtz, S., & Mayer, D. (1968). Rate of adaptation under constant and varied optical tilt. *Perceptual and Motor Skills, 26*, 507-509.

4. Graybiel, A., & Wood, C. (1969). Rapid vestibular adaptation in a rotating environment by means of controlled head movements. *Aerospace Medicine, 40*, 638-643.

5. Lackner, J., & Lobovits, D. (1978). Incremental exposure facilitates adaptation to sensory rearrangement. *Aviation, Space, and Environmental Medicine, 49*, 362-364.

Cross References

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

Handbook of perception and human performance, Ch. 24, Sect. 3.2

5.1119 Adaptation to Tilt and Displacement: Acquisition Rate, Magnitude, and Decay Time

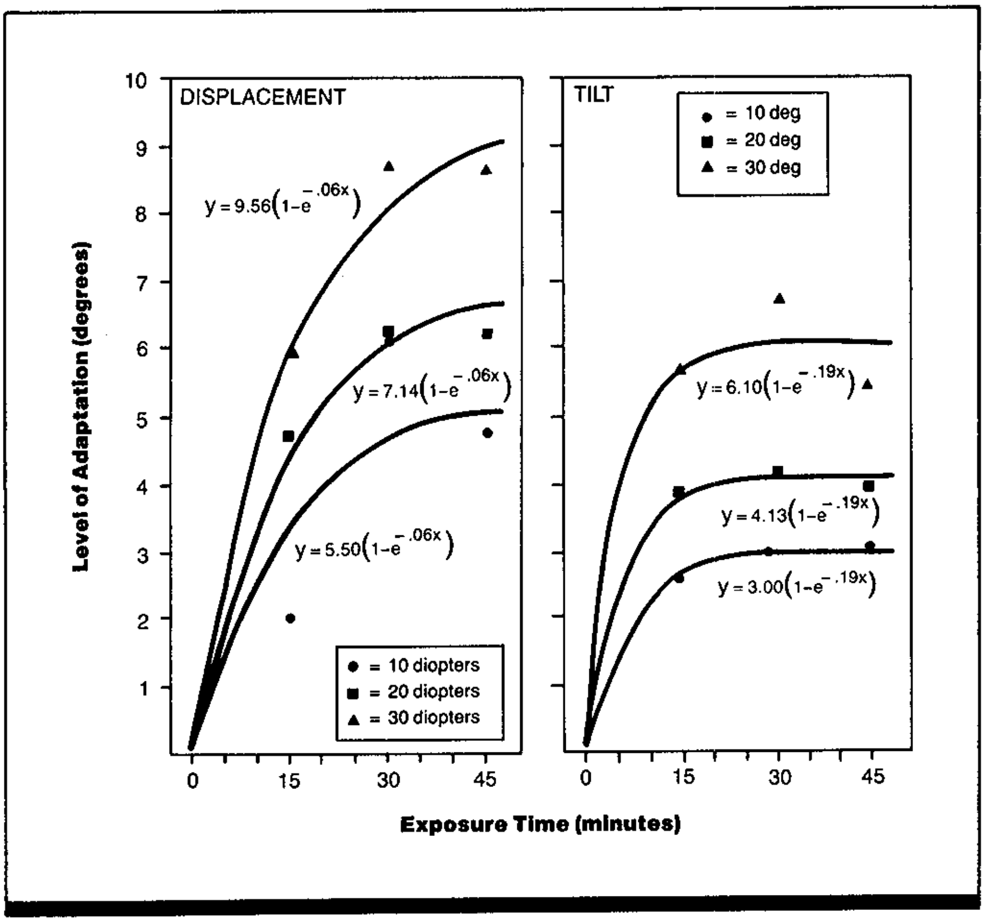

Figure 1. Magnitude of adaptation to tilt and adaptation to displacement as a function of exposure time (for exposed eye). (Adaptation is measured as the amount by which observers' postexposure judgments of verticality or straight ahead depart from the apparent vertical or straight ahead as measured before prisms were worn.) (From Ref. 3)

Key Terms

Altered visual direction; altered visual orientation; exposure duration; prismatic displacement; prismatic rotation; tilt adaptation; visual field displacement; visual field rotation

General Description

Adaptation to prism-induced lateral displacement of the visual field (**altered visual direction**) occurs more slowly than adaptation to optical tilt, but it asymptotes at a higher level than does tilt adaptation. Also, adaptation to displacement decays much more slowly than adaptation to tilt as the observer sits quietly in the dark after prism removal.

Methods

Test Conditions

Acquisition Study

- During tilt session, observer wore **Dove prisms**, positioned by headset over right eye, that tilted visual field by 10, 20, or 30 deg clockwise; during displacement session observer wore **Risley prisms** set in goggle frame over right eye that displaced visual field by 10, 20, or 30 diopters (5.7, 11.4, or 17.1 deg); left eye covered; two sessions with each transformation, each lasting 1.5 hr; 47 hr between displacements and tilt sessions
- Tilt condition test stimulus: 30.48 cm × 0.32 luminous line, 121.92 cm from observer; displacement condition test stimulus; row of three illuminated dots (0.79 × 0.16 cm), 121.92 cm from observer
- Observer moved about hallway while wearing prisms; body covered by black cloak and not visible; observers instructed not to look at hands or touch walls

Decay Study

- Test conditions as above, except observer exposed to only one tilt (30 deg clockwise) and one displacement (30 diopters rightward) condition

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

Acquisition Study

- Independent variables: tilt versus displacement, exposure time, tilt or displacement magnitude
- Dependent variable: level of adaptation, defined as the difference between mean pre- and post-adaptation verticality or straight-ahead settings, for each time interval during, and/or subsequent to, prism adaptation, determined separately for exposed and covered eye
- Observer's task: set luminous line to align with chin-forehead axis (tilt condition); set vertical row of three illuminated dots to appear straight ahead of nose in horizontal plane (displacement condition)
- Acquisition measurements taken before adaptation and 15, 30, and 45 min post-adaptation at each session; all measurements taken without prisms

Decay Study

- Decay measurements taken every 8 min post-adaptation (after prism removal), while observer sat in dark room
- 24 undergraduates (three groups of 8 each) for acquisition experiment; 16 undergraduates (two groups of 8 each) for decay experiment

Experimental Results

- Exposure time significantly affects displacement adaptation, but not tilt adaptation.
- The smoothed curves in Fig. 1 are negatively accelerated exponential growth functions of the form adaptation level $= a(1 - e^{-bt})$, where a is the estimated asymptote of adaptation and b estimates the rate at which adaptation approaches the asymptote as a function of exposure time t. Curves were fitted by the method of least squares.
- Tilt adaptation proceeds at a faster rate than displacement adaptation ($b = 0.19$ versus $b = 0.06$).
- Displacement adaptation asymptotes at a higher level than tilt adaptation (5.50, 7.14, and 9.56 deg for prism displacements of 10, 20, and 30 diopters [equivalent to 5.7, 11.4 and 17.1 deg, respectively] versus 3.00, 4.13, and 6.10 deg from prism tilts of 10, 20, and 30 deg).
- Magnitude of the optical distortion significantly affects the level of adaptation for both displacement and tilt.
- Curves in Fig. 2 are negatively accelerated exponential functions fitted by the method of least squares. For the decay of tilt, which has an asymptote greater than zero, the function has the form adaptation level $= ae^{-bt} + c$, where $a + c$ is the adaptation level at the beginning of the decay period (different for the exposed and unexposed eye), b estimates the rate of decay per unit of time t in either eye, and c is the asymptote for decay (different for the two eyes). Standard error of estimate was 0.10. For the decay of displacement, the function takes the form: adaptation level $= ae^{-bt}$.
- Decay of tilt adaptation occurs more quickly than decay of displacement adaptation.
- Adaptation to tilt appears to decline to an asymptotic value representing less than complete decay within 8 min after prism removal, whereas adaptation to displacement is still declining after 32 min.
- There is no significant difference between the eye exposed to prismatic distortion and the eye covered during prism exposure with regard to either the acquisition or decay of tilt adaptation or displacement adaptation.

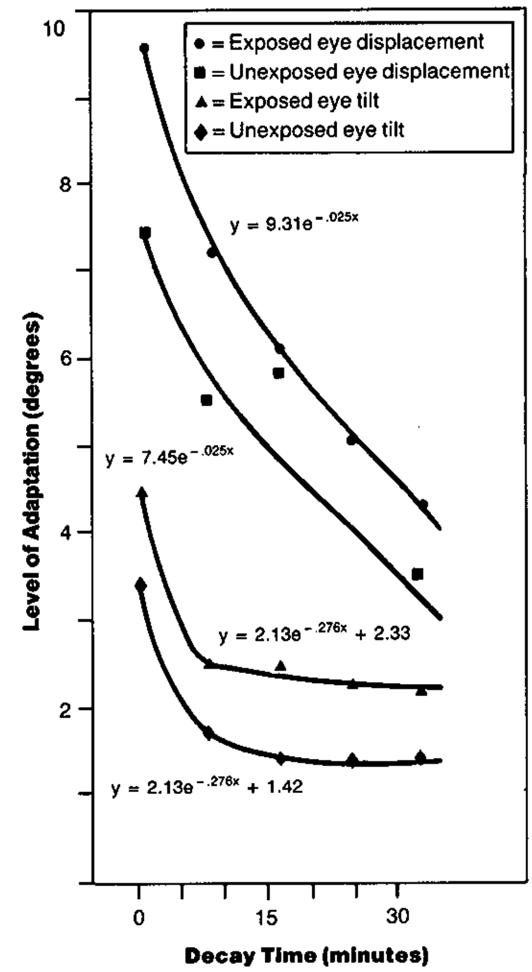

Figure 2. Magnitude of adaptation to tilt and adaptation to displacement as a function of time since removal of prisms for exposed and unexposed eye. (Adaptation measured as in Fig. 1.) (From Ref. 3)

Variability

Nine original observers failed to show at least 1 deg of adaptation to tilt or displacement after 45 min of exposure; these observers were replaced.

Repeatability/Comparison with Other Studies

Results are compatible with those of several other studies of tilt and displacement adaptation (Refs. 1, 4; CRefs. 5.1116, 5.1117). Reference 2 found almost complete adaptation to tilt when preselected fast-adapting observers were used.

Constraints

- Although decay of tilt adaptation appeared to level off at less than complete decay in the study reported here, complete recovery from adaptation after prism removal would be expected given sufficient postexposure time and/or reexposure to normal environment.
- Adaptation declines more rapidly after prism removal when observers are exposed to the normal (undistorted) visual scene than when they sit in the dark.
- A number of factors are known to influence adaptation to tilt and adaptation to displacement and should be considered

in applying these results under different conditions (CRefs. 5.1104, 5.1108, 5.1109, 5.1110, 5.1115).

- Even when prisms are not worn, viewing a physically tilted edge for a few minutes will lead to a small but reliable reduction in its perceived tilt, and an objectively vertical edge viewed immediately after will appear tilted slightly in the opposite direction from the first edge. The "configurational effect" can become confounded with adaptation to prism-induced tilt, although the latter effect is much stronger.
- Adaptation to prism displacement of the visual field varies greatly from individual to individual.
- Adaptation to visual tilt varies greatly from individual to individual.

Key References

1. Ebenholtz, S. (1966). Adaptation to a rotated visual field as a function of degree of optical tilt and exposure time. *Journal of Experimental Psychology, 72,* 629-634.

2. Mikaelian, H. H., & Held, R. (1964). Two types of adaptation to an optically-rotated field. *American Journal of Psychology, 77,* 257-263.

*3. Redding, G. M. (1973). Visual adaptation to tilt and displacement: Same or different processes? *Perception & Psychophysics, 14,* 193-200.

4. Redding, G. M. (1975). Decay of visual adaptation to tilt and displacement. *Perception & Psychophysics, 17,* 203-208.

Cross References

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

5.1109 Adaptation to prismatic displacement of the visual field: effect of response conditions;

5.1110 Adaptation to prismatic displacement of the visual field; cognitive/learning effects;

5.1115 Factors affecting adaptation to visual tilt;

5.1116 Adaptation to visual tilt: acquisition and decay;

5.1117 Adaptation to visual tilt: effect of rotation magnitude

Notes

5.1120 Factors Affecting Adaptation to Loss of Visual Position Constancy

Factor	Effect on Adaptation to Loss of Position Constancy	Source
Type of distorting device	Adaptation to loss of visual position constancy is only partial (9% of theoretical maximum) when wedge prisms are worn	Refs. 3, 6
	Adaptation is substantial or complete when reducing goggles or nonoptical devices are used	Refs. 2, 4, 5, 6
Head motion	Adaptation occurs only with active or passive head movements; no adaptation if head is stationary	Ref. 6
Exposure time	Adaptation increases as a negatively accelerated function of exposure time	Ref. 7
Magnitude of distortion	Adaptation increases as a direct function of the extent of distortion	Ref. 7
Concentrated pre-exposure viewing of normal relationship between head and optical motions	Subsequent adaptation is inhibited after this kind of pre-exposure	Ref. 7
Removal of distorting device	Adaptation decays rapidly and spontaneously after removal of the distorting device	Refs. 8, 9
Direction of optical motion in relation to head motion (normally, optical motion is opposite to head motion)	Adaptation is greater and more decay-resistant when optical motion is in the same direction as the head is moving (e.g., both moving to the right) than when they are in opposite directions (e.g., optical motion to the right, head motion to the left)	Ref. 10
Decay of adaptation to optical motion in the same or orthogonal direction as head motion	Adaptation to optical motion in the same direction as motion (e.g., both up-down) is subject to greater decay than when optical and head motions are in orthogonal directions (e.g., optical motion up-down, head motion right-left)	Ref. 9
Relation between optical motion and eye movements (eye motion, but no head motion during adaptation)	If optical motion is not linked to eye motion, there is no loss of visual position constancy and therefore no adaptation occurs: adaptation occurs when optical motion is linked to eye motion	Ref. 2

Key Terms

Illusory motion; motion sickness; visual position constancy; visual stability

General Description

Visual position constancy refers to the apparent stability of the visual scene during head and eye motion. That is, despite retinal image motion when head or eyes move, the world appears stationary. When an optical or other device disrupts the normal relationship between head (or eye) motion and the resultant retinal image motion, visual position constancy is lost, i.e., the world appears to move when the head (or eye) moves. After a while, observers adapt to this apparent motion and the visual scene again looks stationary. After removal of the distorting device, visual position constancy may again be lost temporarily until the observer recovers completely from the **adaptation**. In extreme cases, the loss of visual position constancy accompanying optical distortion (as well as the aftereffects when the distorting device is removed) may cause motion sickness. Most of the optical devices used to induce and test adaptation to visual rearrangement of space (e.g., displacing prisms, inverting and/or reversing mirrors or prisms) produce loss of visual position constancy.

The table lists a number of factors that affect adaptation to loss of visual position constancy, indicates the nature of the effect, and cites sources of more information.

Applications

Environments where viewing or display media cause distortions that disrupt the normal relationship between head and/or eye movements and retinal image movement (for example, underwater viewing or helmet-mounted displays).

Constraints

Interactions may occur among the various factors affecting adaptation to loss of visual position constancy, but these have generally not been studied.

Key References

1. Hay, J. C. (1974). Motor transformation learning. *Perception, 3,* 487-496.

2. Mack, A., Fendrich, R., & Pleune, J. (1978). Adaptation to an altered relation between retinal image displacements and saccadic eye movements. *Vision Research, 18,* 1321-1327.

3. Pick, H. L., Jr., & Hay, J. C. (1964). Adaptation to prismatic distortion. *Psychonomic Science, 1,* 199-200.

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7. Wallach, H., & Floor, L. (1970). On the relation of adaptation to field displacement during head movements to the constancy of visual direction. *Perception & Psychophysics, 8,* 95-98.

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5.1121 Adaptation to Distortions of Depth and Distance

Method of Inducing Distortion	Optical/Visual Effect	Adaptation Effect	Source
Telestereoscope	Changes effective interocular distance causing an increase (if distance decreases) or decrease (if distance increases) in perceived depth	Adaptation increases as a negatively accelerated function of exposure time (1-10 min), to 20% of theoretical maximum	Refs. 1, 6 CRef. 5.1102
		Attenuation in adaptation occurs if adaptation period preceded by period of undistorted exposure to target	Ref. 5
Right-angle prisms over both eyes so as to produce rotation of visual field in opposite directions in the two eyes	Apparent tilt in depth (either toward or away from observer) of an objectively upright line	Adaptation occurs after 20 min of unconstrained activity while wearing prisms	Ref. 4
Meridional-size lens over one eye (other eye uncovered)	Magnifies the visual image along the meridian perpendicular to its axis. If the lens is oriented vertically, the magnification of the horizontal dimension alters the disparity between the images of the two eyes, inducing a slant in depth of the fronto-parallel plane	After 1 hr of unconstrained exposure in an indoor environment, adaptation reaches 38% of the theoretical maximum	Refs. 2, 3 CRef. 5.909
Combination of spherical lens and wedge prisms	Lenses alter **accommodation** and prisms alter **convergence**; negative lenses and base-out prisms cause a decrease in perceived distance; positive lenses and base-in prisms, an increase	Significant adaptation obtained after as little as 15 min of visuomotor exposure (eye-hand tasks, walking, or head-turning during adaptation period)	Refs. 1, 2, 4, 5
Physical expansion or contraction of moving object	Change in perceived length of motion path	Adaptive changes in apparent distance with 20 min exposure	Ref. 3

Key Terms

Accommodation; convergence; depth perception; distance perception; geometric effect; horizontal retinal image disparity; induced effect; interocular distance; meridional-size lens; right-angle prisms; slant perception; spherical lens; telestereoscope; wedge prism

General Description

Some optical devices can distort the perceived distance of objects or the perceived depth between objects. Distortions of distance can also be produced by nonoptical means. Observers exposed to such distortions of depth or distance adapt to the changes after a relatively brief period ($\leq$1 hr), but **adaptation** generally falls short of the theoretical maximum. The table describes several means of inducing distortions of depth and distance, notes the adaptation effects, and cites sources of more information.

Applications

Underwater viewing through facemasks; viewing through optic media (e.g., helmet-mounted displays) that alter eye **accommodation, convergence**, effective interpupillary distance, or horizontal retinal image disparity.

Constraints

Distortions of perceived distance are almost always accompanied by distortions in perceived object size.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Epstein, W. (1968). Modification of the disparity-depth relationship as a result of exposure to conflicting cues. *American Journal of Psychology, 81*, 189-197.

2. Epstein. W., & Morgan, C. L. (1970). Adaptation to uniocular image magnification: Modification of the disparity-depth relationship. *American Journal of Psychology, 83*, 322-329.

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9. Wallach, H., & Karsh, E. B. (1963). Why the modification of stereoscopic depth perception is so rapid. *American Journal of Psychology, 76*, 413-420.

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Cross References

5.909 Binocular differences in image size and shape (aniseikonia);

5.1102 Visual effects of various optical devices

5.1122 Adaptation to Distortions of Size

Table 1. Adaptation to size distortion as measured by pre- and post-exposure matches of line length (in centimeters). (From Ref. 1)

	(1) Mean of pre-adaptation settings	(2) Mean of post-adaptation settings	(3) Difference between columns 1 & 2
Minifying mirror (Exp. 2)	29.24 (9.78)	25.96 (3.73)	−3.28
Minifying mirror, no movement (Exp. 3)	27.56 (6.02)	25.04 (2.34)	−2.52
Minifying mirror, short exposure (Exp. 4)	30.51 (6.50)	27.84 (1.80)	−2.67
Plane mirror (Exp. 1; control condition)	27.20 (8.13)	27.13 (3.18)	−0.07

Numbers in parentheses show ranges for means reported. Observers matched the length of a line to the length of a remembered standard before and after exposure to a minifying mirror. The level of adaptation to the size distortion introduced by the mirror is indicated by the difference between pre- and post-exposure matches (col. 3).

Key Terms

Magnification; minification; size perception

General Description

Objects viewed in a convex mirror initially appear smaller than they are. After 10 or 30 min of viewing, observers show adaptation to the size distortion and objects appear more nearly their true size.

Applications

Underwater viewing and other environments where there is distortion of object size.

Methods

Test Conditions

- Exp. 1 (control): Observer viewed scene in plane mirror; all other conditions same as for Exp. 2 below
- Exp. 2: Observer viewed scene in 30.48-cm (12-in.) diameter convex (minifying) mirror; observer's head inside large cardboard tube which restricted view to scene in mirror; in mirror, observer could see table top with various objects (pencil and paper, playing cards, checkerboard and checkers) as well as own hands, arms, head, and portions of trunk; visual images of objects located 60.96 cm from mirror were about 50% normal size; 30 min exposure period; during exposure, observer engaged successively for one-third of time in playing cards, playing checkers, and drawing pictures
- Exp. 3: Conditions same as for Exp. 2, except observer engaged in no activities; observer was not allowed to move visible portions of body during mirror exposure and sat quietly with chin held stationary
- Exp. 4: Conditions same as for Exp. 2, except exposure duration was 10 min
- For all experiments, a baseline was established before mirror exposure by presenting a 30.48-cm line with room lights on; in the dark, observer matched the length from memory with a luminous line; 8 trials given; after mirror exposure with mirror removed, observer made two more settings of line length from memory

Experimental Procedure

- Independent variables: type of mirror (plane or convex), movement or no movement, length of exposure
- Dependent variable: level of adaptation, defined as the difference between the mean pre- and post-adaptation settings of line length
- Observer's task: in the dark, adjust a luminous line to appear equal in length to line seen previously in light
- 9 observers in Exp. 1; 15 observers in Exp. 2; 10 observers in Exp. 3; 10 observers in Exp. 4; all were high school students aged 16-18 yr

Experimental Results

- After viewing a visual scene in a convex mirror which produces minification of visual objects, observers adapt to the size change; observers use a shorter line length to match a remembered line after mirror exposure than before exposure, suggesting that the object size associated with a given visual angle on the retina (at a specified distance) has changed. Observed adaptation is about 23% of the theoretical maximum (i.e., adaptation falls short of total compensation for the size reduction).
- Adaptation occurs regardless of whether the observer moves or remains motionless during exposure to the minifying mirror.
- Adaptation occurs with short (10 min) as well as long (30 min) exposure periods.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Studies of magnification in underwater environments indicate that some adaptation also occurs to this distortion (Ref. 2; CRef. 5.1125).

Constraints

- Changes in apparent object size are frequently accompanied by changes in apparent distance. Care was taken in the study reported here to ensure that perceived distance was not altered.

Key References

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Cross References

5.1121 Adaptation of distortions of depth and distance;

5.1123 Factors affecting adaptation to visual distortions of form;

5.1124 Effect of underwater environments on perception;

5.1125 Underwater visual adaptation: effect of experience

5.1123 Factors Affecting Adaptation to Visual Distortions of Form

Key Terms

Figural aftereffects; form perception; prismatic curvature

General Description

One of the visual effects of viewing the world through wedge prisms is apparent curving of straight lines or edges (Fig. 1). When an observer wears prisms for awhile, the apparent curving diminishes. When the prisms are removed, straight lines appear curved in the opposite direction. These results indicate **adaptation** to this distortion of form. Wedge prisms also distort closed figures, such as squares. When viewed through a wedge prism, a square appears trapezoidal and its vertical edges look curved (CRef. 5.1102, Fig. 1). Lateral head movements will cause the square to expand or contract, and up-down head movements will produce seesaw or rocking motion of the form. Observers are able to adapt to all of these distortions. The table lists some characteristics of and factors influencing adaptation to form distortion, describes the effects, and cites sources of more information.

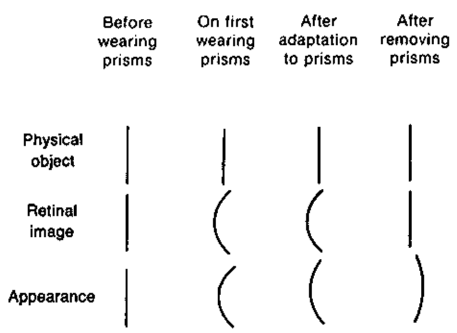

Figure 1. The perception of a straight line before, during, and after adaptation to curvature. (From Ref. 2)

Applications

• Environments where viewing or display media (such as windscreens, goggles, heads-up display surfaces) may introduce optical distortion of the visual scene; underwater viewing through facemasks; optical effects of corrective glasses.

Constraints

• Much smaller curvatures are induced when prisms are attached to contact lenses than when prisms are mounted in goggles. The greater adaptation observed with contact lens prisms may be partially due to the lesser distortion to which observer must adapt.

• Even when prisms are not worn, viewing a physically curved edge for a few minutes will lead to a small, but reliable, reduction in its perceived curvature, and an objectively straight edge viewed immediately after will appear curved slightly in the opposite direction. This "configurational effect" can become confounded with adaptation to prism-induced curvature, although the latter effect is stronger.

• Adaptation to the form distortion caused by wedge prisms is likely to be influenced by many of the same factors that affect adaptation to the visual field displacement caused by wedge prisms (CRefs. 5.1104, 5.110).

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Cross References

5.1102 Visual effects of various optical devices;

5.1104 Adaptation to prismatic displacement of the visual field: effect of exposure conditions;

5.1110 Adaptation to prismatic displacement of the visual field: cognitive/learning effects;

6.317 Figural aftereffects;

Handbook of perception and human performance, Ch. 24, Sect. 6.1

Factor Studied	Effect on Adaptation	Source
Prism-induced distortion of edges or lines		
Exposure time and adaptation rate	Adaptation is a negatively accelerated function of exposure time	Refs. 3, 4, 6, 9
	Adaptation is more rapid when prisms are attached to contact lenses or controlled by eyes than when mounted in goggles	Ref. 1
Magnitude of adaptation	Adaptation reaches ~30% of theoretical maximum (i.e., objective amount of curvature) when prism goggles worn for several weeks	Ref. 7
	Adaptation reaches ~40% of theoretical maximum when contact lens prisms worn for relatively short period	Ref. 1
Body movement versus no body movement during prism exposure	Movement is necessary for adaptation	Ref. 11
Active versus passive body movement during prism exposure	Active movement is not required, but it sometimes results in greater and more rapid adaptation	Refs. 1, 5, 10
Prism-induced distortion of closed figures		
Magnitude of adaptation	Adaptation reaches 51% of theoretical maximum after several days of prism exposure	Ref. 8

5.1124 Effect of Underwater Environments on Perception

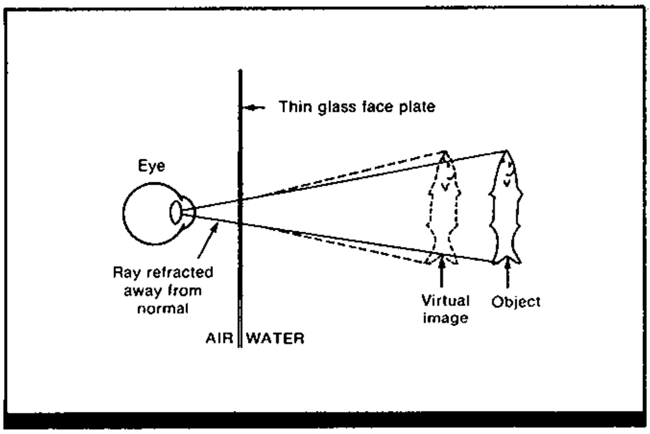

Figure 1. The optical effect of viewing an object underwater through a face mask. (From Ref. 5)

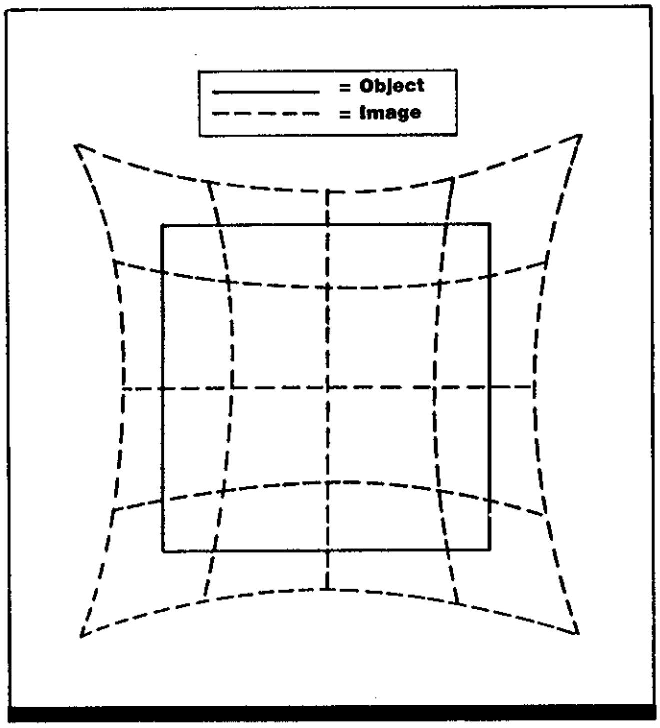

Figure 2. The "pincushion effect": appearance of square when viewed head-on underwater through a face mask. Sides appear bowed toward, and center away from, observer. (From Ref. 11)

Key Terms

Color appearance; depth perception; distance perception; form perception; kinesthesia; motion perception; pincushion effect; proprioception; size perception; stereoacuity; underwater; visual position constancy; visual stability; weight lifting

General Description

When an object is viewed underwater through a face mask, many aspects of its appearance are drastically altered. Water transmits less total radiant energy than air; at 1-m down, 81% of incident energy is transmitted, and at 10-m down, only 37% is transmitted. Scattering of the energy by particles in the water between the eye and the object causes a blurring of the outline and a decrease in contrast between the object and its surround. The result is reduced visibility and distortion of perceived distance. Absorption of light energy by the water varies with water type; different wavelengths are selectively absorbed depending on the clarity of the water. Consequently, color perception is disturbed.

Light waves are refracted as they pass from water to air. This causes the virtual image of an underwater object viewed through a face mask to be located at three-quarters of its actual distance (Fig. 1). Due to this, the image is magnified and the object is perceived as either closer or larger than it actually is.

At short distances, and in clear water, the refraction of light waves, by reducing optical distance, causes real distance to be underestimated. However, at distances >1.2 m, distance is overestimated. This effect is probably due to loss of contrast and the typically low level of visual stimulation underwater.

Light rays at the edges of the visual field must strike the faceplate of a diving mask more obliquely than central rays in order to pass through the lens of the eye. Because of this, peripheral rays are refracted more than central ones. This causes them to be located closer to the observer than more central rays. The result is what is known as the "pincushion effect": a square appears bowed inward, with its interior apparently displaced away from the observer (Fig. 2). Motion perception also suffers under water. The apparent speed of moving objects is distorted. There is also some lack of **visual position constancy**, i.e., a lack of stability of the visual world during head and eye movements.

While visual distortions generally have the greatest im-

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pact in diving, virtually all the senses are altered by an underwater environment. For example, gravitational and kinesthetic cues are distorted and localization of sound is impaired. The table details the effect of an underwater environment on various aspects of perception and cites sources of additional information. With sufficient exposure, divers can adapt to most of the perceptual distortions caused by the underwater environment (CRefs. 5.1125, 5.1126).

Constraints

- Adaptation to an underwater environment varies among individuals.

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Cross References

5.1120 Factors affecting adaptation to loss of visual position constancy;

5.1122 Adaptation to distortions of size;

5.1123 Factors affecting adaptation to visual distortions of form;

5.1125 Underwater visual adaptation: effect of experience;

5.1126 Adaptation after prolonged exposure to an underwater environment;

5.1127 Adaptation to rearrangement of auditory space

Type of Perception	Effect of Underwater Environment	Source
Form	"Pincushion effect": a square appears bowed inward, with its interior apparently displaced away from observer; lines also appear bent away from observer (see Fig. 1)	Ref. 6; CRef. 5.1123
Color	Perception of color is attenuated; under natural light, red, yellow, and orange are most visible in turbid water; green, yellow, and orange are most visible in somewhat cloudy water; and green and blue are most visible, red least visible, in clear water A maximum of three colors can be reliably distinguished for color coding in all types of water; white is least good for color coding in all types of water	Ref. 3
Size	Objects appear enlarged at far and near distances	Refs. 3,8; CRef. 5.1122
Distance	Close distances are underestimated; far distances (>1.2 m) are overestimated	Refs. 3, 4
Depth	Stereoacuity is lower, and decreases as water turbidity increases	Ref. 3
Visual stability	Loss of visual position constancy due to overestimation of image movement correlated with head and eye movement	Ref. 1; CRef. 5.1120
Motion	Overestimation of motion across line of sight; underestimation of motion along line of sight at close distances; overestimation of motion along line of sight beyond ~2 m	Ref. 7
Sound	Sound reaches the ear more quickly than in air but is displaced and more difficult to localize	Ref. 1; CRef. 5.1127
Gravitational cues, kinesthesis, proprioception	Distorted; decrease in apparent weight of objects lifted underwater	Refs. 7, 10

5.1125 Underwater Visual Adaptation: Effect of Experience

Table 1. Underwater distortion of size and distance as a function of diving experience.

Type of Distortion	Underwater Task	Observers' Experience	Number of Observers	Amount of Initial Distortion	Source
Displacement in depth	Observers required to reach under table to corresponding location of object on table; theoretical maximum distortion is 5.60 cm	Never used snorkel, mask	42	5.59 cm	Ref. 1
		Occasionally used snorkel	69	5.00 cm	
		Frequently used snorkel	20	3.30 cm	
		Scuba class: no scuba experience	14	3.23 cm	
		Scuba class: some scuba experience	12	2.64 cm	
		Navy divers	8	2.03 cm	
Size enlargement	Observers required to adjust size of a variable line to 30.48 cm [12 in.]; all observations made underwater, except for controls, who made observations in air	Control	14	0.23 cm	Ref. 4
		Novice divers	11	6.15 cm	
		Experienced divers	11	4.24 cm	
Curvature in depth	Observers required to set rod so that it just noticeably bent toward them and away from them; mean was taken as apparently straight position; maximum distortion is −16 mm	Novice divers	15	−15.58 mm	Ref. 3
		Experienced divers	16	−11.22 mm	

Key Terms

Curvature; distance vision; perceptual adaptation; size perception; underwater

General Description

Upon entering the water, experienced divers (1-15 years of diving) show a certain amount of instantaneous or very rapid **adaptation** to the distortions of perceived size, distance, and curvature that occur with underwater viewing through face masks. That is, experienced divers initially judge object size, curvature, and distance more accurately than do novice divers (students with <8 hours experience underwater) wearing face masks.

Constraints

- The greater accuracy of experienced divers in judging size, distance, and curvature may be due to conscious or unconscious correction for the distortion on the part of the divers as well as to true adaptation.
- Experienced divers may also show greater long-term adaptation to underwater visual distortions than inexperienced divers (CRef. 5.1126).
- Many factors in addition to diving experience influence adaptation to underwater visual distortions (CRef. 5.1126).
- Adaptation to an underwater environment varies from individual to individual.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.1122 Adaptation to distortions of size;

5.1124 Effect of underwater environments on perception;

5.1126 Adaptation after prolonged exposure to an underwater environment

5.1126 Adaptation After Prolonged Exposure to an Underwater Environment

Type of Distortion	Influencing Factors	Effect on Adaptation	Source
Size-distance distortion	Type of underwater activity	Greater adaptation with underwater games than with free swim or practice placing test objects (after 15 min underwater)	Ref. 2; CRef. 5.1122
	Spaced versus **massed practice**	Spaced practice (three 5-min exposure periods) facilitates adaptation	Ref. 2
	Terminal exposure (brief, discrete trials) versus **concurrent** (continuous) **exposure**	Terminal exposure yields greater adaptation	Ref. 3
Size distortion of near objects	Underwater experience	Experienced divers show greater adaptation—almost no adaptation for novices (after 20-40 min of handling familiar objects underwater); aftereffects decay very rapidly (after one or two trials) for all divers	Ref. 5; CRef. 5.1122
Apparent curvature	Underwater experience	All divers adapted to curvature (about 25% of theoretical maximum after 30 min underwater); initial distortion smaller for experienced divers than for novices	Ref. 4; CRefs. 5.1123, 5.1125
	Stationary observation versus active movement	Equal adaptation under each condition	Ref. 8
Illusory motion of the visual field (loss of **visual position constancy**)	Head rotations and eye-hand movements	Marginal adaptation (after 15 min underwater)	Ref. 1; CRef. 5.1120
Distortions of speed and across line of sight	Motion along versus across line of sight	Significant adaptation to speed distortion in both motion directions (after free swim and pegboard game for 10 min)	Ref. 6
Distortion of apparent object weight		Divers adapt to decrease in apparent weight to objects lifted underwater	Ref. 7

Key Terms

Apparent speed; curvature; distance vision; perceptual adaptation; size perception; training; underwater; visual position constancy; weight lifting

General Description

When an observer is underwater wearing a face mask, the distance, size, curvature, and motion of objects are initially misperceived. After some time, the observer adapts and perception becomes more accurate. The speed and magnitude of **adaptation** depend upon, among other things, the amount of previous underwater experience and the type of activity in which the observer engages while underwater. For several types of underwater perceptual distortion, the table lists factors affecting adaptation to the distortion, describes the nature of the effect, and cites sources of more information.

Constraints

- Factors influencing adaptation to underwater distortions may interact, but such interactions generally have not been studied.
- Adaptation to an underwater environment varies from individual to individual.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.1120 Factors affecting adaptation to loss of visual position constancy;

5.1122 Adaptation to distortions of size;

5.1123 Factors affecting adaptation to visual distortions of form;

5.1124 Effect of underwater environments on perception;

5.1125 Underwater visual adaptation: effect of experience

5.1127 Adaptation to Rearrangement of Auditory Space

Type of Rearrangement	Perceptual Effects	Source
Auditory transposition due to functional right-left reversal of the two ears (observer wears pseudo-phones that collect sound on one side of head and feed it to the opposite ear)	Absence of auditory aftereffects indicates no adaptation	Refs. 7, 8
Auditory displacement (observer wears pseudo-phones that rotate sound source forward for one ear and backward for the other)	After 7 hr exposure to a lateral auditory displacement of 22 deg, there is a 10 deg adaptive shift in localization of the sound source (observer's movements unconstrained during adaptation)	Ref. 3
(a) lateral versus radial body movement	Adaptation occurs with motion toward or away from sound source, but not with lateral motion	Ref. 3
(b) **active** versus **passive movement** of the body	Active movement not necessary for adaptation; indirect evidence that it facilitates adaptation	Refs. 2, 4
Auditory-visual discrepancy due to lateral displacement of the visual field (observer wears displacing prisms)	Sounds initially mislocalized in direction of visual displacement; this effect represents intersensory bias or **visual capture**, not adaptation; with continued exposure to displacing prisms, sounds again come to be localized at their objective positions; there are no aftereffects when prisms are removed	Ref. 6; CRef. 5.1113
Auditory-visual discrepancy due to right-left reversal of the visual field (observer wears reversing goggles)	Sound initially heard on correct side and related visual stimulus seen on other; with continued exposure, sound comes to appear to be located at its visible source	Refs. 1, 5; CRef. 5.1007

Key Terms

Auditory adaptation; auditory displacement; auditory space transposition; intersensory bias; sound localization; visual capture

General Description

When auditory space is artificially reversed (i.e., the sound from a source on one side of the head is fed into the opposite ear), observers show no perceptual **adaptation** to the rearrangement. However, when the sound from a source is rotated by a moderate amount relative to its objective position, observers do adapt to the distortion: sounds come to be correctly localized while the sound-displacing device is in place, and sounds appear displaced in a direction opposite to the initial distortion (negative aftereffect) when the device is removed. When optical devices (such as prisms) are worn which alter visual direction and therefore cause a discrepancy between vision and hearing, sounds are usually mislocalized so that they appear to emanate from the apparent visual location of the sound source. The accompanying table lists several types of perceptual rearrangement, describes their effects on auditory localization, and cites sources of more information.

Applications

Environments such as underwater in which the location of sound sources is distorted.

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Cross References

2.801 Sound localization;

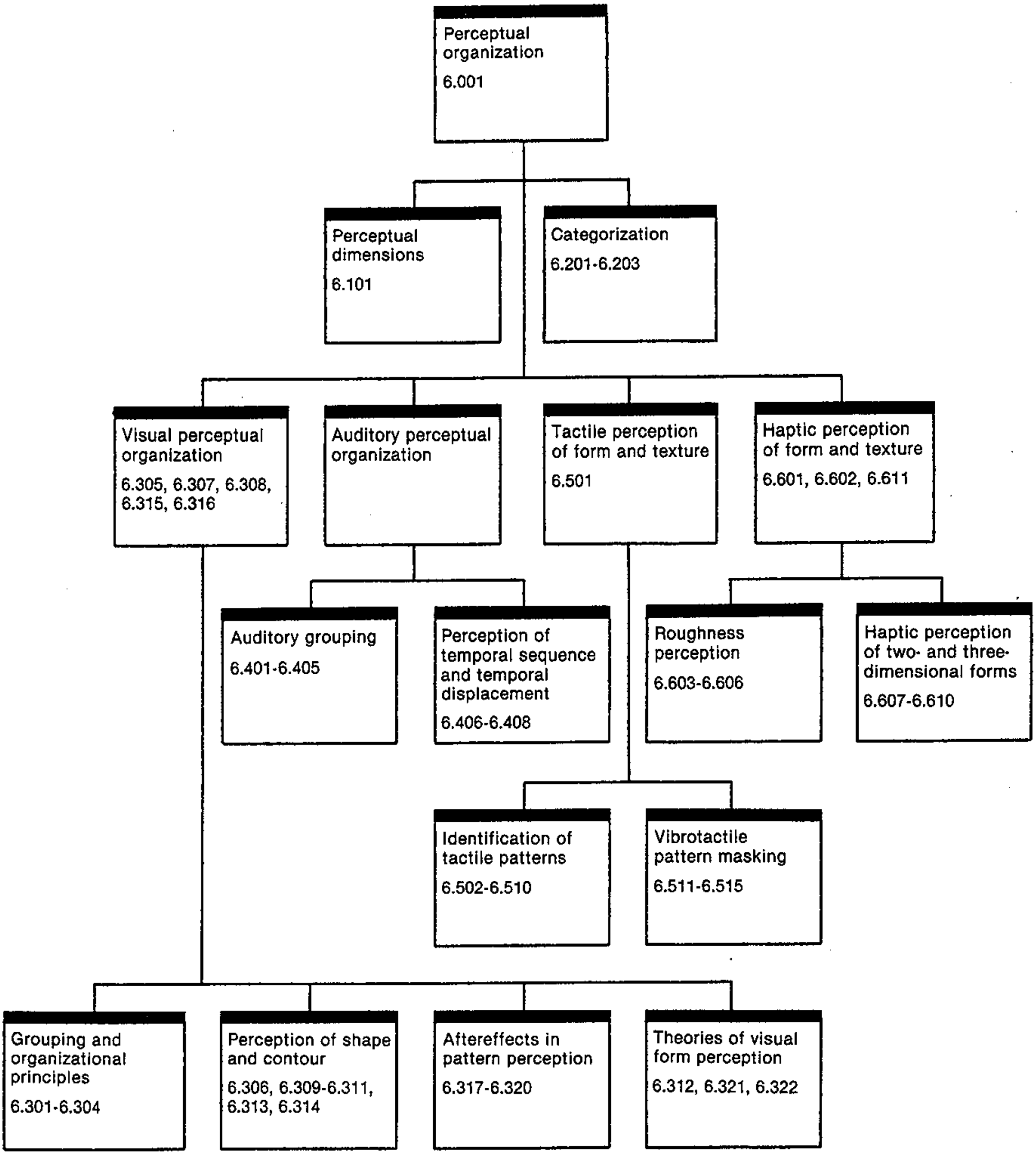
2.815 Effect of visual and proprioceptive cues on localization;

2.816 Localization in noise;

5.1007 Spatial localization in the presence of intersensory conflict;

5.1113 Prismatic displacement of the visual field: visual and auditory judgments of straight ahead

Organization of Entries



Contents

Section 6.6 Haptic Perception of Form and Texture

Key Terms

Glossary

Absolute threshold. The amount of stimulus energy necessary to just detect the stimulus. Usually taken as the value associated with some specified probability of stimulus detection (typically 0.50 or 0.75).

Adaptation. (1) A change in the sensitivity of a sensory organ to adjust to the intensity or quality of stimulation prevailing at a given time (also called **sensory adaptation**); adaptation may occur as an increase in sensitivity (as in dark adaptation of the retina) or as a decrease in sensitivity with continued exposure to a constant stimulus. (2) A semipermanent change in perception or perceptual-motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors induced by this discrepancy (also called **perceptual adaptation**). (CRef. 5.1101)

Afferent. Conveying neural impulses toward the central nervous system, as a sensory neuron; sensory, rather than motor.

Binaural. Pertaining to, affecting, or impinging upon both ears; sometimes used to imply identity of the signals to the two ears. (*See also* **diotic, dichotic.**)

Closure. Perception of a series of pattern elements as a single large unit rather than a number of apparently unrelated parts. (CRef. 6.301)

Cutaneous. Pertaining to the skin or to receptors in the skin, or to sensation mediated by receptors in the skin.

Decibel. The standard unit used to express the ratio of the power levels or pressure levels of two acoustic signals. For power, one decibel = 10 log. P_1/P_2 (where P_1 and P_2 are the powers of the first and second signals, respectively). For pressure, one decibel = 20 log p_1/p_2 (where p_1 and p_2 are the sound pressure levels of the two signals). In most applications, the power or pressure of a signal is expressed relative to a reference value of $P_2 = 10^{-12}$ W/m^2 for power and $p_2 = 20$ μPa (or 0.0002 dynes/cm^2) for pressure.

Dependent variable. The response to a stimulus presentation measured by the investigation to assess the effect of an experimental treatment or independent variable in an experiment; for example, the investigator might measure the absolute visual threshold (dependent variable) for light targets of different diameters to assess the effects of target size (independent variable). (*Compare* **independent variable.**)

Dichotic. Pertaining to listening conditions in which the sound stimulus to the left and right ears is not identical but differs with respect to some property (such as frequency or phase).

Difference threshold. The least amount by which two stimuli must differ along some dimension to be judged as nonidentical. Usually taken as the difference value associated with some specified probability of detecting a difference (typically 0.50 or 0.75).

Diotic. Pertaining to listening conditions in which the sound stimulus to both ears is identical.

Efferent. Conveying neural impulses away from the central nervous system, as a motor neuron serving a muscle or gland; motor, rather than sensory.

Factorial design. An experimental design in which every level or state of each independent variable is presented in combination with every level or state of every other independent variable.

Independent variable. The aspect of a stimulus or experimental environment that is varied systematically by the investigator in order to determine its effect on some other variable (i.e., the subject's response). For example, the investigator might systematically alter the diameter of a target light in order to assess the effect of target size (independent variable) on the observer's absolute visual threshold (dependent variable). (*Compare* **dependent variable.**)

Interstimulus-onset interval. The time between the onset of one stimulus and the onset of a second stimulus. Also called **stimulus-onset interval.**

Kinesthesia. The sense of movement and position of the limbs or other body parts, arising from stimulation of receptors in joints, muscles, and tendons.

Lateralization. Localization of a sound presented (usually dichotically) via earphones in terms of its apparent spatial position along an imaginary line extending from the right to the left ear.

Mask. *See* **masking.**

Masking. A decrease in the detectability of one stimulus due to the presence of a second stimulus (the **mask**) which occurs simultaneously with or close in time to the first stimulus.

Method of adjustment. A psychophysical method of determining a threshold in which the subject (or the experimenter) adjusts the value of the stimulus until it just meets some preset criterion (e.g., just appears detectable) or until it is apparently equal to a standard stimulus.

Method of constant stimuli. A psychophysical method of determining a threshold in which the subject is presented with several fixed, discrete values of the stimulus and makes a judgment about the presence or absence of the stimulus or indicates its relation to a standard stimulus (e.g., brighter, dimmer).

Method of limits. A psychophysical method of determining a threshold in which the experimenter varies a stimulus in an ascending or descending series of small steps and the observer reports whether the stimulus is detectable or not or indicates its relation to a standard stimulus.

Monaural. Pertaining to, affecting, or impinging upon only one ear.

Optacon. From OPtical-to-TActile CONVerter; a reading aid for the blind that converts printed or optical patterns (such as letters) into a corresponding tactile pattern presented to the skin of the index finger pad by means of an array of 144 small vibrators covering an area of approximately 2.7 × 1.2 cm.

Randomized design. An experimental design in which the various levels of the independent variable are presented in random order within a given block of trials or experimental session.

Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).

Sound pressure level. The amount (in decibels) by which the level of a sound exceeds the reference level of 20 μPa (or 0.0002 dynes/cm^2).

Standard deviation. Square root of the average squared deviation from the mean of the observations in a given sample. It is a measure of the dispersion of scores or observations in the sample.

Standard error of the mean. The standard deviation of the sampling distribution of the mean; mathematically, the standard deviation of the given data sample divided by the square root of one less than the number of observations. It describes the variability of the mean over repeated sampling.

Tachistoscope. An apparatus for presenting visual material for a very brief exposure time; the simplest type uses a falling screen or shutter, with an apperture that momentarily reveals the visual stimulus.

Tactile. Of or relating to tactual perception (touch) mediated by the cutaneous (skin) sense.

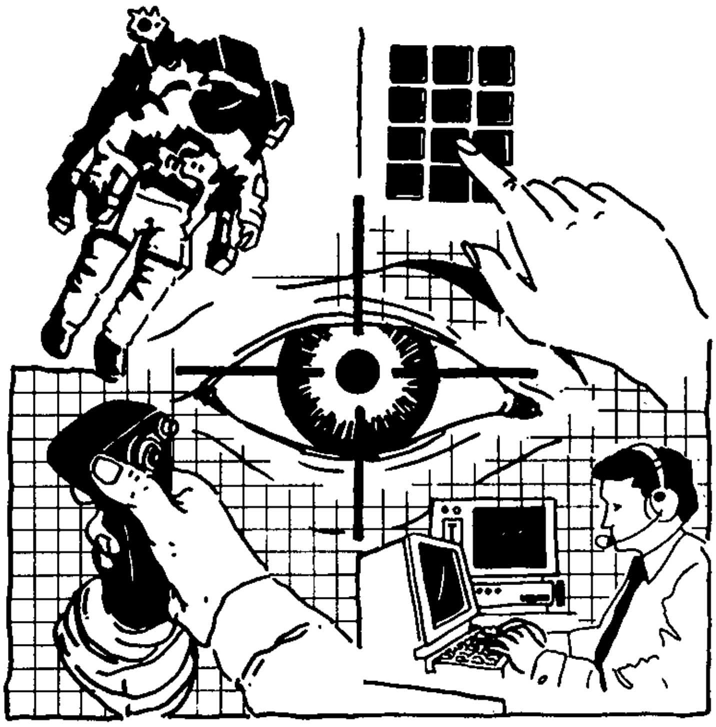
Tactual. Of or relating to the sense of touch, as mediated by the cutaneous (skin) sense and/or kinesthesia.

Threshold. A statistically determined boundary value along a given stimulus dimension which separates the stimuli eliciting one response from the stimuli eliciting a different response or no response (e.g., that point associated with a transition from "not detectable" to "detectable" or from "greater than" to "equal to" or "less than"). (CRef. 1.657) (*See also* **absolute threshold, difference threshold.**)

T-test. A statistical test used to compare the mean of a given sample with the mean of the population from which the sample is drawn or with the mean of a second sample in order to determine the significance of an expermental effect (i.e., the probability that the results observed were due to the experimental treatment rather than to chance). Also known as **Student's t-test.**

Two-alternative forced-choice paradigm. An experimental procedure in which the subject is presented on each trial with one of two alternative stimuli and must indicate which stimulus occurred; a response must be made on each trial even if the subject must guess. Commonly referred to as a "criterion-free" method of determining sensitivity.

Section 6.0 Perceptual Organization



6.001 Perceptual Organization

Key Terms

Connectedness; figure-ground segregation; form perception; Gestalt principles; grouping; multistability; Necker cube; part-whole relations; perceptual coupling; proximity; similarity principle

General Description

The information about our surroundings that is transmitted by our sensory receptors is integrated by the nervous system to generate our perception of the world. Perceptual organization is the process by which we apprehend particular relationships among potentially separate stimulus elements (e.g., parts, features, dimensions); these organizing mechanisms are not yet well understood. Theories of perceptual organization must explain four classes of phenomena: perceptual coupling, grouping or part-whole relationships, figure-ground organization, and multistability.

Perceptual Coupling

Perception of an object is guided by its shape and orientation. But how can the true shape of an object be determined until its orientation is known, and how can its orientation be determined until its shape is known? The perceptual system solves this dilemma by coupling our perceptions of orientation and shape (as well as size and distance, luminance and lightness, etc.). If the shape in Fig. 1a is seen as a circle, its perceived orientation will be different than if it is seen as an ellipse. Theories of perceptual organization must explain how the perceptual system achieves these couplings.

Grouping and Part-Whole Relationships

Grouping and part-whole relationships attempt to explain the perception of complex stimuli such as faces. The whole (face) is defined by its parts or features (eyes, nose, mouth) and the arrangement of these parts. Some theories of perceptual organization hold that subsets of parts are grouped, sometimes at several hierarchical levels, to facilitate perception of the configuration as a whole. Classic Gestalt principles of perceptual grouping include proximity, similarity, closure, connectedness (good continuation), and symmetry (Fig. 3) (CRef. 6.301).

Figure-Ground Segregation

Theories of perceptual organization must also explain how figure-ground segregation is achieved in perception, that is, how and why one part of a scene or pattern is perceived as an object and another part as background. The ambiguous object in Fig. 4 may be perceived as a white triangle atop a black square that lies on top of a white rectangle (the paper); or it can be viewed as a black square with a triangular hole cut out of its center, allowing the white background of the page to show through. In the first case, the white triangle is perceived as a figure lying atop a black square, which serves as the ground. In the second case, the black square is seen as the figure, and both the white rectangle and white triangular region are viewed as part of the same continuous ground beneath the figure. (Other depth organizations are also possible, as shown in the figure.)

(a)

(b)

Figure 1. The coupling of perceived shape and perceived slant (orientation). The isolated ellipse in (a) is also shown in a scenic context rich with depth cues (b). Because of depth cues and familiarity with the objects likely to occur in the scene, the elliptical shape is perceived in (b) as a round hoop oriented at an angle to the picture plane. (From R. L. Gregory, *Eye and brain: The psychology of seeing* [2nd ed.], McGraw-Hill, 1972. Reproduced with permission.)

Multistability

Theories of perceptual organization must also account for why some stimuli are multistable, alternating between two or more distinct organizations, and why others are not. The Necker cube (Fig. 2) can be perceived with at least three organizations: as a two-dimensional design or outline of a cube drawn on paper (Fig. 2a), as a wire (outline) cube seen from above (Fig. 2b), or as a wire cube viewed from below (Fig. 2c). Most observers report that the Necker cube tends to spontaneously change its organization from the perception in Fig. 2b to that of Fig. 2c. Multistability indicates the existence of processes that are attempting to produce a single, stable organization of the stimulus. In the presence of conflicting or inadequate cues, the perceiver is attempting to discern the nature of the stimulus object or situation.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Gregory, R. L. (1972). *Eye and brain: The psychology of seeing.* (2nd ed.). New York: World University Library/McGraw Hill.

2. Miller, G. A. (1962). *Psychology: The science of mental life.* New York: Harper & Row.

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Cross References

6.301 Principles of gestalt grouping and figure-ground organization;

6.306 Reversible or multistable figures;

6.309 Perceived shape: effect of target orientation;

6.310 Perceived shape of partially hidden objects;

Handbook of perception and human performance, Ch. 33, Sects. 1.1, 1.2, 1.3

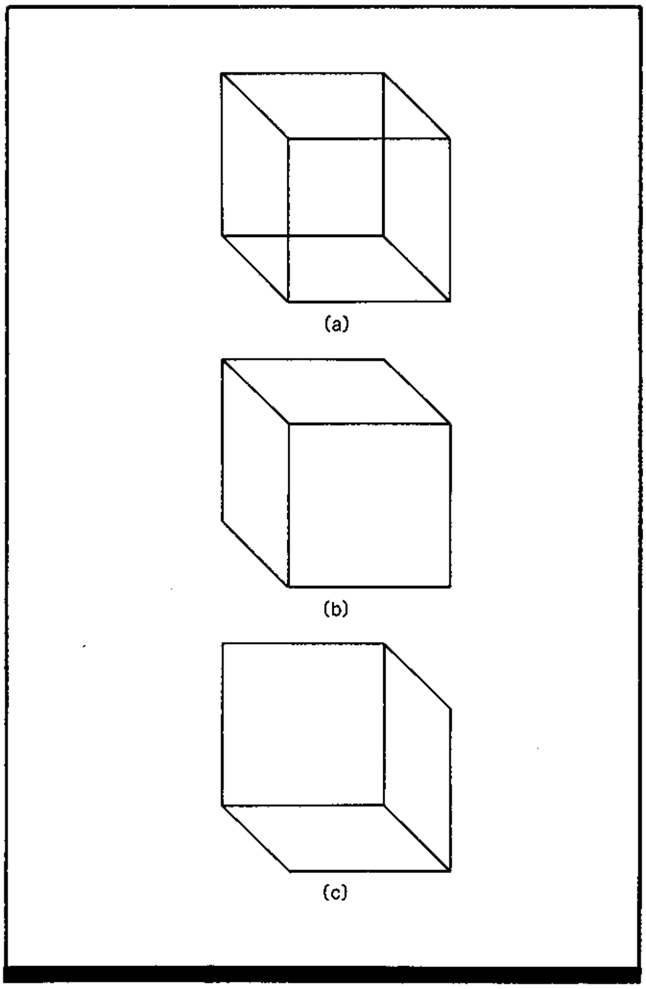

Figure 2. Three views of a cube. (a) The Necker Cube, a perspective drawing of a wire (or outline) cube. It is usually perceived in either of the two orientations shown unambiguously in (b) and (c) with solid cubes. The orientation of the cube in (a) tends to change spontaneously for the observer, a phenomenon known as multistability. (From Ref. 3)

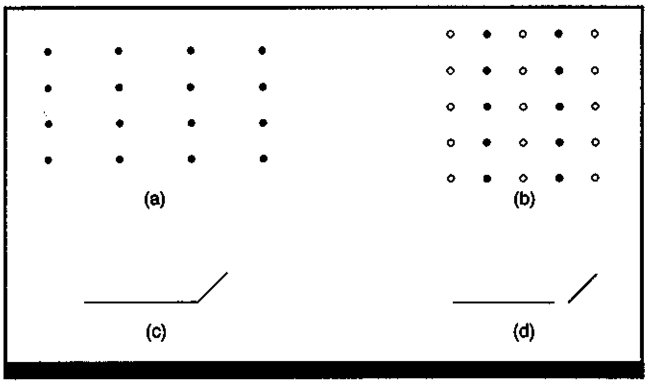

Figure 3. Illustration of three Gestalt principles of grouping. (a) Grouping by proximity. Other things being equal, elements that are nearest to one another will tend to be grouped together. Thus, the dots tend to group into columns rather than rows. (b) Grouping by similarity. Other things being equal, elements that are similar will tend to be grouped together. Hence, the pattern tends to group into columns of identical filled or open dots rather than rows of alternating dots. Not all kinds of similarity yield grouping, however. (c) and (d) Grouping by connectedness. Elements that connect, with smooth contours, form a stronger unit (c) than would be expected based on proximity alone (d). (From *Handbook of perception and human performance*)

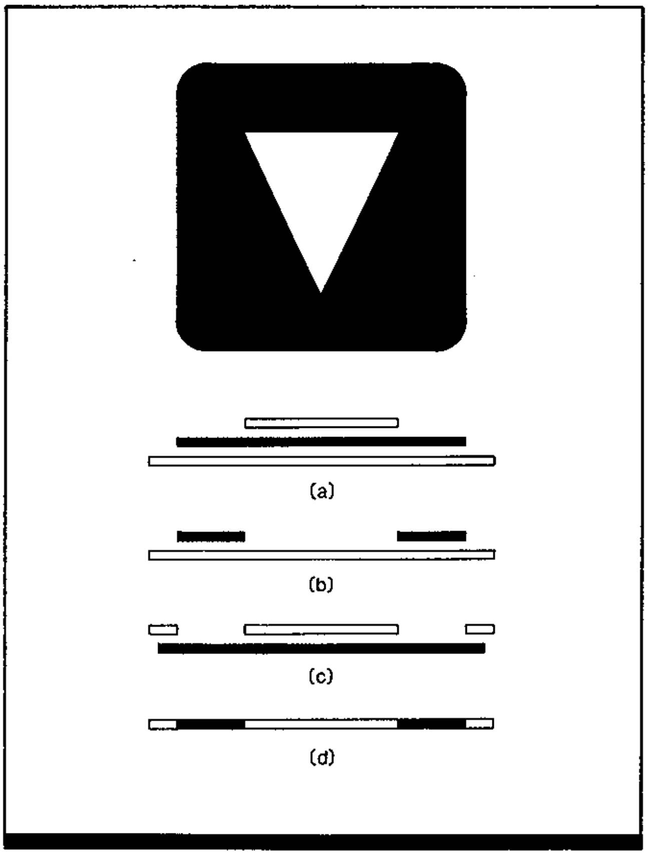

Figure 4. A multistable figure-ground demonstration. The pattern at the top can be perceived in several different depthful organizations, as indicated in the side views shown below. All four of these interpretations are reasonable and correct. The fact that the interpretation in (a) is the one most observers prefer must be explained by the laws of figure-ground organization. (From Ref. 2)

6.101 Classification of Major Perceptual Dimensions

Table 1. Systems for classification of major perceptual dimensions.

System	Definition of Perceptual Dimensions	References
Early Classification Systems		
Helmholtz	*Analytic:* different values on dimension do not fuse into a combined percept, e.g., pitch (auditory chords do not fuse) *Synthetic:* different values fuse into a new percept, e.g., color (red light + green light = yellow light)	Ref. 5
Boring: subjective dimensions	*Quality:* e.g., color, pitch, bitter-sweet *Intensity:* e.g., loudness, brightness *Extensity:* spatial extension *Protensity:* temporal extension or duration *Attensity:* salience, clarity	Ref. 1
Gibson	*Unilateral/intensive:* dimensions which increase from zero to a maximum without change of quality, e.g., brightness *Bilateral/oppositional:* dimension runs from a maximum of one quality through a zero point to a maximum of an opposite quality, e.g., complementary colors red-green *Transitive:* dimension contains different values or qualities without opposition, e.g., pitch	Ref. 4
Contemporary Classification Systems		
Stevens	*Prothetic:* dimensions which change in intensity without change of quality, e.g., brightness *Metathetic:* dimensions which exhibit shifts in quality, e.g., pitch	Ref. 6
Erickson: topographic classification of metathetic dimensions	*Topographic:* qualities that are encoded by an orderly spatial arrangement in the brain, e.g., pitch, visual/somesthetic spatial position *Nontopographic:* neural encoding that is not spatial, e.g., color, taste, temperature	Ref. 2
Garner: perceptually based classification of physical dimensions	*Separable:* when combined in an object, these dimensions remain distinct, e.g., size, color *Integral:* while physically distinct, these dimensions are perceptually difficult to separate, e.g., hue and saturation *Asymmetric:* when dimension *A* remains distinct in combination with *B*, but *B* is integral with *A* *Configural:* dimensions that arise from combinations of perceptually distinct dimensions, e.g., symmetry	Ref. 3

Key Terms

Dimensional analysis; object perception; perceptual dimensions

General Description

A physical object is an entity with definable characteristics, such as a location, shape, and mass. A perceptual object is a psychological representation of that physical object, perceived by an organism through sensory receptors. That representation may carry considerable or scant specific information. We achieve identification of objects and events through perception, probably through analysis or descriptive decomposition of the stimuli along several dimensions. Psychologists have attempted to specify sets of useful dimensions and to classify perceptual dimensions in terms of their formal characteristics, as well as to classify formal relationships between physical and perceptual dimensions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Several well-known classification systems are summarized in Table 1.

Stevens' classification system divides perceptual dimensions into two classes: prothetic dimensions (which change in intensity without a change of quality) and metathetic dimensions (which exhibit shifts in quality). Table 2 shows the characteristic properties of prothetic and metathetic continua. Figure 1 shows the classification of some major perceptual dimensions according to the prothetic/metathetic distinction of Stevens, the topographic/nontopographic scheme of Erickson, and Helmholtz's distinction between analytic and synthetic dimensions. Several task-related variables correlate with Garner's perceptually based classification of physical dimensions (CRef. 7.523).

Applications

Design of machine-based image-processing systems, which use formal structures for image representation and analysis.

Key References

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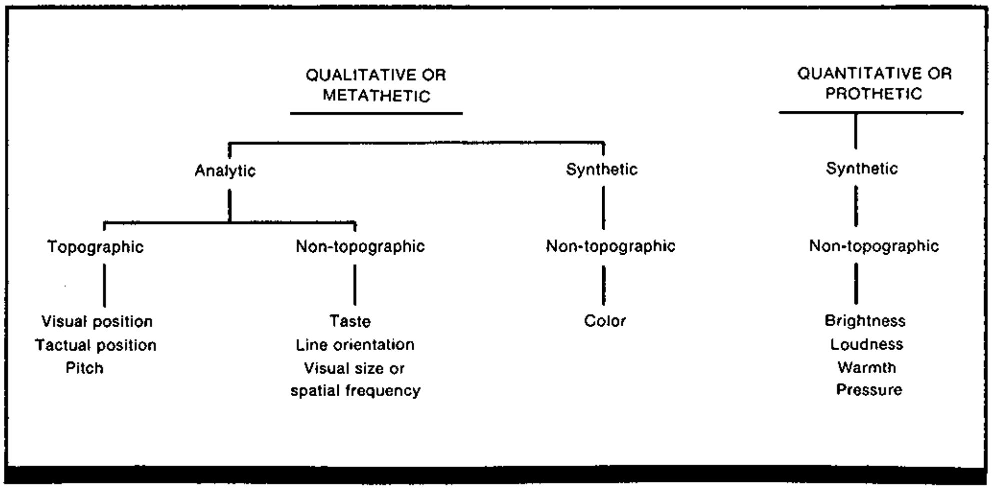

Figure 1. Classification of major perceptual dimensions. Different dimensions are classified according to the topographic/nontopographic distinction (Ref. 2), the analytic/synthetic distinction (Ref. 5), and the metathetic/prothetic distinction (Ref. 6). It is suggested that the distinctions are nested in a hierarchical tree. Examples of dimensions are given under each heading; however, not all dimensions may fit easily into such a scheme. (From *Handbook of perception and human performance*)

Cross References

7.523 Target counting: effects of grouping;

Handbook of perception and human performance, Ch. 35, Sect. 1.4

Table 2. Characteristic properties of prothetic and metathetic continua. (From Ref. 7)

	Prothetic	Metathetic
Prototype	Loudness	Pitch
Main concerns	Quality or degree—how much	Quality or location—what or where
Error behavior	Relative error approximately constant—hence the just noticeable difference measured in sones grows larger when stimulus intensity increases	Absolute error approximately constant—hence the just noticeable difference measured in mels remains constant when stimulus frequency increases
Variability distribution	Approximately log normal	Approximately normal
Time error	Present: stimulus equal to standard is judged greater	Absent: stimulus equal to standard is judged equal
Hysteresis effect	Strong	Little or none
Partition judgments	Disagree with ratio judgments; hence partition scales are nonlinear	Agree with ratio judgments; hence partition scales are linear

6.201 Levels of Semantic Categories

Table 1. Six examples of categorical organization. (From Ref. 2)

Superordinate	Basic Level	Subordinate	
Musical instrument	Piano	Grand piano	Upright piano
Fruit	Grapes	Seedless grapes	Concord grapes
Tool	Hammer	Claw hammer	Ballpeen hammer
Clothing	Socks	Knee socks	Ankle socks
Furniture	Lamp	Floor lamp	Desk lamp
Vehicle	Car	Four-door sedan	Sports car

Key Terms

Cognitive representation; semantic category; visual information processing

General Description

People normally categorize objects hierarchically, with relatively abstract groupings (superordinate categories) subsuming basic-level groups, which can be further subdivided into smaller groups (subordinate categories). For example, the superordinate category "fruit" includes the basic-level category "apple," which can be further divided into subordinate categories such as "Delicious apple" and "MacIntosh apple" (Table 1).

The basic-level category appears to be the most psychologically important level. For example, subjects usually perform better in detecting the picture of an object, deciding whether two representations of objects are the same or different, and verifying whether an object belongs to a specified category when the basic level category name of the object is presented immediately beforehand (priming) but not when the superordinate or subordinate category name is used as a prime (Table 2). Also, unless instructed otherwise, people use basic-level names to label objects.

Constraints

- Basic-level categories change with experience; "airplane" is a basic-level concept for most people, but not for someone familiar with different kinds of airplanes (e.g., a pilot or an airplane mechanic).

Key References

1. Rosch, E. (1975). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General, 104*, 192-233.

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Cross References

6.202 Categorization: effect of exemplar typicality;

6.203 Representation and retention of visual prototypes

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 2. Summaries of four experiments investigating superordinate, basic-level, and subordinate object categories.

Task	Procedure	Results
Detect object and press key to indicate whether on right or left	Eighty undergraduates viewed a display with a color picture of an object on one side and a random form on the other (for 200 msec through visual noise mask, no prime or 1-sec auditory prime of superordinate, basic-level, or subordinate) category name	Percentage of correct object identifications is enhanced with basic-level prime (88%, and impaired with superordinate prime (69%) compared to no prime (81%)
Compare pairs of drawing to determine if physically identical and press appropriate key for same-different judgments	Undergraduates viewed pairs of line drawings (20 subjects) or color pictures (45 subjects) with the word "blank" presented 2 sec after an auditory prime of the superordinate, basic level, or subordinate category name	Correct same-different judgments are significantly faster with basic-level and subordinate primes than for no prime (" blank" only); subordinate primes have no effect
Indicate by key press whether viewed object is member of named category	Undergraduates saw color pictures of objects; category name presented 0.5 sec before display; separate groups (15 subjects each) heard superordinate, basic-level, or subordinate category names	Subjects are significantly faster in verifying that objects belong to a basic-level category than in verifying that they belong to a superordinate or a subordinate category
Verbal labeling	Undergraduates named the objects depicted in a set of color pictures, with separate groups labeling sets that contained objects differing at the superordinate (60 subjects), basic (20 subjects), or subordinate (10 subjects) levels	Subjects almost always label an object with the basic-level category name, regardless of the level at which objects differ

6.202 Categorization: Effect of Exemplar Typicality

Table 1. Summary of data on the effects of priming and typicality on the processing of category membership information.

Materials	Task	Variables	Results	Source
48 true ("A pear is a fruit") and 48 false ("A pear is metal") statements of category membership, randomly intermixed, presented to 20 children, ages 9-11 yrs, and 24 undergraduates	Verify category membership (i.e., indicate whether statement is true or false)	Typicality of category member, true versus false statements; response time and accuracy measured	Verification of category membership is faster and more accurate for typical (e.g., "pear") than for nontypical (e.g., "prune") category members. Typicality has no effect on time or accuracy in judging a category attribution statement as false	Ref. 2
Word pairs and picture pairs of high-, medium-, and low-typicality exemplars of nine categories presented to 60 undergraduates	Indicate whether the items in each pair belong to the same or different categories	Priming (category name given 2 sec in advance) versus no priming (word "blank" given 2 sec in advance), typicality of exemplars, word pairs versus picture pairs, type of match (physically identical, same category, different category); response time and accuracy measured	Generally, same-different category, judgments are faster for high-than for low-typicality pairs, and higher for primed than for nonprimed pairs for both words and pictures (Fig. 1). However, priming interacts with typicality for physically identical matches (which required a "same" judgment)	Ref. 3
32 pairs of **Munsell color chips** representing high- and low-typicality examples of eight color categories presented to 40 undergraduates	Indicate whether items in each pair are physically identical	Typicality of color, priming (color category name given 2 sec in advance) versus no priming (word "blank" given 2 sec in advance), saturation or brightness or color examples; response time and accuracy measured	For "same" responses, matching of highly typical examples is facilitated by priming, but matching of poor examples is impaired by priming when examples vary in either saturation or brightness. There are no differences for "different" judgments	Ref. 4

Key Terms

Cognitive representation; semantic category; visual information processing

General Description

People reliably judge some members of a category to be more typical of the category than others; for example, "apple" better represents the category "fruit" than does "mango." The process of verifying category membership (e.g., "Is an apple a fruit?") partially depends on the typicality of the item for the category being considered. High typicality instances tend to be processed as members of the category more rapidly than low-typicality instances and, under some conditions, to benefit more from advance category information (priming). Table 1 summarizes several studies showing the effects of category typicality on perceptual tasks.

Constraints

- Extensive training with typical and nontypical instances substantially reduces or eliminates the effects of typicality on categorization (Ref. 3).
- Interactions between priming and typicality are often a function of the type of match (e.g., physical or semantic).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

6.201 Levels of semantic categories;

6.203 Representation and retention of visual prototypes

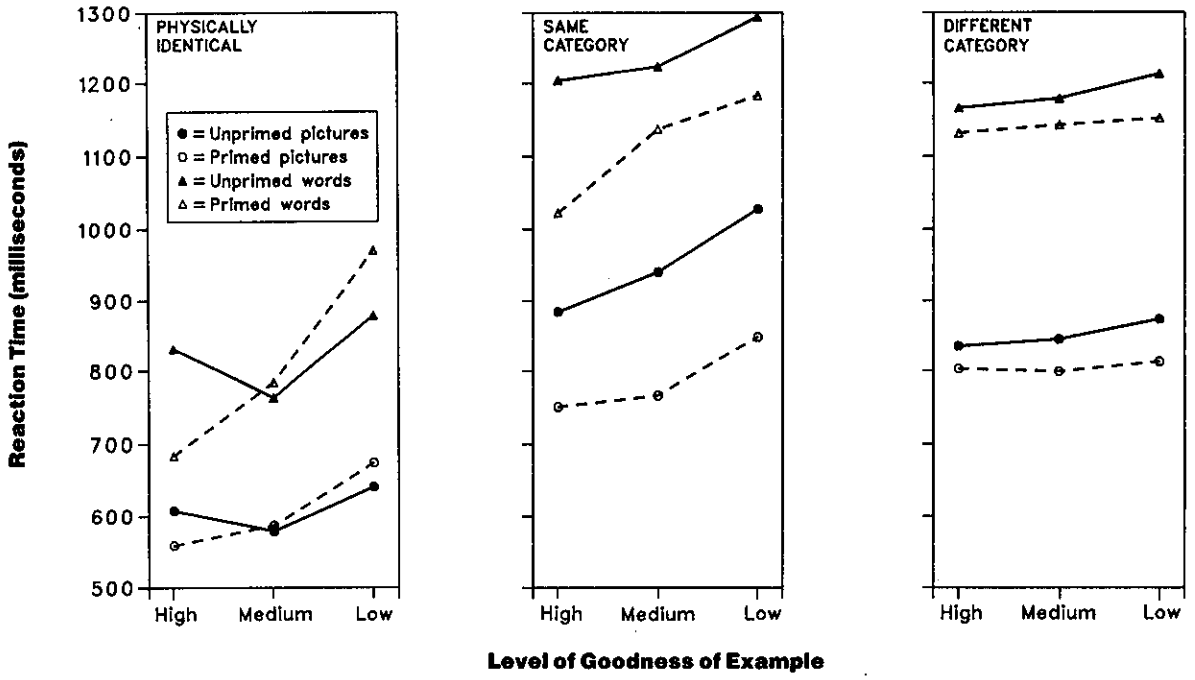

Figure 1. Reaction time to judge whether two words or pictures represented members of the same category as a function of priming and typicality for physically identical, same category, and different category pairs. Solid lines depict data on unprimed trials; dashed lines depict data on primed trials in which category name preceded presentation of word or picture pair. The lower pair of lines in each panel shows results for picture pairs and the upper pair, results for word pairs. (From Ref. 3)

6.203 Representation and Retention of Visual Prototypes

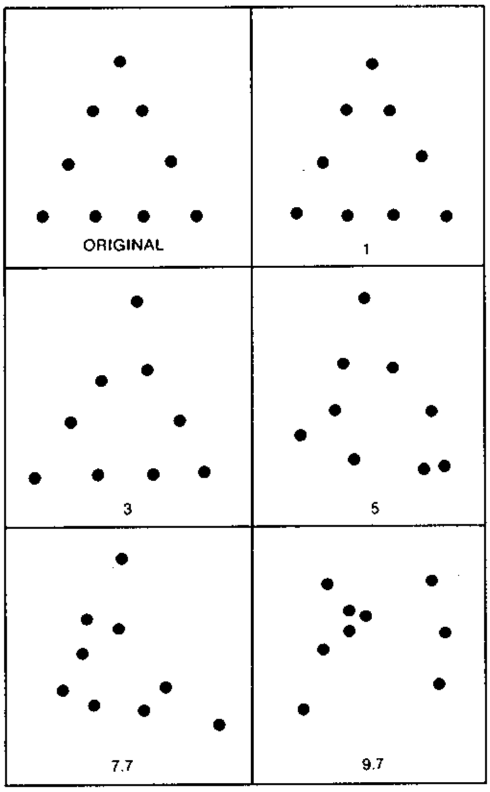

Figure 1. Distortion of a dot pattern. The original triangle pattern is shown in the upper left. The fine distortions were generated using a statistical rule which governed the extent and direction of displacement of each dot from its original position. Level of distortion was controlled by varying the probability of moving each dot into a possible alternative position. The level of distortion (measured in bits per dot) is given at the bottom of each pattern. These dot patterns are similar to those used in Refs. 3 and 4. (From Ref. 2)

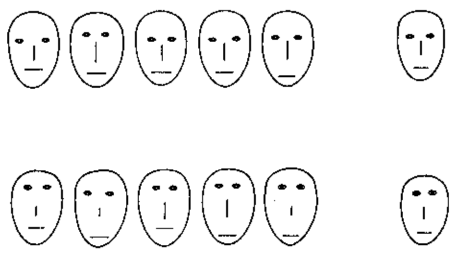

Figure 2. Schematic (Brunswik) faces and average-value prototypes used in Ref. 5. Faces vary along the four nominal dimensions of (a) forehead height, (b) eye separation, (c) nose length, and (d) mouth height. The prototype faces on the right contain the average value for each of the dimensions, as represented in the exemplars shown in the left.

Key Terms

Cognitive representation; pattern memory; pattern perception; pattern recognition; prototype theory

General Description

Exposure to specific examples of a category of visual patterns (category members or exemplars) appears to produce an internalized representation of a prototypical pattern for that category. After exposure to only specific examples of a given pattern category, people categorize a previously unseen prototypical pattern of the category about as quickly and accurately as they categorize the learned examples. In addition, correct categorization of prototypes is at least as resistant to forgetting (and sometimes more so) as are the originally presented exemplars (Table 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Experimental studies of prototype extraction have been largely restricted to relatively artificial and schematic stimuli.
• With appropriate instructions (or task demands), incentive, and practice, people can process individual exemplars better than they process prototypes.
• Models based on individual exemplars can yield the same results (e.g., high accuracy in categorizing previously unseen prototypes).

Key References

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Cross References

6.201 Levels of semantic categories;

6.202 Categorization: effect of exemplar typicality;

Handbook of perception and human performance, Ch. 28, Sect. 1.2

Table 1. Summary of data on acquisition and retention of information about category prototypes based on experience only with category members.

Materials	Task	Variables	Results	References
Dot patterns (Fig. 1); four distortions of each of three prototype patterns; 30 undergraduates	Learning phase: practice classification of patterns into three categories until categorization learned to criterion; test phase: classify test patterns according to category	Nature of test pattern: (a) old distortions; (b) prototypes; (c) new distortions; (d) unrelated patterns; speed and accuracy of categorization measured	Both on the same day and on the day following learning, subjects classify prototype patterns as quickly and accurately as they classify distortions seen earlier, and both are classified faster and more accurately than new distortions	Ref. 3
Dot patterns (Fig. 1); four distortions of each of four prototype patterns; 90 subjects	Learning phase: practice classification of patterns into four categories until categorization learned to criterion; test phase: classify test patterns according to category	Nature of test pattern: (a) old distortions; (b) prototypes; (c) new distortions; speed and accuracy of categorization measured immediately or after 1-week delay	Previously seen distortions are categorized better than prototype patterns, but performance is better for both than for new distortions. After 1-week delay, there is little change in prototype categorization performance, even though there is a large decrease in performance for old distortions; both are still recognized more quickly and accurately than are new distortions	Ref. 4
Schematic faces (Fig. 2); five faces assigned to each of two categories presented for training (training sets did not include prototypes for each category) 149 students	Classify new faces as belonging to category 1 or category 2	Structure of new faces (which included prototype and controls matched for distance from training set); no memory versus memory conditions (i.e., training sets present or absent during categorization of new faces); classification accuracy measured	Subjects categorize prototypes more accurately than they categorize new non-prototypical faces. Categorization performance is best predicted by prototype and weighted-average-distance algorithms	Ref. 5

6.301 Principles of Gestalt Grouping and Figure-Ground Organization

Key Terms

Closure; common fate; figure-ground segregation; form perception; Gestalt principles; good continuation; grouping; proximity; similarity principle; spatial orientation; surroundedness; symmetry

General Description

Gestalt psychologists (Ref. 3) have demonstrated several principles of perceptual organization that specify the conditions under which discrete elements are perceived as grouped together or as associated.

Gestalt principles of grouping include:

Proximity. Elements close to other elements tend to be perceived as a group. In Fig. 1a, the dots appear as rows if the horizontal spacing between dots is less than the vertical spacing; if not, they appear as columns.

Similarity. Elements that resemble each other tend to be perceived as a group. In Fig. 1b, the items are perceived as rows of identical shapes rather than columns of alternating shapes.

Closure. Elements arranged to define a closed region are seen as a perceptually unified shape (Fig. 1c).

Good continuation. Elements tend to be grouped in a way that minimizes abrupt changes in visual direction. In Fig. 1d, the first set of dots is seen as smooth, curving lines. At the point of intersection, we see dots A and B as belonging to one line, C and D as belonging to another. The alternate groupings suggested to the right are usually not perceived.

Symmetry. Elements tend to group in a way that maximizes symmetry. In Fig. 1e, three pairs of symmetrical brackets and three pairs of symmetrical parentheses are seen.

Common fate. For moving figures, elements with common velocity and direction tend to be seen as a group. Recent work subsequent to the early Gestalt work has elucidated the mechanisms more clearly (Ref. 6; CRef. 6.316).

Even in a complex visual scene, human observers generally have no trouble isolating single objects from their backgrounds. The difficulties encountered in programming machines to recognize where one object stops and another begins in a cluttered visual scene emphasize the importance of this accomplishment for the visual system. Using ambiguous displays to study how observers segregate figure from ground, Gestalt psychologists have developed a set of principles specifying the conditions under which a given region will be perceived as figure or as background. These principles include the following:

Surroundedness. A surrounded region tends to be seen as figure while the surrounding region tends to be seen as ground (Fig. 2a: the surrounding region is potentially a figure with a hole in it).

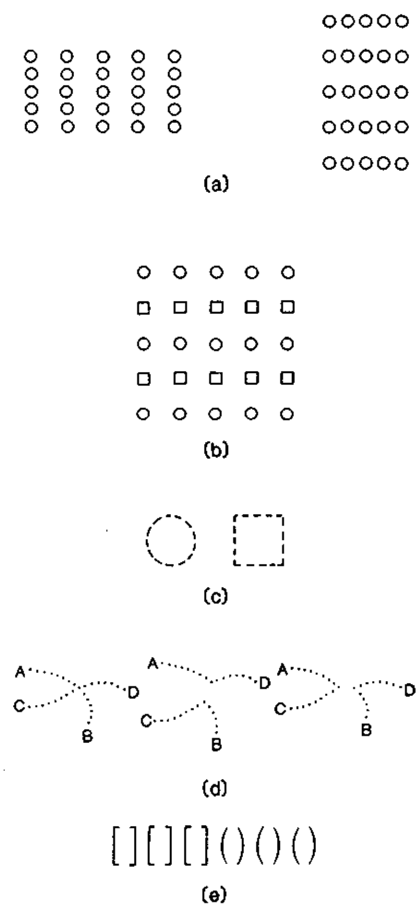

Figure 1. Illustration of five Gestalt principles of grouping: (a) proximity, (b) similarity, (c) closure, (d) good continuation, (e) and symmetry. (From Ref. 5)

Symmetry. A region with symmetry is perceived as figure in preference to a region that is not symmetric (Fig. 2b).

Convexity. Convex contours are seen as figure in preference to concave contours (Fig. 2c). In Fig. 2c, convexity leads to the perception of the black regions as figure, even though this organization opposes the law of symmetry.

Orientation. A region oriented horizontally or vertically is seen as figure in preference to one that is not (Fig. 2d).

Lightness or contrast. A region that contrasts more with the overall surround is preferred as figure over one that does not (Fig. 2e).

Area. A region that occupies less area is preferred as figure (Fig. 2f).

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Constraints

- A number of the well-known principles, particularly proximity and similarity, assume the structure is built of textural elements.
- Principles have been established by the method of demonstration. It is largely unknown how and with what relative power these principles function in normal perception (Ref. 6).

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Cross References

6.001 Perceptual organization;

6.306 Reversible or multistable figures;

6.310 Perceived shape of partially hidden objects;

6.316 Ambiguous movement in figures without texture of fine detail

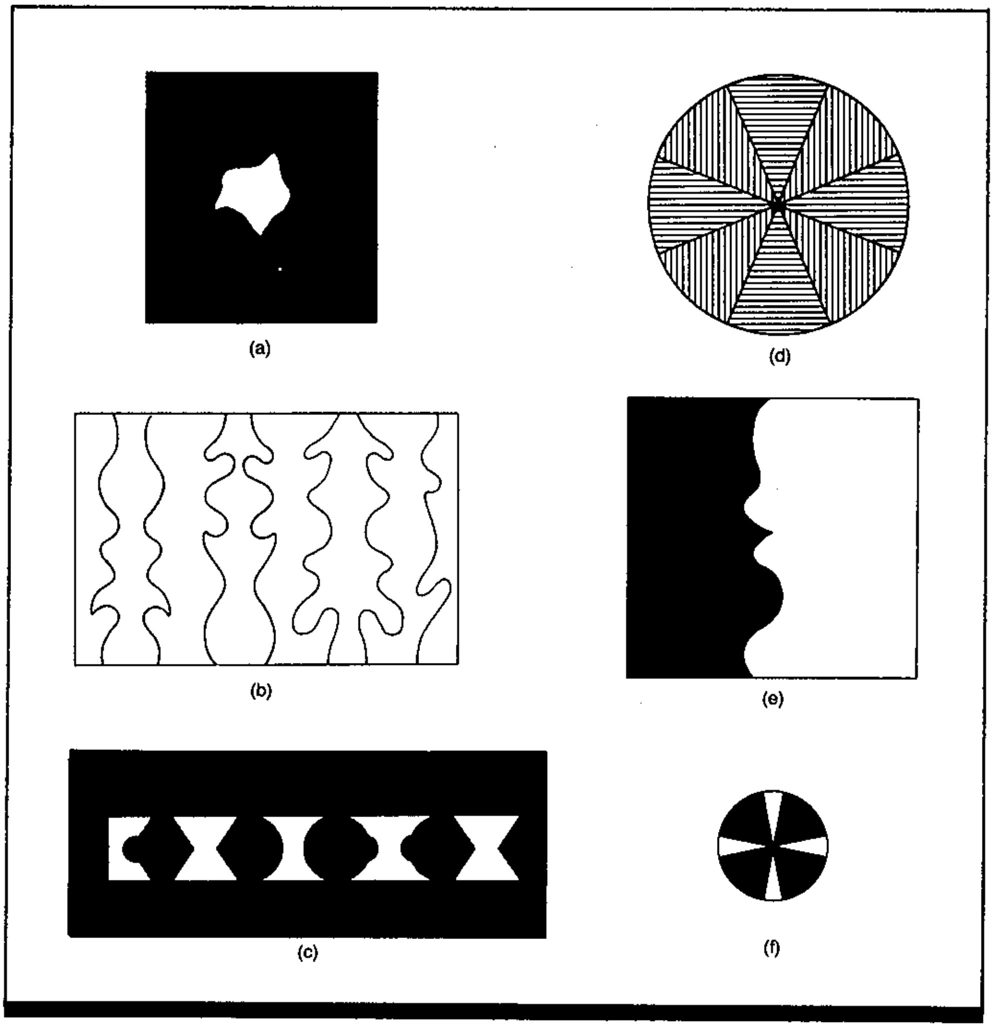

Figure 2. Factors that determine figure-ground organization: (a) surroundedness, (b) symmetry, (c) convexity, (d) orientation, (e) lightness or contrast and (f) area. ([a] from Ref. 6; [b] from Ref. 6; [c] from Ref. 2; [d] from Ref. 6; [e] from Ref. 6; [f] from Ref. 5)

6.302 Gestalt Grouping Information: Effect of Low-Pass Spatial Filtering

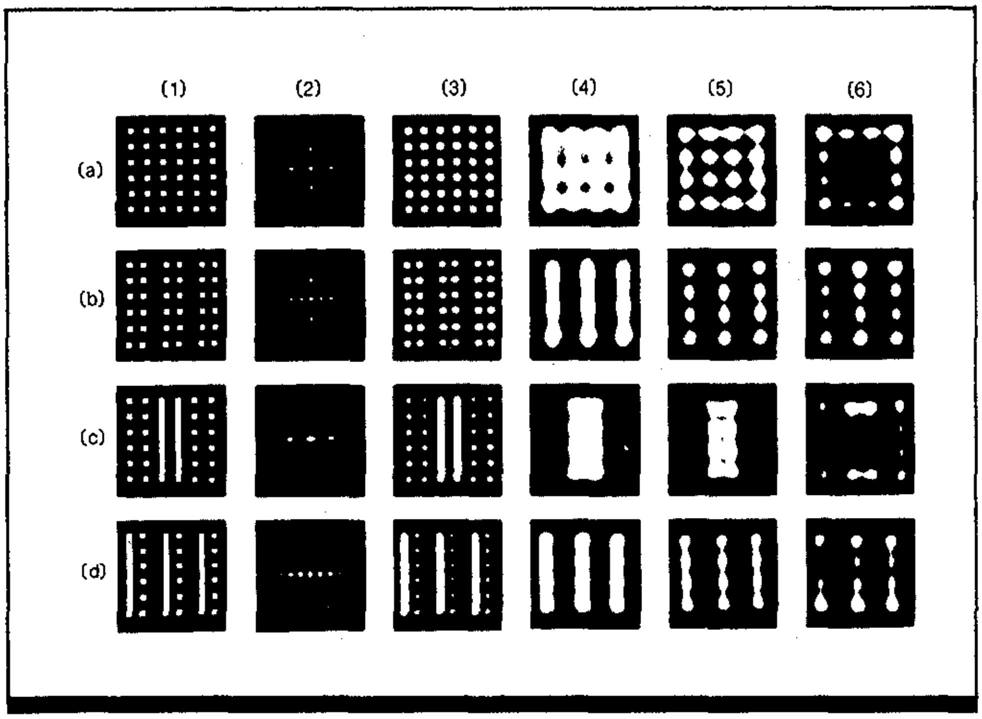

Figure 1. Examples of Gestalt laws of perceptual grouping that can be examined in terms of spatial-frequency filtering: (a) one group; (b) three groups formed by proximity; (c) three groups formed by similarity; and (d) three groups that show the law of proximity is stronger than the law of similarity. The original patterns in column 1 have their Fourier magnitude spectra filtered by a two-dimensional directional filter based on biological data, shown in column 2, which results in the filtered image in column 3. The filtered images created from just the lowest four spatial frequencies are in column 4. The effect of using the overall biological filter before passing only the lowest four frequencies is in column 5. Column 6 contains filtered images where the fundamental frequency or first harmonic is removed to reveal forms comprised of only three spatial frequencies. (From *Handbook of perception and human performance*)

Key Terms

Apparent movement; form perception; Gestalt principles; grouping; proximity; similarity principle; spatial filtering

General Description

Images can be decomposed into their various spectral components using image-processing techniques closely allied to Fourier anlaysis (Ref. 1). Examination of images where only particular bands of spatial frequencies are present indicates a special role for low spatial frequencies in formation of perceived groupings within sets of objects (Gestalt grouping processes, [Ref. 1; CRef. 6.301]). These results are compatible with studies of apparent motion that reveal insensitivity to detailed pattern information for Gestalt grouping processes in motion perception.

First, Gestalt grouping by proximity (CRef. 6.301) is accentuated by low-pass spatial filtering, as illustrated in Fig. 1b. The low-passed images (Columns 4, 5 of the figure) clearly show the organization of dots into three columns, as are perceived in the unfiltered image. Figure 1d shows the same three-column organization when filtered, although the Gestalt principle of grouping by similarity (CRef. 6.301) suggests a different organization. Grouping by similarity is not particularly enhanced by low-pass spatial filtering, as is clear from Fig. 1c.

Gestalt grouping in apparent motion also exhibits properties associated with low-frequency channels (Ref. 2, 3). Two different phenomena can be demonstrated with rows of simple figures, dots, or line segments using two displays that alternate in a typical apparent-motion paradigm. A row of dots is presented first in one position and then shifted laterally by one element space (see Fig. 2). Two possible forms of apparent movement are seen with the displays. When distances are small and the onset intervals between

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displays are short, the element in position *a* appears to move back and forth to position *d* while the elements in positions *b* and *c* remain stationary; this phenomenon is known as element movement. When the distances between elements increase and the interval between presentations increases, all elements appear to shift back and forth by one space; this phenomenon is known as group movement and has been associated with Gestalt principles for a long time (Ref. 4).

It is particularly interesting that preservation of pattern details (i.e., high-spatial-frequency information) is critical for the perception of element movement, but not for group movement. When vertical line segments are replaced by horizontal segments from the first display to the second, element movement is not obtained. When "MITE" is changed to "ITEM," from one display to the next (i.e., only the position of the M is changed), group movement is obtained despite the fact that the forms in each display position are completely different from one display to the next (Ref. 3). These results appear to indicate that the apparent movement process underlying group movement uses blob-like or low-frequency information.

Applications

Image-processing and image storage.

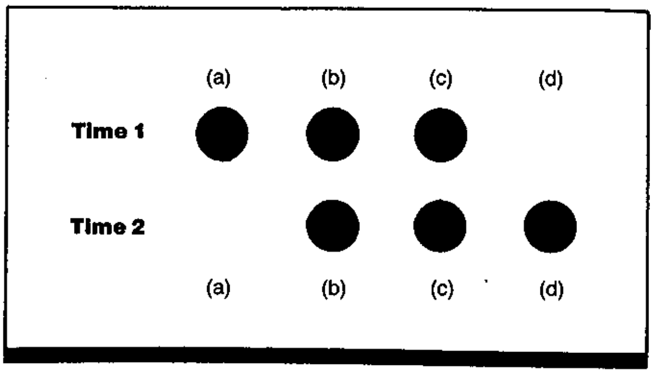

Figure 2. Display for demonstrating apparent motion. Three spots are flashed at positions *a*, *b*, and *c* at time 1; then spots are flashed at positions *b*, *c*, and *d* at time 2. (Spots are superimposed, not vertically displaced, as shown here). Perceptual organization depends upon the interval between the two presentations. When the interval is short, the dot in position *a* appears to move to position *d*, while the other two dots appear stationary (element movement). When the interval is long, the three spots move as a unit and appear to shift one position to the right (group movement).

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Cross References

5.401 Types of visual apparent motion;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.312 Form perception: contribution of different spatial-frequency bandwidths;

Handbook of perception and human performance, Ch. 34, Sect. 5.1

6.303 Simplicity and Likelihood Principles

Key Terms

Gestalt principles; Kanizsa cube; Kopfermann cube; likelihood principle; Prägnanz; simplicity principle

General Description

Accurate perception of our environment requires more than detection of information. The information must also be organized. The mechanisms of perceptual organization are not yet well understood, but there is some evidence to support two major theoretical approaches. These two primary principles of perceptual organization are those of simplicity and likelihood. The simplicity principle, supported by Gestalt psychologists, holds that perception is organized to achieve the simplest or most economical interpretation of the stimulus. In contrast, the likelihood principle, held by Helmholtz and others, states that sensory information will be interpreted as representing the event or object in the environment that is most consistent with the input (i.e., most likely, given the input).

According to Gestalt psychologists, parts are organized into perceptual wholes according to the principle of Prägnanz (or the minimum principle). This principle holds that, of all the possible ways in which the neural representation of a stimulus might be organized, the organization adopted will be the simplest one or the one that minimizes the complexity of the stimulus.

The Gestalt psychologists put little weight on the role of learning in perception. Instead, they place the burden of perceptual organization on the innate structure of the brain, arguing that the brain is organized so that it deals directly with holistic properties of the stimulus, such as configuration, symmetry, and closure of a visual form. The brain organizes its representations of stimuli to create a "better" perception. The Gestalt psychologists believed that decomposing a stimulus into its parts or features is not what occurs in perception.

Evidence for the simplicity principle comes from the method of demonstration, in which an observer views a stimulus and states how it is perceived organizationally. To use this method, stimulus patterns are designed so that several distinct organizations are possible. These patterns are often drawn from particular perceptual classes, including subjective contours (CRef. 6.314), apparent motion, multistable figures (CRef. 6.306), two-dimensional figures perceived in depth (CRef. 6.310), and "impossible" figures (Fig. 3).

The simplicity approach is demonstrated in Fig. 1. Figures 1a and 1b are ambiguous, for each may be interpreted as a flat figure or as a wire (outline) cube viewed from an angle. Generally, Fig. 1a is perceived as a cube and Fig. 1b as a hexagon. This finding illustrates the principle of Prägnanz, as the simplest interpretation is perceived in each case. However, the limitation of this type of argument is demonstrated in Figs. 1c and 1d. Figure 1c is generally perceived as three-dimensional and Fig. 1d as flat, even though both two- and three-dimensional interpretations lead to perception of an irregular asymmetric figure.

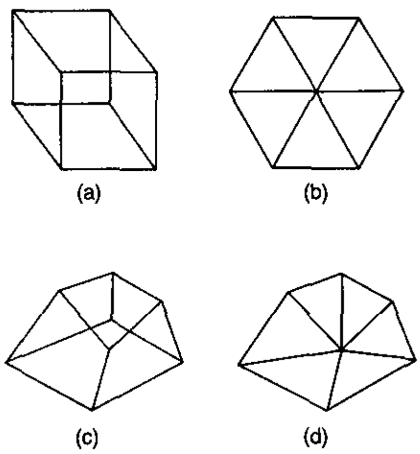

Figure 1. Perspective drawings of two Kopfermann cubes (a, b) and Kanizsa's distorted cubes (c, d). Although (a) and (b) are equally accurate perspective drawings of a wire cube, (a) is more likely to be perceived as a cube and (b) as a flat design. The perceptual effects of (c) and (d) are the same as for (a) and (b), even though the object is depicted as a distorted cube. ([a] and [b] from *Handbook of perception and human performance*; [c] and [d] from Ref. 2)

The likelihood principle suggests that sensations are combined with acquired associations (memory images) to complete the perceptual process. According to Helmholtz, sensory elements are organized by unconscious inference into the most probable object or event in the environment that is consistent with the sensory information arising from it.

Unlike the Gestaltist view, the Helmholtzean view places great emphasis on learning and little emphasis on brain structure. The likelihood principle also asserts that perception follows logical rules of inference, similar to those used in thought.

Evidence for the likelihood explanation comes from the method of demonstration as well as from more controlled experiments (often in the psychophysical tradition) to demonstrate specific predictions. Figure 2 illustrates how perceived depth is influenced by the assumed direction of illumination (from above). However, there are examples in which perception is inconsistent with knowledge (Ref. 5). Figures 3a and 3b are perhaps the best-known "impossible" figures. Rather than interpreting these patterns as flat designs, the visual system attempts to structure them in depth, which turns out to be an impossible task.

The likelihood approach appears to be a stronger explanation for perceptual organization, but this theory has its limitations as well. For instance, the role of knowledge in perceptual organization remains to be clarified (Ref. 5).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.406 Visual apparent motion: effect of perceptual organization;

6.306 Reversible or multistable figures;

6.307 Pattern processing: effect of pattern complexity;

6.310 Perceived shape of partially hidden objects;

6.314 Subjective or illusory contours;

Handbook of perception and human performance, Ch. 33, Sects. 1.1, 1.2, 1.3; Ch. 36, Sects. 2.2, 2.3, 3.3, 5.2

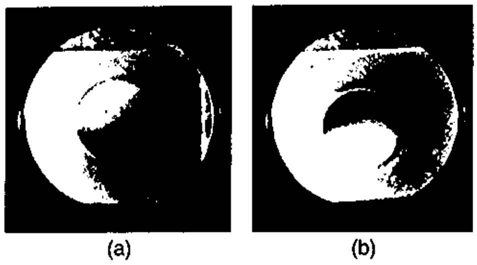

Figure 2. Perceived depth and the assumed direction of illumination: (a) tends to be perceived as a bump extending outward above the page, whereas (b) is seen as a dent inward below the page. If the figure is turned upside down, these depth relationships reverse. The effect appears to be due to an assumption within the visual system that the source of ambient illumination is from above, so that shadows are cast toward the bottom of bumps but toward the top of dents. A similar effect can be seen in photographs of moon craters; if the photographs are inverted, mountains will appear. (From Ref. 4)

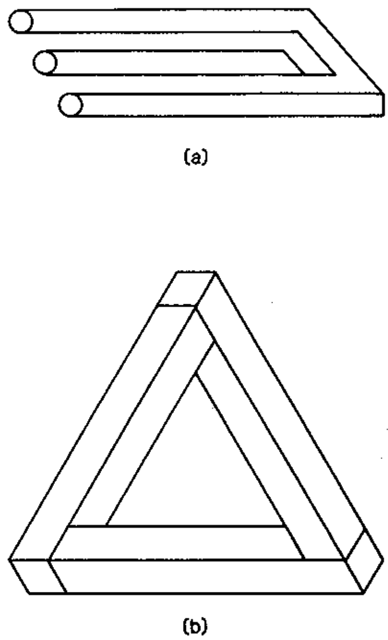

Figure 3. The three-stick clevis and the impossible triangle. These figures present a challenge to all theories of perceptual organization. ([a] is from Ref. 6 and [b] is from Ref. 3)

6.304 Role of Reference Frames in Perception

Key Terms

Frame of reference; motion perception; self-motion; target motion; vection

General Description

How we perceive the orientation and motion of objects often depends upon the relative orientation and motion of other objects in the environment, which serve as frames of reference. The role of reference frames in perception is striking, particularly in the perception of motion. Reference-frame effects can be compelling enough to produce an illusion of translation or rotation of the observer. In addition, object-centered reference frames may play a larger role in pattern recognition than is generally acknowledged (Ref. 4; CRef. 6.309). The shapes of certain objects endow them with intrinsic axes which serve as a reference frame for recognition; for example, in Fig. 1, the orientation of the lines is perceived in the context of a rectangle. Thus, the lines appear to be more tilted from the vertical than they really are because the tilt is perceived in relation to the surrounding rectangle. Yet the line in (a) is not tilted in relation to the rectangle in (b), and vice versa.

Conditions which define a perceptual reference frame include:

1. Surroundedness: when an image *A* surrounds image *B*, then *A* is likely to act as a reference frame for *B*.
2. Relative size: when an image *A* is considerably larger than image *B*, *A* is likely to act as a reference frame for *B*.
3. Common motion: the common motion of objects tends to form a framework for their relative motions.

Reference frames have several perceptual effects, including the following:

1. The direction of motion of a line within an aperture is somewhat determined by aperture shape (CRef. 6.316).
2. Motion of a reference frame can be misinterpreted as motion of the stationary object (induced motion) (Ref. 5; CRef. 5.301).
3. A stationary frame is perceived to represent a stable, upright environment. (A tilted room will make upright objects appear tilted.)
4. One does not perceive the actual motions of objects, but rather vector components of the actual motion within a hierarchy of reference frames (see Fig. 2) (Ref. 1).
5. Plastic (non-rigid) perspective transformations of objects (i.e., changes in the lengths and directions of object contours over time) are generally perceived as motion in depth (Ref. 3).
6. Surrounding an observer with apparent translatory motion leads to a feeling of translation of the body, an effect exploited, for example, in Cinerama-type movie productions. Surrounding a stationary observer with a rotating visual environment leads to perceived rotation of the body and aftereffects of the illusory rotation (Ref. 1; CRefs. 5.503, 1.924).

In complex reference frames, complex biological motions are sufficient for pattern recognition. For example,

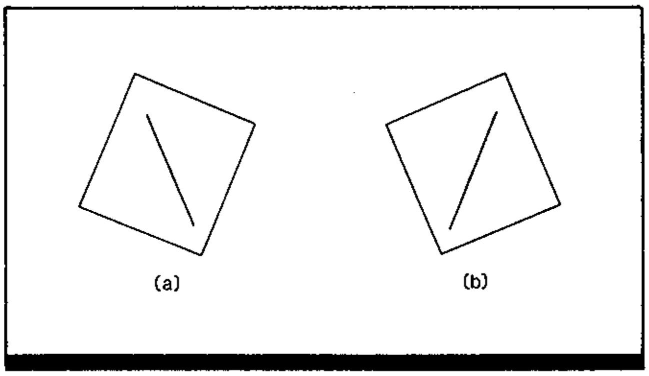

Figure 1. Hierarchical organization of perceived orientation. The perceived orientation of each line is governed by its relationship to the surrounding rectangle. The perceived orientation of each rectangle is governed by its relationship to the page. (From *Handbook of perception and human performance*)

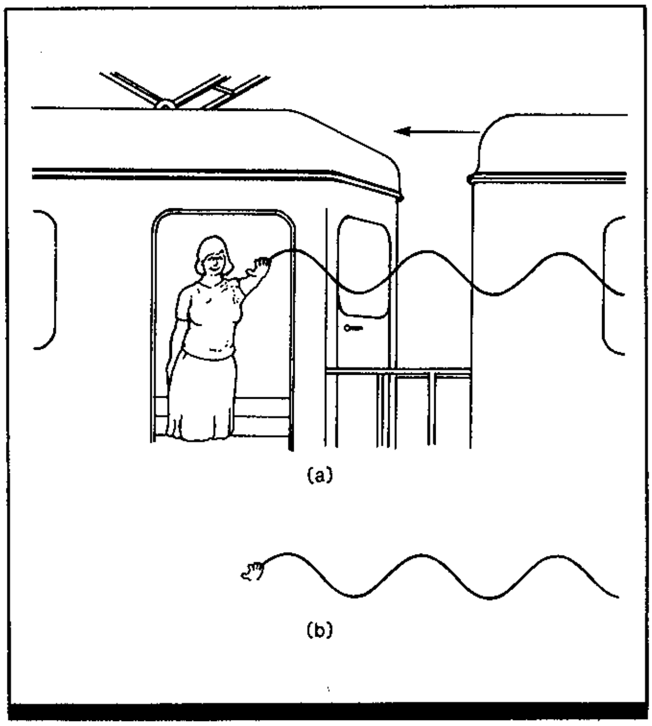

Figure 2. Hierarchical organization of perceived motion. The motion of a person's hand waving from a moving train (a) is perceived as vertical, that is, as up and down, although its path with respect to a stationary frame (and in the retinal image of a stationary eye) is sinusoidal. Were the train and person not visible, as in (b), the hand would be perceived as describing a sinusoidal path. (From *Handbook of perception and human performance*)

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two dancers, dressed in black and outfitted with light-emitting diodes on forearms, upper arms, torso, calves, thighs, etc., are filmed. The pattern of moving lights is readily recognized as a dancing couple (Ref. 2). The recognition of biological motion apparently involves vector decomposition into a hierarchical system of pendulum-like movements with a common translatory component.

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Cross References

1.924 Optokinetic nystagmus and circularvection (illusory self-motion);

5.301 Induced motion: determinants of object-relative motion;

5.503 Factors affecting illusory self-motion;

6.309 Perceived shape: effect of target orientation;

6.316 Ambiguous movement in figures without texture of fine detail;

Handbook of perception and human performance, Ch. 33, Sect. 1.7

6.305 Anorthoscopic Perception

Key Terms

Anorthoscopic perception; information portrayal; object perception; sequential presentation; simulation

General Description

If a figure drawn on a card is moved behind a cover with a slit in it so that only a portion of the figure is visible at a time, it is still seen as a complete figure (Fig. 1). This is known as anorthoscopic perception, presumably because it is an anomalous method of presentation.

In general, anorthoscopic effects are promoted by cues that indicate that a surface is being moved laterally relative to a vertical slit. These include:

- the texture that defines surfaces
- a slit width great enough to show changing slope and curvature of figure (Fig. 2)
- dashes to define figure boundaries of intermittently seen figures (Ref. 4)
- periodic visibility of ends of figure.

Generally, anorthoscopic perception does not depend on eye movements and occurs when eyes are fixated. However, under some conditions where anorthoscopic perception would not otherwise occur, the effect can be produced by providing a moving fixation point for the eyes to track (Ref. 5).

If a single contour oscillates vertically behind a stationary vertical slit, there is no anorthoscopic percept (Ref. 2); however, one can be produced by induced motion of the slit by moving a peripheral surround horizontally (CRef. 5.406; Ref. 6).

Anorthoscopic perception fails:

- with very narrow slits which give rise to compelling illusions of vertical motion (CRef. 6.316)
- when a slit is not seen as such because the surface it interrupts is not visible (Ref. 7)
- when a slit takes on figural properties.

Alternatively, if a slit takes on properties of ground, anorthoscopic perception succeeds (Ref. 7; CRef. 6.301).

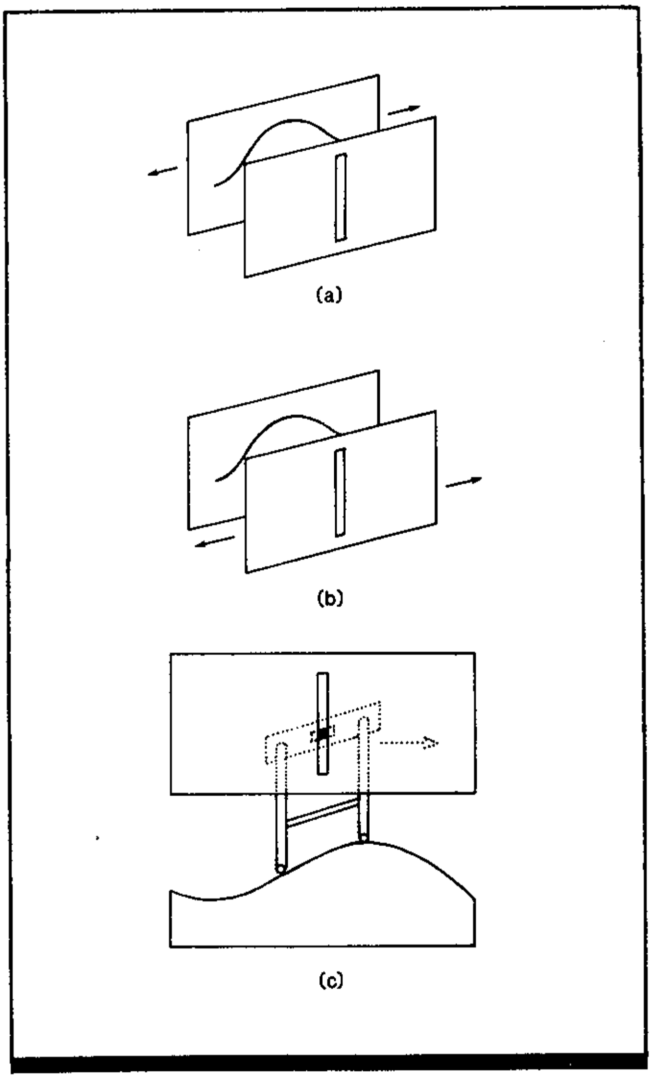

Figure 1. Anorthoscopic perception. (a) In the traditional method, a figure is moved back and forth behind a narrow stationary slit in an opaque surface. (b) In a more recent variation, the slit is moved back and forth over a stationary figure. (c) A method for simulating the traditional method shown as a. (From *Handbook of perception and human performance*)

Constraints

- With free viewing, a figure generally appears compressed along the horizontal axis (Fig. 3, Ref. 1).
- If eyes track a spot moving in the direction opposite to the slit, then the mirror image of the figure is perceived (Fig. 3, Ref. 5).

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Cross References

5.406 Visual apparent motion: effect of perceptual organization;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.316 Ambiguous movement in figures without texture of fine detail;

Handbook of perception and human performance, Ch. 33, Sects. 2.3, 4.3

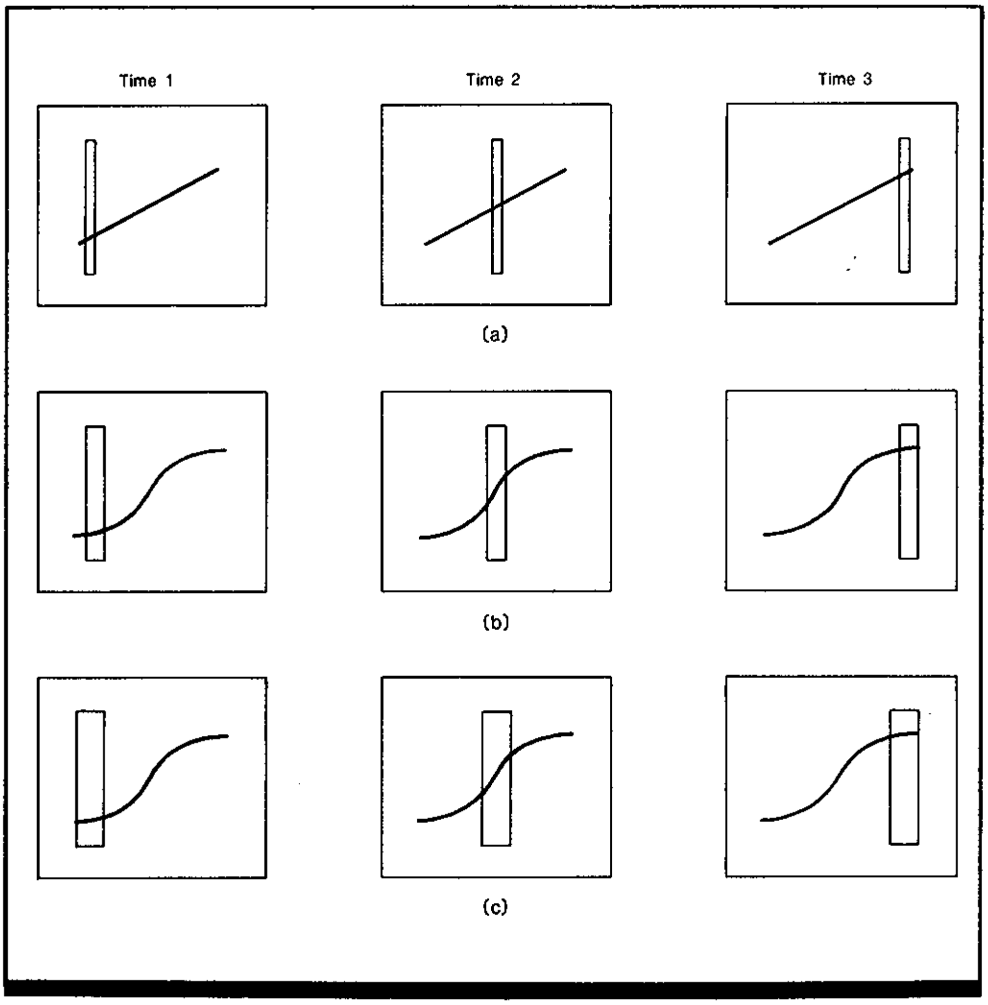

Figure 2. Providing an anorthoscopic effect by changing the slope (*b* versus *a*) or curvature (*c* versus *a*) of the portion of the figure visible through the slit. (From Anorthoscopic perception, I. Rock. Copyright © 1981 by Scientific American. All rights reserved.)

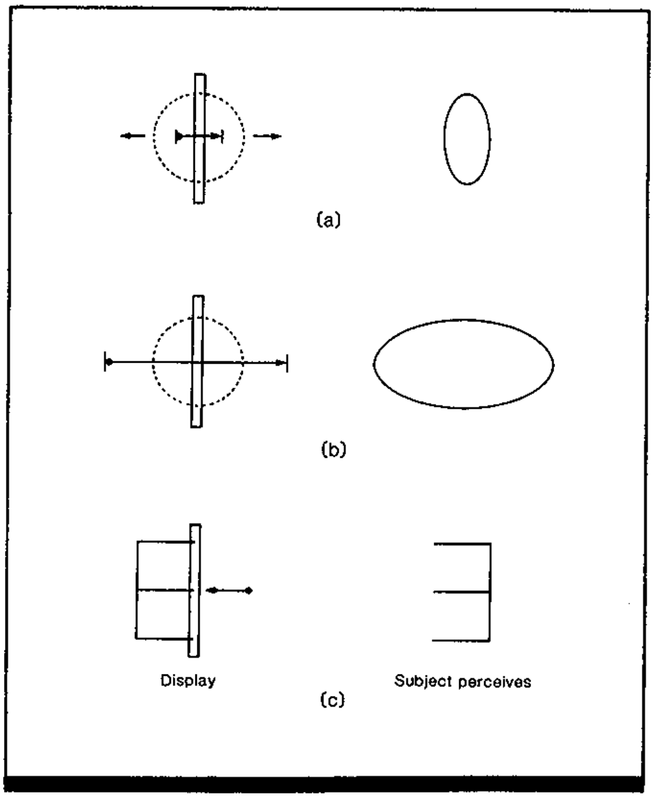

Figure 3. In tracking a moving target point, various distortions of the shape of the perceived figure occur. (a) If the target point moves more slowly than the figure, the figure appears to be compressed. (b) If the target moves faster than the figure, the figure appears to be elongated. (c) If the target moves in one direction and the figure in the opposite direction, the figure appears left-right reversed (mirror image). (From *Handbook of perception and human performance*)

6.306 Reversible or Multistable Figures

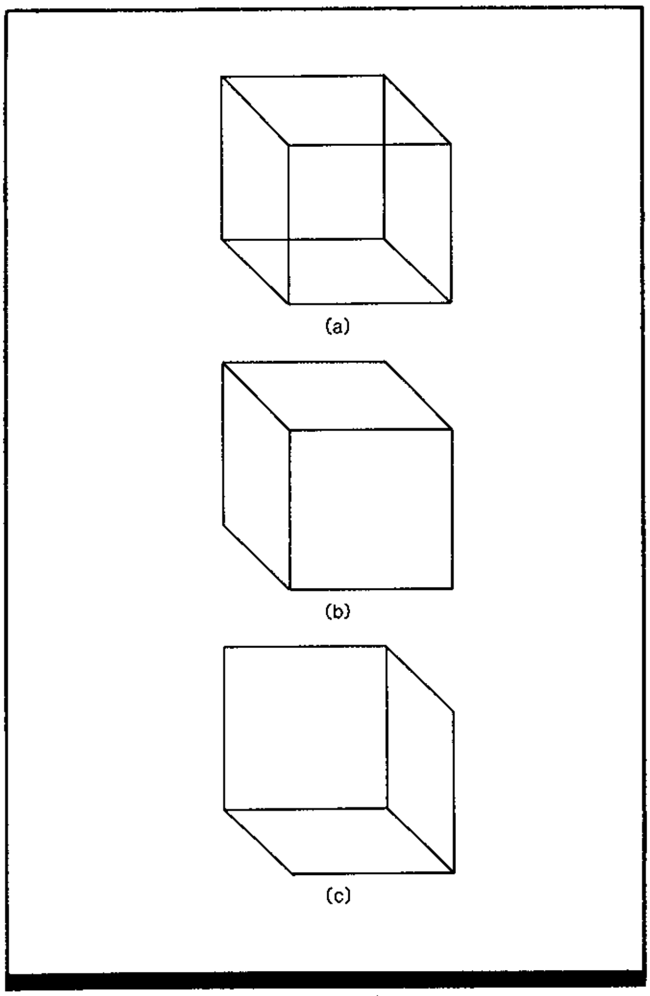

Figure 1. Three views of a cube. Panel (a) shows the well-known Necker cube, a perspective drawing of a wire (outline) cube. It is usually perceived in one of the two orientations shown unambiguously in panels (b) and (c) with solid cubes. The Necker cube has two types of internal vertices: a "Y" vertex, at the upper left and lower right corners of the internal square and a "cross" vertex at the upper right and lower left corners of the internal square. If a horizontal or vertical line segment is removed from the "cross" vertex, that corner unambiguously indicates a particular view of the cube. (From *Handbook of perception and human performance*)

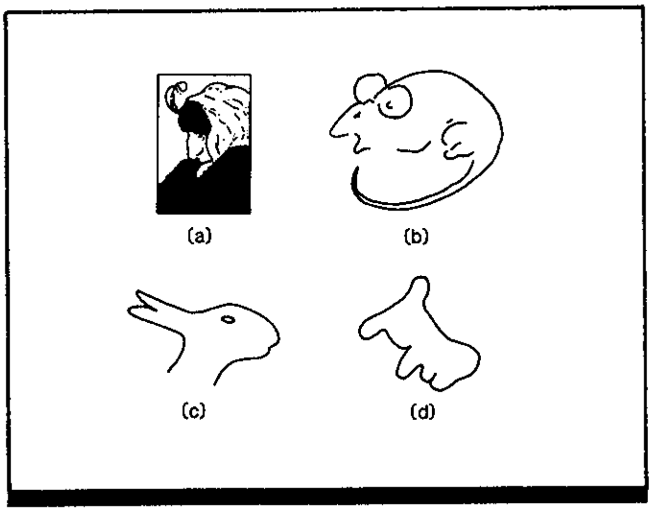

Figure 2. Ambiguous figures that can be perceived as representing different familiar objects: (a) Boring's young woman or old woman, (b) rat or man (from Ref. 2), (c) Jastrow's duck or rabbit, (d) chef or dog (from Ref. 6).

Key Terms

Form perception; multistability; Necker cube; reversible figure

General Description

A stimulus that either does not give rise to one dominant percept, or that permits easy shifting from one organization to another, is called a reversible or multistable figure. When a line drawing, for instance, permits two alternative interpretations, only one of the interpretations is perceived at one time. Typically, during prolonged viewing, the observer sees first one interpretation and then the other. Reversals occur at irregular intervals. Figures 1 and 2 show examples of multistable or reversible figures. The accompanying table summarizes recent research on reversible figures, which indicates that interpretation is affected by, among other things, the experience and direction of gaze of the viewer.

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Constraints

- The actual mechanisms responsible for multistability are not yet understood.

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Cross References

Handbook of perception and human performance, Ch. 33, Sect. 1.9; Ch. 36, Sect. 1.1

Table 1. Some factors and characteristics in the perception of reversible figures.

Factor	Description	Source
Rate of pattern reversal	Classically considered to accelerate over time, but this effect more likely is attributable to the long latency of the initial reversal	Refs. 3, 4
	Absolute number of reversals depends upon the subject's knowledge of the figure's reversibility (i.e., more reversals for observers who know beforehand that the figure is reversible); long initial latency occurs for both naive and informed observers	
Previewing of unambiguous patterns	Informed observers familiar with reversible figures tend to see the alternative interpretation of the ambiguous figure after viewing an ambiguous version favoring one interpretation	Ref. 3
Rated strength of interpretation	Correlates with length of exposure to a particular interpretation of ambiguous figure	Ref. 5
Multiple patterns	Groups of Necker cubes tend to reverse together	Ref. 7
	Groups of triangles tend to reverse apparent "direction" together	Ref. 1
Fixation patterns	Parts of figures that tend to be visually fixated differ for alternative interpretations of ambiguous figures	Ref. 7
	With Necker cube, figure tends to reverse when "Y" vertices are fixated (Fig. 1)	Ref. 7
	With Necker cube, observer tends to fixate "Y" vertex associated with most forward corner of current interpretation, which then reverses	
Disambiguation and observer set	When Necker cubes are ambiguous at one "cross" vertex and unambiguous at the other (Fig. 1), figure still reverses; when ambiguous corner is fixated, observer can also have some success at shifting perceptions when prepared to see one or another interpretation	Ref. 5

6.307 Pattern Processing: Effect of Pattern Complexity

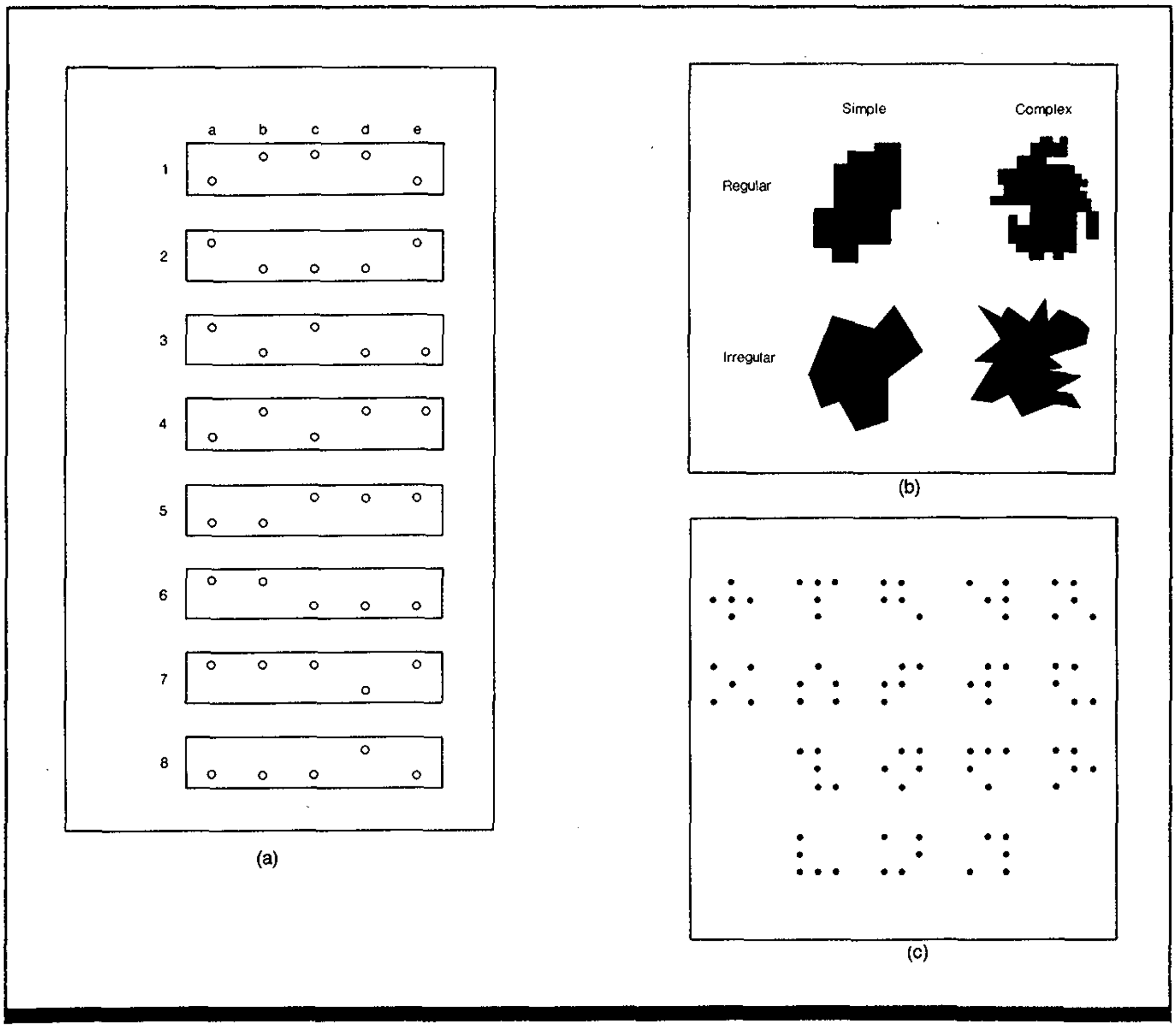

Figure 1. Example of stimuli used to investigate the effect of pattern complexity on information-processing tasks. (a) Display containing ten lights, arranged as two rows of five lights each, used in Ref. 3. Patterns are created by illuminating one of the two lights in each of the five columns. In one condition, only the lights in the three rightmost columns (c, d, and e) are illuminated; in the other conditions, the lights in columns a and b are added, but these are completely redundant with the other three lights (that is, the lights in columns c, d, and e alone still uniquely identify each of the patterns). (b) Four examples of the patterns used in Ref. 6. The patterns vary in "simplicity," measured by the number of sides the pattern contains, and "regularity," measured by whether the pattern is constrained to contain only right angles or can contain angles of any magnitude. (c) Representative sample of the patterns used in Ref. 5 as well as by many other investigators. The patterns are created by filling in five of the nine cells of an imaginary 3 x 3 matrix, subject to the constraint that each row and column in the matrix contain at least one dot. The patterns in the leftmost column are the "best" (and most symmetrical) configurations and come from a rotation and reflection (R & R) subset of one, which means that only one pattern results as the stimulus is rotated in 90° increments or is reflected. The patterns in the next two columns are of intermediate goodness and come from an R & R subset of size four. The patterns in the two rightmost columns are poor and come from R & R subsets of size eight. ([a] from Ref. 7; [b] from Ref. 6; [c] from Ref. 9)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Pattern complexity; pattern identification; pattern perception; temporal pattern perception; visual information processing

General Description

Pattern complexity affects performance on a variety of information-processing tasks. In general, increasing the complexity of stimulus patterns decreases the accuracy and speed of task execution. The table summarizes some of these effects.

Key References

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Cross References

6.308 Pattern processing: context effects;

Handbook of Perception and Human Performance, Ch. 36, Sect. 7.3

Pattern	Task	Outcome	Source
Lights arranged in rows (Fig. 1a)	Learn unique verbal labels for unique patterns of lights; respond with appropriate label when pattern presented	When complexity is increased by increasing number of lights in patterns, labels take longer to learn, and speed of responding slows	Ref. 3
Geometric forms (Fig. 1b)	View pattern A, then select it from a set of patterns of the same complexity and regularity	Complex patterns are identified more slowly but more accurately than are simpler patterns	Ref. 6
Dot patterns (similar, but not identical to Fig. 1c)	Identify and reproduce patterns	Symmetrical patterns are identified more accurately than random patterns	Ref. 6
		Increasing the size of the matrix on which patterns are based decreases accuracy	Ref. 1
Dot patterns (Fig. 1c)	Speed sort decks of cards with one of a pair of patterns on each card	Two simple patterns are sorted most quickly; two complex patterns, slowest; with one simple and one complex pattern, sorting time intermediate	Ref. 5
Dot patterns (Fig. 1c)	Identify pattern under **backward masking** conditions	Simple patterns are identified more accurately than are complex patterns	Ref. 2
Dot patterns (Fig. 1c)	Decide whether flashed pattern is a member of a previously memorized set of patterns	Speed advantage in recognizing simple patterns increases with size of the memory set	Ref. 4
Auditory patterns produced by alternation and repetition of a pair of tones	Reproduce patterns	Complex patterns (classified by number of perceived starting points) are reproduced less rapidly and less accurately than are simpler patterns	Ref. 7

6.308 Pattern Processing: Context Effects

Key Terms

Embedded figure; form perception; object superiority effect; pattern masking

General Description

Observers can identify a briefly flashed line segment more often when it is embedded in a drawing that appears unitary and three-dimensional than when it is embedded in a less coherent, flat design. This phenomenon is known as the *object superiority effect*. Under certain conditions, an object's context facilitates its identification compared to no context at all (Ref. 5). Line identification is enhanced when the line is relevant to the overall pattern structure, the context pattern is three-dimensional, and the context pattern is a closed (rather than open) pattern; the salience of local configurations also affects line identification (Refs. 2, 3).

Applications

Development of camouflage techniques; design of machine pattern-recognition routines.

Methods

Test Conditions

- Target lines were four diagonal line segments which differed in orientation and location relative to fixation; target lines were embedded in context patterns shown in Fig. 1; stimuli displayed on CRT
- Display duration was one of three values selected for each observer to yield 50, 60 or 70% identification accuracy
- Display followed immediately by 100-msec masking stimulus composed of large square dots to minimize persistence of image
- All possible combinations of target, context pattern, and duration were presented five times per daily session
- Three hundred sixty or 420 trials per subject for each context pattern

Experimental Procedure

- Independent variables: target line position and orientation, context pattern, display duration
- Dependent variable: percentage of targets correctly identified
- Observer's task: identify which of the four diagonal line segments was present in each display
- 6 observers completed six sessions with context patterns *a, b, c, e*; 9 observers completed seven sessions with context *a, d, f*

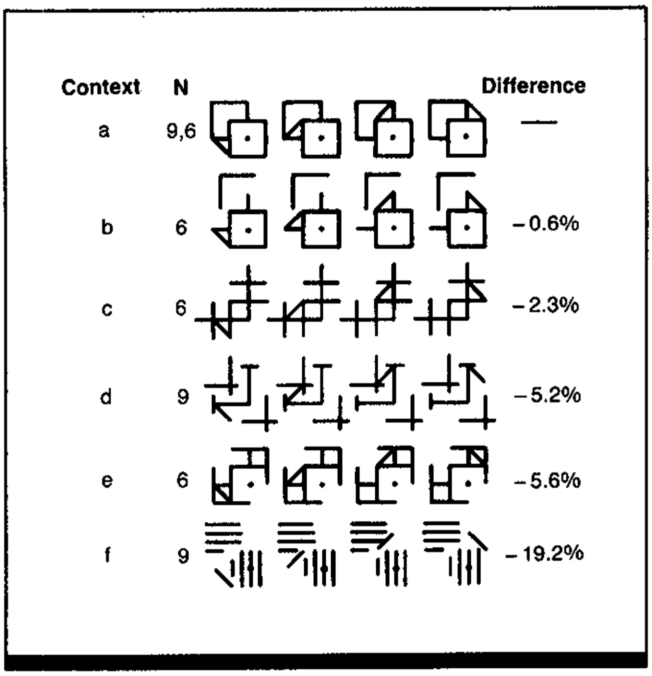

Figure 1. Relative accuracy in identifying line segments when presented in various contexts. The target line segments are the diagonal lines in each of the four context pattern variants. "Difference" value is the mean decrease in accuracy for each context compared to context *a*. *N* is the number of subjects tested with each context. (From Ref. 4)

Experimental Results

- All observers are more accurate in identifying line segment embedded in context pattern *a* than in patterns *d, e,* or *f*, regardless of stimulus duration. Lines are thus easier to identify in a unitary three-dimensional picture than in a less well-structured pattern.
- Target line position and orientation have no effect on performance.

Variability

Analysis of variance and Dunnett's multiple computation test were used to determine significance of the independent variables and interactions.

Repeatability/Comparison with Other Studies

The object superiority effect has been reported numerous times (Refs. 2, 3, 4, 5) and may be considered analogous to the word superiority effect (CRef. 8.104).

Constraints

- Location of the fixation point (i.e., visual-field position of the target) can affect the object superiority effect (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

6.307 Pattern processing: effect of pattern complexity;

6.309 Perceived shape: effect of target orientation;

8.104 Letter recognition: effect of context

6.309 Perceived Shape: Effect of Target Orientation

Key Terms

Form perception; pattern recognition; shape perception; spatial orientation

General Description

The spatial orientation of a pattern affects its perceived shape. Consequently, the identity of two patterns which differ only in orientation may not be readily evident. This is illustrated by the patterns of Fig. 1 which are, in fact, of the same shape. In addition, one may fail to recognize a pattern one has seen before, if it is presented in an unfamiliar orientation (Fig. 2). Exceptions to the principle occur when an observer can consistently assign top, bottom, and sides to a figure despite changes in orientation.

The following are some findings regarding the effects of orientation on perceived shape:

- A very familiar figure (Fig. 3c) is recognized even when seen in an unfamiliar orientation (Ref. 1).
- A figure with a prominent intrinsic axis (Fig. 3d) and some degree of symmetry about that axis does not look very different in other orientations.
- Mirror image reversal does not greatly affect perceived shape (Fig. 3e).
- Knowledge about a figure's orientation (i.e., where the top is located) opposes changes in perceived shape.
- For fairly complex forms, however, the ability to assign a consistent top or bottom may be insufficient for proper shape recognition. This finding is illustrated by the script in Fig. 3f and the amusing facial illusion in Fig. 4.
- A figure's shape usually does not appear different if its orientation is changed *only* with respect to retinal coordinates (as, for example, when the observer is tilted and the figure remains upright; Fig. 3b) (Ref. 2).

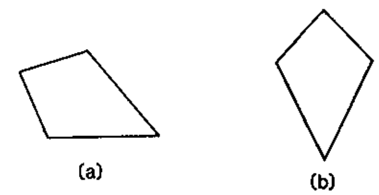

Figure 1. Although (a) and (b) are the same figure, they look quite different by virtue of their differing orientations. (From *Handbook of perception and human performance*)

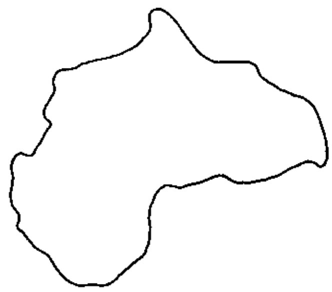

Figure 2. This outline is not recognizable unless one knows that its top is tilted to the left. (The outline is of Africa.) (From *Handbook of perception and human performance*)

Key References

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Cross References

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.620 Visual acuity with target motion: effect of direction of movement and target orientation;

1.634 Contrast sensitivity: effect of target orientation;

5.924 Stereoacuity: effect of target orientation;

5.924 Stereoacuity: effect of target orientation;

6.311 Perception of shape distortion;

6.315 Mental rotation of objects;

Handbook of perception and human performance, Ch. 33, Sect. 2.2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

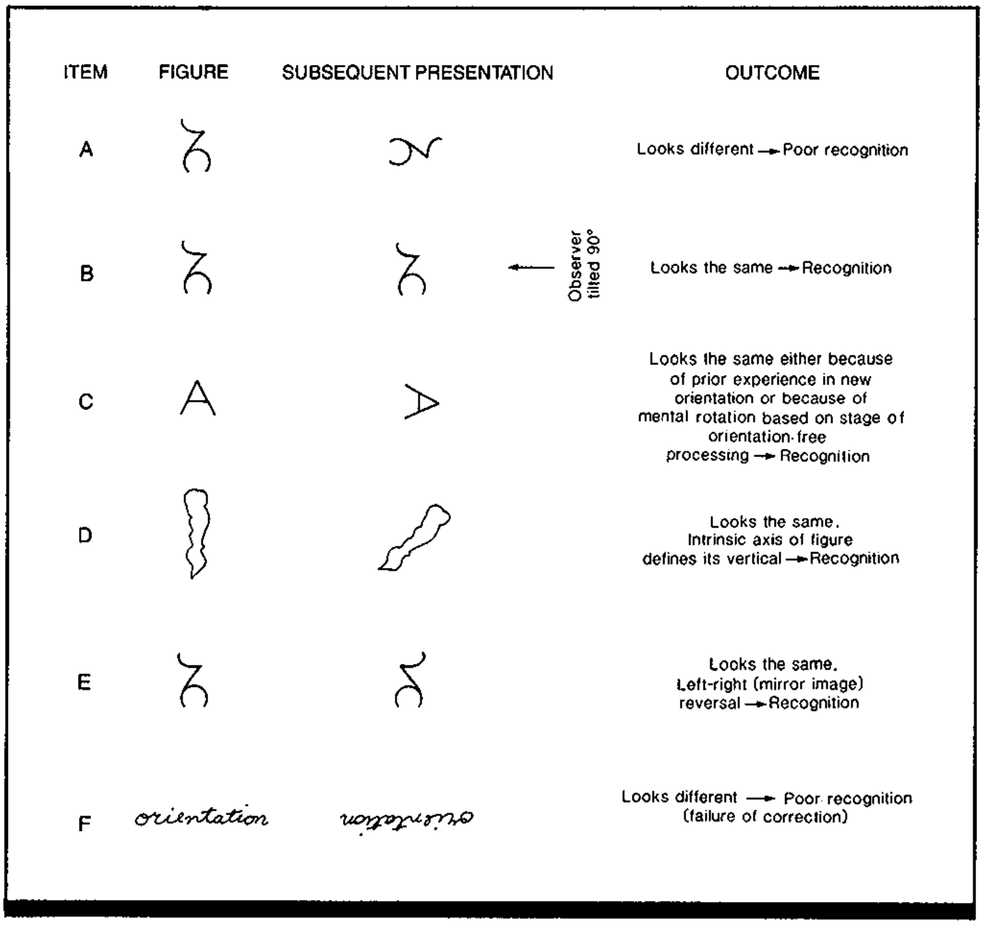

Figure 3. Effects of a change in orientation on subsequent recognition of a pattern. (From *Handbook of perception and human performance*)

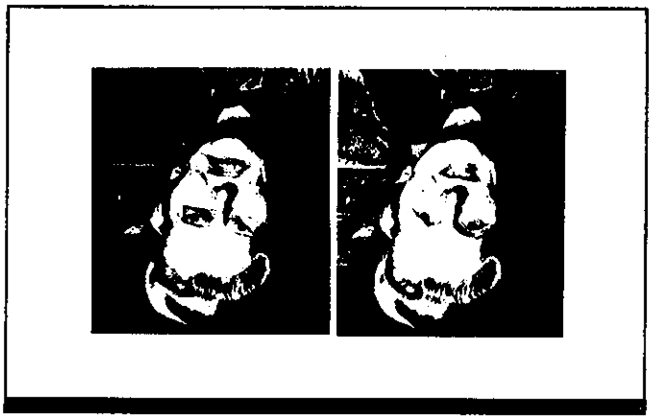

Figure 4. The extreme distortion in one of these pictures of Margaret Thatcher is not detected until the pictures are turned around 180 deg. (From Ref. 3)

6.310 Perceived Shape of Partially Hidden Objects

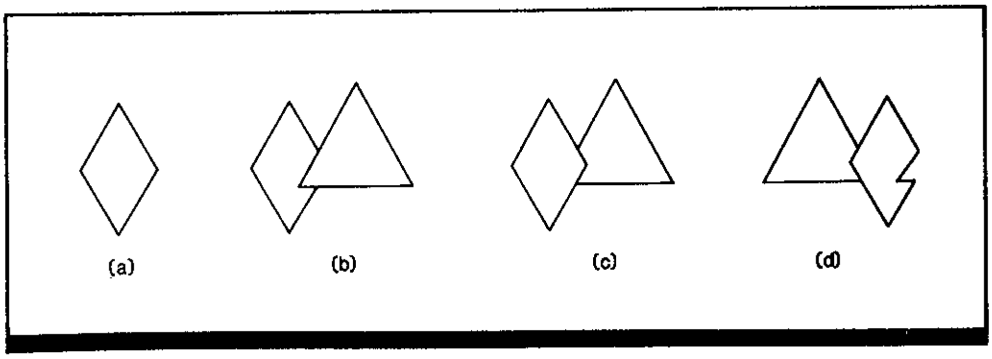

Figure 1. Figural completion. Although not all of the diamond is visible in (b), one tends to perceive it as (amodally) complete. Experiments show that reaction time is almost as rapid to identify the incomplete diamond in (b) as to identify the complete one in (c). Performance is significantly poorer with presentation of a truncated diamond (d) based on what is directly visible in (b). (From *Handbook of perception and human performance*)

Key Terms

Amodal perception; depth perception; Gestalt principles; good continuation; interposition; simplicity principle

General Description

Because the image on the retina of the eye is a two-dimensional projection of surfaces in three-dimensional space, it is common for objects in the retinal image to be partially occluded (hidden) by other objects. We often perceive the occluded object in its entirety, a phenomenon known as *amodal perception*. ("Amodal" is a poor term since it implies that the perception arises from no particular sensory modality; the phenomenon is a visual perception in the absence of corresponding visual stimulation in the given retinal region.) The equivalence of an amodally completed percept to one in which the figure is seen in its entirety has been demonstrated by pattern recognition studies in which the observer is first shown a drawing of a target pattern, such as the diamond in Fig. 1a, and then tested with patterns such as Fig. 1b-d in which the target pattern is sometimes incomplete. The diamond shape is recognized equally quickly in Figs. 1b and 1c. It takes longer to detect the diamond-like shape in Fig. 1d despite the fact that it produces exactly the same retinal image as does Fig. 1b. Listed below are several principles thought to govern amodal perception as well as illustrations of their relative effectiveness.

Good continuation

According to this well-known Gestalt principle of pattern organization (CRef. 6.301), pattern elements tend to be grouped into a whole in a way that minimizes abrupt changes in visual direction. Good continuation can be effective in determining what region the shared contour belongs to and what the amodally completed object should look like. In Fig. 2a, good continuation of the cross of the T vertices defines the square as being in front. Amodal extension of the center poles of the T's leads to the perception of a single right-angled corner hidden by the square and generally perceived by observers. This use of T junctions has been successful in machine vision (Ref. 2).

Experience

In normal perception, occluded objects are often familiar and their shapes well known. Familiarity is an important determinant of amodal completion; our experience with familiar objects can affect the outcome of organizational processes that determine figure and ground. In Fig. 2c, the presence of a facelike contour gives the right-hand shape the appearance of an object in front, despite the presence of good continuation cues that cause a similar shape to be seen as behind in Fig. 2d (Ref. 3; CRef. 6.301).

Parsimony

For Fig. 2b, experience and good continuation of T vertices are insufficient to determine the shape of the occluded object. Most observers report that it appears pentagonal. That is, the missing part is filled in, in the simplest way possible.

Simplicity

According to the simplicity principle, perception is organized to achieve the simplest or most economical interpretation of the stimulus (CRef. 6.303). This principle may be operative in amodal completion, but few subjects viewing the examples in Fig. 2b report the hexagonal shapes that such a theory would predict (Ref. 1).

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Applications

Occlusion is a problem for machine pattern recognition systems. The concept of amodal completion and the strategies used in human pattern recognition should be valuable to programmers working on solutions to these problems.

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Cross References

5.901 Monocular distance cues;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.303 Simplicity and likelihood principles;

Handbook of perception and human performance, Ch. 33, Sect. 2.3

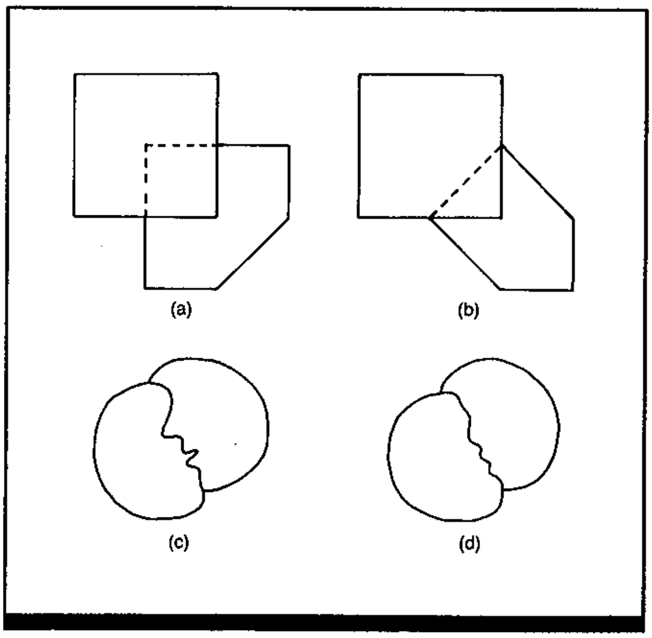

Figure 2. Amodal completion governed by (a) good continuation and (b) parsimony. The perceived interposition in (c) would seem to be based on familiarity with faces, since otherwise the nature of the T organization favors the reverse organization based on good continuation seen in (d). (From *Handbook of perception and human performance*)

6.311 Perception of Shape Distortion

Table 1. Minimum percentage increase or decrease in the length of the horizontal or vertical sides of a square for the square to appear as a rectangle. (From Ref. 3)

	Square Size in Degrees				
	7.84	3.92	1.96	0.98	Mean
Horizontal distortion	1.4%	1.2%	1.4%	1.4%	1.4%
Vertical distortion	1.3%	1.4%	1.6%	1.4%	1.4%

Key Terms

Form perception; shape discrimination; visual distortion

General Description

Horizontal or vertical distortion of a square shape will not be perceived if the distortion is less than 1.4% of the original length. Unlike other visual functions, shape discrimination does not vary systematically with target size and illumination.

Applications

Design of display symbology where discrimination among rectilinear shapes is required and/or psychological "distortion tolerances" must be considered (e.g., through an airplane windshield).

Methods

Test Conditions

- Basic set of targets comprised of 25 × 25 mm square and 20 rectangles with one dimension of 25 mm and other dimension of 20-30 mm, varied in 0.5 mm steps; three series made by reducing originals to 1/2, 1/4, and 1/8 original size
- Visual-angle dimensions for square: original = 7.84 deg, 1/2 = 3.92 deg, 1/4 = 1.96 deg, and 1/8 = 1.25 deg; 0.5-mm one-step dimension change caused a visual angle change of 10 min arc for original size, 5 min arc for 1/2 size, 2.5 min arc for 1/4 size, and 1.25 min arc for 1/8 size
- Black figures photographed onto slides so variable dimension could be presented as either horizontal or vertical
- Illumination of 318, 31.8, 3.2, 0.32, 0.03, or 0.003 cd/m^2 (100, 10, 1, 0.1, 0.01, or 0.001 mL, respectively); for three highest levels, 5-min dark adaptation and then 2-min light adaptation; for 0.32 cd/m^2 7-min dark adaptation and then 2-min light adaptation; for two lowest levels, 40-min dark adaptation and then 5-min light adaptation
- Target or adapting light observed through a metal tube projected into a darkened room; tube contained an artificial pupil 3 mm in diameter and a double convex lens; accommodation was for infinity
- Targets presented for 2 sec each; 8-sec interstimulus interval
- For first experiment, each session limited to targets of a single series (e.g., 1/8 of original size); for second experiment, a session containing some targets from each size series was used to prevent observers from basing judgments on changes in area of blackness or opacity; for the third experiment, targets were presented in pairs

Experimental Procedure

- Independent variables: target luminance, size of target series, dimension of distortion
- Dependent variable: smallest detectable change in the horizontal or vertical dimension, defined as the standard deviation of "plus" responses; table plots smallest detectable changes as a percentage of baseline size
- Observer's task: respond "plus" if the square appeared distorted by stretching or elongation and respond "minus" if figure distorted by contraction (in either horizontal or vertical dimension)
- 5 observers

Experimental Results

- The difference threshold for shape distortion of a square (smallest perceivable length change in the horizontal or vertical sides of a square) is 1.4% of the original length of the side, averaged across all experimental conditions.
- The difference threshold for shape distortion of a square is roughly the same regardless of the original size of the square or whether distortion is in the horizontal or vertical dimension.
- Difference threshold shows no consistent differences due to illumination level (data not shown).

Variability

Chi-square tests and analyses of variance were used. The smallest perceivable distortion varied between 0.9% and 2.1% for individual subjects.

Repeatability/Comparison with Other Studies

The results obtained do not resemble the changes in visual acuity or intensity discrimination with changes in illumination level. Difference thresholds for distortion are on the same order as difference thresholds for line length and judgments of squareness (Ref. 3).

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Constraints

- The targets used were rectangles; different results might be obtained using different geometric forms.
- The targets were viewed against a homogeneous background. Different results might be obtained if other figures were positioned near the figures being judged.
- Different luminance contrasts might yield different results.

Key References

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6.312 Form Perception: Contribution of Different Spatial-Frequency Bandwidths

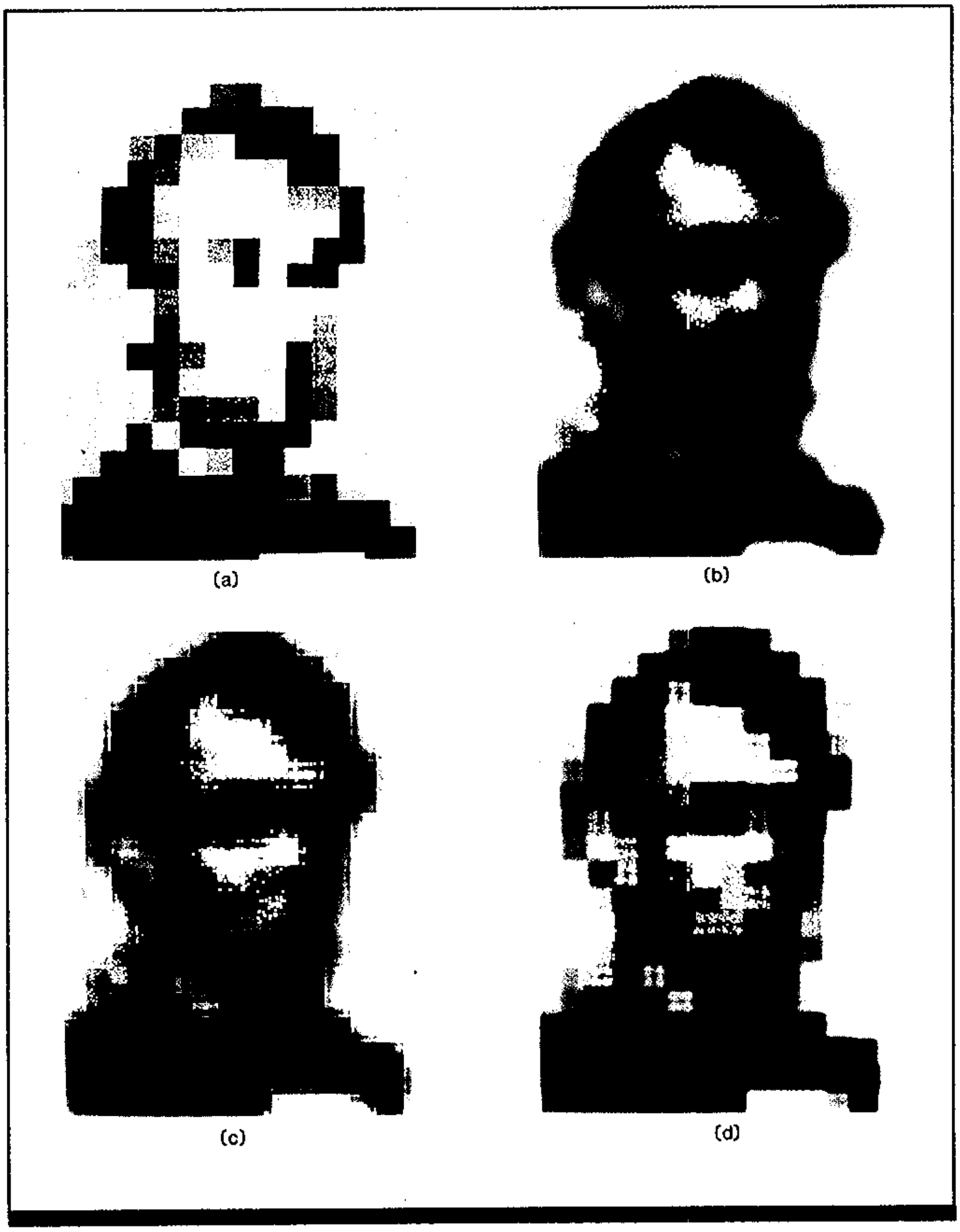

Figure 1. (a) A photograph of Abraham Lincoln low-pass filtered and digitized into 300 square sections. (b) The digitized image low-pass filtered, with all frequencies higher than 10 cycles per picture-width removed. (c) Filtering with only intermediate frequencies of 10-40 cycles per picture-width removed. (d) Filtering with only frequencies above 40 cycles per picture-width removed. (From Ref. 4)

Key Terms

Digitization; form perception; image processing; pattern recognition; spatial filtering; visual masking

General Description

Current image-processing technology allows spatial filtering of images so that the information (image content) contained in discrete spatial-frequency bandwidths can be directly viewed. Such filtering makes it evident that different types of form information are contained in different spatial-frequency bandwidths. Spatial filtering also allows exploration of the effects on form perception of various image transformations, such as digitization, which may obscure image features. These explorations reveal the source of masking in digitization to be limited to bandwidths close to the picture information, rather than due to the sharp edges introduced by such digitization (Ref. 2). These results also have implications for theories of human vision that postulate bandpass filtering as a fundamental operation in pattern

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

recognition. Figures 1 and 2 are illustrative of this approach. The principles they illustrate are described below.

Obscurement of Facial Features by Digitization

Digitization introduces quantization noise into an image that can impede identification of the form (Fig. 1a; Ref. 2). The harmful effects of digitization can be reduced by blurring as illustrated in Fig. 1b. Figures 1c and 1d were designed to precisely locate the source of masking in the quantized image. In Fig. 1d, the highest frequency components of the noise have been removed, but the picture remains obscure; this makes unlikely an explanation of the benefits of blurring that stresses removal of only the highest frequencies introduced by digitization. In Fig. 1c, the high-frequency components of the noise are preserved, but the spatial frequencies in a two-octave band above the picture information have been removed. Visibility is improved, suggesting that the quantization noise that is relatively close in spatial frequency to the picture information is the source of masking.

Applications

Identification of spatial frequency components conveying critical form information and the source of camouflaging noise in processes like digitization should enable the development of image-processing and image-storage technologies that are maximally efficient for the purposes designed.

Constraints

- It should be kept in mind that a processed image is subject to filtering by the viewer's visual system, as well as by the filtering operations of the image processor.

Key References

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Cross References

5.107 Geometric illusions: contribution of low-spatial-frequency information;

Handbook of perception and human performance, Ch. 7, Sect. 3.2; Ch. 34, Sect. 9

Spatial Features Contained in Different Bandwidths of an Image

The images of Fig. 2 are bandpass-filtered images of the original figure shown at the top that are two octaves wide, with the center frequency of the bands increasing in one-octave steps. At the lowest spatial frequencies, only a vague object shape is recognizable. At somewhat higher frequencies, the object is clearly a face; at still higher frequencies, sufficient detail is presented to recognize a young woman. The highest filtered frequency carries precise information about her facial features. The poor contrast of the high-frequency images clearly illustrates the reduced energy at high frequencies (and our poor sensitivity to these frequencies). This high-frequency information is particularly susceptible to disruption by movement, long viewing distances, poor illumination, display scan structure, etc. (Ref. 1).

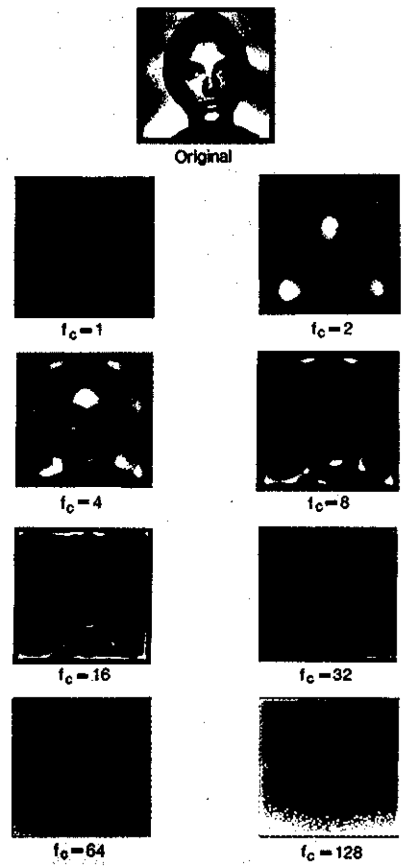

Figure 2. A hierarchy of filtered portraits. The original portrait (top center) was filtered several times using two-octave-bandwidth channel filters. The center frequencies of the filtered bandwidths are one octave apart, starting from 1 cycle per face width (center frequencies are indicated below each panel). (From Refs. 2 and 3)

6.313 Perception of Chromatic and Achromatic Borders

Key Terms

Achromatic border contrast; border contrast; border distinctness; brightness induction; chromatic border; edge effect

General Description

The level of contrast (luminance difference) between two adjacent areas is a determining factor in whether they will be viewed as a single homogeneous field or as two distinct fields separated by an edge or border. The solid curve in Fig. 1 illustrates the expected effect of luminance contrast on border distinctness for achromatic (colorless) fields, derived from experiments using small, centrally viewed targets at photopic luminance levels. Contrast between two areas must be approximately 0.04 (4%) for the perception of a minimally distinct border. When contrast reaches ~0.3, the border appears very distinct. Increasing the contrast beyond ~0.4 has little additional effect on the strength of the border.

The perception of a border between two fields is slightly enhanced when at least one of the fields is chromatic (that is, has hue). The dashed curve in Fig. 1 illustrates the expected distinctness of a border separating two fields of differing color (green and white, in this instance). Even when luminance contrast is zero, a border is perceived that is as distinct as an achromatic border would be for fields with a luminance contrast of about 0.1. This value (0.1, in this instance) is referred to as *equivalent achromatic contrast* (EAC). (Larger EAC values indicate a more distinct border.)

It is important to mention that, when the border between them is minimally distinct, differently colored fields will not, in general, appear equally bright. Conversely, if the observer is instructed to adjust the luminance contrast so that the fields are equally bright, the border will not usually appear minimally distinct. This is because observers differ in their sensitivity to light of different wavelengths and because chromatic border perception seems to be governed by the same laws that apply to flicker photometry rather than heterochromatic brightness matching (CRefs. 1.109, 1.303).

In some cases, fields that differ in chromaticity will not form a distinct border at all when their luminance contrast is zero. This occurs for colors that lie along tritanopic confusion lines (Ref. 5, pp. 463-471 and 604-619). It has therefore been theorized that blue cones do not contribute to border distinctness. In such instances, the border appears to "melt," although the difference between the fields' colors remains visually obvious (Ref. 4).

Degree of border distinctness, as a function of luminance contrast, tapers off more rapidly for chromatic areas than for achromatic ones. At some contrast level (about 0.25 for green and white areas), chromatic and achromatic fields have the same strength of border. Beyond that point, border distinctness will be higher for achromatic areas than for chromatic areas with the same luminance. Thus, the addition of chromatic contrast to fields that already differ in luminance does not always enhance, and may actually reduce, border distinctness.

Border perception for chromatic targets can be studied by placing a chromatic target adjacent to an achromatic standard and adjusting the luminance of the chromatic target until a border is just seen. Then, the luminance contrast of a nearby achromatic pair of stimuli is adjusted until the distinctness of their border matches that of the chromatic/achromatic pair. This adjustment yields the chromatic/achromatic pair's EAC. The results from an experiment of this type, which used monochromatic colors, are shown in Fig. 2. Such experiments have been used to measure the saturation of a chromatic target, where the EAC for a given chromatic target is taken as an index of its saturation.

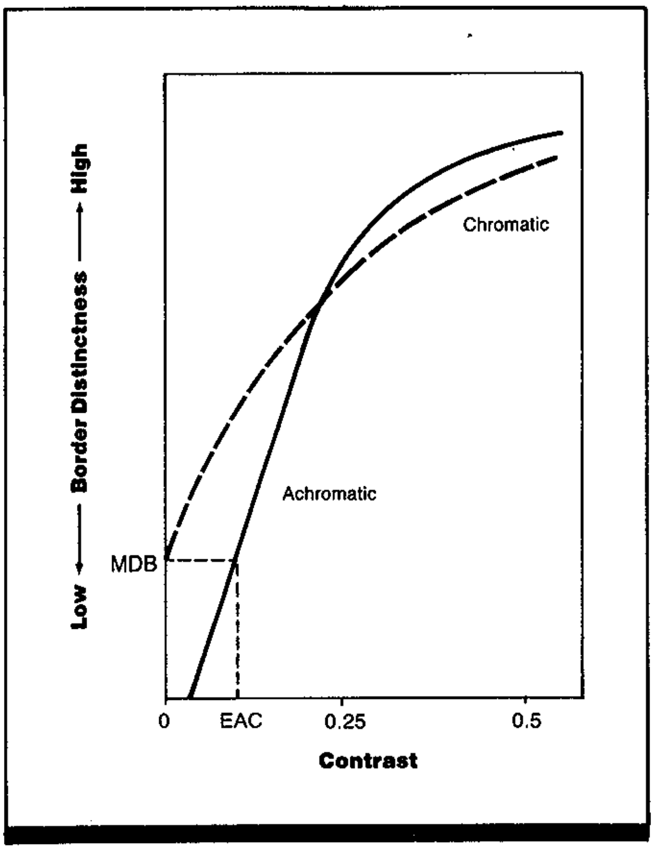

Figure 1. Schematic illustration of the distinctness of a border or boundary between two fields as a function of luminance contrast for: (1) two achromatic fields (solid curve) and (2) a green and a white field (dashed curve). MDB indicates minimally distinct border. Luminance contrast is defined as Michelson contrast (the difference in the luminances of the two fields divided by the sum of the luminances of the two fields). An equivalent achromatic contrast (EAC) yielding the same border distinctness as the MDB of a chromatic pair may be found by drawing a horizontal line from the chromatic to the achromatic curve and a vertical line from this point to the horizontal axis. (From Ref. 1)

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Applications

Development of metrics for assessing the legibility of colored symbols.

Constraints

• Whether the chromatic field is more or less luminous than its adjacent white field does not significantly affect border distinctness for equal luminance contrasts (Ref. 3).
• Equivalent achromatic contrast (EAC) values are lowest in the green-yellow central portion of the visible spectrum (Ref. 3).
• Higher but more variable equivalent achromatic contrast values are obtained at lower overall retinal illuminance levels (Ref. 3).
• Individual differences are extremely important in the perception of borders.
• If a highly chromatic field is juxtaposed with a white field and a determination of minimally distinct border is made, the chromatic field will appear definitely brighter than the achromatic one; the more saturated the chromatic field, the greater the brightness difference.
• Chromatic borders, as described here, are observed under relaxed viewing of fields subtending at least 1 deg of visual angle; such borders can be made to disappear if the fields are small and/or intensely fixated, or are stabilized on the retina using techniques that compensate for eye movements.
• Small, centrally fixated photopic fields were used in the studies for which data are shown; results may not hold for large luminous areas or those observed with peripheral vision.
• Slight artifacts at the edge of boundaries, always present in the real world, would be expected to yield different results than were obtained here, where pains were taken to ensure that the target fields barely touch without overlapping.
• Since chromatic borders are only minimally more distinct that achromatic borders (and at some contrast levels are less distinct), a more important function of color is to allow the absolute chromatic identification of regions within boundaries largely defined by achromatic vision (Ref. 3).
• Achromatizing lenses are rarely, if ever, used in practical applications. Therefore, boundaries in applied settings should always be more distinct than these results imply.

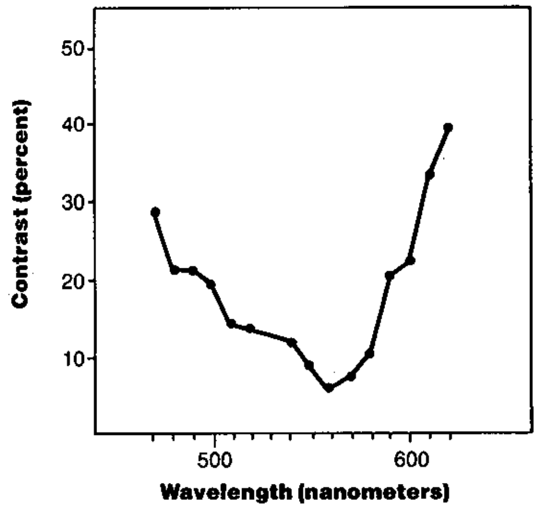

Figure 2. Equivalent achromatic contrast for monochromatic stimuli, as a function of wavelength. Each monochromatic test area is juxtaposed with a white (achromatic) standard and its luminance adjusted to produce a minimally distinct border. Then, the luminance contrast of a nearby achromatic pair is adjusted to yield an equally distinct border. The resulting luminance contrast of the achromatic pair is taken as the equivalent achromatic contrast for the monochromatic/achromatic pair. (From Ref. 1)

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Cross References

1.109 Photometric techniques for measuring spectral sensitivity;

1.303 Equal-brightness and equal-lightness contours for targets of different colors (spectral content);

Handbook of perception and human performance, Ch. 9, Sect. 2.4

6.314 Subjective or Illusory Contours

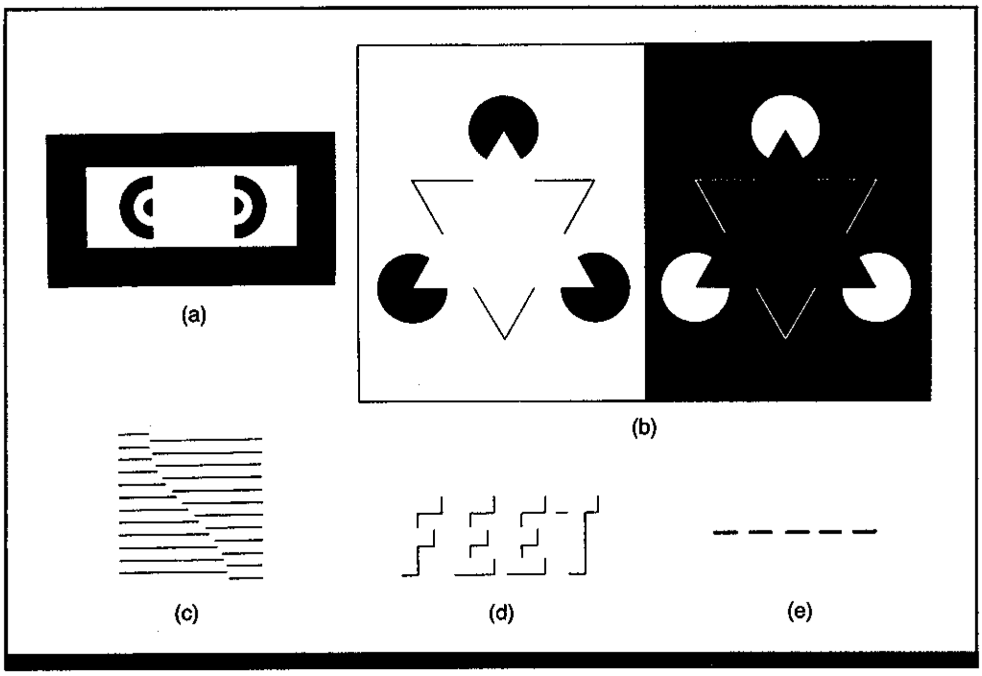

Figure 1. (a) Schumann's original demonstration of subjective contours. (b) Two of Kanizsa's subjective triangles. (c) Illusory contour without differences in brightness due to contrast; the line, however, does have a lustrous appearance. (d) The word FEET spelled using illusory contours. The contours do not result from occlusion cues, but from cues indicating the presence of unseen objects casting shadows. (e) A simple dashed line. The line is not filled in perceptually across the gaps, which indicates that illusory contours are not merely a matter of closure or of "filling in" ([a] from Ref. 13; [b] from Ref. 9; [c] from Ref. 10; [d] from Ref. 3)

Key Terms

Form perception; illusory contours; subjective contours; visual illusions

General Description

Abrupt luminance changes signal contours in normal perception. Under certain conditions, illusory (or subjective) contours can be produced, where no luminance gradient exists. These subjective contours can be constructed to create well-defined illusory figures with well-defined contours. The figures will appear to be in front of, and covering, parts of the actual contours that produce the illusion (inducing contours). The illusory figure will generally also appear to be of different brightness than the background. Figures 1-3 show examples of subjective contours. The accompanying table lists factors that affect the illusion, as well as some known properties of subjective contours.

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Cross References

Handbook of perception and human performance, Ch. 33, Sect. 2.3; Ch. 36, Sects. 5.3, 5.4

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

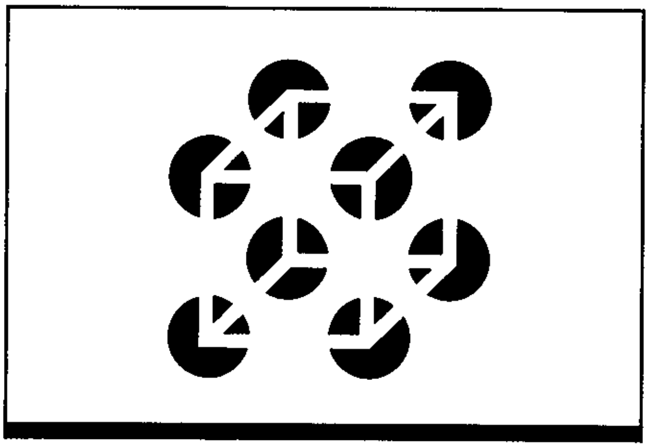

Figure 2. The illusory-contour Necker cube provides a powerful demonstration that illusory contours are not the result of some automatic perceptual process. This figure can be viewed as a white Necker cube floating above a set of eight black disks. If the figure-ground organization is reversed, however, it can be seen as a white Necker cube against a black background as seen through a white screen containing eight round holes. In the former case, illusory contours are seen; in the latter they are not. (From Ref. 1)

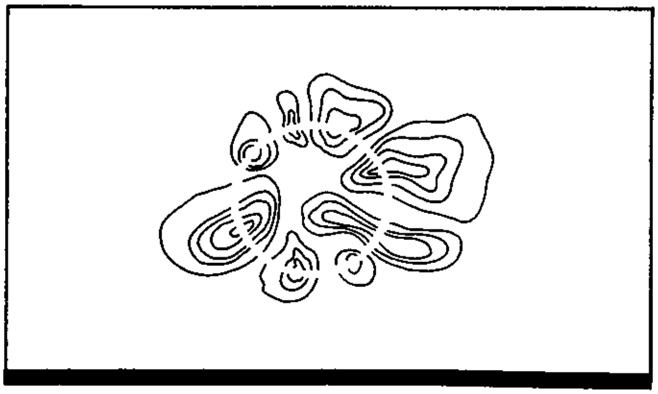

Figure 3. The greater the number of aligned fragments whose incompletion is accounted for by the perception of a figure (here a circle) that is partially occluding them, the more immediate, compelling, and stable is the illusory-contour figure perceived. (From Ref. 8)

Table 1. Factors affecting perception of subjective contours.

Factor	Influence on Subjective Contours	Source
Brightness gradients	Brightness gradients between inducing contours and background appear to facilitate the illusion; purely chromatic gradients are less effective	Ref. 2
Spatial frequency filtering	Subjective contours are more clearly seen in low-pass-filtered images	Ref. 6
Type of inducing contour	Line endings are particularly effective inducing contours for the illusion (Fig. 3)	Ref. 5
	Line endings are effective inducing contours even when no consistent inter-position cues exist (Fig. 1c)	Ref. 10
Depth cues	Random-dot stereograms produce their own variant of subjective contours	Ref. 7
	Binocular disparity cues consistent with an illusory object located in front of the rest of the pattern strengthen the illusion; inconsistent cues weaken the illusion	Ref. 11
Incompleteness of inducing contours	To the extent the inducing contours appear interrupted, the illusion is aided; figural properties which give inducing contours completeness, such as symmetry, reduce or eliminate the illusion	Refs. 10, 12
Contours in the region bounded by subjective contours	Contours in the region of the subjective figure tend to reduce the illusion, contradicting occlusion cues	Ref. 12
Experience	Perception of these subjective contours such as those of Fig. 1d requires experience with alphabet	Ref. 3
Perceptual organization	Subjective contours may be perceived under one interpretation of an ambiguous figure and not the other (Fig. 2)	Ref. 1
Detection thresholds	Despite uniformity of physical luminance, detection thresholds for spots of light are raised within the region of higher apparent brightness enclosed by the subjective contour	Ref. 4
Masking	Subjective contour **masks** raise real contour thresholds in an orientation-specific manner	Ref. 14

6.315 Mental Rotation of Objects

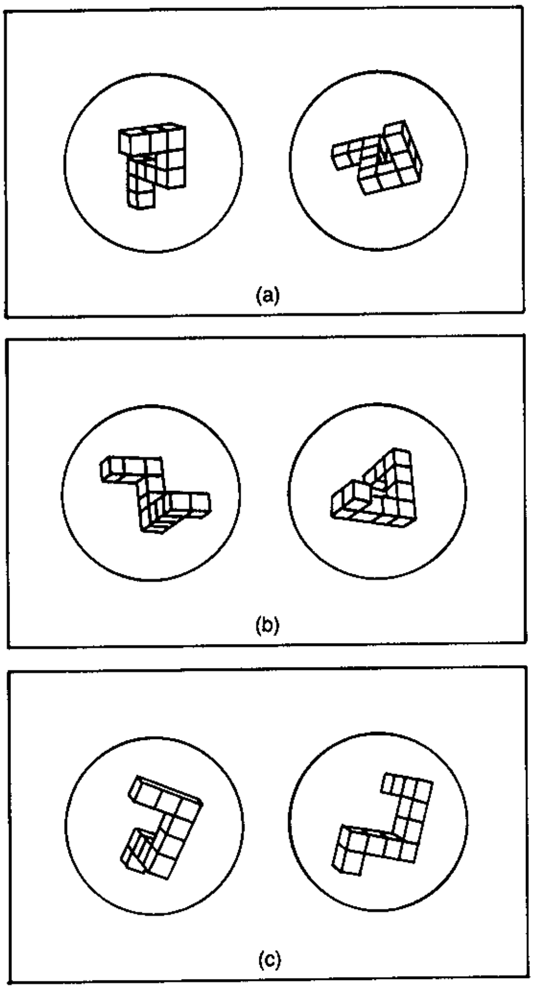

Figure 1. Examples of pairs of perspective line drawings presented to subjects: (a) a "same" pair differing by a rotation of 80 deg in the picture plane; (b) a "same" pair differing by a rotation of 80 deg in depth; (c) a "different" pair, which cannot be brought into congruence by any rotation. (From Ref. 4)

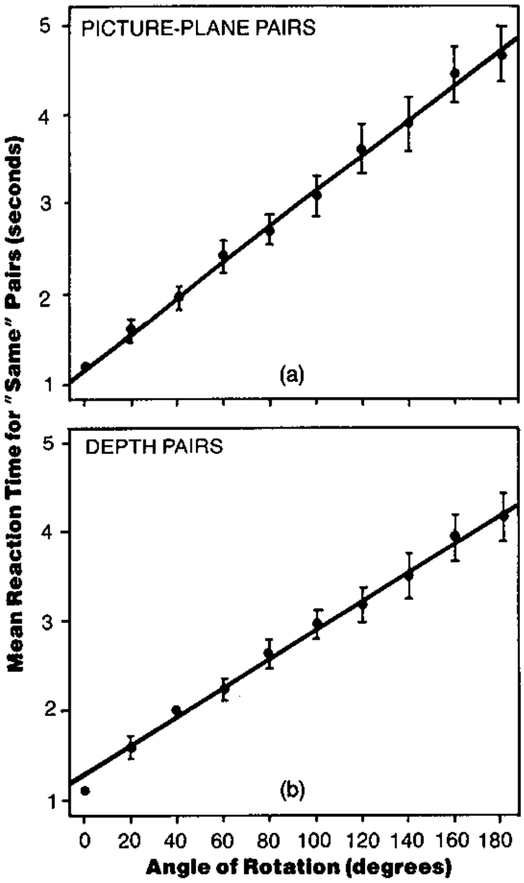

Figure 2. Mean reaction time to judge pairs of perspective line drawings as portraying objects of the same three-dimensional shape. Reaction times are plotted as a function of angular rotation (a) for pairs differing by a rotation in the picture plane, and (b) for pairs differing by a rotation in depth (see Fig. 1). (From Ref. 4)

Key Terms

Form perception; mental rotation

General Description

Observers can often determine that two two-dimensional images portray the same three-dimensional object even though the two images depict the object in very different orientations. When an observer must determine whether pairs of forms such as those in Fig. 1 are identical or mirror images of one another, the time to make the decision when pairs are identical is a linear function of the angular difference in portrayed orientations. This suggests that the observer performs this task by a mental process analogous to physical rotation of one or more of the figures until their orientations match and, as such, it has been interpreted as evidence for the reality of such processes as mental rotation and visual or spatial imagery (Refs. 1, 3, 4).

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Methods

Test Conditions

• Test stimuli were seven perspective drawings of five pairs of objects and their mirror images (Fig. 1)
• Pairs of images on cards were placed 9 deg of visual angle apart. Half the "same" pairs differed in fered in orientation by some multiple of 20 deg in the picture plane, called "picture plane pairs"; the other half of the "same" pairs differed by some multiple of 20 deg about a vertical axis, called "depth pairs"; for each "same" pair there was a corresponding "different" pair in which one of the images was a mirror image
• Each observer saw 400 unique pairs of 20 depth and 20 picture-plane images at each of 10 angular differences: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180 deg

Experimental Procedure

• Reaction time task
• Independent variables: angular rotational difference of images, type of rotation (depth or picture plane), same or mirror image object
• Dependent variable: response time
• Subject's task: indicate whether pair was "same" or "different" by a lever pull
• 8 observers

Experimental Results

• Reaction time to correctly identify two perspective drawings as portraying the same object (Fig. 2) is a linear function of the angular difference in the orientation of the objects in the drawings for both depth and picture plane rotations.
• On average, observers take almost 1 sec longer to identify a pair of drawings as representing different objects than to identify them as portraying the same object.

Variability

Error bars are conservative estimates of standard error, based on eight subject component means.

Constraints

• A number of stimulus factors, such as complexity and familiarity, may affect the slope of the function.
• Individuals differ in performance; those high in spatial ability, or claiming to have good mental imagery, show shallower slopes.

Key References

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Cross References

6.309 Perceived shape: effect of target orientation

6.316 Ambiguous Movement in Figures Without Texture or Fine Detail

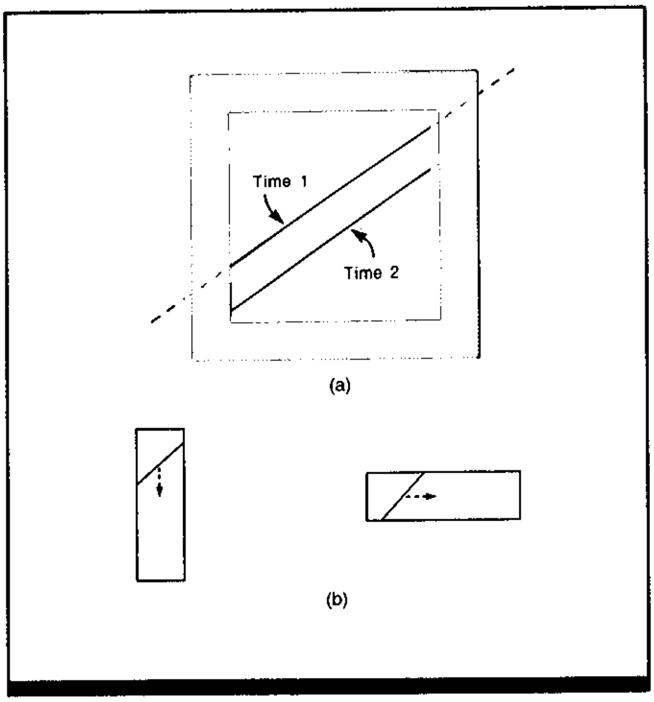

Figure 1. (a) The direction of motion of a line behind a square aperture is ambiguous. The segment visible at Time 2 appears the same whether movement is vertical, horizontal, or oblique. (b) With an elongated aperture, observers tend to perceive motion of the line as parallel to the long axis. (From *Handbook of perception and human performance*)

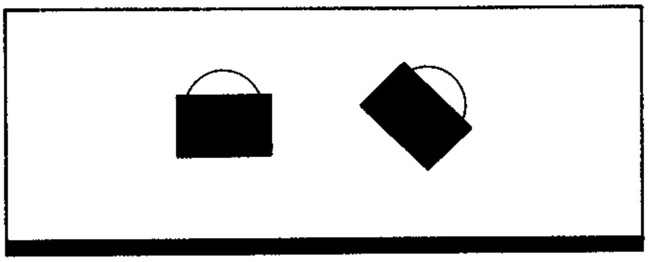

Figure 2. When this figure is rotated, observers tend to perceive that the circle remains stationary and that different portions of it are revealed as the rectangle rotates. (From *Handbook of perception and human performance*)

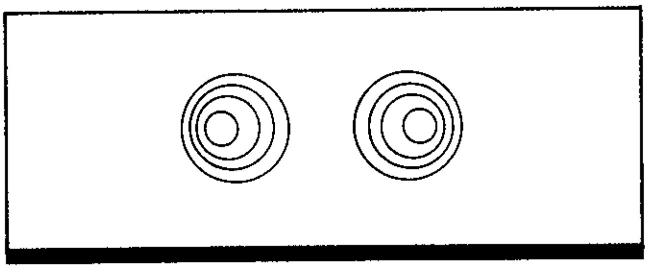

Figure 3. When figures such as these are rotated, the result is a powerful illusory impression of depth, termed the stereokinetic effect. The rotating images appear to be truncated cones or tunnels. The illusion of depth follows a period in which the pattern is seen as not rotating; rather the inner circles appear to shift laterally. (From *Handbook of perception and human performance*)

Key Terms

Ambiguous movement; event perception; machine vision; multistability; phenomenal rest; rotation; simulation; stereokinetic effects; visual illusions

General Description

Where lack of texture or detail in a line or figure contour makes it objectively impossible to differentiate unique parts of the contour, the direction in which the contour is moving may become ambiguous. For some rotating figures, this correspondence problem also arises in determining the phenomenal identity of contours over time (CRef. 5.406).

Multistability

If a straight line moves behind an aperture so that its endpoints are not visible, the direction of its motion becomes ambiguous. In general, the perceived direction of the line is determined by the shape of the aperture. If the aperture is elongated, the line is generally seen to move in a direction parallel to the long axis of the aperture (Fig. 1b). If the aperture is relatively square (Fig. 1a), a multistable perception can result (CRef. 6.306). That is, the direction of line motion alternates between parallel to one set of sides of the aperture and parallel to the other sides (Ref. 2).

Phenomenal Rest

When a circular disk rotates about its center, the only indication of this rotation is the circular trajectory of texture elements on the disk. In the absence of discernible perception of texture, rotation can be ambiguous, and, in fact, the disk is perceived to be stationary. Phenomenal rest (Ref. 1) is a strong tendency in perception. When the form in Fig. 2 is rotated, a rectangle is perceived to rotate around and partially occlude a stationary disk. If an ellipse is rotated, it will give rise to the illusion that it is undergoing plastic changes in shape but not rotating.

Stereokinetic Effect

The concentric circles illustrated in Fig. 3 are displaced so that their centers are not aligned. When patterns such as these are rotated, the initial impression of rotation is replaced by the illusion that the inner circles are shifting laterally and that the figure has depth, being a truncated tunnel or cone. This is known as the stereokinetic effect.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Machine vision, particularly the analysis of events extended over time.

Key References

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Cross References

5.406 Visual apparent motion: effect of perceptual organization;

6.306 Reversible or multistable figures;

Handbook of perception and human performance, Ch. 33, Sect. 4.2

6.317 Figural Aftereffects

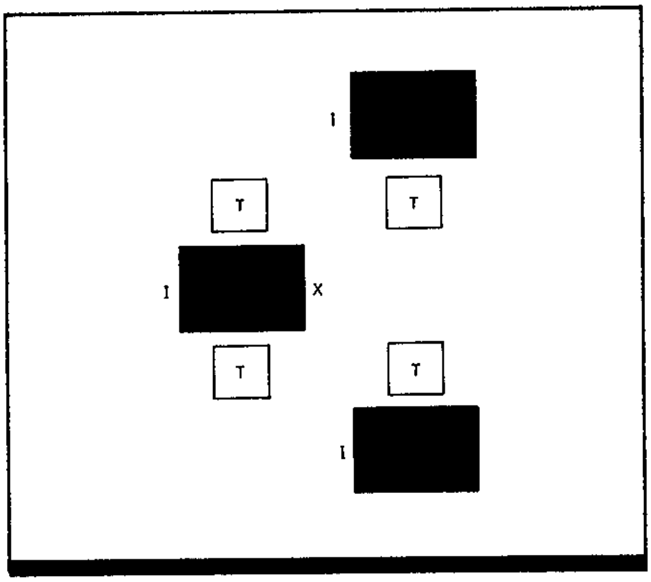

Figure 1. Aftereffect of displacement. The observer first fixates point *x* while viewing the inspection pattern of dark rectangles marked *I*. The pattern then disappears and the test pattern of equally spaced squares (*T*) appears, while the observer continues to fixate point *x*. The result is that the two squares on the left appear farther apart vertically than the squares on the right. (From *Handbook of perception and human performance*, after Ref. 7)

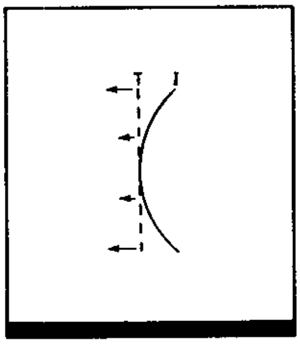

Figure 2. Aftereffect of curvature. When the observer views the curved line *I* and then views a straight solid test line (represented by the dashed line *T*), the test line *T* will appear slightly convex to the right as indicated by the arrows. (From *Handbook of perception and human performance*, after Refs. 2, 3)

Key Terms

Figural aftereffects; induction; perceptual displacement; visual illusions

General Description

Figural aftereffects occur when the appearance of all or part of a figure differs from its physical reality because of the influence of a previously observed figure. (The same effects may occur with simultaneous presentations under certain conditions; see Ref. 1.) To obtain figural aftereffects, one figure, called the inducing figure, is presented and removed. When a second figure containing one or more pattern elements is then presented, the apparent position of all or part of the figure is displaced from its actual position. For example, when observers first view for several minutes a display consisting of only the black rectangles of Fig. 1, and then view a display consisting of only the white squares, the white squares on the left will appear farther apart vertically than the squares on the right; that is, the white squares will appear displaced away from the positions previously occupied by the black rectangles. Fig. 2 illustrates another figural aftereffect. When observers view a curved line for a brief period, a straight line presented immediately after it will appear curved in the opposite direction. The apparent size, orientation, and distance of test figures can also be altered by prior inspection of appropriate inducing patterns (CRefs. 5.805, 6.319).

The magnitude and duration of figural aftereffects are influenced by a number of factors, including the distance between the contours of the test and inducing figures, the type of inducing figure, the type of test figure, the length of inspection time for the inducing figure, and the time interval between presentations of the inducing and test figures, as well as visual variables such as luminance and contrast.

For the target patterns shown in Fig. 3, the strength of the displacement aftereffect increases as inspection time for the inducing figure increases, up to an asymptote of ~40-75 sec (Fig. 4). The decay of the aftereffect begins almost immediately after the end of the inducing figure inspection period, and has almost completely disappeared after ~100 sec (Fig. 5). (These values might vary with differences in illumination and contrast.)

At least some part of figural aftereffects is due to a central nervous system process (rather than a process occurring at the retina or some other peripheral level), since aftereffects with monocular viewing are only ~70% of the effect with binocular viewing. (Ref. 2).

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Constraints

• The magnitude and duration of figural aftereffects are influenced by inspection time, interval between presentation of inducing and test figures, and the contrast, area, and luminance of the inducing figure (Ref. 5).

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Cross References

5.805 Illusions of perceived tilt;

6.318 Feature-selective adaptation and masking;

6.319 Spatial frequency aftereffect (perceived spatial frequency shift);

6.320 Contingent aftereffects;

Handbook of perception and human performance, Ch. 33, Sect. 2.6

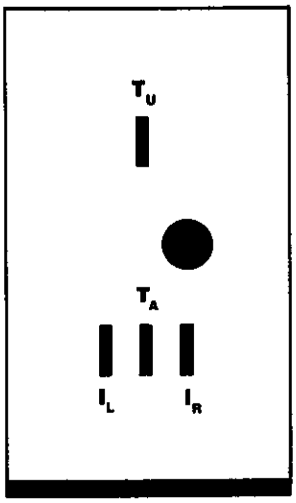

Figure 3. Target pattern for studying displacement aftereffects. Observers inspected an inducing figure consisting of the circular fixation point and either line I_L or I_R. Then lines T_A and T_U were presented. The test line T_A appears displaced away from the location of the previously viewed line; the appearance of line T_U is not affected. To measure the magnitude of displacement, observers adjusted the position of line T_L so that it appeared vertically aligned with line T_U. (From Ref. 6)

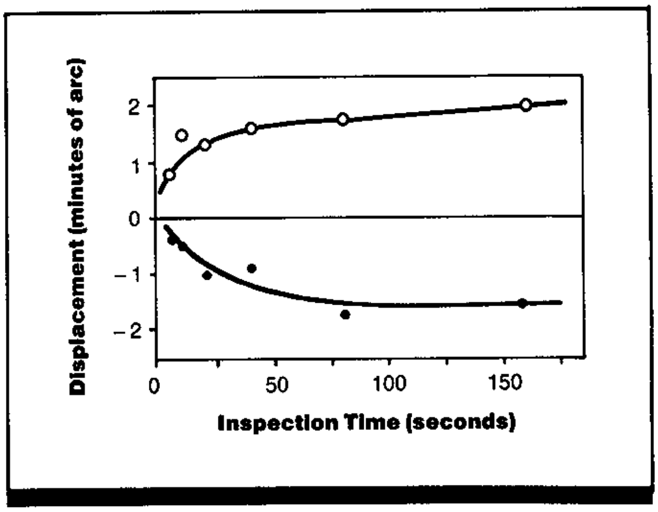

Figure 4. Magnitude of the displacement aftereffect as a function of duration of inspection of the inducing figure. Three observers viewed the test and inducing patterns shown in Fig. 3. Positive values are for inducing line I_L and indicate that the test line T_A was displaced to the right; negative values show leftward displacements with inducing line I_R. (From Ref. 6)

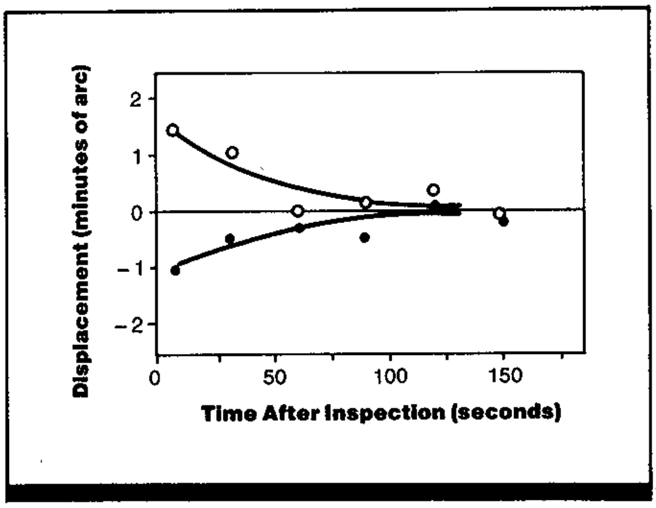

Figure 5. Decline in the displacement aftereffects as a function of the delay between the offset of the inducing figure and the presentation of the test figure. Three observers viewed the test and inducing patterns shown in Fig. 3. Positive and negative values have the same meaning as for Fig. 4. Curves were fit by inspection. (From Ref. 6)

6.318 Feature-Selective Adaptation and Masking

Key Terms

Aftereffect; auditory aftereffect; color; dimensional analysis; direction of motion; event duration; motion-in-depth; pattern perception; pitch perception; retinal image disparity; selective adaptation; spatial orientation; visual illusions; visual masking

General Description

Exposure to one target pattern can affect the visibility or appearance of a second target pattern. When the first stimulus and the second are well separated in time, the phenomenon is known as **adaptation**. When the two targets overlap in time or follow one another by a very brief interval, the effects are termed **masking**. Both adaptation and masking have been shown to be feature-selective. That is, exposure to one target will affect the visibility or appearance of another target only if the second target has a similar value along some pertinent perceptual dimension. For example, exposure to one bar pattern will decrease the detectability of a second bar pattern of identical size and contrast, but only if the orientations of the two patterns are very similar; if the orientations differ (e.g., if one bar pattern is horizontal and the other vertical), no interference will occur.

As an experimental procedure, adaptation entails prolonged exposure to a pattern generally rich in a visual feature. Thus, for orientation-specific adaptation, an observer would view a pattern of bars with a given orientation for a period typically lasting from a minute to an hour. Then the pattern would be removed and the observer would be tested for perception of a similar bar pattern that differed slightly in orientation. Adaptation can have several aftereffects with respect to subsequently viewed patterns:

Threshold changes. Detection thresholds for the test pattern are typically raised in cases where the test pattern shares characteristics with the adaptation pattern. Thus, orientation-specific adaptation leads to selective threshold elevation for patterns that share the same or nearly the same orientation as the adapting pattern.

Aftereffects. Aftereffects are illusions or misperceptions of patterns following adaptation. The types of aftereffects depend upon the feature adapted.

Complementary aftereffects exist for dimensions in which pattern features are organized in complementary fashion (e.g., color or direction of motion). Exposure to a given feature value during the adaptation period leads to the apparent presence of the complementary feature in patterns that are neutral in that dimension. For example, after adaptation to downward motion, a motionless pattern may appear to move upward.

Neighbor shifts occur where dimensions are continuously valued. Test patterns close to, but not identical to, the adapting pattern in value along the adapted dimension appear to be shifted away from the adapting value. For example, adaptation to a vertical bar pattern may cause a bar pattern that is slightly tilted from vertical to appear more tilted than it really is.

Masking differs from adaptation in that the masking pattern is presented simultaneously with or in very close temporal proximity to the test pattern. Brief exposure to a high-energy masking pattern selectively elevates detection thresholds for patterns viewed immediately afterward that share dimensional qualities with the adapting stimulus.

The strength of adaptational aftereffects under different conditions provides a measure of the selectivity of adaptation. If the strength of a motion aftereffect, for example, is unaffected by changes in the color of the test pattern, the aftereffect is said to be independent of the adapting color, and the dimensions of color and motion direction are considered separable. If the motion aftereffect is slightly weaker when the tilt of the test contours is changed, direction of motion is considered imperfectly separable from orientation.

Table 1 summarizes a number of studies on feature-selective adaptation and masking. The left column lists various dimensions that have been investigated. Filled cells cite studies that have found evidence of various adaptation aftereffects or masking selective for that dimension, as well as evidence for the separability or nonseparability of the given dimension from other dimensions.

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Table 1. Evidence for selective adaptation and selective masking. (From *Handbook of perception and human performance*)

Dimension	Threshold Change	Complementary Aftereffects	Neighbor Shift	Masking	Imperfectly Separable From	Can Be Independent of
Spatial frequency	Refs. 6, 41 CRef. 1.651		Refs. 10, 11	Refs. 40,46	Orientation and contrast (Ref. 9); disparity (Ref. 21); color (Ref. 34); eye tested (Ref. 11)	Eye tested (Ref. 5); luminance phase (Ref. 31); color (Ref. 34)
Orientation	Ref. 25 CRef. 1.652	(With concentric or radial lines) Ref. 35	Refs. 14, 24	Ref. 13	Line length (Ref. 24); color (Ref. 27)	Eye tested and luminance phase (Ref. 13); spatial frequency (Ref. 37); edge versus line (Ref. 24)
Direction of movement	Refs. 33, 38, 44	Refs. 17, 20			Orientation (Refs. 22, 39)	Color (Ref. 17); orientation (Ref. 22); contrast versus disparity edges (Ref. 42)
Depth **(lateral retinal image disparity)**	Refs. 7, 21		Ref. 8		Spatial frequency (Ref. 21)	
Changing size	Ref. 43	Ref. 4				Sign of contrast, sideways motion (Ref. 43)
Motion in depth	Ref. 3	Ref. 4				Spatial frequency, orientation (Ref. 36)
Color	Refs. 28, 45	Refs. 12, 47				Spatial frequency (Ref. 48)
Brightness or contrast	Ref. 26	Refs. 29, 47				
Spatial position			Ref. 32			
Curvature		Ref. 23				
Duration (auditory and visual)			Refs. 30, 49			
Pitch	Ref. 2		Ref. 2 CRef. 2.707			
Phonetic Features			Refs. 15, 16, 19			Ear tested (Ref. 2); physical cue (e.g., frequency of burst and direction of **formant** transition (Ref. 18)

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Cross References

1.651 Spatial frequency (size) adaptation;

1.652 Orientation-selective effects on contrast sensitivity;

2.707 Pitch shift following adaptation to a tone;

5.212 Motion aftereffects;

6.320 Contingent aftereffects;

Handbook of perception and human performance, Ch. 35, Sect. 3.2

Notes

6.319 Spatial Frequency Aftereffect (Perceived Spatial Frequency Shift)

Key Terms

Figural aftereffects; selective adaptation; size perception; visual illusion

General Description

Long exposure (adaptation) to periodic targets, such as sine-wave gratings, distorts the apparent spatial frequency of subsequently presented test targets of spatial frequencies within two octaves (4:1 ratio) of the adaptation frequency. The apparent spatial frequency of the test target is shifted away from the spatial frequency of the adapting target. Thus, test targets lower in spatial frequency than the adapting target appear lower after adaptation than with no adaptation, whereas test targets higher in spatial frequency appear higher after adaptation than before.

Methods

Test Conditions

- Spatial sine-wave luminance gratings, generated on upper and lower cathode ray tubes 1.75 × 1.25 deg of visual angle; varied independently in contrast and spatial frequency, while mean luminance on both CRTs (1.7 cd/m^2) kept constant
- Range of spatial frequencies, 1.05-28.3 cycles/deg, tested in 1/4-octave steps
- Adapting grating presented on upper screen, paired with a blank lower screen (zero contrast); during test, same spatial frequency presented on both screens; subject could adjust spatial frequency of lower grating via potentiometer
- Adaptation interval: 3 min initially, 10 sec between trials
- Viewing distance: 2.9 m
- Horizontal bar between CRTs, fixated throughout

Experimental Procedure

- Method of adjustment; matching paradigm; trials blocked by adaptation spatial frequency
- Independent variables: adapting spatial frequency, test spatial frequencies
- Dependent variable: ratio of spatial frequency apparently matching test frequency after adaptation, to spatial frequency apparently matching test frequency before adaptation, expressed as a percentage
- Subject's task: adjust spatial frequency of lower grating target to match spatial frequency of upper target
- 2 experienced and practiced subjects

Experimental Results

- After adaptation, apparent spatial frequency is distorted for frequencies neighboring, but not equal to, the adapting frequency.
- Spatial frequencies lower than the adapting frequency ap-

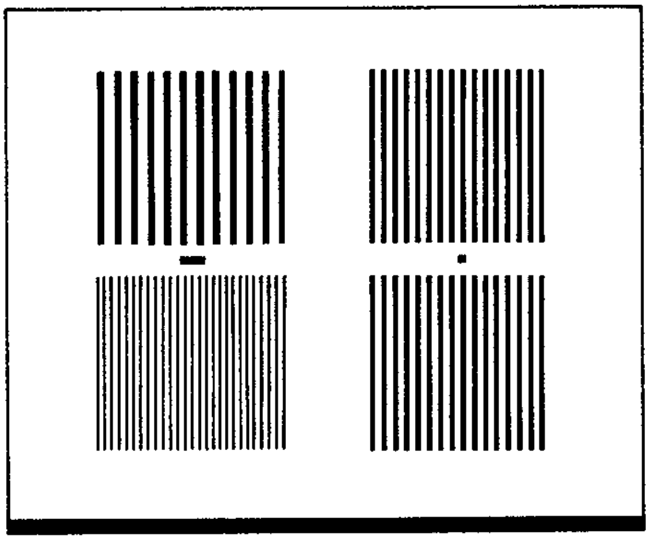

Figure 1. Demonstration of spatial frequency aftereffect. The test gratings illustrated on the right side are identical in spatial frequency. On the left side, the top grating is of a lower frequency, whereas the lower grating is of a higher frequency than the test gratings. Following adaptation to the left gratings by scanning the center fixation bar for at least 1 min, the test gratings will appear to differ in spatial frequency when the right center bar is fixated. The top grating will appear to be of higher spatial frequency, showing a shift away from the wider bars of the upper adapting grating. Similarly, the lower test grating will appear to be of lower spatial frequency. (From Ref. 1)

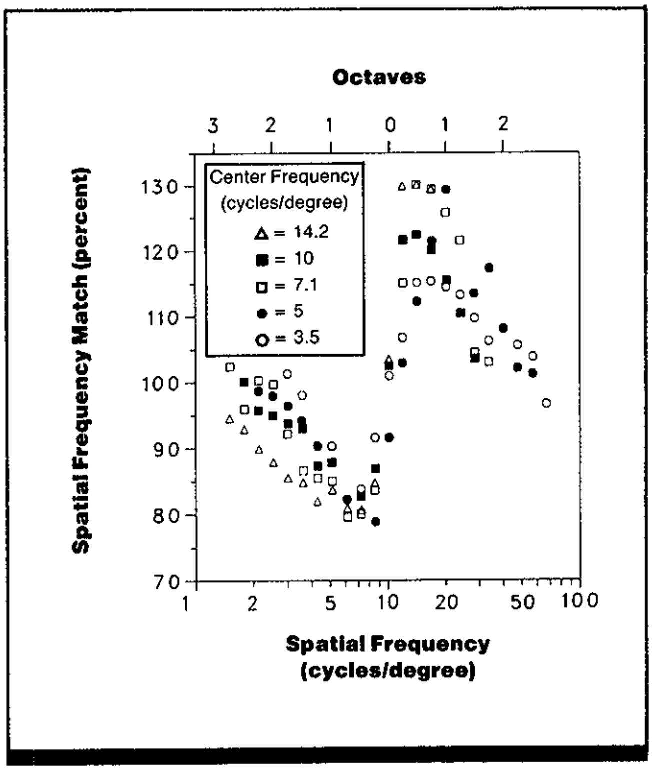

Figure 2. Perceived spatial frequency shift. Ordinate plots matched spatial frequency after adaptation as a percent of matched spatial frequency without adaptation. A value of 100 indicates a perfect match, whereas values above and below 100 indicate that following adaptation the upper grating appear to be of higher or lower frequency, respectively. Results are shown for five adapting frequencies between 3.5 and 14.2 cycles/deg, indicated by the different symbols. The data are superimposed at 10 cycles/deg to facilitate comparison (data from 1 subject). Spatial frequency of the test grating is shown in cycles per degree on lower abscissa and in octaves from the adapting frequency on the upper abscissa. (From Ref. 1)

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pear even lower after adaptation, while those higher than the adapting frequency appear even higher.

• Maximum perceptual distortion occurs for spatial frequencies ~1/2-octave above and below the adapting spatial frequency; some distortion is observable for frequencies up to two octaves away.

• Figure 3 illustrates a theory of the effect, based on multiple channels model of spatial processing.

Variability

Variability not reported; other data from this study show standard error of the means for 1 subject to be ~2%.

Constraints

• Since the effect occurs with the eye continuously moving, retinal afterimages probably play no role.

• Adaptation to high-contrast patterns also increases contrast thresholds to subsequently presented patterns (CRefs. 1.626, 1.651).

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Cross References

1.626 Target detection: effect of prior exposure (adaptation) to a target of the same or different size;

1.651 Spatial frequency (size) adaptation;

5.805 Illusions of perceived tilt;

Handbook of perception and human performance, Ch. 7, Sect. 3.2.

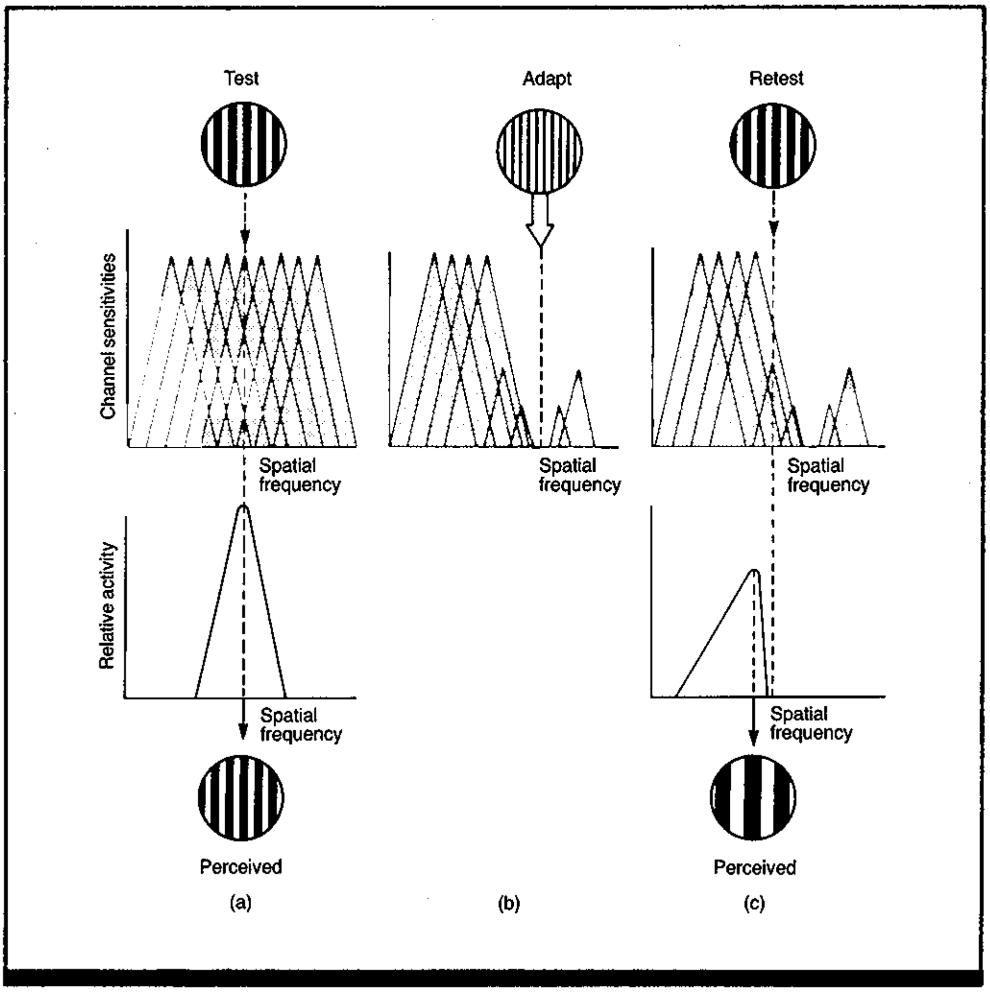

Figure 3. Illustrative model for apparent frequency shift following adaptation. (a) Sensitivity of multiple pathways, each selective to a small but overlapping range of spatial frequencies, is shown prior to adaptation in the upper diagram (sensitivities are arbitrarily made equal only for the purpose of illustration). It is assumed that the appearance of a target is determined by the tuning characteristics of the most active channel. Prior to adaptation, the most active channel corresponds to that which is optimally tuned to the frequency presented, resulting in an accurate perception of the test grating frequency. (b) Adaptation to the grating of a different frequency selectively depresses activity in those mechanisms sensitive to the pattern. The magnitude of the depression is greatest at the channel tuned to the adapting grating, and is symmetrically less for channels tuned to nearby frequencies. If the adapting pattern is presented as a test, no frequency shift is perceived; the symmetric pattern of depression still peaks at the "correct" frequency. (c) When a nearby test frequency is presented following adaptation, peak activity is shifted (in this case to a channel tuned to lower frequencies). In general, higher test frequencies will appear still higher, and lower test frequencies will appear even lower. (From Ref. 2)

6.320 Contingent Aftereffects

Key Terms

Aftereffect; auditory aftereffect; auditory illusion; contingent aftereffects; dimensional analysis; direction of motion; even duration; pattern perception; pitch perception; retinal image disparity; selective adaptation; spatial orientation; temporal order; visual illusions

General Description

A visual aftereffect is an illusory perception which results from prolonged exposure (adaptation) to a target pattern that is compelling in one dimensional quality, such as a particular color or direction motion. When the observer is subsequently exposed to a test pattern that is neutral in quality along the relevant dimension, a perceptual distortion results, which is opposite to the original pattern in terms of the relevant dimension. As an example, prolonged viewing of a downwardly moving pattern causes a subsequently viewed stationary pattern to appear to move upward, a motion aftereffect known as the waterfall illusion. A special type of aftereffect is the contingent aftereffect, in which the illusory perception in one dimension is contingent upon the test pattern's similarity to the adapting target along a second dimension. For example, a color aftereffect (in which a color complementary to the adaptation color is perceived) may appear only if the test target has the same orientation as the adapting target.

Testing for contingent aftereffect requires somewhat elaborate procedures to eliminate all simple, noncontingent aftereffects so that only pure contingent aftereffects are produced. Pairs of opposite qualities on the two dimensions to be studied are selected, for example, horizontal and vertical on the orientation dimension, and red and green on the color dimension. These qualities are paired during the adaptation period, e.g., red and black vertical stripes and green and black horizontal stripes are shown. The red and green patterns are presented in alternation to prevent the formation of chromatic afterimages, as simple color aftereffect increasing with presentation duration. Following adaptation to these patterns, black and white vertical stripes appear greenish, while black and white horizontal stripes appear reddish, an orientation-contingent color aftereffect.

General characteristics of contingent aftereffects include the following:

1. They are relatively difficult to produce, requiring long adaptation periods.
2. They may represent a form of perceptual learning; aftereffects have been demonstrated months after a single adaptation period (Ref. 15).
3. For color aftereffects at least, it has not been possible to produce aftereffects contingent on complex shapes (Ref. 5).

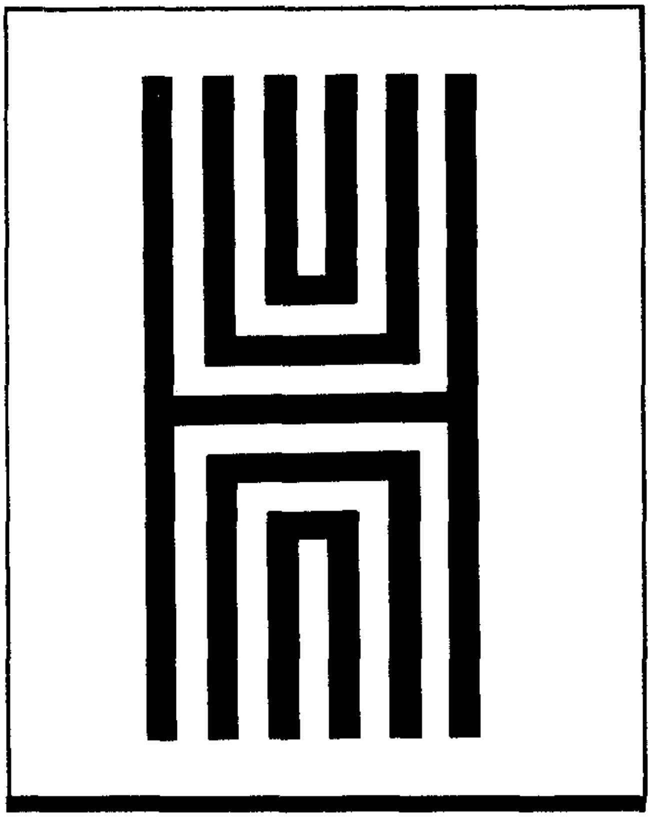

Figure 1. When this perceptually reversible figure is seen as a horizontally striped diamond superimposed on a background of vertical stripes, its stripes are seen with a greenish tint after previous adaptation to horizontal magenta stripes. The color aftereffect is not apparent when the horizontal stripes are seen as parts of concentric outline rectangles. (From Ref. 16)

4. Contingent aftereffects depend on perceptual organization. Figure 1 shows a test figure used to demonstrate this dependence. Orientation-specific color aftereffects (such as described above) are seen with this test figure only when it is perceptually organized as a diamond on a striped background; when it is seen as a set of concentric rectangles, the aftereffect disappears (Ref. 16). Previous adaptation biases the perceptual organization that produces a contingent aftereffect (Ref. 13).

Table 1 summarizes studies which report contingent aftereffects. The column headings refer to the properties tested, and the row headings refer to the properties on which adaptation was made contingent.

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Cross References

5.212 Motion aftereffects;

6.317 Figural aftereffects;

6.318 Feature-selective adaptation and masking;

6.319 Spatial frequency aftereffect (perceived spatial frequency shift);

Handbook of perception and human performance, Ch. 35, Sect. 3.2

Table 1. Evidence for contingent aftereffects. (From *Handbook of perception and human performance*)

	Tested on						
Specific to	**Color**	**Spatial Frequency**	**Movement**	**Orientation**	**Disparity**	**Auditory Duration**	**Auditory Voicing**
Color		Refs. 10, 17	Refs. 4, 12	Ref. 7			
Spatial frequency	Refs. 2, 6, 9		Ref. 18	Ref. 21			
Movement	Refs. 8, 15	Ref. 12			Ref. 1		
Orientation	Ref. 11	Ref. 21	Ref. 12				
Disparity			Ref. 1				
Angles or curvature	Refs. 14, 20						
Intensity			Ref. 2				
Configuration or pattern	Effect not obtained (Ref. 5)						
Pitch and temporal order						Ref. 19	Ref. 8

6.321 Theories of Pattern Recognition

Key Terms

Coding theory; cognitive representation; constraint theory; feature theory; frame theory; Gestalt principles; information theory; object perception; pattern recognition; prototype theory; template theory

General Description

Theories of pattern recognition attempt to explain how objects are perceived by specifying the mental structures and processes used to transform patterns of sensory input into perceptual experience. The accompanying table describes the major classes of pattern-recognition theory and comments on their strengths and weaknesses.

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Cross References

4.301 Information theory;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.322 Mathematical coding theory;

7.523 Target counting: effects of grouping

Theory	Description	Comments	Source
Template theories	Postulate that pattern recognition involves matching sensory input against specific, labelled representations (item plates) in memory	Number of stored templates to account for normally recognizable patterns would be very large	Refs. 9, 10, 16
	Matching process involves noting congruence between the input and the stored representation to determine if there is sufficient overlap for identification	Does not allow for abstraction of common properties necessary to group objects into classes	
		Because the matching process uses overall, global stimulus properties, small details influencing classification might be overlooked (e.g., difference between O and Q)	
	One theoretical variant states that complex patterns are composed of a set of simpler templates and thus pattern description is hierarchical	Because of these difficulties, template theories have not been seriously considered as complete models of human pattern recognition	

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Theory	Description	Comments	Source
Feature theories	Postulate that the visual system analyzes and represents sensory input via abstract, primitive information units called features (e.g., lines, angles, curves)	Solve the storage problems faced by template theories; only a small set of distinctive features is necessary to discriminate patterns	Refs 1, 5, 9, 16
	Distinctive features are those that distinguish between two patterns or classes of patterns	Abstraction possible because patterns with common sets of features can be grouped	
	Simplest kind of features are abstracted by single neurons in the primary visual cortex	Fails to capture the structure of a pattern; does not specify how features are organized to yield a specific pattern	
Gestalt theory	Whole patterns are not reducible to simple summations of the local parts (features)	Valuable in its recognition of the importance of relationships among stimulus elements	Refs. 6, 11, 15; CRef. 7.523
	Perceptual wholes have properties that are invariant with uniform transformation Gestalt laws (e.g., similarity, **closure**) specify the organization of informational content of input (CRef. 6.301)	Gestalt laws are purely descriptive; they do not specify processes involved in arriving at a particular pattern; further, they are not rules that can be aplied to a pattern to obtain a pattern description	
Prototype theory	Input pattern is compared to a prototype, a memory representation that is the statistical central tendency of all patterns belonging to that category	Prototype theory is parsimonious; people store only a single representation rather than all category instances	Refs. 12, 13, 14, 17
	Categorization determined by similiarity of input to prototype, measured by comparison along various dimensions (e.g., length, width); some dimensions may be given more weight than others	Prototypes represent structures of patterns because they allow for weighted combinations of features Prototypes do not represent atypical members or the variability of a category	
	Category prototype is more resistant to forgetting than most category instances		
Information-theoretic approaches	Likelihood of perception of a particular pattern is determined by the size of the set of possible patterns; set size for a particular pattern is determined by the number of unique patterns obtained by transformation (e.g., rotation, reflection), and is a measure of redundancy (CRef. 4.301)	Represent potential quantifications of the descriptive Gestalt laws (i.e., grouping laws reduce the amount of information in a pattern interpretation) Experiments validating the set-size approach used only a limited number of transformations	Refs. 2, 3, 7, 18; CRef. 6.322
	The coding theory approach specifies the amount of information contained in a single figure and states that the preferred perceptions are those with the least information (CRef. 6.322)	Both set size and coding theory approaches provide means to quantify perceptual structures without specifying processes for the organizational rules that produce the structures	
Artificial-intelligence theories	Constraint theory analyzes contour intersections and assumes that contours intersect in limited ways in real-world scenes; consequently, simultaneous consistency of intersections over the entire scene can lead to a unique interpretation (however, some patterns will remain ambiguous, that is, support more than one perceptual interpretation)	Tests of constraint theory limited to very simple block-world scenes; constraint theory does not incorporate the role of multiple perspectives or higher-level knowledge in pattern recognition	Refs. 4, 19, 20
	Frame theory employs data structures for representing stereotyped situations (e.g., being in a certain kind of room); different frames are created with different perspectives on a scene, and previous frames are linked to newer ones to form a frame system; the frame system represents view-invariant object properties, operations performed on objects (e.g., movement), and perceptual expectations to new situations	Frame theory does not actually take contours as input and produce perceptual structures; it does not have well-specified perceptual mechanisms Frame theory is a first approximation to a theory of the "higher-level" knowledge that mediates perception	Ref. 8

6.322 Mathematical Coding Theory

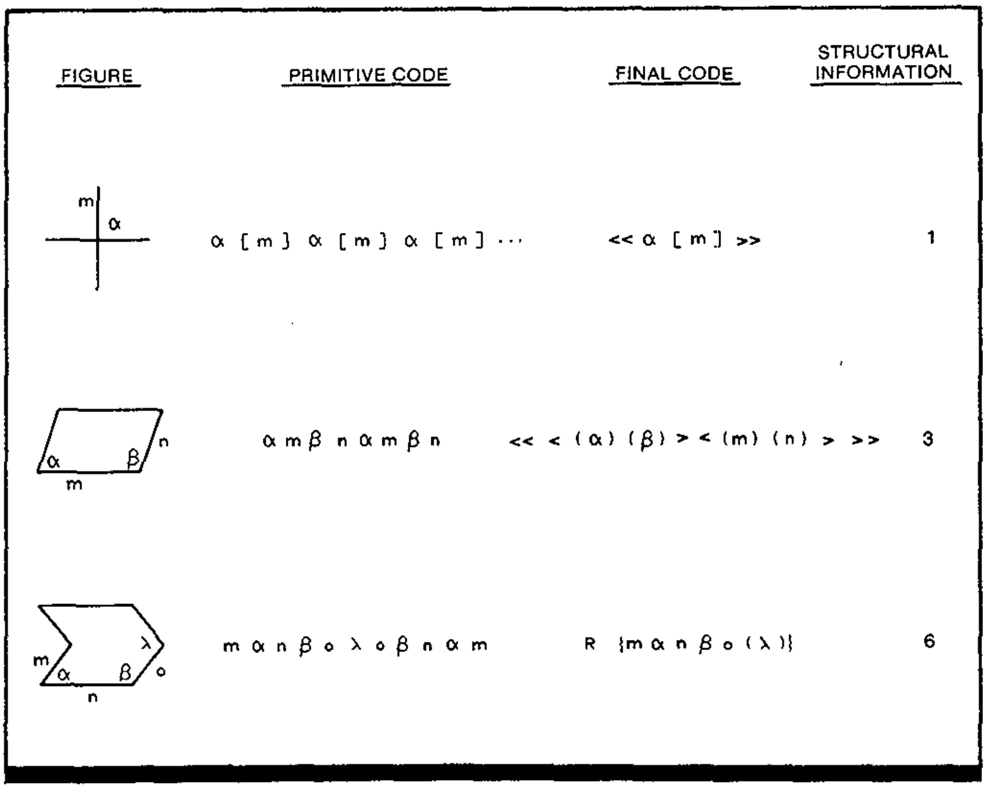

Figure 1. Leeuwenberg's perceptual coding language. To apply Leeuwenberg's coding language to a figure, each line and each angle is symbolized in the primitive code (second column), and this primitive code is simplified and reduced to a final code (third column) by using various coding rules to remove redundant symbols and incorporate the redundancy in symbolic form. The figure illustrates several ways to symbolize redundancy: continuation <<>>, alternation <>, iteration (), and reversal R. Hierarchical organization is symbolized by brackets [ ], and chunking is symbolized by accolades { }. The number of symbols in the final code (fourth column) can be used as a measure of structural information. (From Ref. 5)

Key Terms

Coding theory; pattern perception; perceptual coding

General Description

Coding theory is one approach to quantifying a pattern's structure. Its formal mathematical coding language describes the structure of two- and three-dimensional visual patterns. As developed by Leeuwenberg (Refs. 3, 4), coding theory generates a symbolic list-like description of a given pattern, and then applies a set of information-reduction rules to factor out redundancies in the code and enable derivation of a new code that symbolizes the pattern and redundancies.

Applications

Can be used to determine the amount of information that must be processed in figures used in displays, to predict decomposition of complex figures, and to predict interpretation of ambiguous figures.

Method of Application

The first step in applying the model (i.e., describing a pattern) is to write a sequence of symbols that forms a primitive code representing all pattern elements. Angles are represented by the first ten letters of the Greek alphabet, and line elements by the second ten letters. Several aspects of line patterns, including scale and orientation information, are not considered as contributors to the amount of structural information in a pattern interpretation; these aspects are represented by Roman letters.

Rules are applied to the primitive code to remove redundancy by incorporating it symbolically, so that only the truly informative aspects remain. Various symbols represent continuation (<<>>), alternation (<>), and iteration (()). A maximally reduced code is called a final code. Coding theory posits an efficiency principle which states that the perceptually preferred interpretation is the interpretation containing the minimal amount of structural information. Some examples of coding rules are given in Table 1, and derivation of final codes for some two-dimensional patterns is given in Fig. 1.

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Empirical Validation

The judged complexity of continuous line drawings and the amount of structural information in patterns as determined by coding theory are highly correlated ($r = 0.97$); the judged complexity of dot figures is also highly correlated with the amount of structural information ($r = 0.83$; Ref. 3).

A pattern similar to that on the left in Fig. 2 was presented to observers for 5 sec, and then they were shown two decompositions such as those on the right of Fig. 2. Observers were asked to choose the decomposition that looked most like the one they had made for themselves. For 13 of 14 figures presented, the decomposition preferred by 83% of observers was that predicted on the basis of code efficiency (Ref. 5).

Judged complexity of complex three-dimensional figures and information content as measured by coding theory correlate positively ($r = 0.94$) for 12 subjects (Ref. 4).

Perceived dimensionality of figures having both two- and three-dimensional interpretations (Fig. 3) depends upon relative information content of the two interpretations. The more efficient interpretation is the preferred interpretation (Refs. 2, 4).

Constraints

• Coding theory does not contain a process that generates a symbolic description. It provides analytical tools for quantifying perceptual structure without providing a means to discover the rules that produce the structures in the first place.

• Coding theory does not account for total amount of information in a pattern, just structural information. For example, an octagon with equal sides and a square are considered equally complex by coding theory because of the redundancies in both patterns, even though the octagon contains more line segments and angles.

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Cross References

6.321 Theories of pattern recognition;

Handbook of perception and human performance, Ch. 28, Sect. 1.1

Table 1. Examples of reduction of primitive codes to final codes. (From Ref. 5)

Rule	Primitive Code	Final Code	Units of Structural Information
1. Continuation	αααααα...	<<α>>	1
2. Iteration	αααα	4.(α)	2
3. Chunking	αβαβαβ	3.{αβ}	3
4. Alternation	αβαγγβα	(α)><(β)(γ)(δ)>	4
5. Reversal	αβγγβα	R{αβγ}	4
6. Reversal	αβγβα	R{αβ(γ)}	4

NOTE: In the final code, each element except for the brackets contributes to the amount of structural information of the code.

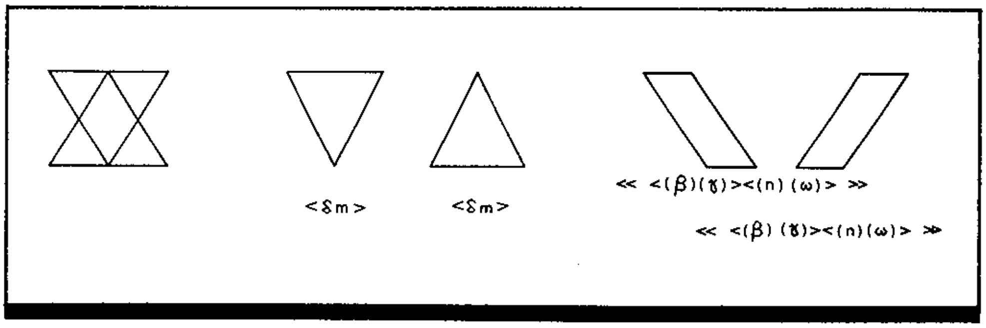

Figure 2. Examples of stimuli used to test observers' preferences for decomposition of ambiguous line drawings. (From Ref. 5)

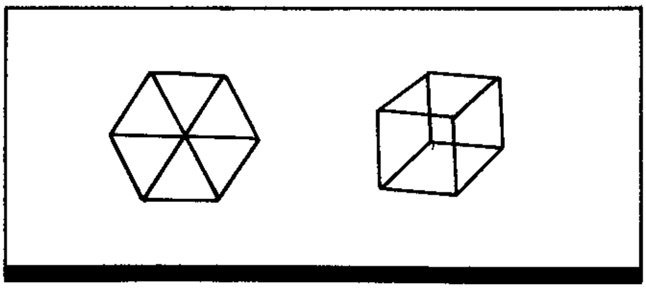

Figure 3. Examples of stimuli used to test observers' preferred dimensionality of line drawings with both two-dimensional and three-dimensional interpretations. A cube requires four units of information, according to coding theory. However, the pattern on the left requires only two units of information when described as a two-dimensional pattern, whereas the pattern on the right requires nine units of information as a two-dimensional pattern. Thus if people choose the perceptual interpretation with the smallest information content, they will perceive the left figure as two dimensional and the right figure as three dimensional. (From Ref. 4)

6.401 Auditory Grouping

Key Terms

Auditory pattern perception; Gestalt principles; good continuation; laterality; proximity; similarity principle; sound frequency; temporal pattern perception; timbre

General Description

Every auditory event can be characterized in terms of its value along the following dimensions:

- frequency (pitch)
- amplitude (loudness)
- temporal position
- spatial location
- multidimensional attributes, such as timbre.

Whether stimuli comprising a sequence are perceived as coming from the same source depends on which dimension or dimensions are most salient (or most attended to), and how the stimuli conform to the Gestalt perceptual principles of similarity, proximity, good continuation, closure, and common fate (CRef. 6.301 for definitions of these principles). Frequency appears to be the most sensitive dimension; however, under specific conditions, other dimensions may dominate the percept. The table lists dimensions that affect auditory grouping and principles derived to explain the effects, describes the experimental tasks and results, and lists sources of more information.

Repeatability/Comparison with Other Studies

A related issue is whether two sounds in close temporal proximity are heard as one (fused) or two sounds (CRefs. 2.708, 2.709, 6.405). Fusion is a special case of grouping in that only two near-simultaneous sounds are involved rather than sequences, and they are heard as one sound or as two.

Key References

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Cross References

2.708 Pitch discrimination under simultaneous masking;

2.709 Pitch discrimination under nonsimultaneous masking;

6.301 Principles of Gestalt grouping and figure-ground organization;

6.402 Grouping of tone sequences by frequency;

6.403 Grouping of tone sequences: effect of frequency separation and presentation rate;

6.404 Grouping of tone sequences by ear of input;

6.405 Perceptual segregation of phase-shifted tones;

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Summary of studies on auditory grouping.

Principle/Associated Dimension	Description of Experimental Stimulus	Experimental Results	Source
Good continuation/ frequency	Repeating sequence of alternating high and low tones with frequency separation varied	When frequency separation is sufficiently great, the sequences segregate into two streams; the addition of frequency glides inhibits such segregation	Ref. 1
Similarity/sound quality (spectral variations corresponding to timbre)	Three-tone ascending line with two alternating timbres	For small differences in timbre, the percept is defined by pitch. But as spectral energy differences increase, two descending lines are perceived, distinguished on the basis of timbral characteristics	Ref. 8
Proximity or similarity/ amplitude	Interleaved melodies with varied loudness differences	The melodies become distinguishable as amplitude differences are increased	Ref. 5
	Pure tone sequences with amplitudes alternating between two values	When the amplitude difference is <5 dB, a single stream is perceived, but two parallel streams are perceived with greater differences	Ref. 3
Proximity/frequency	Sequence of two tones, differing in frequency, alternating at rate of ten per sec	The sequence is heard as a single string when the frequency difference is <15%; otherwise the stimulus is heard as two repeating tones	Ref. 6; CRef. 6.403
	Two well-known melodies, with component tones alternating at a rate or eight per sec	When pitch ranges overlap, identification is difficult, but the melodies are easily identified when pitch ranges are separated	Ref. 5
	Chords forming simultaneous ascending and descending scales presented dichotically with tones from each scale's sequence alternating from left to right ear	Tones grouped by frequency rather than ear of input, so that simultaneous ascending and descending tone sequences (but not complete scales) are heard	
Proximity/temporal position and spatial location differences	Melodies with component tones either (a) delivered simultaneously to both ears, (b) distributed randomly between the ears, (c) presented to one ear, with a "drone" delivered simultaneously to the other ear, or (d) presented with a drone in the same ear	The best identification performance is found with **binaural** delivery of the melody. Performance is poor when component tones are distributed randomly between the ears or when a drone is delivered in the same ear as the melody. But, with the drone in one ear and the melody in the other, performance level is again high. These results indicate that simultaneous signals from two locations are more easily integrated into a singular percept than are signals from different locations which are separated in time	Ref. 2
	Two tones of different frequencies presented simultaneously one to each ear with alternating frequency in each ear	Perception is of a single tone that switches from ear to ear and from high to low	CRef. 6.404
Proximity/temporal position differences	Pure tone sequences presented with two alternating intertone intervals, but constant frequency, duration, and amplitude	The first tone in each alternating group is heard as accented when intervals differ by 5-10%. With an increased interval difference, the accent is perceived as stronger and accompanies the second tone	Ref. 7

6.402 Grouping of Tone Sequences by Frequency

Key Terms

Auditory grouping; auditory illusion; dichotic listening; scale illusion; sound frequency

General Description

When **dichotically** presented musical scales can be channeled (heard as a stream) either by frequency or by ear of input, channeling occurs by frequency. Grouping by frequency is found when a C-major scale (eight tones) is presented simultaneously in both ascending and descending forms. As a tone from the ascending scale is delivered to one ear, a tone from the descending scale is delivered to the other ear. Successive tones from each scale alternate from ear to ear (Fig. 1).

Full ascending or descending scales are not heard, and subjects do not report hearing a tone stream corresponding to the input delivered to either ear. Rather, the primary percept is a sequence corresponding to the four higher-frequency tones which alternately descends and then ascends. Most subjects also report hearing a secondary sequence of the lower-frequency tones ordered in a direction opposite that of the primary sequence. Subjects reporting both streams hear all presented tones, segregated by frequency range, whereas those hearing the primary stream by itself hear only the four higher-frequency tones (Table 1).

Among subjects who hear both the higher and the lower streams, most report a lateralization illusion whereby the lower tones are heard in one ear and the higher tones are heard in the other ear. Of this group, right-handed subjects most often hear the higher-tone stream in the right ear, while left-handed subjects show a less consistent lateralization (Table 2).

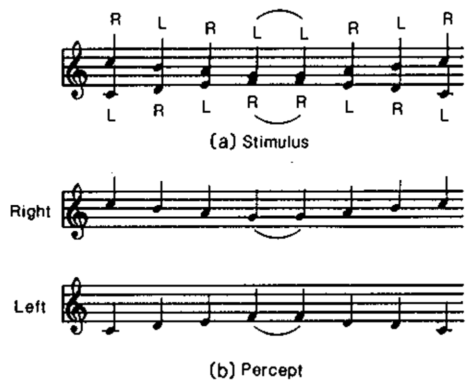

Figure 1. Auditory grouping by frequency proximity. (a) Stimulus configuration; ear of presentation for each component was the reverse of that shown here for half the subjects; (b) perceived tone sequences (the scale illusion). (From Ref. 1)

Methods

Test Conditions

- Stimuli presented via headphones
- Eight equal-amplitude (75-dB) sinusoidal tones defining a C-major scale; each tone 250 msec in duration; frequencies of C = 259, D = 290, E = 326, F = 345, G = 388, A = 435, B = 488, and C = 517
- Ascending and descending scales presented alternately and simultaneously to each ear (see Fig. 1); no gaps between tones

Experimental Procedure

- Independent variables: handedness of subject (left or right); ear of presentation for each tonal component
- Dependent variables: perceived pattern, ear localization
- Subject's task: report orally what was heard
- 70 university students (41 right-handed, 29 left-handed)

Experimental Results

- Subjects do not perceive a full ascending or descending scale, nor do they channel by ear of input.
- Most right-handed subjects and roughly half the left-handed subjects report hearing two streams, one consisting of higher-frequency tones which descend and then ascend, and one consisting of lower-frequency tones which ascend and then descend (Table 1).
- All subjects who do not hear both streams report hearing a single, higher-frequency stream
- 30 of 34 right-handed subjects and 11 of 15 left-handed subjects who hear two streams also report a lateralization illusion (i.e., all higher tones are heard in one ear and all lower tones are heard in the other ear).
- Among right-handed subjects who hear lateralized patterns, there is a tendency ($p < 0.001$) to hear higher tones in the right ear. Lefthanders do not, however, display such a tendency (Table 2).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Grouping by frequency range has also been obtained with scales presented through loudspeakers in a normal room environment.

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Constraints

- In response to dichotic sequences with alternation from one octave to another, subjects commonly hear single tones alternating both by octave and by ear (CRef. 6.401).
- Other research indicates that channeling by location rather than frequency occurs when the frequency originating from one side of auditory space is followed by the same frequency from the opposite side (Ref. 2).
- Many factors, such as sound quality, sound amplitude, and the spatial and temporal position of stimulus components, can influence auditory grouping and must be considered in applying these results under different conditions (CRefs. 6.401, 6.403, 6.404).

Key References

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Cross References

6.401 Auditory grouping;

6.403 Grouping of tone sequences: effect of frequency separation and presentation rate;

6.404 Grouping of tone sequences by ear of input;

Table 1. Numbers of righthanders and lefthanders perceiving both the higher and lower pitch sequences (streams) in the scale illusion and those perceiving only the higher pitch sequence. (From Ref. 1)

	Stream	
Handedness	**Both**	**Single**
Right	34	7
Left	15	14

NOTE: The righthanders tended significantly to hear both streams; however, the lefthanders did not show such a tendency.

Table 2. Lateralization patterns for subjects who perceived all higher tones in one ear and all lower tones in the other. (From Ref. 3)

	Localization		
Handedness	**RR**	**LL**	**Both**
Right	21	1	8
Left	2	5	4

RR: Higher tones lateralized in the right ear and lower tones in the left ear on both presentations; LL: higher tones lateralized in the left ear and lower tones in the right ear on both presentations; Both: higher tones lateralized in the right ear and lower tones in the left ear on one presentation, with opposite localization pattern on the other.

6.403 Grouping of Tone Sequences: Effect of Frequency Separation and Presentation Rate

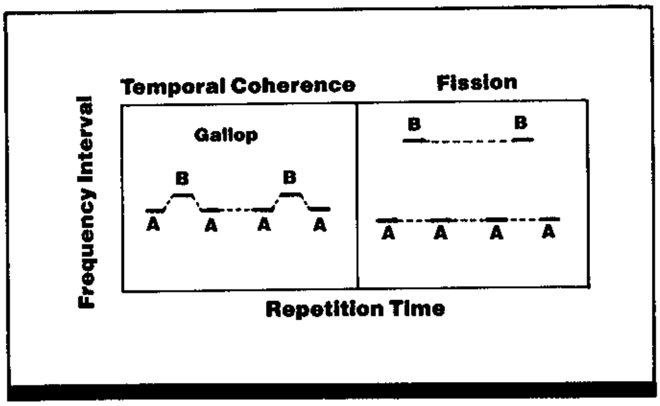

Figure 1. Perception of tone sequence *ABA ABA*. When temporal coherence is heard, a very characteristic "gallop" rhythm is perceived. When fission is heard, two separate tone streams are perceived, one twice as fast as the other. (From Ref. 4)

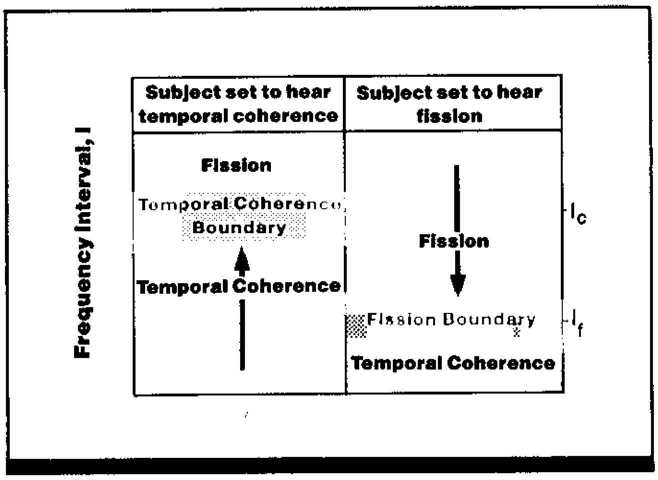

Figure 2. Effect of attentional set on the boundaries between temporal coherence and fission. I_c is the frequency separation of the tones at the temporal coherence boundary; I_f is the frequency separation at the fission boundary. (From Ref. 4)

Key Terms

Attentional set; auditory grouping; frequency separation; presentation rate; temporal coherence; temporal fission

General Description

Temporal coherence is the subjective impression that a tonal sequence forms a single connected series. Fission, on the other hand, is the perception that a sequence is disconnected or separated into two or more distinct streams (Fig. 1). Both repetition rate or tempo (*T*) and the melodic interval (frequency interval, *I*) separating the tones, affect whether coherence or fission is perceived in a sequence of tones.

Coherence and fission boundaries can be determined in terms of frequency separation and presentation rate, such that only coherence or only fission is perceived outside these limits (Figs. 2, 3). Between these limits is an area in which sequences are perceived either as coherent or as separated, depending on attentional set (i.e., whether the subject tries to hear the sequence as a single stream or separated).

Generally, when subjects attempt to hear coherence and when presentation rate is slowed (i.e., repetition time is increased), coherence is perceived over a substantially increased range of frequency separations. When subjects attempt to hear fission, however, decreases in presentation rate have only a weak effect on the percept (Fig. 3).

Methods

Test Conditions

- Diotic headphone presentation of two tones (*A*, *B*) at 35 dB above threshold; tones presented in sequence *ABA ABA*. . . ; tone duration 40 msec, rise and decay times of 5 msec; *B* tone frequency (f_B) of 1000 Hz; *A* tone frequency (f_A) varied as sweep function to cross f_B, 80-sec period, range of ± 15 semitones relative to f_B (12 semitones = 1 octave); sweeping produced the perception of alternating fission and cohesion; tone repetition time (*T*) varied randomly from 60-150 msec in 10-msec intervals
- Two sessions; testing in soundproof booth; for each *T* value, for eight frequency sweeps, subject instructed either to hold "gallop" (coherence) percept or to follow *A* tones (fission), as long as possible; response button used to indicate when the specified percept (coherence, fission) was lost

Experimental Procedure

- Modified Békésy tracking procedure, repeated measures
- Independent variables: tone repetition time, frequency between tones *A* and *B*; attentional set (to perceive coherence or fission)
- Dependent variable: frequency separation for given repetition time at which perception of coherence or fission ceased
- Subject's task: listen for coherence or fission and press button when that percept could no longer be heard
- 3 subjects, at least 1 practiced

Experimental Results

- Figure 2 illustrates how attentional set affects the boundaries between temporal coherence and fission. The boundary between the perception of fission and the perception of temporal coherence occurs at a lower frequency separation when the subject is set to hear fission than when the subject is set to hear coherence.
- The frequency separation at which fission is heard is roughly independent of repetition time (horizontal lower function in Fig. 3).
- For temporal coherence, on the other hand, maximum frequency separation increases repetition time; that is, temporal coherence can be maintained with larger tone intervals in slow tone sequences than in fast ones.

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• Attentional set strongly determines whether fission or coherence is perceived for repetition times in the range of 60-150 msec (Fig. 3).

Variability

The fission boundary value in terms of frequency separation found for one subject was about half that found for the other two subjects.

Repeatability/Comparison with Other Studies

Reference 3 found that, for tone sequences, as frequency separation of successive tones is increased, a reduction in presentation rate is required to maintain the impression of a coherent stream.

Consistent results are found when an extended range of presentation rates is used (48 msec $\leq T \leq$ 200 msec for the coherence boundary, 48 msec $\leq T \leq$ 800 msec for the fission boundary). In medium ranges (0.1-0.4 sec), the fission boundary is almost independent of presentation rate. For very fast presentation rates ($T \leq$ 0.1 sec), the coherence boundary is also horizontal and close to the fission boundary (Ref. 4).

Constraints

• Fission-coherence boundaries may be affected by practice (Ref. 3).
• Many factors, such as sound quality, sound amplitude, and the spatial and temporal position of stimulus components, can influence auditory grouping and must be considered in applying these results under different conditions (CRefs. 6.401, 6.402, 6.404).

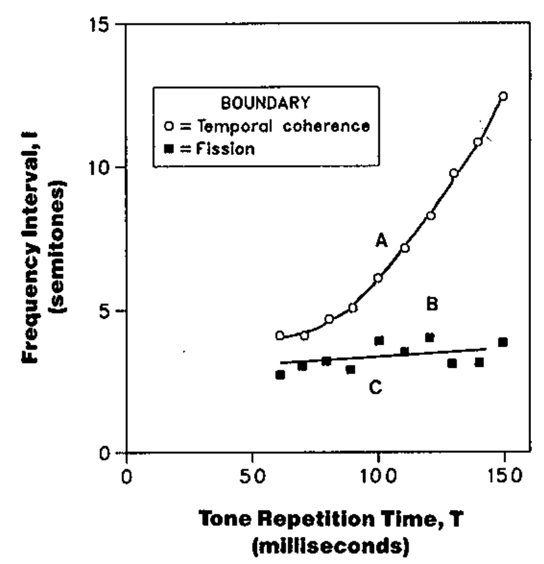

Figure 3. Perception of temporal coherence and fission in a tone sequence as a function of tone frequency separation and repetition time (repetition time = 1/presentation rate). In region A, the tone sequence could be heard only as two separate streams (fission); in region C, the sequence could be heard only as a single stream (coherence); and in region B, the sequence could be heard either way. (From Ref. 4)

Key References

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Cross References

6.401 Auditory grouping;

6.402 Grouping of tone sequences by frequency;

6.404 Grouping of tone sequences by ear of input;

Handbook of perception and human performance, Ch. 32, Sect. 1.3

6.404 Grouping of Tone Sequences by Ear of Input

Key Terms

Auditory grouping; auditory illusion; dichotic listening; ear dominance; frequency separation; octave illusion

General Description

When two identical sequences of high and low tones are delivered simultaneously, one to each ear, but the sequences are offset in time, so that when the right ear receives the high tone, the left ear receives the low tone, and vice versa, the percept is often of a single tone that switches from ear to ear and whose pitch simultaneously shifts between high and low (see Fig. 1). This effect has been termed the octave illusion. The pitches heard correspond to the frequencies delivered to only one ear (ear dominance); however, each tone is lateralized toward the ear receiving the higher frequency, regardless of whether a pitch corresponding to the higher or the lower frequency is perceived. Which ear is followed for pitch depends on the relative amplitudes of the tones in the left and right ears and the frequency and temporal relationships between successive tone pairs, as well as the natural ear dominance of the individual.

Methods

Test Conditions

Study 1 (Ref. 3)

- Two conditions: (1) two 250-msec tones in octave relation (400 and 800 Hz), presented simultaneously one to each ear, no gap between tones, and alternated from ear to ear such that when high tone was in right ear, low tone was in left ear and vice versa; (2) two 250-msec tones presented, the first forming an octave (400, 800 Hz), the second forming a minor third (504 and 599 Hz), presented simultaneously and alternated from ear to ear (see Fig. 2)
- For each sequence 70-dB sound pressure level (SPL) tone in one ear, other ear equally often received 70-, 73-, 76-, 79-, 82-, or 85-dB SPL tone; subjects in sound-insulated booth; dichotic listening through earphones; 20 tone pairs per sequence; one-half of sequences began with high tone to left ear, one-half began with high tone to right ear

Study 2 (Ref. 3)

- Same as Study 1 except following two conditions: (1) two presentations of an octave-interval chord (400 and 800 Hz), with tone sequence of high-low to one ear, low-high to other, tones of each chord presented simultaneously; (2) similar presentation of two 2-tone chords formed by 366/732 Hz and by 259/518 Hz, or by 308/616 Hz and 435/870 Hz; no gaps between tones

Study 3 (Ref. 3)

- Same as Study 1 except following two conditions: (1) 750-msec gap between two 250-msec tones alternated in octave relation (400 and 800 Hz) from ear to ear; (2) same as Condition 1 except 250-msec 599-Hz tone interpolated in middle of 750-msec gap; the tone was presented simultaneously to both ears.

Study 4 (Ref. 4)

- Dichotic tone pairs in octave relation (400 and 800 Hz) alternated from ear to ear as in Fig. 1; four conditions: (1) sequences of 250-msec tones, no gaps between tones within a sequence, 10-sec gap between sequences; (2) pairs of 250-msec tones, no gaps between tones within a pair, 10-sec gap between pairs; (3) pairs of 250-msec tones, 2.75-sec gap between tones within a pair, 10-sec gap between pairs; (4) pairs of 3-sec tones, no gaps between tones within a pair, 10-sec gap between pairs. 400 and 800 Hz tones in all conditions.

Experimental Procedure

- Repeated measures
- Independent variables: Study 1: amplitude relation of tones, frequencies of successive tone pairs; Study 2: amplitude relation of tones, frequencies of successive tone pairs; Study 3: amplitude relation of tones, tone present or absent in 750-msec interval; Study 4: amplitude relation of tones, duration of gap between tones, tone duration
- Dependent variable: which ear, if either, was followed for pitch

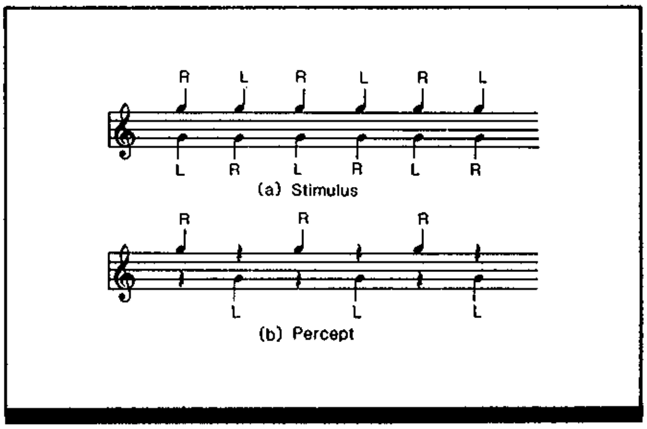

Figure 1. Stimulus pattern giving rise to the octave illusion. The pattern of tones shown in (a) most frequently gives rise to the perception shown in (b). (Musical notation is approximate.) Ear dominance is assessed by determining which ear is followed for pitch (panel [b] shows percept for a right-ear-dominant listener; left-ear-dominant listener would hear the reversed frequency sequence, i.e., low, high, low, . . .). (From Ref. 2)

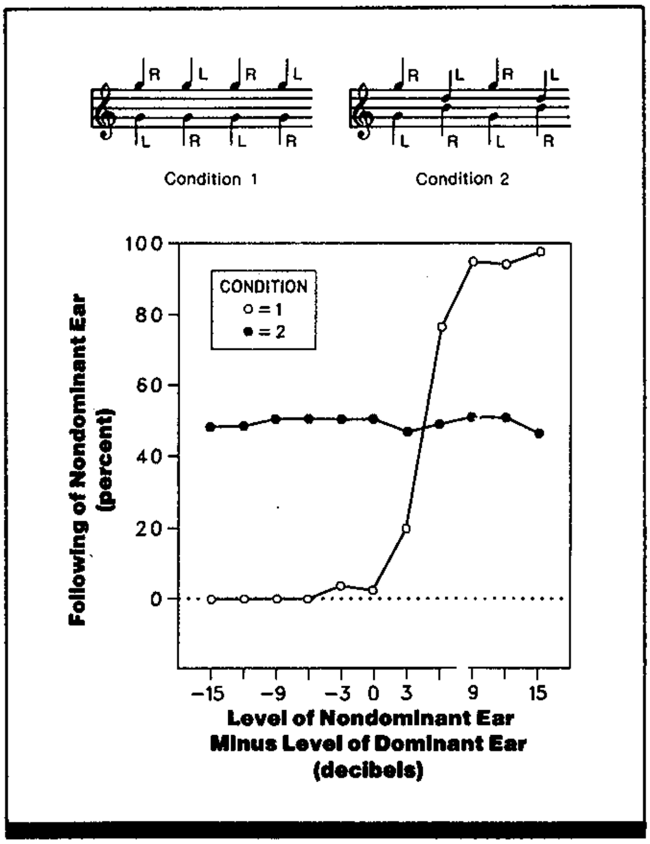

Figure 2. Perceived pitch of continuous two-tone sequences (Study 1). Stimulus patterns are shown at top. The percentage of sequences on which the nondominant ear was followed for pitch is given as a function of the difference in amplitude between the tones in the nondominant and dominant ears. (From Ref. 3)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Subject's task: judge whether sequence began with high tone and ended with low tone or vice versa
• Three sessions of 72 trials (except 48 trials per session in Study 1, Condition 2; 96 trials per session in Study 2, Condition 2)
• 4 subjects in each study, selected on basis of high performance on pitch memory tasks (Study 1) or on basis of ear dominance (Studies 2 and 3)

Experimental Results

• In Studies 1 and 2, when all tone pairs form octave intervals (Condition 1), the frequency sequences presented to one (dominant) ear are followed until the relative amplitude in the nondominant ear reaches a critical level. Then, the nondominant ear is followed (Fig. 2, open circles).
• When tone pairs of two frequency separations are alternated (Condition 2), no ear dominance is found (Fig. 2, closed circles), indicating that ear dominance requires that the two ears receive the same frequencies in succession.
• In Study 3, ear dominance is reduced by introduction of a gap between tone pairs; the reduction is even greater when a 250-msec tone is presented in the middle of the 750-msec gap (Fig. 3).
• In Study 4, the strength of ear dominance is reduced with increases in the interval between onsets of same frequency presentations at the two ears, regardless of whether the increase in onset interval is caused by increasing tone duration or by introducing a silent gap between tone pairs (Fig. 4).

Variability

Quantitative information about variability was not provided, but the effects were statistically significant.

Repeatability/Comparison with Other Studies

Table 1 (Ref. 2) indicates the distribution of various auditory percepts by handedness among subjects who were not screened in the manner of Studies 1-3. Alternating 250-msec tones in an octave relation (400 and 800 Hz) were

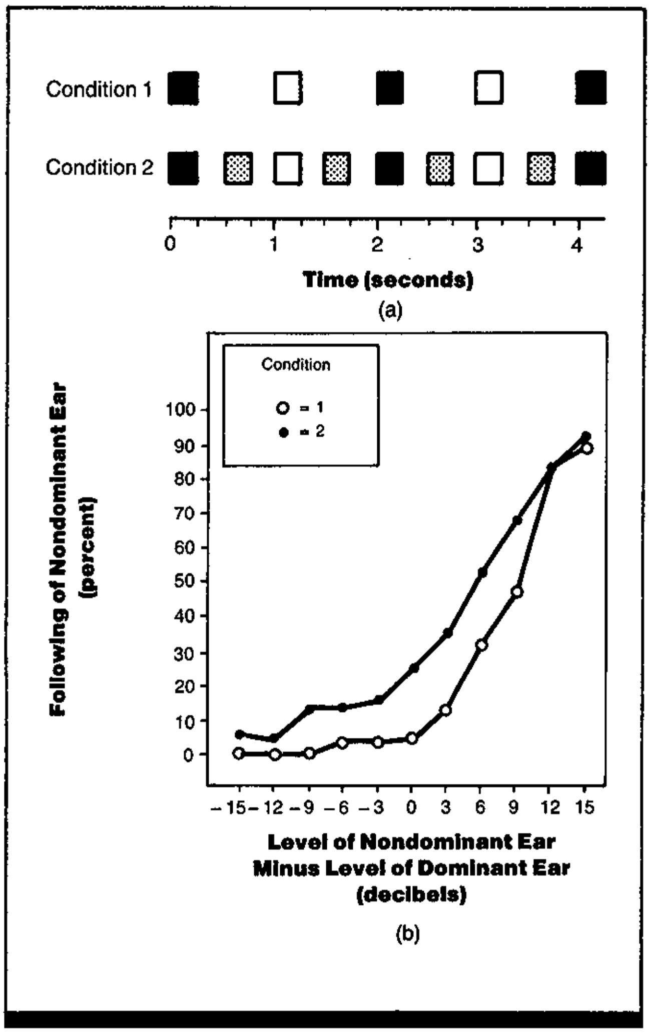

Figure 3. Perceived pitch of two-tone sequences with 750-msec gap between tone pairs (Study 3). Stimuli were alternating octave-interval pairs with or without a third interpolated tone, as shown in Fig. 1a. (Dark and light boxes are tones to left and right ears, respectively.) Percentage of sequences on which the nondominant ear was followed for pitch is shown as a function of the difference in amplitude between the tones in the nondominant and dominant ears, and whether or not a tone was presented in the gap between tone pairs. (From Ref. 3)

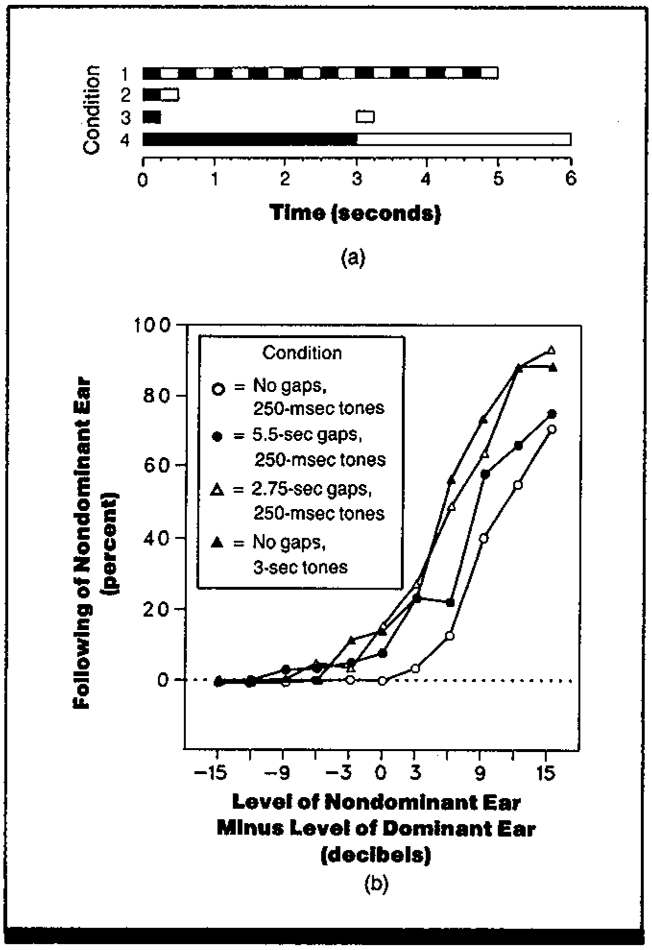

Figure 4. Perceived pitch of two-tone sequences with different onset intervals between tone pairs (Study 4). (a) Stimulus configurations; alternating black and white bars represent alternating tone pairs; temporal relation between onsets of tone pairs is shown; tone pairs were alternating octave-interval tones similar to those in Fig. 1a; (b) Percentage of sequences on which the nondominant ear was followed for pitch is shown as a function of the difference in amplitude between the tones in the nondominant and dominant ears. (From Ref. 4)

used, with amplitude constant at 70 dB SPL. The majority of listeners perceived the octave illusion. Fewer perceived a single-pitched tone which alternated from ear to ear; some subjects heard other complex percepts. The proportions of subjects hearing either single pitch or complex percepts varied by handedness (Ref. 1).

Ear dominance effects have also been found using a single dichotic chord where component tones switched from ear to ear after a 1-sec delay (Ref. 5).

In dichotic tasks where frequencies are separated but do not alternate in pitch range from ear to ear, grouping most often occurs on the basis of frequency (CRef. 6.402).

Constraints

- Many factors influence auditory grouping and must be considered in applying these results under different conditions (CRefs. 6.401, 6.402, 6.403).

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Cross References

2.708 Pitch discrimination under simultaneous masking;

6.401 Auditory grouping;

6.402 Grouping of tone sequences by frequency;

6.403 Grouping of tone sequences: effect of frequency separation and presentation rate;

Handbook of perception and human performance, Ch. 32, Sect. 1.2

Table 1. Distribution of righthanders and lefthanders obtaining different categories of percept in the octave illusion (From Ref. 2)

Handedness	Octave	Single pitch	Complex
Right (53 subjects)	58%	25%	17%
Left (33 subjects)	52%	9%	39%

Octave: heard octave illusion; single pitch: heard single-pitched tone alternating from ear to ear; complex: heard some other complex pitch pattern

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

6.405 Perceptual Segregation of Phase-Shifted Tones

Key Terms

Auditory illusion; auditory pattern perception; interaural phase differences; pitch perception

General Description

When the phase of one component of a complex tone is different from the phase of the other components, the out-of-phase component can be perceptually segregated from the rest. For example, when a complex tone comprised of 12 sequential harmonics of a 200-Hz tone is played so that all the components but one are in phase and the out-of-phase harmonic is periodically changed in ascending or descending order, the out-of-phase harmonics can be heard as a scale. Whether the scale is ascending or descending can be perceived almost perfectly when the phase angle displacement is 40 deg or more. For phase angles smaller than 10 deg, performance is at chance level, indicating that a phase displacement this small does not result in perceptual segregation of out-of-phase tone from the complex.

Methods

Test Conditions

- Stimuli were complex tones made up of 12 equal-amplitude, consecutive harmonics of 200 Hz ranging from 600-2800 Hz, presented in sine phase; at ~333 msec intervals, phases reset to 0 deg for all components except one, which was set to a different phase angle (1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 120, 150, or 180 deg out of phase); out-of-phase components formed an ascending or descending scale.
- **Monaural** earphone (Grayson-Stadler TDH-49) presentation to subject in acoustic booth.

Experimental Procedure

- Within-subjects design
- Two-alternative forced-choice procedure
- Independent variables: phase of target tone; ascending or descending scale
- Dependent variable: percent correct identification of direction of scale
- Subject's task: indicate whether tone sequence is ascending or descending
- 8 subjects, university staff members and students

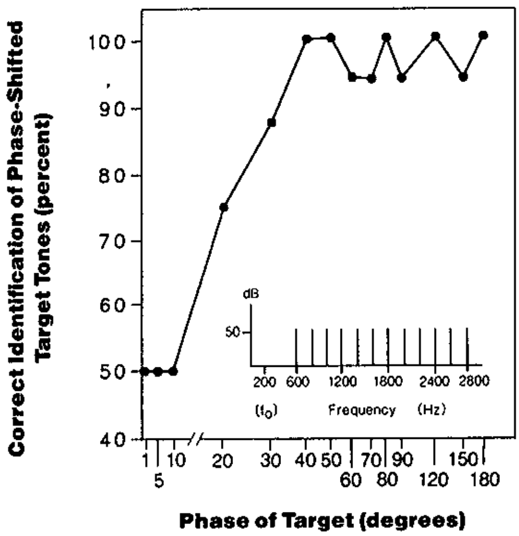

Figure 1. Perception of the pitch sequence of phase-shifted tones. Accuracy in identifying whether the pitches of successively phase-shifted tones formed an ascending or descending scale is shown as a function of the phase difference between the phase-shifted tone and the other tones comprising the 12-tone complex. The frequencies and amplitudes of the components of the complex tone are shown in the inset (f_0 is the fundamental frequency). (From Ref. 3)

Experimental Results

- Identification of the pitch sequence of out-of-phase tones as ascending or descending is no better than chance when the phase of the tone differs by 10 deg or less from the phase of the other components of a complex tone.
- Identification is ~100% accurate for phase shifts of ⩾40 deg; that is, tones are clearly segregated perceptually by phase for phase differences of this magnitude.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The phenomenon of tone segregation by phase is robust over a wide range of frequencies, especially high frequencies (Ref. 3).

When eight tones comprising a G-major scale are presented **dichotically** and the tones are interaurally phase-shifted in sequence, subjects hear a melody which appears to come from one spatial location, and noise which appears to come from a different spatial location (Ref. 2).

Constraints

- Tone segregation by phase shift occurs only under dynamic conditions, i.e., when tones are phase-shifted in sequence. When each phase-shift segment making up these stimuli is presented alone, the pitch of the out-of-phase tone cannot be discriminated.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

6.401 Auditory grouping;

6.402 Grouping of tone sequences by frequency;

6.404 Grouping of tone sequences by ear of input;

Handbook of perception and human performance, Ch. 32, Sect. 1.1

6.406 Detection of Temporal Displacement in Tone Sequences

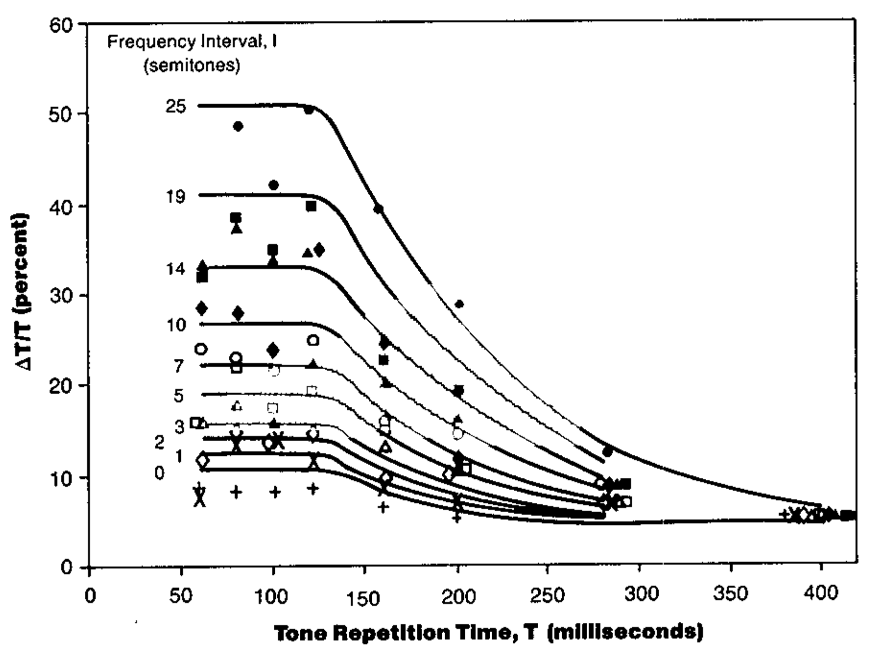

Figure 1. Threshold for detecting the temporal displacement of one tone in continuous sequences of two alternating tones (Exp. 1). Smallest detectable temporal displacement of a tone (ΔT) as a percentage of tone repetition time T (where repetition time = 1/presentation rate) is shown as a function of repetition time. Data are shown for several tone frequency separations (I), measured in semitones (where 1 semitone = 1/12 of one octave). These data are derived from Fig. 6.3 of Ref. 2. The set of curves is constructed by using the formula $\Delta T/T = a + bI$ with $a = 0.11$ and $b = 0.016$ semitone for $T \leq 120$ msec, and by drawing the best smooth curve through the experimental points by eye for larger values of T. The shaded area shows the range of values where temporal coherence is perceived (i.e., the alternating tones sequences *ABAB*...are heard as a single tonal stream, rather than as two separate streams, one of tone *A* and the other of tone *B*). (From Ref. 2)

Key Terms

Auditory pattern perception; frequency separation; presentation rate; rhythm; temporal displacement; temporal pattern perception

General Description

When tones of two frequencies are alternated (*ABAB*), the detection of the temporal displacement of *B* relative to *A* is affected by both the presentation rate and the frequency separation between *A* and *B*. Increasing the presentation rate increases the threshold for detection of temporal displacement; increasing the frequency separation between the tones also increases the displacement threshold. The temporal displacement threshold is considerably lower when one two-tone pair is compared to a preceding two-tone pair (two-alternative forced-choice procedure) than when a continuous tone sequence is presented and subjects must detect temporal displacement (tracking procedure).

Methods

Test Conditions

Experiment 1

- Diotic headphone presentation of two tones (*A*, *B*) at 35 dB above threshold in alternating sequence (*ABAB*...); tone duration 40 msec, rise and decay times of 5 msec; *B* tone frequency (f_B) of 1000 Hz; *A* tone frequency varied, defining frequency intervals relative to f_B of 0, 1, 2, 3, 4, 7, 10, 14, 19, and 25 semitones (12 semitones = 1 octave); tone repetition time of 62, 82, 101, 120, 158, 202, 278, 398 msec, presented randomly; *A* tone repetition time $T_A = 2T$; *B* tone repetition time $T_B = 2T \pm 1\%$
- Subject, in soundproof booth, pressed button indicating that tone *B* was no longer halfway between *A* tones; subject's response switched T_B from $2T + 1\%$ to $2T - 1\%$ or vice versa

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experiment 2

- Same as Exp. 1 except: each trial consisted of two two-tone (A,B) pairs; 500 msec between pair presentations; interval between first tone pair was 100 msec; interval between second pair was the same or shorter; 50-msec tone duration; f_B = 500, 1000, 2000 Hz; f_A varied between $f_B/4$ and $4f_B$

Experimental Procedure

Experiment 1

- Modified Békésy tracking procedure
- Independent variables: tone repetition time, frequency separation of A and B
- Dependent variable: smallest noticeable temporal displacement of B (ΔT); data are plotted in terms of threshold defined as $\Delta T/T$ (where T is tone repetition time)
- Subject's task: signal perception of temporal displacement of B tone relative to A tone rate by pressing button
- One adult male subject

Experiment 2

- Two-alternative forced-choice paradigm
- Independent variables: temporal interval between tones of second pair (same or shorter than first); frequency separation of tones in pair
- Dependent variable: just noticeable temporal displacement (ΔT), defined as displacement for which responses were 75% correct; data are plotted in terms of threshold defined as $\Delta T/T$ (where T is tone repetition time)
- Subject's task: indicate whether interval between second pair of tones was same or shorter than interval between first pair of tones
- One adult male subject

Experimental Results

- The threshold for detecting a temporal displacement between two tones is lower (displacement detection is better) when determined by a forced-choice procedure than when determined by a continuous tracking procedure (Fig. 2).
- When measured by a continuous tracking procedure, displacement thresholds are constant for repetition times <120 msec (faster presentation rates). For repetition times between 120-278 msec (slow rates), thresholds decrease as repetition time increases (Fig. 1).
- Temporal displacement thresholds increase as frequency separation of the tones increases (Fig. 2).

Variability

Although only one subject was tested, pilot experiments with other subjects yielded comparable results (Ref. 2). In general, forward detection thresholds (where T_B shifted from $T_A + 1\%$ to $T_A - 1\%$) exceeded backward detection thresholds (where T_B shifted from $T_A - 1\%$ to $T_A + 1\%$) when repetition time was $\leq$120 msec. The spread of this systematic difference increased slightly with greater thresholds, and varied approximately in the range of 2-15 msec (Ref. 2).

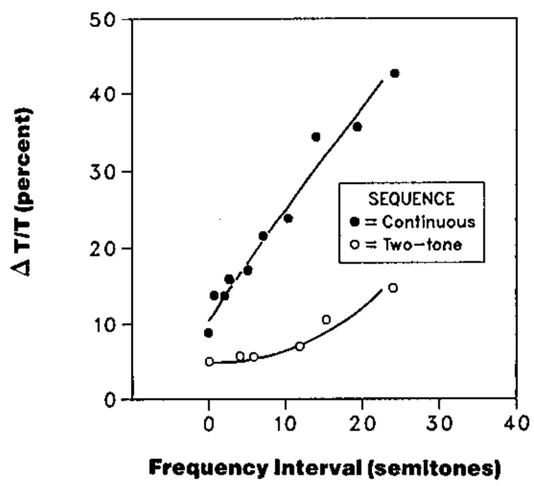

Figure 2. Threshold for detecting temporal displacement in tone sequences as a function of frequency separation of the tones (in semitones). Thresholds were measured for continuous sequences of two alternating tones using a tracking procedure (Exp. 1), or for pairs of tones using a two-alternative forced-choice procedure (Exp. 2). (From Ref. 2)

Repeatability/Comparison with Other Studies

Minimum detectable temporal gap between tones has been found to increase with increased tone frequency separation (CRef. *Handbook*). Temporal gap discrimination accuracy with two-tone sequences is reduced with increased frequency intervals (Ref. 1).

Temporal coherence (sequence connectedness) is perceived over greater tone intervals when two-tone sequences are used than when continuous sequences are used (Ref. 2). When subjects attempt to perceive temporal coherence, decreases in presentation rate significantly increase the range of frequency separation over which coherence is preserved (CRef. 6.403).

Constraints

- Why temporal intervals are better distinguished in short sequence than in continuous sequences is not understood (Ref. 2).

Key References

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Cross References

6.403 Grouping of tone sequences: effect of frequency separation and presentation rate;

Handbook of perception and human performance, Ch. 32, Sect. 1.3

6.407 Auditory Perception of Sequence

Key Terms

Auditory pattern recognition; interstimulus interval; temporal order

General Description

When auditory stimuli are presented in a sequence, how their order is perceived depends upon the time interval separating their onsets. When small intervals (~10 msec) separate the onsets of two events, a single, fused sound is heard. Differences in the quality of this fused sound may serve as a basis for order judgments (Refs. 1, 7). For example, such differences in **dichotically** presented sounds can function as **lateralization** cues (Ref. 1). With somewhat longer intervals, order judgments may be made using figural or global sequence properties, although listeners may not be able to specify individual elements. Finally, with longer intervals (>500 msec), listeners can make order judgments by analyzing individual pattern components.

The ranges of interstimulus onset intervals associated with these modes vary substantially and are affected by training, the experimental paradigm used, and stimulus parameters. The order of continuously cycling stimuli, for example, is usually more difficult to identify than stimulus order in patterns that are clearly separated by pauses. Also, order detection increases in difficulty as the number of stimuli in the sequence increases.

Table 1 summarizes results from a number of studies investigating order perception for two events, for three or more events, and for continuously cycling patterns.

Table 1. Perception of the order of auditory events.

Description of Conditions	Results	Source
Two Stimuli		
Clicks, hisses, and tones paired; amplitude varied; highly trained subjects	20 msec minimum inter-stimulus onset interval needed for 75% correct order judgments	Ref. 6; CRef. 6.408
Buzzes, hisses, and tones paired; repeated listening	Correct ordering not accomplished on first presentation (even at 150-msec separation); accurate judgments at 30 msec separations with repeated listening	Ref. 3
Spectrally varied sound sequences; rate of presentation was gradually increased	Correct naming achieved with separation as small as 5 msec	Ref. 9
Three or More Stimuli		
Three 20-msec tones with a fourth "irrelevant" tone	Order identification performance worse when fourth tone included	Ref. 4
Three sounds presented singularly in one of six possible permutations	Correct identification of permutation slightly above chance with 15 msec separation; improved at 45 msec separation and again at 150 msec separation	Ref. 4
Presentation of single patterns, repeated single patterns, and continuously cycled patterns without breaks	Performance worst with continuous cycling; three different streams of sounds heard for a pattern presented under the different formats	Ref. 7
Continuous Cycling Patterns		
Six 100-msec tones from alternating frequency ranges (1-1/2 octave range separation) presented as repeating sequences; a three-tone pattern then presented in isolation and subject judged whether this pattern had occurred in that order in preceding sequence	Performance exceeded chance only when the three tones were from the same frequency range	Ref. 2
Sequence composed of high tone, low tone, buzz, and hiss; each sound presented for 200 msec or more	Correct order judgments made when item presentation duration >500 msec	Ref. 10
Four-element sequences delivered slowly enough for correct naming; presentation speed gradually increased	After learning names for different sequences, subjects could make correct judgments with presentation rates as fast as 10 msec per item	Ref. 9

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Applications

Auditory presentations where item order is important.

Constraints

- Estimates of interstimulus-onset-interval ranges over which order perception occurs can be confused by association learning. Subjects may, for example, learn to associate labels with sound qualities so that order may be reported correctly without perception of individual stimuli.

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Cross References

5.1022 Order perception with heteromodal stimulus sequences;

6.403 Grouping of tone sequences: effect of frequency separation and presentation rate;

6.408 Auditory perception of sequence: effect of interstimulus onset interval;

Handbook of perception and human performance, Ch. 32, Sect. 4.1

6.408 Auditory Perception of Sequence: Effect of Interstimulus-Onset Interval

Key Terms

Auditory pattern perception; interstimulus interval; temporal order; two-click threshold

General Description

Two brief sounds will be heard as distinctly separate sounds when there is an interval (temporal gap) as short as 10 μsec between them (Ref. 4). This has been called the two-click threshold. However, a much longer separation interval (~20 msec) is needed to distinguish the order of onsets of successive sounds (Ref. 2). Combining the results of several experiments using differing types of paired sounds, Fig. 1 shows the minimum temporal interval necessary before most subjects can correctly identify the order of occurrence for two successive sounds.

Applications

Accurate discrimination of the order of sounds is required for auditory pattern perception.

Methods

Test Conditions

- Pairs of sounds presented **monaurally** with varied intervals between onsets of pair members; combinations of sounds within pairs shown in Table 1
- Experiment 1: Low-high tone pairs were 250 and 300, 250 and 1200, 250 and 4800, 1000 and 1200, or 1000 and 4800 Hz; low-high narrow noise bands had center frequencies of 440 and 4000 hz; temporal interval between onsets from −60 to +60 msec; tone duration was ~500 msec and pairs occurred every 1800 msec; sounds terminated simultaneously
- Experiment 2: 250-, 1000-, or 4000-Hz tone and broadband noise; tones and noise equated at 80 phons; rise time of ~20 msec
- Experiment 3: Click and 2400-4800-Hz filtered noise or 300-600-Hz filtered noise with 2-, 7- or 15-msec rise time; 70-dB sound pressure level (SPL) noise and click peak amplitude equal to pure tone with 96-dB root-mean-square SPL
- Experiment 4: Click and 1000-Hz tone with rise time, duration, and level varied for tone; peak amplitude of click equivalent to 80-dB root-mean-square SPL
- Experiment 5: 1000-Hz bandpass click and 4000-Hz bandpass click

Experimental Procedure

- Method of constant stimuli with forced-choice procedure
- Independent variable: characteristics of sounds (see table)
- Dependent variable: minimum temporal interval between onsets of sounds for correct judgment of order
- Subject's task: judge which of two sounds occurred first
- 4 or 5 subjects per experimental group

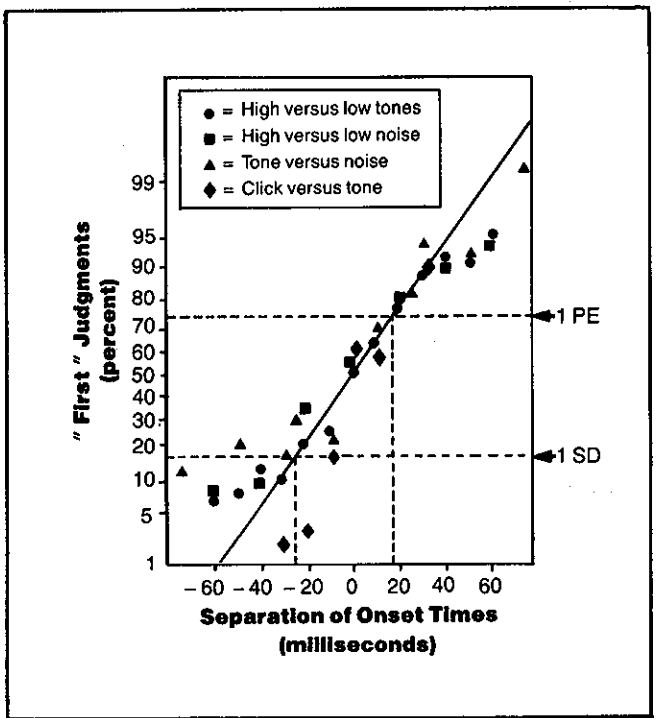

Figure 1. Judgments of the order of two sounds. The percentage of times a given stimulus was judged to occur first is plotted as a function of the temporal interval separating the onsets of the two sounds of each pair. Negative values on abscissa indicate that the sound judged to occur first actually followed the other sound by the indicated interval. Straight line was drawn by eye to fit points falling between about 20 and 90 percent on normal-probability ordinate. Points, corresponding to one probable error, PE (75% judgment), and one standard deviation, SD (16% judgment), are shown. (From Ref. 2)

Experimental Results

- Temporal separation of ~17 msec produces 75% correct identification of order of successive sounds (Fig. 1).
- The results are similar regardless of the acoustic qualities of the paired sounds. (Data in Fig. 1 represent averages within similar experimental conditions. Data for noise versus either 1000- or 4000-Hz tone not included because of possible contamination by masking. Data for noise versus click not included because of problem with temporal intervals.)

Variability

The probable error (PE) line at 75% means that the correct identification of order will occur 75% of the time with a 17-msec separation between onsets of sounds. Line indicating one standard deviation (25 msec) is shown in Fig. 1.

Repeatability/Comparison with Other Studies

The minimum separation threshold of ~20 msec also applies to other sensory modalities (Ref. 3), whether or not the stimuli in the pair are in the same or differing modalities (e.g., auditory versus visual). Results thus suggest that a central mechanism mediates the perception of temporal ordering of events.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Differences in stimulus rise time or duration may change length of minimum interval.
- Subjects can also use information about interval between sound offsets to determine order.

Key References

1. Green, D. M. (1971). Temporal auditory acuity. *Psychological Review, 78*, 540-551.

*2. Hirsh, I. J. (1959). Auditory perception of temporal order. *Journal of the Acoustical Society of America, 31*, 759-767.

3. Hirsh, I. J., & Sherrick, C. E. (1961). Perceived order in different sense modalities. *Journal of Experimental Psychology, 62*, 423-432.

4. Leshowitz, B. (1971). Measurement of the two-click threshold. *Journal of the Acoustical Society of America, 49*, 462-466.

Cross References

5.1022 Order perception with heteromodal stimulus sequences;

6.406 Detection of temporal displacement in tone sequences;

6.407 Auditory perception of sequence

Table 1. Characteristics of pair members for each of the five experiments. (From Ref. 2)

Experiment	Sounds	Bandwidth	Duration	Different with Respect to
1	Tones versus tones, noise bands versus noise bands	Both narrow	Both long	Frequency
2	Tones versus noise	One narrow One wide	Both long	Quality
3	Click versus noise	Both wide	One short One long	Duration
4	Click versus tone	One wide and short One narrow and long		Duration, Quality
5	High click versus low click	Both narrow	Both short	Frequency

6.501 Modes of Display for Two-Dimensional Multielement Tactile Patterns

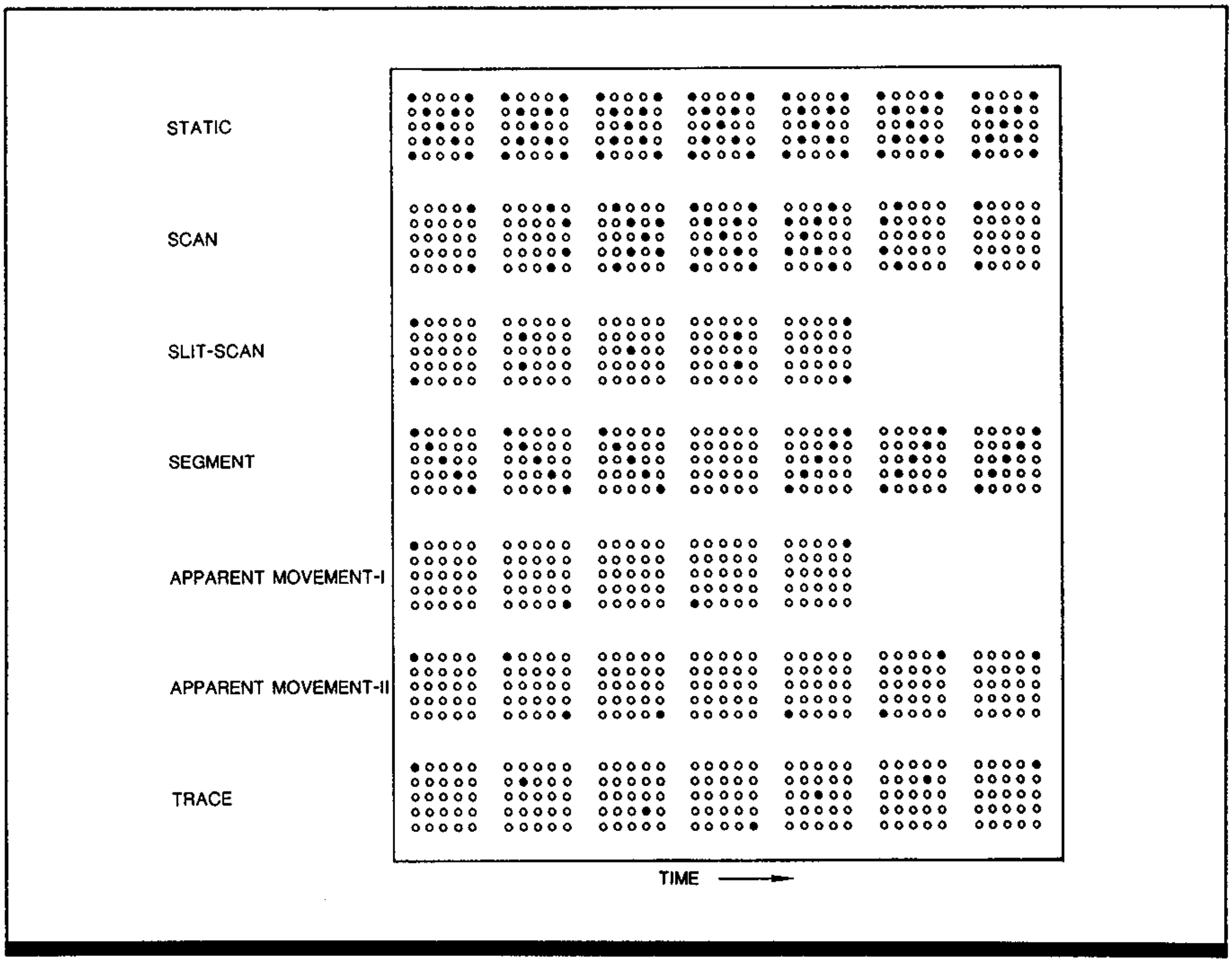

Figure 1. Seven display modes for presenting the letter "x" to the skin. Filled circles are active stimulators in a 5 x 5 array of stimulators. Successive frames show sequence of active stimulators at successive points in time. Because of space limitations, only seven of ten frames in the trace mode are depicted. (From Ref. 1)

Key Terms

Tactile communication; tactile pattern discrimination; touch; vibrotactile display

General Description

Seven modes of displaying multielement tactile patterns are described below and illustrated in Fig. 1. Patterns (arrays of points) are generally presented by vibrotactile stimulators with piezoelectric elements or solenoid-driven stimulators or by airjets that deliver a pressure-controlled pulse of air through each nozzle. Airjet stimulators provide relatively uniform stimulation over uneven cutaneous surfaces.

Static: The entire pattern makes simultaneous contact with the skin and the contact continues in the same location for the entire presentation period. To prevent loss of pattern perception over time, the experimenter often introduces a very slight motion (jitter) of the pattern about a fixed position on the skin or tactile display. The static and jitter modes yield similar results with only minor differences.

Scan: There is relative movement of the pattern, generally from right to left, across the skin surface; the entire pattern is in contact with the skin for at least part of the stimulus presentation period. In braille and **Optacon** reading, the patterns move across the skin with the reader controlling the movement.

Slit-scan: A pattern is presented as if scanned through a vertical slit moving from left to right across the stationary pattern. The points within each vertical section are pre-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

sented simultaneously; the vertical sections are presented sequentially.

Segment: Elements of a pattern are presented sequentially stroke by stroke or segment by segment.

Apparent Movement I: This mode is similar to the segment mode but only the endpoints of each segment or stroke are displayed rather than all of the points defining the segment. The stimulator defining each point is activated and then turned off before the next stimulator is activated. The phenomenon of tactile apparent movement (CRef. 3.120) can give the impression of a line stroke between stimulated points without stimulation of the intermediate positions if the endpoint stimulations are properly timed.

Apparent Movement II: This mode differs from Apparent Movement I only in that the activations of two end point stimulators partially overlap in time.

Trace: The points defining a pattern are presented sequentially as if the pattern were being traced on the skin.

Applications

The study and practical implementation of tactile communication systems, including systems for the blind.

Constraints

- Many factors in addition to display mode influence the perception of tactile patterns. (CRef. 6.502)

Key References

1. Loomis, J. M., & Lederman, S. (1986). Tactual perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

Cross References

3.120 Apparent movement of vibrotactile and electrocutaneous stimuli;

6.502 Factors affecting identification of tactile patterns;

6.503 Identification of vibrotactile patterns: effect of display mode and body location;

6.504 Identification of vibrotactile patterns: effect of exposure duration and intensity;

6.509 Tactile pattern discrimination: effect of pattern element commonality and body locus;

6.510 Vibrotactile code learning

6.502 Factors Affecting Identification of Tactile Patterns

Factors Affecting Perception	Type of Pattern	Effects	Source
Presentation mode: static, scan, slit-scan, or segment	**Vibrotactile** letter patterns (Roman letters and Japanese phonetic letters)	Identification of patterns on back or abdomen is poorest for static presentation mode (all parts of letter presented simultaneously) and best for segment mode (natural writing strokes presented sequentially). For patterns presented to fingertips or palm, static mode is equal to or better than other modes except at very short display durations	CRef. 6.503
Display duration	Vibrotactile upper-case Roman letters	Identification accuracy increases with increasing display time for patterns presented to either finger or palm	CRef. 6.503
Display intensity	Vibrotactile upper-case Roman letters	At short display times, identification accuracy increases with increasing intensity of vibration; identification accuracy does not vary with intensity at long display times	CRef. 6.504
Character height	Raised braille characters, raised or vibrotactile upper-case Roman characters	Identification accuracy increases with increasing character height	CRef. 6.506
Type of character	Raised braille characters, raised or vibrotactile upper-case Roman characters	Identification accuracy poorer for vibrotactile characters than for raised characters of the same height	CRef. 6.506
Display width	Vibrotactile Roman letters	Identification accuracy increases with display width provided display is all to one finger; when display width requires stimulation of two fingers, identification accuracy is no better than widths fitting on a single finger and may not be as good	CRef. 6.507
Masking			
Interval between presentation of target pattern and mask	Vibrotactile target pattern and mask	Identification accuracy of target pattern decreases as interval between target and mask decreases	CRefs. 6.505, 6.514, 6.515
Duration of mask	Vibrotactile target pattern and mask	Identification accuracy decreases as mask duraation increases	CRef. 6.513
Distance between target pattern and mask	Vibrotactile target pattern and mask	Identification accuracy decreases as distance decreases	CRef. 6.512
Sequence of target pattern and mask	Vibrotactile target pattern and mask	Identification of a target pattern is less accurate when masks follow the target rather than precede it	CRefs. 6.505, 6.513, 6.514

Key Terms

Letter recognition; tactile communication; tactile pattern discrimination; target identification; touch; vibrotactile display; vibrotactile masking

General Description

The ability to identify (discriminate or recognize) tactile patterns varies with the spatial and temporal characteristics of the patterns. For different types of tactile patterns, the table lists factors that affect perception, describes the nature of the effects, and cites sources of further information.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Cross References

6.503 Identification of vibrotactile patterns: effect of display mode and body location;

6.504 Identification of vibrotactile patterns: effect of exposure duration and intensity;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.506 Identification of tactile patterns: effect of character height;

6.507 Identification of vibrotactile patterns: effect of display width;

6.511 Factors affecting vibrotactile pattern masking;

6.512 Vibrotactile pattern masking: effect of distance between target and mask;

6.513 Vibrotactile pattern masking; effect of type and duration of mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask;

6.515 Vibrotactile pattern masking: effect of delay between target and mask for spatially non-overlapping masks

6.503 Identification of Vibrotactile Patterns: Effect of Display Mode and Body Location

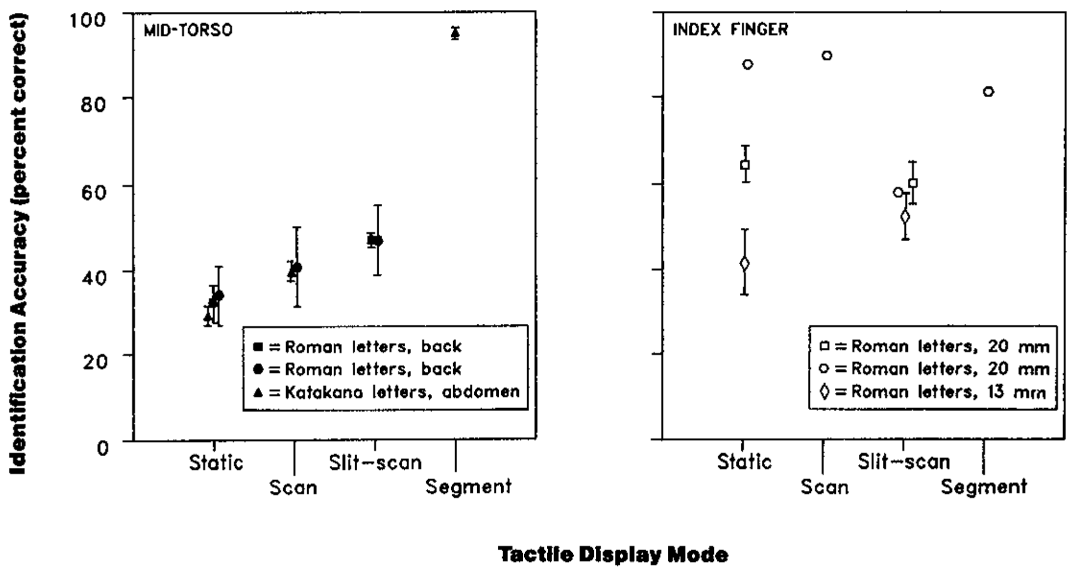

Figure 1. Accuracy of letter identification as a function of body location, display mode, and type of stimulus. ■ = Ref. 1, ● = Ref. 3, ▲ = Ref. 6, ○ = Ref. 2, ◊ = Ref. 4, and □ = Ref. 4. (From *Handbook of perception and human performance*)

Key Terms

Letter recognition; tactile pattern discrimination; target identification; touch; vibrotactile display

General Description

Accuracy of identifying vibrotactile letter patterns varies with presentation mode and body location. For patterns presented to the back or abdomen, performance is poorest for a static mode of presentation (the entire pattern makes simultaneous contact with the skin); performance is best (nearly perfect) for a segment mode (pattern is presented sequentially in stroke-by-stroke fashion). For patterns presented to the index finger, the static mode is equal or superior to all other display modes.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- Vibrotactile letter patterns presented to the skin: Japanese phonetic letters (Katakana characters) used in Ref. 6; all other studies used uppercase Roman alphabet letters
- Refs. 1 and 3 presented stimuli to the back by means of the Tactile Vision Substitution System (TVSS) in which a 20 x 20 matrix of vibrotactile stimulators is driven at 60 Hz and 10 dB above threshold by a signal from a television camera; Refs. 2 and 4 presented stimuli to the fingertip by means of an **Optacon** display (a 6 x 24 array of pins, driven at 230 Hz for one experiment); in Ref. 6 a 10 x 10 matrix of vibrators was positioned on subject's abdomen
- Four different presentation modes were used: static, in which all elements of the stimulus pattern were activated or deactivated simultaneously; scan in which the letter pattern passed across the array from right to left; slit-scan, in which the letter pattern was exposed sequentially, as if scanned by vertical slit; and segment, in which the letter pattern was presented stroke by stroke in a sequence approximating that of naturally writing the letter

Experimental Procedure

- Independent variables: body locus (location) of stimulator, presentation mode
- Dependent variable: percent of letters correctly identified
- Subject's task: indicate which letter was presented to the skin
- Reference 1: 4 subjects (2 males and 2 females), 1 with previous practice; Ref. 2: 4 practiced subjects; Ref. 3: 7 subjects (3 blind and well-practiced, 4 blindfolded); Ref. 4: 4 unpracticed females; Ref. 6: 8 subjects (4 blind)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• For vibrotactile letter patterns presented to the mid-torso, the static mode of presentation results in the poorest performance and the segment mode leads to the best performance.
• For index finger presentations, sequential modes of presentation are not superior to the static mode.

Variability

Standard error bars represent ± 1 standard error of the mean.

Repeatability/Comparison with Other Studies

The static mode also yields the poorest recognition performance for Katakana characters presented to the palm (Ref. 5).

Constraints

• Which presentation mode yields the best performance is a function of stimulus duration, body locus, and stimulus size. Longer stimulus durations may yield better recognition performance (Ref. 2). The relative superiority of sequential over static modes may disappear when sequentially presented letters can be processed as if the components occurred simultaneously (e.g., the components occur very close together in time). For example, recognition performance for vibrotactile letter patterns presented to the index finger does not vary with display mode for display durations <5 msec (duration defined as the maximum duration of any pattern element).
• Other factors (such as stimulus intensity) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef 6.502).

Key References

*1. Apkarian-Stielau, P., & Loomis, J. M. (1975). A comparison of tactile and blurred visual form perception. *Perception & Psychophysics, 18*, 362-368.

*2. Craig, J. C. (1981). Tactile letter recognition: Pattern duration and modes of pattern generation. *Perception & Psychophysics, 30*, 540-546.

*3. Loomis, J. M. (1974). Tactile letter recognition under different modes of stimulus presentation. *Perception & Psychophysics, 16*, 401-408.

*4. Loomis, J. M. (1980). Interaction of display mode and character size in vibrotactile letter recognition. *Bulletin of the Psychonomic Society, 16*, 385-387.

5. Shimazu, Y. (1982). Tactile letter display for a reading aid. *Proceedings of the Eighth Congress of the International Ergonomics Association*, Tokyo, Japan.

*6. Shimazu, Y., Saida, S., Wake, T., Nakamura, A., & Ohzu, H. (1982). Optimum design of tactile display for a reading aid. In J. Raviv (Ed.), *Uses of computers in aiding the disabled* (pp. 383-391). Amsterdam: North-Holland.

Cross References

3.106 Pressure and vibration sensitivity;

6.501 Modes of display for two-dimensional multielement tactile patterns;

6.502 Factors affecting identification of tactile patterns;

6.504 Identification of vibrotactile patterns: effect of exposure duration and intensity;

6.506 Identification of tactile patterns: effect of character height;

6.507 Identification of vibrotactile patterns: effect of display width;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

6.504 Identification of Vibrotactile Patterns: Effect of Exposure Duration and Intensity

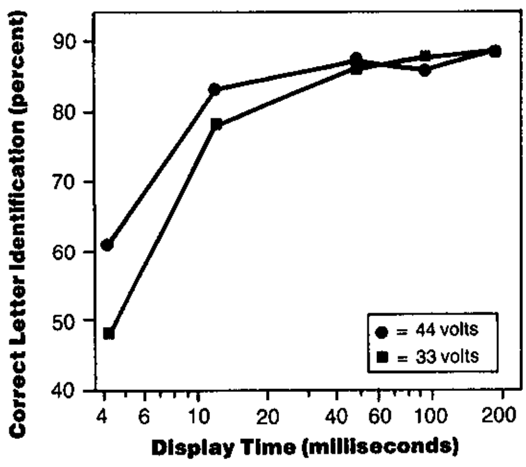

Figure 1. Accuracy of tactile letter identification as a function of display time for two levels of intensity. (From Ref. 1)

Key Words

Letter recognition; tactile pattern discrimination; touch; vibrotactile display

General Description

For short presentation times, identification of vibrotactile letter patterns is more accurate with a greater intensity of vibration. For longer presentation times, identification accuracy does not vary with intensity.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- Uppercase letters presented to fingertips by an **Optacon** (6 x 24 array of pins) vibrating at 230 Hz; letter patterns generated by selective simultaneous activation of pins
- Letter patterns presented for durations of 4.3-200 msec at vibration intensity setting of 33 or 44 V (maximum for the Optacon)
- For each trial 50-msec cue stimulus presented warning signal 1 sec before experimental stimulus

Experimental Procedure

- 40-trial block for each duration; blocks presented in random order; ~50 min experimental session
- Independent variables: presentation duration, vibration intensity
- Dependent variable: percent of letters correctly identified
- Subject's task: press a key on a keyboard corresponding to perceived letter pattern; feedback given after each trial
- 3 subjects with extensive practice

Experimental Results

- Identification of briefly presented vibrotactile letter patterns is better for displays of higher amplitude (intensity). At longer presentation times, higher stimulus amplitude (intensity) does not yield better performance.

Variability

Standard errors of the means ranged from 4% at the shorter durations to 2% at the longer durations.

Constraints

• Results apply only to a static presentation of display (pins activated simultaneously). Different results are obtained if the pattern moves across the display, which is the normal mode for Optacon displays.

• Many factors (such as part of the body stimulated and stimulus intensity) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef. 6.502).

Key References

*1. Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception and Performance*, *6*, 151-166.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.511 Factors affecting vibrotactile pattern masking

6.505 Identification of Vibrotactile Patterns: Temporal Resolution

Key Terms

Backward masking; forward masking; letter recognition; masking; tactile pattern discrimination; target identification; temporal integration; temporal resolution; touch; vibrotactile display; vibrotactile pattern

General Description

Vibrotactile patterns presented closely together in time (either as signals or as **masks**) may be completely integrated (i.e., may not be resolved as separate patterns) if the interval between the onsets of the stimuli is <10 msec. Very little, if any, temporal integration occurs with **interstimulus-onset intervals** >50-100 msec.

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted, and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- Vibrotactile patterns presented to subject's left index fingertip via an **Optacon** display (6 column x 24 row array of pins) vibrating at 230 Hz and 35-V amplitude to each pin; only top 18 rows used for display
- Experiment 1: pairs of stimuli were different halves of letters (uppercase B, E, M, R, or W); letters divided into halves along vertical, horizontal, or one of two diagonal axes; stimulus (letter halves) durations of 4 msec (with interstimulus-onset interval of 0, 9, 13, 17, 22, 30, 56, 104, or 200 msec), 13 msec (with interstimulus-onset interval of 0, 4, 9, 17, 30, 56, 156, or 254 msec) or 26 msec (with interstimulus-onset interval of 0, 4, 13, 30, 56, 104, 204, or 304 msec); presentation of only one-half of letter as control condition
- Experiment 2: stimuli were 26 uppercase letters presented either (a) alone, (b) followed after 4 msec by uniform energy mask lasting 13 msec (all pins in 6 x 18 array activated), or (c) followed after 4 msec by a pair of complementary pattern masks (separated by various intervals) that formed an energy mask if presented together; one set of measurements used energy mask and 26 different pairs of pattern masks with mask duration of 13 msec and target duration of 26 msec; another set of measurements used energy mask and only one set of pattern masks with mask and target durations of 26 msec; presentation of single pattern mask provided control condition; interval between pattern masks for first measurements was 4, 9, 17, 43, 90, or 190 msec and for second measurements was 4, 13, 30, 56, 104, or 204 msec
- Experiment 3: stimuli were uppercase X and O (targets) and the complements of each pattern (masks) (see Fig. 1); 26-msec stimulus duration; one set of measurements had mask presented after target; another set of measurements had mask presented either before or after target; interstimulus-onset intervals in both conditions were 4, 9, 13, 30, 56 or 104 msec
- Trials blocked by interstimulus-onset interval and by stimulus duration
- Subject heard white noise via earphones to cover any auditory cues from equipment

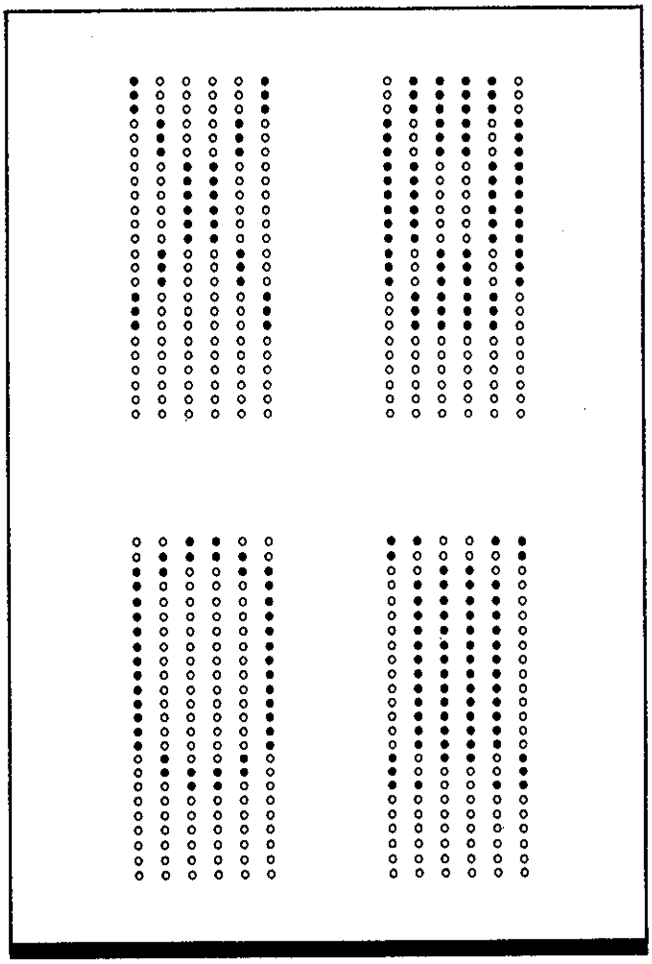

Figure 1. Representations of the target stimuli, X and O (left), and their complements (right) used in Exp. 3. (From Ref. 3)

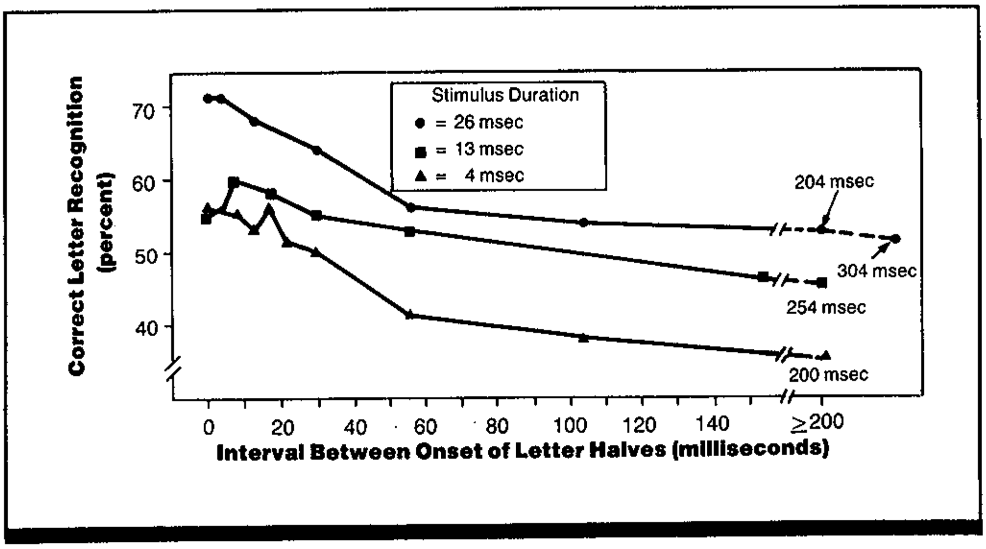

Figure 2. Percent correct recognition of vibrotactile letters as a function of interval between the onsets of each half of the letter (Exp. 1). Duration of each letter half varied as indicated. (From Ref. 3)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Five-alternative forced-choice procedure
- Independent variables: stimulus duration, interstimulus-onset interval
- Dependent variable: percent correct letter recognition (Exps. 1,3); amount of masking, defined as difference in percent correct letter recognition with and without mask present (Exp. 2)
- Subject's task: identify letter and press response key to indicate which letter was presented; no feedback provided in Exp. 1 but provided for each trial in Exps. 2 and 3
- Subjects were college students who were paid employees of the lab, with extensive practice; (Exp. 1) 3 subjects for 4-msec data and 4 subjects for 13- and 26-msec data; (Exp. 2) 3 subjects for 13-msec data and 4 subjects for 26-msec data; (Exp. 3) 3 subjects

Experimental Results

- Correct letter identification declines as the onset interval between the first and second halves of letters increases from 9 to 100 msec (Fig. 2).
- The amount of masking increases as the onset interval between two complementary pattern masks increases from 9 to about 50 msec (Fig. 3).
- Letter recognition becomes increasingly accurate as the interval between onset of a letter and its complement increases from 9 to approximately 30 msec (Fig. 4).
- The above results show that the skin is capable of complete temporal integration of vibrotactile patterns presented at intervals of <10 msec. There is little, if any, temporal integration of patterns presented at intervals >50-100 msec.

Variability

For each experiment, standard errors were 4% and were independent of experimental condition.

Repeatability/Comparison with Other Studies

Other studies have reported temporal integration occurring over longer periods of time.

Constraints

- Increasing target or mask intensity (e.g., by increasing mask duration) can influence the shape of the integration or masking function. Higher intensity masks may continue to have a masking effect for longer interstimulus-onset intervals.
- Many factors (such as mode of display and part of the body stimulated) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef. 6.502).

Key References

1. Craig, J. C. (1980). Modes of vibrotactile pattern recognition. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 151-166.

2. Craig, J. C. (1982). Vibrotactile masking: A comparison of energy and pattern maskers. *Perception & Psychophysics, 31,* 523-599.

*3. Craig, J. C. (1982). Temporal integration of vibrotactile patterns. *Perception & Psychophysics, 32,* 219-229.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.511 Factors affecting vibrotactile pattern masking;

6.512 Vibrotactile pattern masking: effect of distance between target and mask;

6.513 Vibrotactile pattern masking: effect of type and duration of mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask

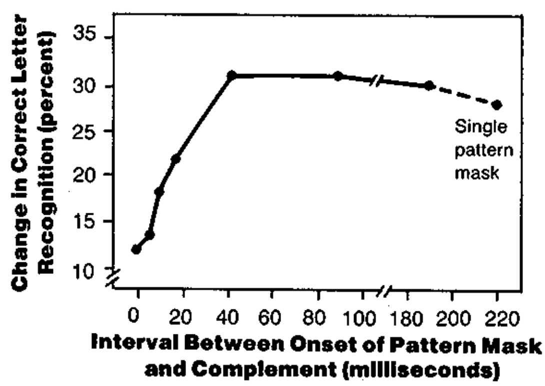

Figure 3. Amount of masking (measured as decline in correct letter recognition with mask over performance without mask) produced by a pattern mask and its complement as a function of the interval between onset of the pattern mask and complement (Exp. 2). (From Ref. 3)

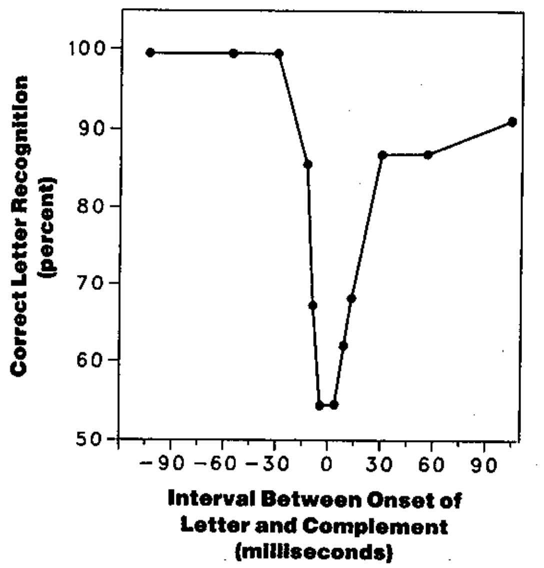

Figure 4. Percent correct letter recognition as a function of interval between the onsets of a letter (X or O) and its complement (Exp. 3). Negative values along abscissa indicate that the complement came first. (From Ref. 3)

6.506 Identification of Tactile Patterns: Effect of Character Height

Key Terms

Braille character recognition; letter recognition; tactile pattern discrimination; target identification; touch; vibrotactile display

General Description

Identifiability of raised uppercase letters and letters presented by a vibrotactile display increases as the height of the characters increases. Characters presented by means of a vibrotactile display (e.g., the **Optacon**) are less recognizable than raised tactile characters of the same height.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted, and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- Raised uppercase Roman letters and Optacon stimuli, as described below, presented to distal pad of index finger
- Raised letters elevated 0.9 (Ref. 5) or 1.5 (Refs. 3, 6) mm above surface; letter heights of 3-8.6 mm; letter width usually 60% of letter height (Refs. 5, 6) (M and W, ~80% of height, Ref. 3)
- In Ref. 5, subjects allowed to make slight circular motions of finger while in contact with stimulus; Ref. 3 used a static mode of presentation; Ref. 6 used both static condition and scan condition in which subjects could explore letters in any way using fingertip
- Subjects allowed 2 sec per letter in Ref. 5 and up to 4 sec in Refs. 3 and 6
- Refs. 1 and 4 used Optacon vibrotactile display with selected pins activated from a 6 x 24 array to produce patterns corresponding to uppercase letters; Ref. 1 used scan display mode (letter pattern passes across the array from left to right) and Ref. 4 used static display mode (all elements of stimulus are activated or deactivated simultaneously) with 1.5 sec presentation

Experimental Procedure

- Independent variables: character height, character type (raised tactile or vibrotactile)
- Dependent variable: percent correct recognition of letters
- Subject's task: indicate letter of alphabet presented by tactile display
- Ref. 1: 4 blind subjects; Ref. 3: 5 untrained subjects; Ref. 4: 4 untrained subjects; Ref. 5: 5 subjects, 1 experienced; Ref. 6: 4 subjects, with no experience and no feedback; all subjects except those in Ref. 1 had normal vision

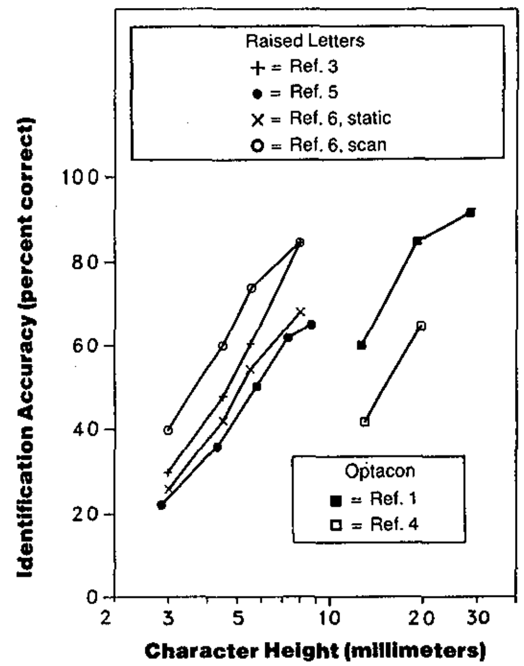

Figure 1. Character recognition accuracy for tactual perception of raised and vibrotactile (Optacon) letter patterns. (From *Handbook of perception and human performance*)

Experimental Results

- The ability to identify raised uppercase Roman characters and Roman characters presented on the vibrotactile display of the Optacon increases with increasing character height.
- Characters of equivalent size are less recognizable when presented on the vibrotactile display of the Optacon than when presented as raised tactile characters.

Variability

Reference 3 reported that performance was similar for all subjects. No variability information was given in Refs. 1, 4, 5, and 6.

Constraints

- Many factors (such as mode of display, part of the body stimulated, and stimulus intensity) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef. 6.502).
- Based on these limited data, comparisons between legibility of raised letters and letters presented via a vibrotactile display (Optacon) may not be meaningful.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Bliss, J. C. (1969). A relatively high-resolution reading aid for the blind. *IEEE Transactions on Man-Machine Systems, MMS*-10, 1-9.

2. Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 151-166.

*3. Johnson, K. O., & Phillips, J. R. (1981). Tactile spatial resolution. I. Two-point discrimination, gap detection, grating resolution, and letter recognition. *Journal of Neurophysiology, 46,* 1177-1191.

*4. Loomis, J. M. (1980). Interaction of display mode and character size in vibrotactile letter recognition. *Bulletin of the Psychonomic Society, 16,* 385-387.

*5. Loomis, J. M. (1981). On the tangibility of letters and braille. *Perception & Psychophysics, 29,* 37-46.

*6. Phillips, J. R., Johnson, K. O., & Browne, H. M. (1983) A comparison of visual and two modes of tactual letter recognition. *Perception & Psychophysics, 34,* 243-249.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.507 Identification of vibrotactile patterns: effect of display width;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

6.507 Identification of Vibrotactile Patterns: Effect of Display Width

Key Terms

Tactile pattern discrimination; target identification; touch; vibrotactile display; word recognition

General Description

Text (words) with letters consisting of patterns of dots can be presented to a subject's fingertips through arrays of vibrating pins. As the display width increases from 2-8 columns for a single finger, the percentage of words correctly discriminated increases. When the display width increases by an additional 2-8 columns, requiring stimulation of a second finger, accuracy is reduced to the level attained for six-column stimulation of just one finger.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- Tactile stimulators consisted of two 12 row x 8 column arrays of metal pins protruding through 1-mm holes of a plastic plate conforming to the curvature of a fingertip; pins vibrated at 240 Hz; patterns of active pins formed letter displays that moved from the right to left across the index and middle fingers of the left hand; each letter was seven columns wide; two columns between letters
- Width of the display window varied from 2-16 columns (8 columns per finger) for presentations of 100-word blocks of text; randomized order of presentation for different window widths

Experimental Procedure

- Independent variable: window width as measured by number of columns in letter displays available to the subject
- Dependent variable: percent of words correctly identified
- Subject's task: verbally report the presented text
- 16 blocks of text (1600 words) per data point
- 3 subjects with extensive practice reading a 6 x 24 array on a single finger; 1 subject had 3 hr of two-finger practice

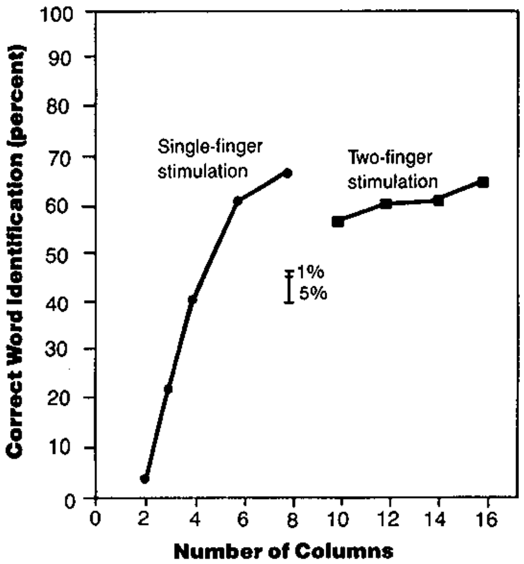

Figure 1. Accuracy of word identification as a function of the number of active tactile display columns. The tolerance bars give the 1% and 5% two-tailed *t* values for comparing any pair of data points. (From Ref. 1)

Experimental Results

- As the width of a tactile letter display for a single finger increases, the identification accuracy of words (text) increases.
- When display width includes concurrent stimulation of a second finger, identification accuracy is reduced to approximately the level attained for six-column stimulation of a single finger.

Variability

An analysis of variance for the seven widest window widths indicated there were no significant differences in subjects' performance for these widths. One percent and 5 percent error bars are shown in Fig. 1.

Constraints

- Number of columns in display is confounded with number of fingers used.
- Subjects' training was mostly with one-finger displays.
- Many factors (such as mode of display, part of the body stimulated, and stimulus intensity) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef. 6.502).

Key References

*1. Hill, J. W. (1974). Limited field of view in reading lettershapes with the fingers. In F.A. Geldard (Ed.), *Cutaneous communications systems and devices* (pp. 95-105). Austin, TX: The Psychonomic Society.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.506 Identification of tactile patterns: effect of character height;

6.510 Vibrotactile code learning

6.508 Tactile Versus Visual Recognition of Characters

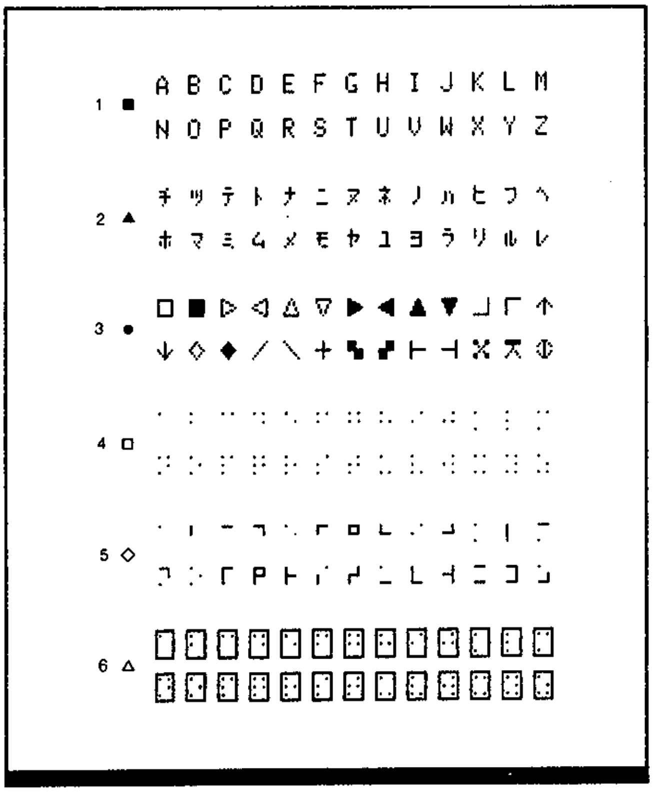

Figure 1. Six of the seven character sets used to compare tactile and visual character recognition: (1) upper case Roman letters; (2) subset of Katakana characters (Japanese); (3) set of graphic symbols; (4) standard English braille alphabet; (5) braille characters with line segments joining adjacent horizontal or vertical dots; and (6) Set 4 with constant spatial surround. Set 7 was the same as Set 6, but with a wider surround. Characters of Sets 4, 5, and 6 correspond to the Roman letters of Set 1 having the same relative position in the figure; characters in Sets 2 and 3 were arbitrarily assigned the labels of the corresponding Roman letters. (From *Handbook of perception and human performance,* based on Ref. 4)

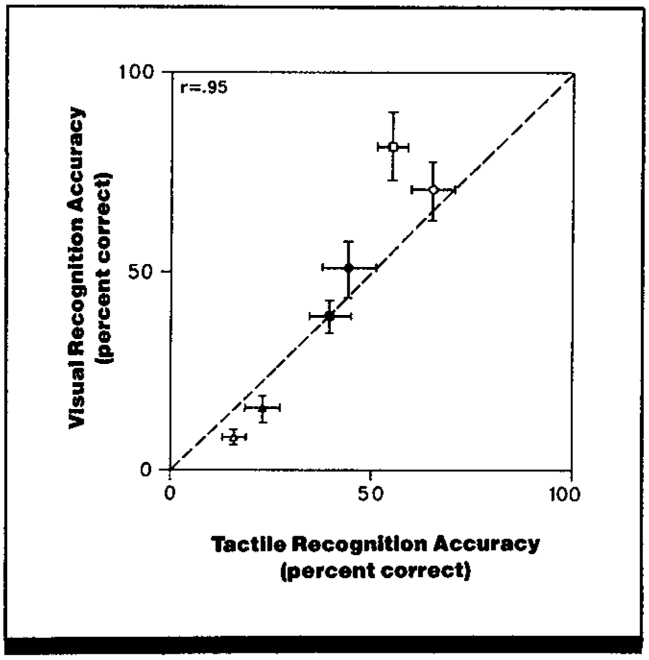

Figure 2. Comparison of visual (y-axis) and tactile (x-axis) performance on a character recognition task. The dashed diagonal indicates equivalent performance on both tasks. Error bars are for one standard error of the mean. Symbols represent character sets as keyed in Fig. 1. The correlation coefficient *r* indicates high correlation between accuracy on the visual task and accuracy on the tactile task. (From *Handbook of perception and human performance,* based on Ref. 4)

Key Terms

Letter recognition; tactile pattern discrimination; tactile pattern recognition; target identification; touch; visual pattern discrimination; visual pattern recognition

General Description

Tactile recognition of characters is about as accurate as visual recognition when visual targets are filtered so that the effective spatial bandwidths are matched for the two modalities. Different types of characters differ widely in tactile and visual legibility.

Applications

Design of tactile display and communication systems; situations in which a choice must be made between visual and tactile communication, display, or feedback.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Target from the six character sets shown in Fig. 1 plus a character set like Set 6 but with a wider constant surround; each character inscribed in a space 5.8-mm high; identical height and width for corresponding tactile and visual targets
- Tactile targets presented via slight motion of distal pad of index finger over raised characters
- Visual targets were photographic transparencies optically low-pass, spatial frequency filtered (and therefore blurred by diffusion); filter had Gaussian spatial impulse function with half-amplitude width of 5.8 mm to equate visual and tactile stimuli; foveal viewing in darkened room
- Alternating sessions of tactile and visual tasks
- Prior to recognition tasks, subjects overlearned association between verbal labels (Roman letters) and sets with unfamiliar characters

Experimental Procedure

- Independent variable: character set, presentation mode (visual or táctile)
- Dependent variable: percent correct identification of characters
- Subject's task: identify character presented
- 6 subjects

Experimental Results

- Tactile character identification performance is similar to visual performance when visual targets are blurred to match effective spatial bandwidths of tactile targets. Under these conditions, variation in legibility across character sets is similar for vision and touch.
- Legibility is limited by the spatial bandwidth of the characters.
- Tactile recognition of simple two-dimensional patterns is determined by cutaneous spatial resolution. However, visual performance is better than tactile performance for the more legible character sets; thus there may be some difficulty with perceptual integration of information in the tactile mode, at least at this level of training.
- Legibility of braille is not a function of the punctographic nature of the characters, since the legibility of the line characters of Set 5 is similar to that of the braille characters of Set 4 (which was used as the basis for the line characters).
- The intrinsic spatial filter of cutaneous processing for the fingerpad can be approximated by a two-dimensional Gaussian impulse response function with half-amplitude width of roughly 5.8 mm.

Variability

Each error bar in Fig. 2 indicates one standard error of the mean.

Repeatability/Comparison with Other Studies

Other studies (Refs. 1, 3) support these results.

Constraints

- Many factors (such as mode of display, part of the body stimulated, and stimulus intensity) affect tactile pattern perception and should be considered in applying these data under different conditions (CRef. 6.502).
- Individual differences between subjects and perceptual learning influence performance.

Key References

1. Johnson, K. O., & Phillips, J. R. (1981). Tactile spatial resolution: I. Two-point discrimination, gap detection, grating resolution, and letter recognition. *Journal of Neurophysiology, 46,* 1177-1191.

2. Loomis, J. M. (1981). On the tangibility of letters and braille. *Perception & Psychophysics, 29,* 37-46.

3. Loomis, J. M. (1982). Analysis of tactile and visual confusion matrices. *Perception & Psychophysics, 31,* 41-52.

*4. Loomis, J. M. (1983, November). *Tactile and visual legibility of seven character sets.* Paper presented at the meeting of the Psychonomic Society, San Diego, CA.

Cross References

5.111 Haptic perception of proportion;

5.1016 Intermodal and cross-modal spatial pattern recognition;

6.502 Factors affecting identification of tactile patterns;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

6.509 Tactile Pattern Discrimination: Effect of Pattern Element Commonality and Body Locus

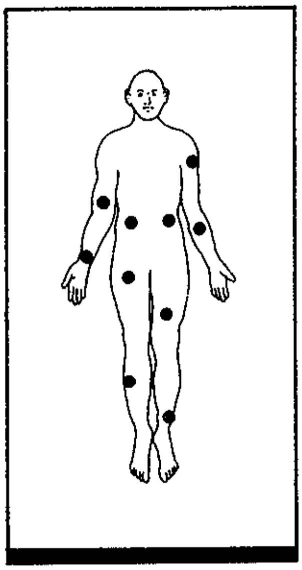

Figure 1. Location on body of 10 Bice inertia-type vibrotactile stimulators in Ref. 1.

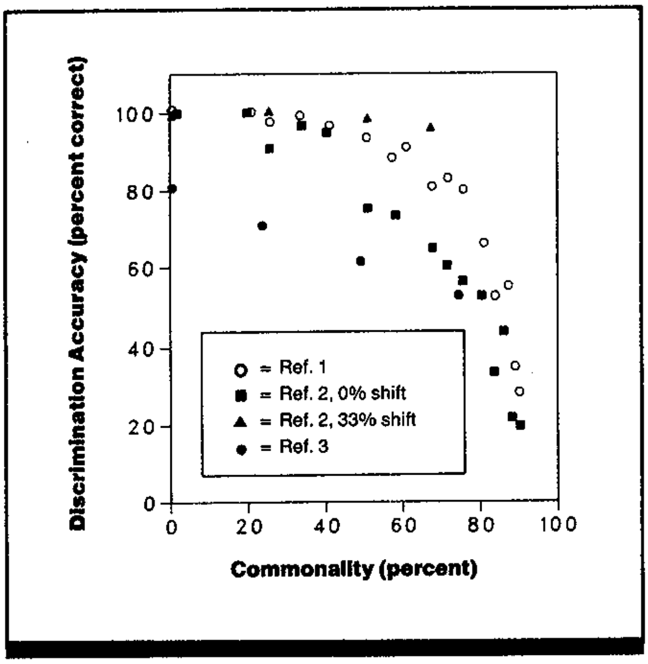

Figure 2. Accuracy in discriminating two successively presented vibrotactile patterns as a function of the percent of pattern elements (stimulated points) common to the two patterns of the pair. Patterns were presented to the front of the body (Ref. 1), to the fingertips of the right and left hands (Ref. 2), and to the thigh (Ref. 3). In Ref. 2, 0% or 33% of the pattern elements were shifted from one hand to the other in the second pattern of each pair. (From *Handbook of perception and human performance*)

Key Terms

Tactile pattern discrimination; target discrimination; touch; vibrotactile display

General Description

Ability of subjects to discriminate between two patterns of vibrotactile stimulation decreases as the percentage of stimulation points common to both patterns of a test pair increases. Performance is better for whole-body patterns than for patterns where all vibrators are limited to the thigh. Discriminability with distributed finger displays stimulating noncorresponding points on the two hands is equivalent to that of whole body displays.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted, and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

See Table 1.

Experimental Procedure

- Two-alternative forced-choice procedure
- Independent variables: number of vibrators activated in each pair of patterns, number of common vibrators activated in each pair of patterns (Refs. 1, 2, 3), symmetry (Ref. 3)
- Dependent variable: percent correct discrimination on trials where patterns were different
- Subject's task: indicate whether two successive vibrotactile patterns were same or different
- 6 subjects with some practice (Refs. 1, 2); 10 subjects (Ref. 3)

Experimental Results

• The discriminability of two multi-element vibrotactile patterns is inversely related to the number of elements in each pattern and the number of pattern elements that are the same in the two patterns (degree of commonality) (Fig. 2).
• The function relating discriminability to commonality is the same for 4-8 element patterns, with all pattern elements contributing equally to error production (Ref. 1).
• Discriminability is better for displays in which the individual vibrotactile stimulators are more widely spaced over the body surface (Ref. 3).
• Discriminability is as good for distributed finger displays stimulating noncorresponding points on the two hands as for whole-body displays (Ref. 2).
• Discriminability is better for closely spaced stimulation points with vibrotactile stimulators that limit the propagation of stimulation (Ref. 2).
• There is no effect of symmetry (versus randomness) on pattern discrimination (Ref. 3).

Variability

No variability information given for Refs. 1 and 2. Ref. 3 performed analyses of variance to test the significance of independent variables and interactions.

Constraints

• Performance with distributed finger displays is as good as performance with distributed whole-body displays only when the fingers are stimulated on noncorresponding points; accuracy is lower when corresponding points are stimulated.
• Type of vibrotactile stimulation influences outcome, especially when stimulated points are close together.
• Results may differ for other body regions.
• Many factors influence perception of tactile patterns and should be considered in applying these results under other conditions (CRef. 6.502).

Key References

*1. Geldard, F. A., & Sherrick, C. E. (1965). Multiple cutaneous stimulation: The discrimination of vibratory patterns. *Journal of the Acoustical Society of America, 37,* 797-801.

*2. Gilson, R. D. (1968). Some factors affecting the spatial discrimination of vibrotactile patterns. *Perception & Psychophysics, 3,* 131-136.

*3. Gottheil, E. F., Cholewiak, R. W., & Sherrick, C. E. (1978). The discrimination of vibratory patterns on a tactile matrix. *Bulletin of the Psychonomic Society, 11,* 21-24.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.503 Identification of vibrotactile patterns: effect of display mode and body location;

6.510 Vibrotactile code learning;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

Table 1. Details of test conditions.

	Ref. 1	Ref. 2	Ref. 3
Stimulus	10 vibrators (Fig. 1)	10 vibrators	8x8 vibrotactile display divided into 2x2 submatrices (blocks)
Location on body	Front of body: five vibrators on noncorresponding points on each side (Fig. 1)	One on each finger; 2.5 cm further from fingertip on right hand to stimulate noncorresponding points on the two hands	Front of thigh
Intensity	15 dB sensation level (SL)	15 dB SL	0.01 kg force
Duration	200 msec; 2 bursts/sec	200 msec at 60 Hz	250 msec at 250 Hz
Patterns	50 pairs of same and different patterns; one to nine vibrators per pattern; same number of vibrators in each pair of patterns	50 pairs of same and different patterns; one to nine vibrators per pattern; same number of vibrators in each pair of patterns; 0% or 33% of elements shift from one hand to other in transition from first to second pattern	32 patterns; 16 four-block and 16 eight-block patterns; 480 pattern pairs; patterns varied in symmetry, number of elements, and number of common pattern elements; patterns different in half the pairs
Interval between patterns in each pair	0.5 sec	0.5 sec	1.0 sec

6.510 Vibrotactile Code Learning

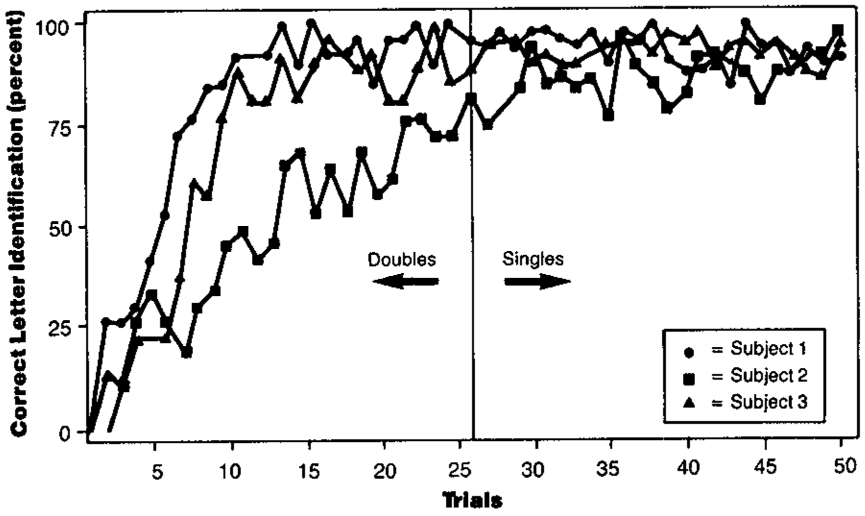

Figure 1. Percent correct identification of vibrotactile letter-codes as a function of learning trial. Learning curves are shown for 3 subjects. (From Ref. 1)

Key Terms

Learning; practice; tactile coding; tactile pattern discrimination; vibrotactile display

General Description

A code formed by assigning letters, numbers, and four words (*and, in, the, of*) to vibrotactile signals that vary in body locus, duration, and intensity can be learned to ~90% accuracy after ~12 hr of practice. After 35 hr of training, sentences transmitted using this vibrotactile code could be understood by one subject at the rate of 38 five-letter words per min.

Applications

Design of tactile displays and tactile communication systems including systems for those with visual disabilities.

Methods

Test Conditions

- Five contactors generating 60-Hz vibration, positioned on the front rib cage (ventral thorax); vibration superimposed on 100 gm steady pressure
- Each contactor could be driven at three levels of intensity and at three durations (0.1, 0.3, 0.5 sec), producing 45 possible vibrotactile signals; 40 signals were assigned the labels of 26 letters, 10 digits, and the words *and, in, the,* and *of*
- Each learning trial contained two presentations of each stimulus (i.e., two complete alphabets) in random order, with the constraint that each stimulus was presented twice in succession ("doubles") for the first half of the learning trials; ~12 hr total training
- After training, subjects tested with English words and short messages transmitted in the vibrotactile code

Experimental Procedure

- Independent variable: training time
- Dependent variable: percent correct identification of vibrotactile signals
- Subject's task: indicate letter of alphabet represented by each vibrotactile signal
- 3 subjects, with no previous practice

Experimental Results

- An alphabetic vibrotactile code using cutaneous signals varying in body locus, duration, and intensity can be learned to ~90% accuracy in 12 hr of training.
- After 35 hr of training, sentences in the vibrotactile code can be received at a rate of 38 five-letter words per min, which is much faster than normal rates for reception of Morse code.

Variability

No information on variability was given.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Ease of learning and receiving a vibrotactile code would be expected to vary with signal characteristics, such as range of intensities and durations, number of body locations, and number of code characters to be discriminated.
- Learning rates may vary considerably for different subjects.

Key References

*1. Geldard, F. A. (1957). Adventures in tactile literacy. *American Psychologist, 12,* 115-124.

2. Geldard, F. A. (1960). Some neglected possibilities of communication. *Science, 131,* 1583-1588.

*3. Howell, W. C. (1956). *Training on a vibratory communication system.* Unpublished master's thesis, University of Virginia, Charlottesville, VA.

Cross References

6.502 Factors affecting identification of tactile patterns

6.511 Factors Affecting Vibrotactile Pattern Masking

Factor	Effect	Source
Interval between target and mask	Masking increases as the interval decreases	CRefs. 6.505, 6.514, 6.515
	Masking is maximal when the mask follows the target by ~50 msec	CRef. 6.515
Interval between two masks	Masking increases as the interval between two masks preceding or following the target increases up to 50 msec, then decreases as the interval between the two masks increases from 50-100 msec	CRef. 6.505
Duration of mask	Masking increases as the duration of the mask increases	CRef. 6.513
Distance between target and mask	Masking increases as distance decreases	CRef. 6.512
Sequence of target and mask	Masking is greater for masks that follow the target (backward masking) than for masks that precede the target (forward masking)	CRefs. 6.513, 6.514, 6.515
Type of mask	Masking is greater for a spatially overlapping pattern mask (a letter-part masking a letter-pattern) than for an energy mask (a rectangular field masking the letter-pattern)	CRef. 6.513
Mode of pattern presentation	Masking is greater for static mode of pattern presentation (elements of pattern array are activated together) than for scanning mode (elements of pattern array are activated sequentially from right to left)	CRef. 6.514

Key Terms

Backward masking; forward masking; letter recognition; simultaneous masking; tactile pattern discrimination; tactile pattern recognition; target identification; touch; vibrotactile masking

General Description

Pattern masking is a reduction in the detectability or identifiability of a target by the introduction of another pattern that overlaps or is contiguous with the target in time or space. In research on vibrotactile masking, patterns are typically generated on the skin by an electronic tactile display, often one originally designed as a communication device for those with visual disabilities (e.g., an **Optacon**). With these displays, both target and mask are produced by activation of an array of tactile vibrators positioned on the skin. The table lists a number of factors that affect vibrotactile masking, describes the nature of the effects, and cites sources of further information.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Constraints

- Interactions among these factors may influence the magnitude of masking effects, but such interactions have not generally been studied.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception and Performance, 6*, 151-166.

2. Craig, J. C. (1982). Temporal integration of vibrotactile patterns. *Perception & Psychophysics, 32*, 219-229.

3. Craig, J. C. (1982). Vibrotactile masking: A comparison of energy and pattern maskers. *Perception & Psychophysics, 31*, 523-529.

4. Loomis, J. M., & Apkarian-Stielau, P. (1976). A lateral masking effect in tactile and blurred visual letter recognition. *Perception & Psychophysics, 20*, 221-226.

5. Weisenberger, J. M., & Craig, J. C. (1982). A tactile metacontrast effect. *Perception & Psychophysics, 6*, 530-536.

Cross References

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.512 Vibrotactile pattern masking: effect of distance between target and mask;

6.513 Vibrotactile pattern masking: effect of type and duration of mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask;

6.515 Vibrotactile pattern masking: effect of delay between target and mask for spatially non-overlapping masks

6.512 Vibrotactile Pattern Masking: Effect of Distance Between Target and Mask

Key Terms

Letter recognition; simultaneous masking; tactile pattern discrimination; target identification; touch; vibrotactile display; vibrotactile masking

General Description

The ability to identify vibrotactile letter patterns masked by columns of steady vibrotactile stimulation decreases with decreasing distance between the target array and the mask.

Methods

Test Conditions

- 10 column x 15 row matrix of vibrotactile contactors used to present target and masking stimuli to the backs of subjects; only the 2 central columns were used for targets; vertical and horizontal spacing between contactors was 12 mm and vibration frequency was 60 Hz
- Letter targets (capital letters) presented by scanning mode (letters temporally swept across the two central columns) in no-mask and Mask 3 conditions; in Mask 1 condition, one column of masking stimulation presented on each side of the two-column target with three silent columns between; in Mask 2 condition, two masking columns presented on each side of the target with two silent columns between; in Mask 3 condition, two masking columns presented on each side with no intervening silent columns; all 26 letters used as targets for all conditions
- Masks activated 4-5 seconds before the letter presentation and remained on for several seconds after letter offset

Experimental Procedure

- Independent variable: mask condition
- Dependent variable: percentage of letters correctly identified
- Subject's task: indicate letter presented, feedback provided
- 2 male and 2 female subjects

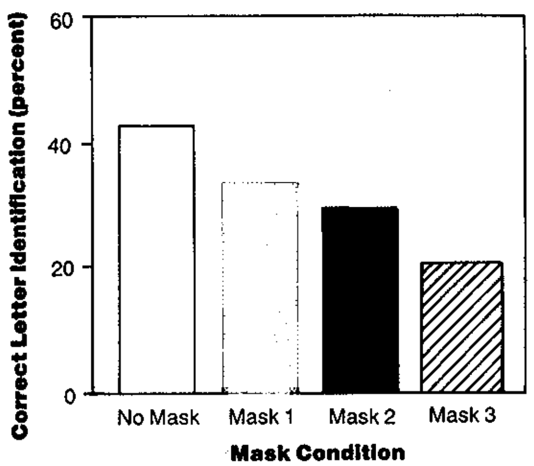

Figure 1. Accuracy of tactile letter identification as a function of mask condition. Distance between target and mask decreases from Mask 1 to Mask 3 condition (see Methods for details of each condition). (From Ref. 1)

Experimental Results

- As the distance between a vibrotactile letter target and a masking vibrotactile array decreases, the ability to recognize letter patterns decreases ($p < 0.001$).
- There is no significant difference in masking for Mask 1 and Mask 2 conditions (one column of masking on each side of letter, separated by three silent columns from letter, and two-column mask separated by two silent columns).

Variability

The data plotted in Fig. 1 represent the average results for the last five (out of ten) testing sessions. The results for each session are the average of 26 judgments, one for each letter of the alphabet.

Constraints

- This study does not consider transient masking associated with mask onset. Thus the findings can be generalized only to situations in which the onset of the mask precedes the onset of the target by enough time to eliminate any transient masking.
- Many factors affect tactile pattern perception and vibrotactile masking and should be considered in applying these data under different conditions (CRefs. 6.502, 6.511).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Loomis, J. M., & Apkarian-Stielau, P. (1976). A lateral masking effect in tactile and blurred visual letter recognition. *Perception & Psychophysics, 20,* 221-226.

Cross References

3.117 Vibrotactile stimulation: detectability in the presence of masking;

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns; temporal resolution;

6.511 Factors affecting vibrotactile pattern masking;

6.513 Vibrotactile pattern masking: effect of type and duration of mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask;

6.515 Vibrotactile pattern masking: effect of delay between target and mask for spatially non-overlapping masks

6.513 Vibrotactile Pattern Masking: Effect of Type and Duration of Mask

Key Terms

Backward masking; forward masking; tactile pattern discrimination; tactile pattern masking; target identification; touch; vibrotactile display

General Description

Identification of a vibrotactile letter pattern is less accurate when the letter is masked by a pattern **mask** (parts of letters) than by a rectangular field mask, and by a mask that follows the target letter rather than precedes it. For all types of masking, identification accuracy decreases as the duration of the mask increases; however, increasing the mask duration has a greater effect for masks that follow the target.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- **Optacon** tactile display used for stimulus presentations to left index fingertip; display was a 6 column x 18 row array of selectively activated pins vibrating at 230 Hz
- Target was randomly chosen letter of the alphabet presented for 26 msec; mask was either a uniform stimulation or energy mask (all pins in the display activated) or a pattern mask consisting of a randomly selected pattern corresponding to parts of letters
- Mask either preceded target (forward masking) or followed target (backward masking) by 4 msec; mask durations of 13, 22, and 52 msec
- Cue stimulus presented for 26 msec as warning signal 1 sec before target letter

Experimental Procedure

- One block of 30 trials per session for no-mask condition and each of 12 masking conditions
- Independent variables: type of mask, duration of mask
- Dependent variable: percent of letters correctly identified
- Subject's task: press key on keyboard to indicate perceived target letter; feedback provided after each trial
- 420 trials for no-mask condition; 210 trials for masking conditions
- 1 male and 3 female laboratory employees with extensive practice

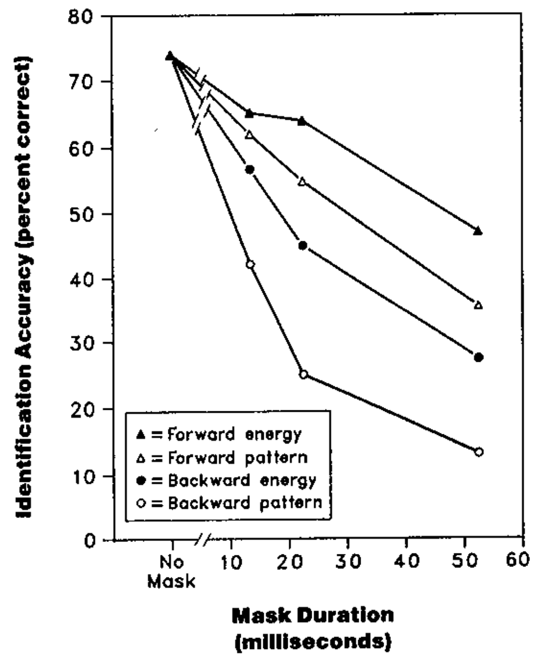

Figure 1. Accuracy of vibrotactile letter identification as a function of mask duration and mask type. Pattern mask (letter segments) or energy mask (rectangular field) was presented before (forward masking) or after (backward masking) the target. (From Ref. 3)

Experimental Results

- The ability to identify a vibrotactile letter pattern (target) is reduced by the presentation of a second stimulus (mask) preceding or following it in time.
- Identification accuracy is reduced more by a mask consisting of letter segments than by an energy mask (rectangular field).
- Identification accuracy for a target is reduced more when the mask follows the target (backward masking) than when the mask precedes the target (forward masking).
- Identification accuracy for a target decreases as the duration of a mask increases; the decrease in performance is greater for backward masking than for forward masking.

Variability

The standard errors of the means for data presented in Fig. 1 ranged from 1.5-3% and did not vary with test condition.

Repeatability/Comparison with Other Studies

Greater masking by a pattern which follows rather than precedes the target has been reported elsewhere (Refs. 1, 2).

Constraints

- Many factors affect tactile pattern perception and vibrotactile masking and should be considered in applying these data under different conditions (CRefs. 6.502, 6.511).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception & Performance, 6*, 151-166.

2. Craig, J. C. (1982). Temporal integration of vibrotactile patterns. *Perception & Psychophysics, 32*, 219-229.

*3. Craig, J. C. (1982). Vibrotactile masking: A comparison of energy and pattern maskers. *Perception & Psychophysics, 31*, 523-529.

Cross References

3.117 Vibrotactile stimulation: detectability in the presence of masking;

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.511 Factors affecting vibrotactile pattern masking;

6.512 Vibrotactile pattern masking: effect of distance between target and mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask;

6.515 Vibrotactile pattern masking: effect of delay between target and mask for spatially non-overlapping masks;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

6.514 Vibrotactile Pattern Masking: Effect of Presentation Mode and Sequence of Target and Mask

Key Terms

Backward masking; forward masking; letter recognition; tactile pattern discrimination; target identification; touch; vibrotactile display; vibrotactile masking

General Description

The ability to identify letter patterns presented to the fingertip by a vibrotactile array is reduced when a vibrotactile **mask** is presented close to the target in time. A vibrotactile mask that follows the target (backward masking) reduces recognition more than a mask that precedes the target (forward masking). With both types of masking, recognition accuracy is greater for targets in which all letter pattern elements are presented simultaneously than for targets in which the elements are presented in a scanning fashion across the array.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- **Optacon** tactile display used for stimulus presentation to index fingertip; display was a 6 column x 18 row array of selectively activated pins vibrating at 230 Hz
- Target (uppercase letter) and mask presented either in a static mode, in which all elements were presented simultaneously and remained on for 100 msec, or in a scan mode, in which array elements were activated sequentially from right to left across the display with a display duration of 104 msec
- All pins were activated for mask; mask was presented in the same mode and for same duration as the target letter and was presented between 0 and 250 msec either before (forward masking) or after (backward masking) the target letter presentation

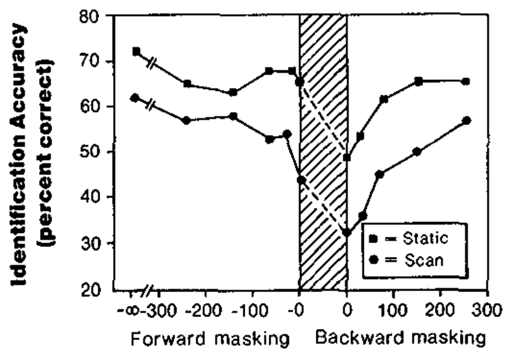

Figure 1. Accuracy of letter identification as a function of mode of presentation and interval between target and mask. (Mask presented before target for forward masking, after target for backward masking. The point −∞ represents the condition in which no mask is present. (From Ref. 1)

Experimental Procedure

- Independent variables: mode of presentation, interval between offset of first stimulus (target or mask) and onset of second stimulus
- Dependent variable: percent of letters correctly identified
- Subject's task: press key on keyboard to indicate the perceived target letter
- 800 trials per data point in the static condition; 1000 trials per data point in the scan condition
- 9 undergraduates with extensive practice (four in the static condition and five in the scan condition)

Experimental Results

- Recognition accuracy for tactile letter patterns is reduced by a vibrotactile mask which precedes (forward masking) or follows (backward masking) the target.
- Backward masking reduces recognition more than forward masking. Backward masking is not very effective for target-mask intervals >150 msec.
- With both forward and backward masking, letter recognition accuracy is greater for targets in which all elements are activated simultaneously (static mode) than for targets in which the component elements are activated sequentially in a scanning pattern from right to left.

Variability

The standard error of the mean was 3-4% for all conditions.

Repeatability/Comparison with Other Studies

The greater masking by a pattern which follows rather than precedes the target has been reported elsewhere (Refs. 2, 3).

Constraints

- No analysis of variance was reported, even though large individual differences have been found for cutaneous pattern recognition. However, a pre-task selection procedure was used to assure subjects' performances were in the upper 10% of the sample.
- Many factors affect tactile pattern perception and vibrotactile masking and should be considered in applying these data under different conditions (CRef. 6.502, 6.511).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception and Performance, 6*, 151-166.

2. Craig, J. C. (1982). Temporal integration of vibrotactile patterns. *Perception & Psychophysics, 32*, 219-229.

3. Craig, J. C. (1982). Vibrotactile masking: A comparison of energy and pattern maskers. *Perception & Psychophysics, 31*, 523-529.

Cross References

3.117 Vibrotactile stimulation: detectability in the presence of masking;

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.511 Factors affecting vibrotactile pattern making;

6.512 Vibrotactile pattern masking; effect of distance between target and mask;

6.513 Vibrotactile pattern masking: effect of type and duration of mask;

Handbook of perception and human performance, Ch. 31, Sect. 3.1

6.515 Vibrotactile Pattern Masking: Effect of Delay Between Target and Mask for Spatially Non-Overlapping Masks

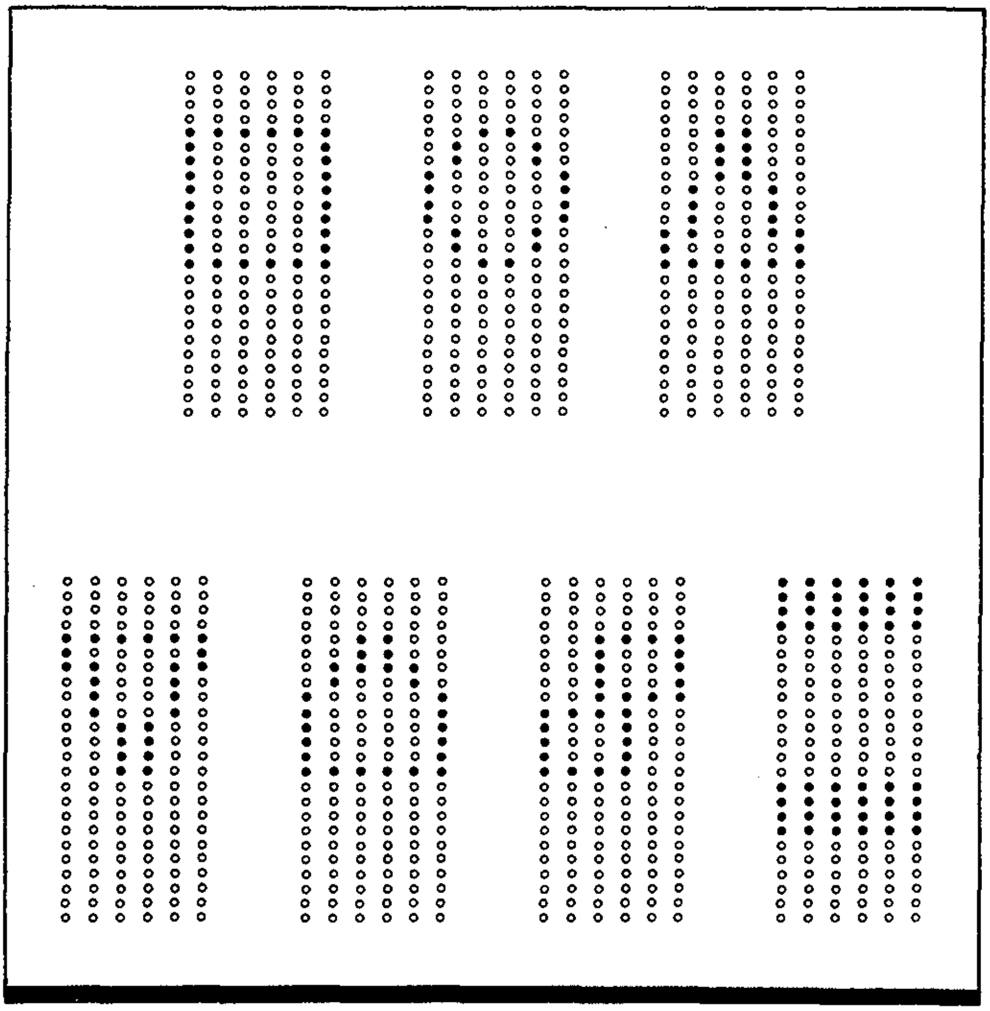

Figure 1. Patterns used in study of vibrotactile masking. Pattern in lower right corner is masking stimulus; other patterns are target stimuli. (From Ref. 2)

Key Terms

Backward masking; forward masking; metacontrast; simultaneous masking; tactile pattern discrimination; target identification; touch; vibrotactile display; vibrotactile masking

General Description

Identification of vibrotactile patterns is reduced when the patterns are **masked** by a spatially non-overlapping vibrotactile pattern (a mask) presented before, during, or after the target. For masks that occur before the target (forward masking), the amount of masking increases as the interval between the onsets of target and mask decreases. When the mask occurs after the target (backward masking), the amount of masking increases as the target-mask onset interval increases up to ~50 msec, then decreases as target-mask onset interval increases further. Thus the maximum amount of masking occurs when the mask is presented ~50 msec after the target.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Design of tactile display and communication systems, including systems for environments where normal hearing or vision is disrupted, and systems for persons with sight and/or hearing disabilities.

Methods

Test Conditions

- **Optacon** tactile display used for stimulus presentations to top 2.7 cm of left index fingertip; display was a 6 column x 24 row array of selectively activated pins vibrating at 230 Hz
- Target was one of six geometric shapes produced by activating a pattern of pins from column 1-6 and rows 5-14 of the display (see Fig. 1); mask was produced by activating all pins in the four rows above (1-4) and four rows below (15-18) the target (Fig. 1) or no mask was presented; both target and mask presented for 26 msec
- Interval between onset of target and onset of mask (target-mask onset interval) ranged from 0-429 msec; mask presented either before (forward masking) or after (backward masking) the target or concurrently with the target
- 360 trials per target-mask onset interval, presented in 30-trial blocks
- Warning signal presented 1 sec before target by activating pins in all columns of row 12

Experimental Procedure

- Independent variable: target-mask onset interval
- Dependent variable: percent of patterns correctly identified
- Subject's task: identify a vibrotactile pattern by pressing a key on a keyboard corresponding to one of six possible patterns
- 1440 trials per data point
- 1 male and 3 female undergraduates with extensive practice

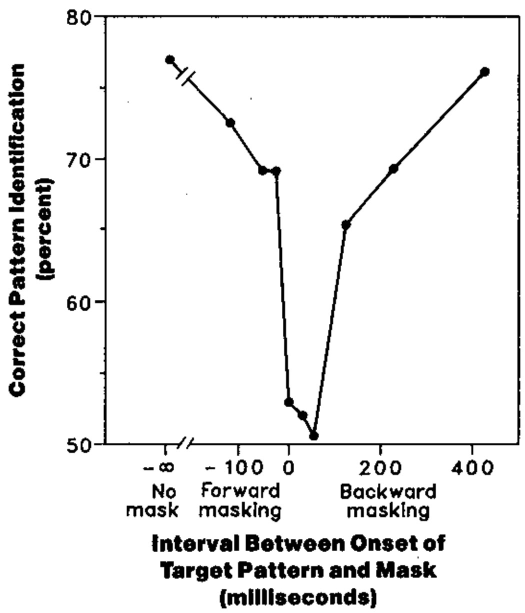

Figure 2. Accuracy of pattern identification as a function of time between target and mask onsets. (Mask presented first for forward masking, second for backward masking.) (From Ref. 2)

Experimental Results

- When a spatially non-overlapping vibrotactile mask precedes a vibrotactile target pattern, correct identification of the pattern decreases (degree of masking increases) as the mask-target onset interval decreases.
- When the mask follows the target, masking increases as the target-mask onset interval increases to ~50 msec, and then begins to decrease as the target-mask onset interval continues to increase.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Similar effects are found for visual targets (e.g., Ref. 1) and for vibrotactile letter-patterns masked by spatially overlapping masks (CRef. 6.514).

Constraints

- Many factors affect tactile pattern perception and vibrotactile masking and should be considered in applying these data under different conditions (CRefs. 6.502, 6.511).

Key References

1. Alpern, M. (1953). Metacontrast. *Journal of the Optical Society of America, 43*, 648-657.

*2. Weisenberger, J. M., & Craig, J. C. (1982). A tactile metacontrast effect. *Perception & Psychophysics, 31*, 530-536.

Cross References

3.117 Vibrotactile stimulation: detectability in the presence of masking;

6.502 Factors affecting identification of tactile patterns;

6.505 Identification of vibrotactile patterns: temporal resolution;

6.511 Factors affecting vibrotactile pattern masking;

6.512 Vibrotactile pattern masking: effect of distance between target and mask;

6.513 Vibrotactile pattern masking: effect of type of duration of mask;

6.514 Vibrotactile pattern masking: effect of presentation mode and sequence of target and mask;

Handbook of perception and human performance, Ch. 31. Sect. 3.1

6.601 Modes of Tactual Perception

Table 1. Modes of tactual perception. (From Ref. 4)

Subject's Control Over Limb Movement	Type of Information Available to Subject	Label of Tactual Mode
No Control	1 Cutaneous information	Tactile perception
	2 Afferent kinesthetic information	Passive kinesthetic perception
	3 Cutaneous information plus afferent kinesthetic information	Passive haptic perception
Control	4 Afferent and efferent kinesthetic information	Active kinesthetic perception
	5 Cutaneous information plus afferent and efferent kinesthetic information	Active haptic perception

Key Terms

Cutaneous sensitivity; haptic perception; kinesthesia; proprioception; tactual perception; touch

General Description

The sense of touch provides information about objects and events through stimulation of receptors within the skin (cutaneous perception) or in muscles and joints (kinesthesia). The term "tactual perception" is used to refer inclusively to all perceptions mediated by the kinesthetic and/or cutaneous sense systems. "Tactile perception" refers to perception mediated solely by cutaneous stimulation, such as when objects are pressed against the skin or patterns are traced on the skin. "Kinesthetic perception" refers to perception mediated exclusively by kinesthesis, as when a limb describes a pattern of movement in the air or when cutaneous stimulation is eliminated by skin anesthesia. Kinesthetic activity can be further delineated with respect to the control exercised by the subject in producing limb movement. "Passive kinesthetic perception" results from limb movement imposed on a subject by an experimenter or an apparatus; thus, only **afferent** (sensory) information concerning movement is available. "Active kinesthetic perception" is based on self-produced movement, i.e., movement executed as a direct consequence of the subject's intention. Both afferent information and **efferent** information (information regarding motor impulses sent by the brain to control body movements) are available to subjects under active conditions. "Haptic perception" refers to perceptions in which both cutaneous and kinesthetic senses act as channels of information. Haptic perception describes most of our everyday tactual experience and activity. The various types of tactual perception are summarized in Table 1.

Constraints

- Information acquisition is the basis of perception; and by providing different sources of information, the different tactual modes may result in qualitatively different percepts (CRef. 6.607).

Key References

1. Davidson, P. W. (1972). The role of exploratory activity in haptic perception: Some issues, data, and hypotheses. *American Foundation for the Blind Research Bulletin, 24*, 21-27.

2. Gibson, J. J. (1962). Observations on active touch. *Psychological Review, 69*, 477-490.

3. Krueger, L. E. (1970). David Katz's Der Aufbau der Tastwelt (The world of touch): A synopsis. *Perception & Psychophysics, 7*, 337-341.

4. Loomis, J. L., & Lederman, S. (1986). Tactual perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol II. Cognitive processes and performance*. New York: Wiley.

Cross References

6.602 Tactile-kinesthetic scanning motions;

6.607 Tactual discrimination of two-dimensional shape: effect of tactual mode

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

6.602 Tactile-Kinesthetic Scanning Motions

Key Terms

Kinesthesia; manual scanning; tactile-kinesthetic scanning; touch

General Description

Tactile-kinesthetic scanning motions are used to acquire information about tactile objects, much as eye movements are used to acquire information about the visual world. Tactile-kinesthetic activity can be divided into two classes of movement; micromotions, which serve only to keep tactile (cutaneous) images from fading, and macromotions, which include exploratory motions for searching tactile space and pursuit motions for examining particular features. Motion pauses (fixations) are also characteristic of both manual and visual scanning of objects.

Variability in tactile-kinesthetic scanning characteristics is far greater than that found for eye movements; this variability is an important factor in tactile perception because the type of tactile-kinesthetic scanning used determines what information is acquired and thus ultimately determines perception. For example, a subject who simply grasps a form (without subsequent movement) is acquiring different information from the subject who traces a shape's contours, or one who touches the entire object in a more global fashion, constantly changing the positions of the fingers and moving the object itself. Thus, the same physical object can be perceived differently because different hand movements may expose different attributes of the object. A general finding is that veridicality of perception increases as exploratory behavior becomes more global or active, thereby allowing for more information acquisition (CRef. 6.607).

Tactile-kinesthetic scanning involves arm movements as well as hand movements. These motions involve various components of movement about the wrist, elbow, or shoulder joints. Where spatial characteristics of a stimulus are judged, variability in arm movement can have a significant impact on perception; impressions of angularity, curvature, distance, direction, and orientation are all affected by the nature of the arm movements used in judging those attributes.

As is the case in studying eye movements, an examination of tactile-kinesthetic scanning motions can be a useful tool in understanding the types of information used by people as well as how the information is obtained and applied.

Key References

1. Davidson, P. W. (1972). Haptic judgments of curvature by blind and sighted humans. *Journal of Experimental Psychology, 93*, 43-55.

2. Davidson, P. W. (1972). The role of exploratory activity in haptic perception: Some issues, data, and hypotheses. *American Foundation for the Blind Research Bulletin, 24*, 21-27

3. Gibson, J. J. (1962). Observations on active touch. *Psychological Review, 69*, 477-490.

4. Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton-Mifflin.

5. Revesz, G. (1950). *Psychology and art of the blind.* London: Longmans, Green and Co.

6. Zinchenko, V. P., & Lomov, B. F. (1960). The functions of hand and eye movements in the process of perception. *Problems of Psychology, 1*, 12-26.

Cross References

6.607 Tactual discrimination of two-dimensional shape: effect of tactual mode

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

6.603 Perceived Roughness: Effect of Groove Width, Land Width, and Contact Force

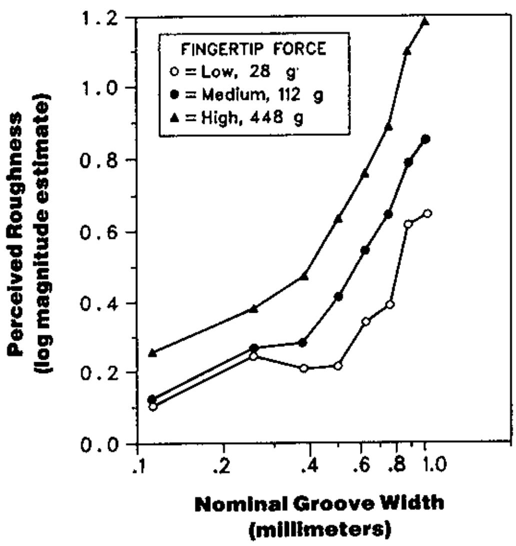

Figure 1. Perceived roughness of grooved plates as a function of groove width and finger force. (Space between grooves constant at 0.25 mm.) (From Ref. 2)

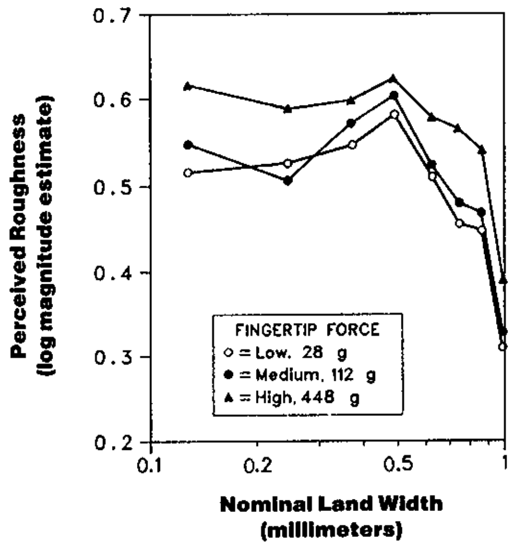

Figure 2. Perceived roughness of grooved plates as a function of land width and finger force. (Groove width constant at 0.25 mm.) (From Ref. 2)

Key Terms

Roughness; texture; touch

General Description

Judged roughness of grooved surfaces felt with the fingers increases as groove width and contact force of the fingertip increase. Perceived roughness decreases as the flat surface between narrow grooves (land width, or ridge width) increases, but only for the widest land widths studied. For wide grooves, perception of roughness does not change as land width increases.

Methods

Test Conditions

- Subjects explored grooved aluminum plates with the middle finger of the preferred hand while applying low (28 g), medium (112 g), or high (448 g) force; finger force was varied by requiring subjects to counterbalance a weight on a balance arm
- Plates had regularly spaced parallel grooves, with either a 0.25-mm width between groves (land width) held constant while groove width varied, or a 0.25-mm or 0.625-mm groove width held constant while land width varied

Experimental Procedure

- Method of magnitude estimation
- Independent variables: finger force, groove width, land width
- Dependent variable: judged magnitude of roughness
- Subject's task: move middle finger across a set of grooved plates with a force necessary to keep a balance arm level and assign numbers to the plates in proportion to their apparent roughness
- 6 subjects judged roughness as a function of groove width (Fig. 1); 4 subjects judged roughness as a function of land width (Fig. 2); all subjects had some practice

Experimental Results

- The apparent roughness of a grooved surface felt with the finger increases as finger force increases (Fig. 1).
- Apparent roughness increases as groove width increases (Fig. 1).
- The apparent roughness of a surface decreases with increasing land width (for narrow grooves), but only at the widest land widths (Fig. 2). There is no land width effect when grooves are wide.

Variability

An analysis of variance was performed to assess the significance of the variables and interactions. There were significant individual differences.

Repeatability/Comparison with Other Studies

An early study found that light pressure makes surfaces feel smoother (Ref 1). Reference 3 found that perceived roughness of sandpaper increases as particle size increases.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Perceived roughness is influenced by shear force, skin temperature, and vibration (CRefs. 6.604 6.605, 6.606).

Key References

1. Katz, D. (1925). *Der Aufbau der Tastwelt* (The world of touch). Leipzig: Barth.

*2. Lederman, S. J. (1974). Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure. *Perception & Psychophysics, 16*, 385-395.

3. Stevens, S. S., & Harris, S. R. (1962). The scaling of subjective roughness and smoothness. *Journal of Experimental Psychology, 64*, 489-494.

Cross References

6.604 Perceived roughness: effect of skin temperature and groove width;

6.605 Perceived roughness: effect of shear force;

6.606 Perceived roughness: effect of adaptation to vibration;

Handbook of perception and human performance, Ch. 31, Sect. 5

6.604 Perceived Roughness: Effect of Skin Temperature and Groove Width

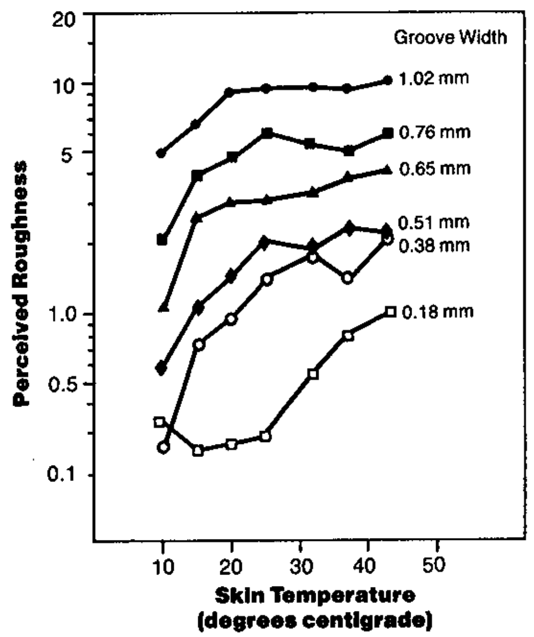

Figure 1. Perceived roughness of grooved plates as a function of skin temperature and groove width. (From Ref. 1)

Key Terms

Roughness; texture; touch

General Description

The apparent roughness of grooved plates felt with the fingertips increases as skin temperature increases above normal and decreases as skin temperature decreases below normal. These effects are most pronounced for smoother surfaces (groove widths <0.5 mm). The effect of cooling is greater than the effect of warming for all groove widths.

Methods

Test Conditions

- Subjects sat with the right arm lying palm up on the bottom of a box in which air temperature was controlled by means of vented cold air from an air-conditioning unit and heat from a pair of heat lamps mounted at the ceiling of the box
- Tactile stimuli were six metal plates (14 x 1.1 x 0.5 cm) with parallel grooves spaced 0.25 mm apart; groove width varied from 0.18-1.02 mm; stimulus plates were maintained at 32°C (approximately normal skin temperature)
- Skin temperature, monitored by thermistors attached to the palmar surface of the index finger, varied between 10 and 43°C; at each of 7 skin temperatures, six plates were presented in random order at the rate of 1 plate per 10 sec; stimulus sets were presented for skin temperatures changing in ascending (from 22°C) or descending (from 43°C) order following a practice set at 32°C, with one order per session

Experimental Procedure

- Method of magnitude estimation
- Independent variables: skin temperature, groove width
- Dependent variable: judged magnitude of roughness
- Subject's task: feel stimulus plates and assign numbers in proportion to the magnitude of perceived roughness
- 8 female and 2 male young adults with some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Perceived roughness of grooved plates increases with increasing groove width.
- Perceived roughness increases with increasing skin temperature, although the effect of raising skin temperature above normal is smaller and less consistent than the effect of lowering skin temperature below normal.
- The effect of temperature on perceived roughness increases as groove width decreases, i.e., as surfaces became smoother.

Variability

No information on variability was given.

Constraints

- The interaction between stimulus temperature and skin temperature was not studied.
- Perceived roughness is also influenced by land width, contact force, shear force, and vibration (CRefs. 6.603, 6.605, 6.606).

Key References

*1. Green, B. G., Lederman, S. J., & Stevens, J. C. (1979). The effect of skin temperature on the perception of roughness. *Sensory Processes, 3*, 327-333.

Cross References

6.603 Perceived roughness: effect of groove width, land width, and contact force;

6.605 Perceived roughness: effect of shear force;

6.606 Perceived roughness: effect of adaptation to vibration

6.605 Perceived Roughness: Effect of Shear Force

Key Terms

Roughness; texture; touch

General Description

The judged roughness of a surface increases as the shear force between the scanning fingers and the felt surface decreases.

Methods

Test Conditions

- Four textured surfaces were constructed from single layers of glass beads distributed on a smooth base; textures varied by passing beads through a series of four sieves of progressively larger aperture size to vary range of bead diameters on each surface
- Three conditions of shear force (verified by measurements) were used; in the high shear condition the beads were firmly attached to the base and covered with two taut layers of tissue paper over which the middle three fingers were moved; in the medium shear condition the beads were also firmly attached to the base and the top layer of tissue paper was moved by the fingers over the single-papered beaded surface; in the low shear condition, a double layer of tissue paper was moved by the fingers over surfaces on which the beads were allowed to roll freely (subjects were unaware the beads could move)
- Two judgments per condition
- Each data point is the mean of 70 observations

Experimental Procedure

- Method of magnitude estimation
- Independent variables: physical roughness, as measured by the sieve aperture width through which each set of beads could pass; shear force
- Dependent variable: apparent roughness, as measured by the number assigned to each surface relative to the number "10" assigned to the roughest surface in the medium shear condition
- Subject's task: assign numbers to felt surfaces in proportion to their apparent roughness
- 35 undergraduates with some practice

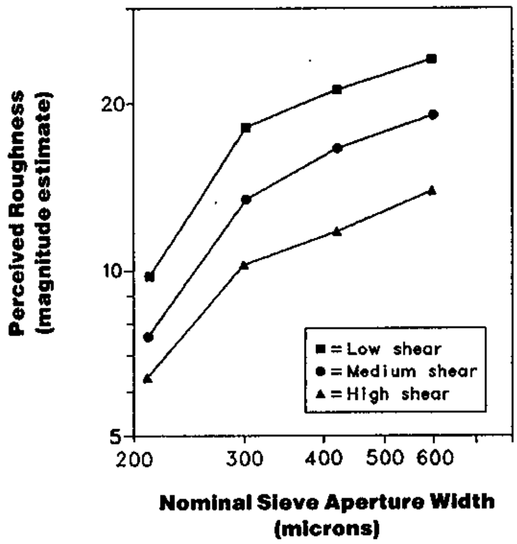

Figure 1. Perceived roughness of a beaded surface as a function of physical roughness (measured in terms of bead size) and shear force. (From Ref. 3)

Experimental Results

- The apparent roughness of a textured surface increases as the average width of surface elements increases (i.e., as average bead size increases).
- The apparent roughness of a surface of constant texture increases as the shear force between the scanning fingers and that surface decreases.

Variability

An analysis of variance was conducted to assess the significance of the independent variables and interactions.

Repeatability/Comparison with Other Studies

The perceived roughness of some abrasives covered by paper is greater when scanned by the finger covered with an additional piece of paper than by the bare finger; however, such roughness enhancement does not apply to all surfaces (Ref. 2).

Constraints

- Perceived roughness is also influenced by contact force, skin temperature, and vibration (CRefs. 6.603, 6.604, 6.606).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Gescheider, G.A. (1965). Cutaneous sound localization. *Journal of Experimental Psychology, 70*, 617-625.

2. Green, B. G. (1981). Tactile roughness and the "paper effect." *Bulletin of the Psychonomic Society, 18*, 155-158.

*3. Lederman, S. J. (1978). "Improving one's touch" and more. *Perception & Psychophysics, 24*, 154-160.

4. Stevens, S. S., & Harris, J. R. (1962). The scaling of roughness and smoothness. *Journal of Experimental Psychology, 64*, 489-494.

Cross References

6.603 Perceived roughness: effect of groove width, land width, and contact force;

6.604 Perceived roughness: effect of skin temperature and groove width;

6.606 Perceived roughness: effect of adaptation to vibration;

Handbook of perception and human performance, Ch. 31, Sect. 5.1

6.606 Perceived Roughness: Effect of Adaptation to Vibration

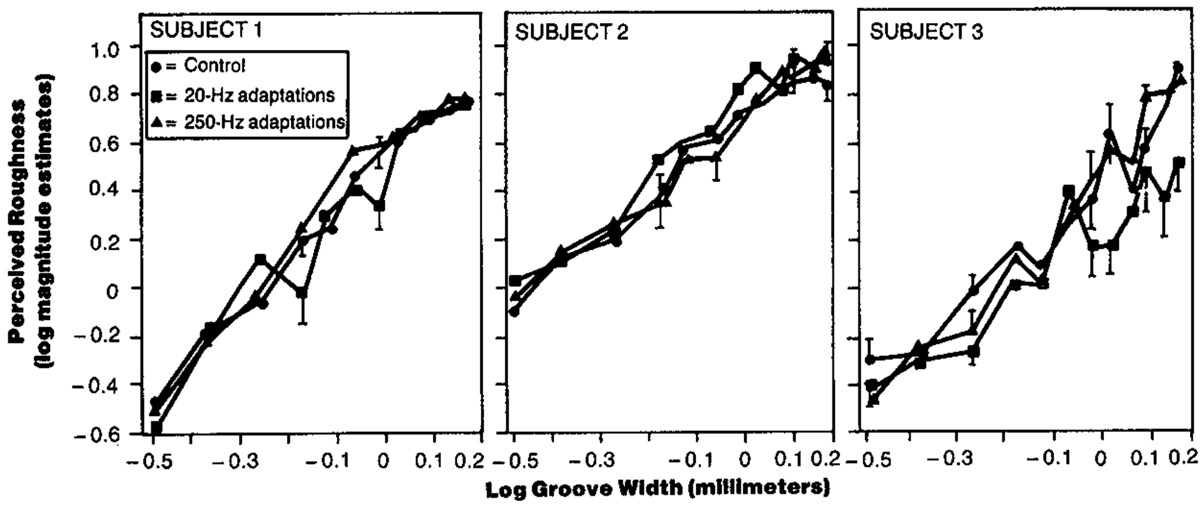

Figure 1. Perceived roughness of grooved surfaces as a function of groove width and frequency of vibration to which fingertip was adapted before scanning surfaces (control condition = no vibration adaptation). (From Ref. 1)

Key Terms

Roughness; texture; touch; vibration; vibrotactile adaptation

General Description

The perceived roughness of a grooved surface explored with the fingertips increases as groove width increases. Perceived roughness is not changed by exposing the fingers to prolonged vibration.

Methods

Test Conditions

- Tip of middle finger rested on a 1.3-cm^2 vibrotactile contactor; finger adapted to 10 min of 20-Hz or 250-Hz vibration, or finger simply rested on contactor without vibration (control condition)
- Following adaptation to vibration or the control condition, finger moved from contactor to one of 12 plates engraved with square-wave gratings (bar patterns); groove width varied from 0.335 to 1.44 mm and land width (flat surface between grooves) varied from 0.295 to 1.535 mm
- After examining plates for a maximum of 3 sec, finger was moved back to contactor for 30 sec

Experimental Procedure

- Method of magnitude estimation
- Independent variables: vibration frequency, groove width
- Dependent variable: judged roughness
- Subject's task: assign numbers to surfaces in proportion to their perceived roughness
- Four trials per data point per session; two sessions per subject
- 3 young adults with some practice

Experimental Results

- Perceived roughness of a grooved surface increases as the groove width increases.
- Perceived roughness of a grooved surface explored by the fingertip does not vary when the finger is adapted to 20 Hz or 250 Hz vibration.

Variability

Data shown are for individual subjects. Bars show standard errors for points with error ranges that are at least partially non-overlapping for the means of the three conditions; the ranges of all other mean triads overlap completely.

Constraints

- Perceived roughness is influenced by land width, contact force, shear force, and skin temperature (CRefs. 6.603, 6.604, 6.605).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Lederman, S. J., Loomis, J. M., & Williams, D. A. (1982). The role of vibration in the tactual perception of roughness. *Perception & Psychophisics, 32,* 109-116.

Cross References

6.603 Perceived roughness: effect of groove width, land width, and contact force;

6.604 Perceived roughness: effect of skin temperature and groove width;

6.605; Perceived roughness: effect of shear force

6.607 Tactual Discrimination of Two-Dimensional Shape: Effect of Tactual Mode

Table 1. Effect of tactual mode on discrimination of two-dimensional shape.

Tactual Mode	Type of Target	Results	Source
Active haptic (fingertip allowed to move over target) versus tactile (fingertip pressed against target)	Two-dimensional (2-D) alphabetic characters and 2-D solid geometric shapes	Active haptic mode superior to tactile mode	Ref. 1
Active haptic (subject moves either palm or fingers over object) versus passive haptic (target drawn on the palm) versus tactile mode (target pressed on the palm)	Geometric outline and alphabetic shapes	Active haptic superior to passive haptic and passive haptic superior to tactile mode if subjects allowed unlimited exposure time; when exposure limited to 2 sec, performance is worse for both active and passive haptic modes but not for tactile mode, compared with untimed exposure; active haptic (with fingers) is still superior to other methods	Ref. 4
Active haptic (subject moves palm over target) versus passive haptic (target twisted under subject's palm by experimenter) versus tactile mode (target rests on or is pressed into subject's palm)	Geometric outline shapes	Active haptic mode equal to passive haptic mode; both methods superior to tactile mode	Ref. 2
		Active haptic superior to both passive haptic and tactile mode (which are equal to each other)	Ref. 5
Active haptic (subject explores target with fingers) versus passive haptic (target rotated under subject's palm by experimenter) versus tactile mode (target pressed into subject's palm)	Geometric outline shapes	Active haptic superior to passive haptic and passive haptic superior to tactile mode	Ref. 3
Active haptic (subject traces a raised-line drawing with the finger) versus passive haptic (finger moved by experimenter along the pattern or pattern moved under the passive finger) versus passive kinesthetic (finger moved by experimenter along the pattern path without actually contacting the pattern)	Raised-line drawings of familiar objects	Passive haptic equal to passive kinesthetic; both superior to active haptic	Ref. 6
Active haptic (subject traces contour of target with index finger) versus passive haptic (target) moved under fingertip by experimenter) versus tactile mode (target pressed against fingertip)	Geometric outline shapes	Active haptic equal to passive haptic; both superior to tactile mode	Ref. 7

Key Terms

Form perception; kinesthesia; shape discrimination; touch

General Description

The ability to judge the shape of objects from **tactual** information alone depends on tactual mode—that is, on the degree of observer control over the acquisition of information and on the type of information available (**cutaneous, kinesthetic**, or both). A typical, but not universal, finding is that perception is best when subjects actively move their hands over the object rather than come into passive contact with it (either by having the object pressed against the skin or by having the hand moved passively over the object by an experimenter or apparatus). Three tactual modes are passive and do not involve the subject's control over limb movement: (1) *tactile perception* in which the object contacts the skin with no movement of the hands or limbs, or of the object; (2) *passive kinesthesis*, in which the hand or limb is moved by an experimenter or apparatus without cutaneous

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

stimulation, as if to trace a pattern in the air; and (3) *passive haptic perception*, in which the hand or limb is moved across an object by an experimenter or apparatus (rather than by the subject), or the object is moved across the skin. Two tactual modes are active (subjects themselves control limb movement), and thus subjects receive both cutaneous and kinesthetic stimulation: (4) *active kinesthesis*, in which the subjects, through their own volition, move the hand or limb, as in describing an imaginary or suggested pattern in the air, but do not contact the actual object with the skin; and (5) *active haptic perception*, in which subjects move a hand or limb across an object in contact with the skin. The table presents some representative findings comparing the effects of tactual mode on the discrimination of two-dimensional object shape.

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Cross References

6.601 Modes of tactual perception

6.608 Haptic Discrimination of Letter Forms: Effect of Orientation

Key Terms

Haptic form perception; image reversal; letter recognition; touch; visual form perception

General Description

The time required for subjects to decide whether letters presented visually or haptically (by touch) are in normal or mirror-image configuration increases with angular departure of the letters from upright, reaching a maximum at 180 deg. Response latency (**reaction time**) is much longer for discrimination by touch than by sight and are longer for mirror-image letters than for normal letters.

Methods

Test Conditions

- Targets were the letters "P" and "F"; visual targets were printed in black on white index cards; haptic targets were each 1 cm thick x 8 cm high x 4 cm wide, fixed to a board placed in the horizontal plane on a table top in front of seated subject
- Visual targets presented by **tachistoscope**; haptic targets presented to blindfolded subjects, who used one hand to explore targets.
- Letters presented in either normal or mirror-image (reversed) condition and at angular departures of 0-360 degrees (measured clockwise) from upright; trials with "F" and "P" alternated so that subject knew in advance the identity of the letter but not its orientation or reflection condition

Experimental Procedure

- **Two-alternative forced-choice** procedure
- Independent variables: presentation condition, reflection condition, angular departure from upright
- Dependent variable: response latency (reaction time), defined as the interval between viewing or contacting the target and verbally responding
- Subject's task: indicate whether target is in its normal or mirror-image condition
- 12 college students

Experimental Results

- Response latency for deciding whether visually or haptically presented letters are in normal or mirror-image configuration increases with increasing angular departure from upright, reaching a maximum at 180 deg (letters are upside-down).
- Response latencies are longer when letters are presented by touch (haptically) than when they are presented visually.
- Response latencies are significantly longer for mirror-image letters ($p < 0.01$), and the latency increase at 180 deg is particularly large for the haptic condition.

Variability

An analysis of variance was used to assess the effect of the independent variables and interactions.

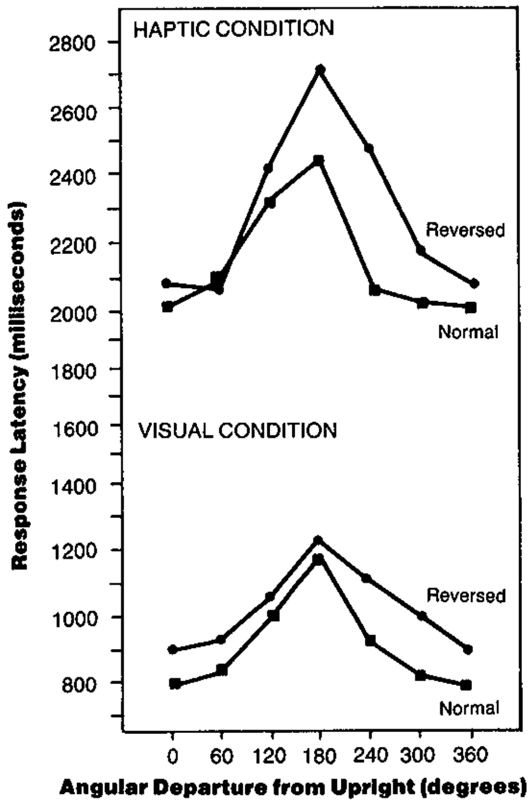

Figure 1. Response latency for discriminating normal and mirror-image (reversed) letters by vision and by touch (haptic condition) as a function of angular departure of letters from upright. (From Ref. 1)

Repeatability/Comparison with Other Studies

Quantitatively similar reaction times were also found for blind subjects except that reaction times for 0-deg (upright) letters were shorter for blind subjects than for sighted subjects (Ref. 1). Similar results (increased reaction times with increased clockwise rotation to 150 deg) have been found for sighted and blind subjects using geometric forms instead of letters (Ref. 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.808 Haptic and visual perception of target orientation;

5.1016 Intermodal and cross-modal spatial pattern recognition;

Handbook of perception and human performance, Ch. 31, Sect. 5.2

6.609 Haptic Perception of Curvature: Effect of Curve Orientation and Type of Arm Movement

Key Terms

Curvature illusion; haptic form perception; manual scanning; touch

General Description

When felt by the hand, a horizontally curved strip of plastic is judged to be more convex than it actually is, so that concave curves (ends bent toward the subject) feel phenomenally straight. The illusion is not as great for vertical (ends bent upward or downward toward a vertical axis). For both orientations, the illusion is reduced if the curve is scanned with the arm extended (arm rotates about the shoulder) rather than with the arm bent (forearm rotates about the elbow).

Methods

Test Conditions

- Stimuli were 1.5-mm thick strips of plastic (horizontal curves) or posterboard (vertical curves), 200-mm long and 19-mm high, and straight horizontal and vertical strips; curvature (measured as arc height, or perpendicular distance from midpoint of arc's chord to midpoint of arc) was 2, 4, 6, or 8 mm for both concave and convex directions
- For horizontal curves, the midpoint of the curve was closer to the subject (convex curve) or farther away from the subject (concave curve) than the curve's endpoints; for vertical curves the midpoint was lower (convex) or higher (concave) in the vertical plane than the endpoints
- Blindfolded subjects scanned the curves by sweeping the tip of the index and middle fingers across the top or front edge of the stimulus; arm movements were either a "forearm movement," in which the forearm rotated around the elbow (placed in an elbow rest), or a "whole-arm movement," in which a subject "locked" the elbow and the arm rotated around the shoulder
- Stimuli presented in random order
- Four trials per stimulus

Experimental Procedure

- Method of single stimuli; three-alternative forced-choice discrimination (concave, convex, or straight)
- Independent variables: type of arm movement, orientation of curve, stimulus curvature (arc height)
- Dependent variables: absolute thresholds for concavity and convexity and point of subjective equality (phenomenal straightness) determined by least squares solution for the method of single stimuli from the percentage of concave and convex responses at each curvature
- Subject's task: indicate apparent direction of curvature (concave, convex, or straight) for curves felt by hand
- 80 subjects (20 subjects in each condition)

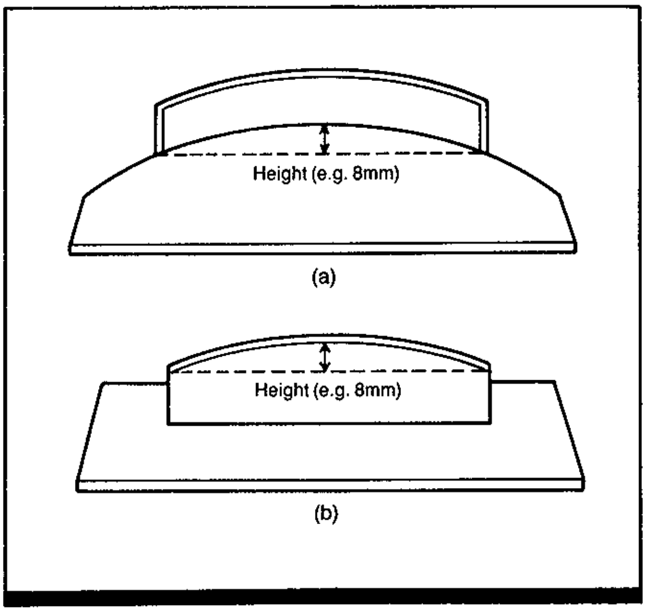

Figure 1. (a) Horizontal and (b) vertical concave curves. (From Ref. 2)

Experimental Results

- Curves scanned by the hand are judged as more convex than they actually are (the curvature illusion).
- The curvature illusion occurs primarily for horizontal curves; it is virtually eliminated for vertical curves.
- Scanning with whole-arm movements pivoting about the shoulder results in a much smaller illusion than scanning with forearm movements pivoting around the elbow.

Variability

Standard deviations of curvature thresholds appear in Table 1.

Repeatability/Comparison with Other Studies

The curvature illusion has been reported in numerous studies (Refs. 1, 3, 4).

Constraints

- Blind subjects use scanning strategies that differ from those of sighted subjects and make more objective judgments of curvature.
- Different finger positions (e.g., gripping with hand rather than touching with fingertips) yield differing amounts of error in curvature judgment.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

5.110 Haptic perception of length: effect of orientation;

6.610 Haptic perception of curvature: effect of manual scanning method

Table 1. Haptic perception of curvature for horizontal and vertical curves with two types of scanning movements. (From Ref. 2)

	Curvature Thresholds (mm)					
	Convex (−)		Concave (+)			
Condition	**AL**	**SD**	**AL**	**SD**	**IU (mm)**	**PSE (mm) (phenomenal straightness)**
Horizontal curves						
Forearm movement	−1.57	5.30	+7.55	10.54	9.12	+1.48
Whole-arm movement	−2.82	5.28	+4.03	6.57	6.85	+0.23
Vertical curves						
Forearm movement	−4.07	8.23	+2.14	3.85	6.21	+0.16
Whole-arm movement	−0.33	5.86	+1.45	3.35	1.77	+0.80

AL = absolute threshold (minimum arc height in mm required to perceive convexity or concavity; positive values indicate concave curvature, negative values convex curvature); SD = standard deviation about the absolute threshold value; PSE = point of subjective equality (arc height in mm at which stimulus edge appears straight); IU = interval of uncertainty (indicator of variability associated with the PSE).

6.610 Haptic Perception of Curvature: Effect of Manual Scanning Method

Key Terms

Curvature illusion; haptic form perception; manual scanning; touch

General Description

When congenitally blind subjects or sighted subjects wearing blindfolds judge the direction of an edge's curvature, concave curves appear to be straighter than they actually are (curvature illusion). Blind subjects use a scanning technique that yields more accurate judgments than the techniques typically used by sighted, blindfolded subjects. When the sighted subjects are restricted to using the scanning technique preferred by the blind, judgment becomes more accurate (Table 3).

Methods

Test Conditions

- Stimuli were 1.5-mm thick plastic strips, 200-mm long and 19-mm high, bent to form curves; curves were convex (ends bent away from subject) or concave (ends bent toward subject); curvature (measured as arc height, perpendicular distance from midpoint of chord connecting ends of arc to midpoint of arc) was 2, 4, 6, or 8 mm for both concave and convex directions; a straight plastic strip was also used (CRef. 6.609 for illustration of stimuli)
- All subjects were blindfolded before exploring the target curves with their fingers; spontaneous scanning behavior was videotaped and categorized in regard to method (Fig. 1); in a subsequent experiment, subjects were restricted to using one of the more popular methods of exploration (Table 3)
- Four trials per stimulus

Experimental Procedure

- Method of single stimuli; three-alternative forced-choice discrimination (concave, convex, or straight)
- Independent variables: stimulus curvature (arc height), scanning method
- Dependent variable: mean number of errors in categorizing direction of curvature; absolute threshold for concavity and convexity and point of subjective equality (phenomenal straightness) determined by least squares solution for the method of single stimuli from the percentages of "concave" and "convex" responses at each curvature
- Subject's task: indicate apparent direction of curvature (concave, convex, or straight)
- 16 congenitally blind and 16 normally sighted subjects used for videotaping and categorizing scanning methods: 60 normally sighted subjects used to assess effect of restricting scanning method to particular types (20 subjects per scanning type)

Experimental Results

- Concave curves scanned manually tend to appear straighter than they actually are. Convex curves and straight edges are perceived correctly more often than concave curves (Tables 2 and 3).
- The congenitally blind make significantly fewer errors than sighted subjects in judging curvature by touch. Blind subjects characteristically use a grip scanning method in judging curvature, whereas sighted subjects most often use top sweep and pinch methods (see Fig. 1).
- When sighted subjects are restricted to using the grip scanning method preferred by the blind, judgment of concave curvature is more accurate than that of subjects using either the pinch ($p < 0.01$) or top sweep method ($p < 0.02$) (Table 3).

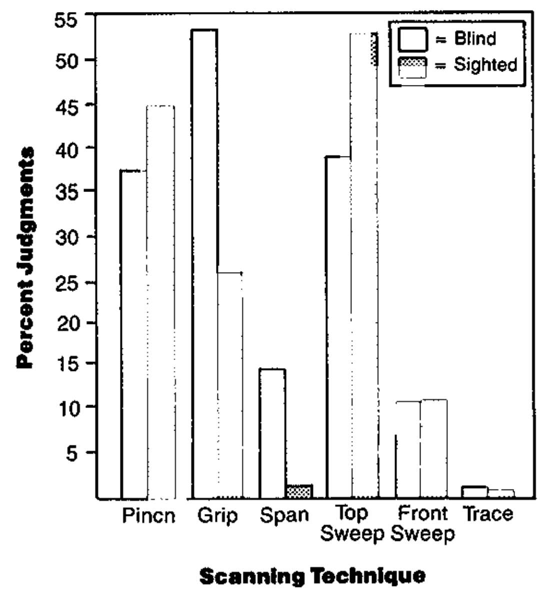

Figure 1. Percentage of curvature judgments made using different scanning classes by the blind and sighted. (From Ref. 1)

Table 1. Types of scanning techniques used by subjects to judge the direction of curvature of a curved strip

Pinch:	edge is held in a pincer between thumb and one or more other fingers while hand slides smoothly across curve
Grip:	three or four fingers curl over front edge of curve while pulling back slightly against it; hand shifts back and forth across curve
Span:	fingers are spread apart and outstretched to span the curve with the whole hand; this is a passive scanning technique
Sweep:	either top or front edge of curve is swept with one or more fingers held straight out and together
Trace:	one or two fingers are held with the fingertips pointing straight down and swept across the inside of the curved strip

Variability

Standard deviations of the mean for each scanning method given in Table 2 are based on 36 judgments of curvature.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

5.110 Haptic perception of length: effect of orientation;

6.609 Haptic perception of curvature: effect of curve orientation and type of arm movement

Table 2. Haptic perception of curvature by blind and sighted subjects. (From Ref. 1)

	Curvature Thresholds (mm)					
	Convex (−)		Concave (+)			
Condition	AL	SD	AL	SD	IU (mm)	PSE (mm) (phenomenal straightness)
Sighted	−1.65	6.03	+5.09	5.73	6.74	+1.80
Blind	−1.27	5.50	+3.27	6.09	4.54	+0.88

AL = absolute threshold (minimum arc height in mm required to perceive convexity or concavity; positive values indicate concave curvature, negative values convex curvature); SD = standard deviation about the absolute threshold value; PSE = point of subjective equality (arc height in mm at which stimulus edge appears straight); IU = interval of uncertainty (indicator of variability associated with the PSE)

Table 3. Mean number of incorrect categorizations as a function of scanning method. (From Ref. 1)

Scanning Method	Mean	Standard Deviation
Grip (pooled)	11.95	2.88
Grip with thumb	12.70	2.83
Grip without thumb	11.20	4.85
Pinch (pooled)	14.45	2.87
One-finger pinch	15.30	3.38
Four-finger pinch	13.60	2.26
Top sweep	14.45	3.49

Table shows results for 60 sighted subject: 20 used grip method, 20 used pinch method, and 20 used top sweep method. There were 36 judgments per subject and values were pooled for stimulus type (convex, concave, or straight)

6.611 Perception of Viscosity of Liquids

Key Terms

Viscosity; kinesthesia; manual scanning; tactile-kinesthetic scanning; touch

General Description

The apparent viscosity of a liquid increases at approximately the square root of physical viscosity (in centipoises). This relationship is the same for judgments made by shaking the liquid, stirring the liquid while blindfolded, or stirring while seeing.

Methods

Test Conditions

- 150 ml of seven different blends of clear silicon fluids having viscosities of 10.3-95,000 centipoises (0.0103-95 N s/m^2) were placed in clear 300-ml cylindrical glass jars
- Three observation conditions were used: viewing the liquid while shaking the jar, viewing the liquid while stirring with a rod, and stirring the liquid without viewing (while blindfolded)

Experimental Procedure

- Magnitude estimation; liquids presented in random order, but an extreme stimulus was never presented first
- Independent variables: physical viscosity, observation condition
- Dependent variable: judged viscosity of each liquid
- Subject's task: assign a number to the apparent viscosity of the first liquid presented and then assign numbers to subsequent liquids in proportion to apparent viscosity of the first liquid
- 10 subjects per observation condition; 6 subjects participated in two of the three observation conditions

Experimental Results

- The apparent viscosity of a liquid increases as a power function of physical viscosity, i.e., $V_A = V_P^k$, where V_A is apparent viscosity, V_P is physical viscosity measured in centipoises; as determined in this study, k is equal to 0.42-0.46; i.e., apparent viscosity increases approximately as the square root (0.5 power) of physical viscosity.
- The relation of apparent viscosity to physical viscosity is the same, regardless of the sense modality (tactual-kinesthetic and/or visual) used to evaluate viscosity.

Variability

The vertical bars indicate the interquartile ranges of the means of 20 judgments for each stimulus after removal of variability due to subject's use of different measurement scales.

Repeatability/Comparison with Other Studies

The association between various adjectives used to describe liquids and the rheological properties of the liquids has been examined in Ref. 1.

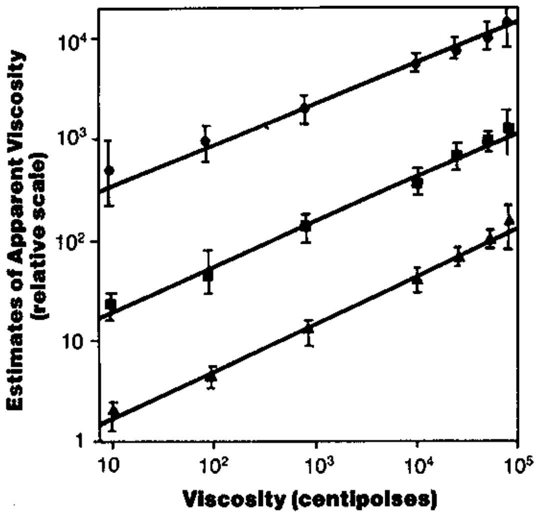

Figure 1. Magnitude estimates of apparent viscosity as a function of actual viscosity. Circles are data obtained when subjects viewed liquid while shaking container; squares, when subjects stirred liquid while blindfolded; and triangles, when subjects viewed liquid while stirring it. For clarity, the functions are separated vertically by one log unit. (1 centipoise = 0.001 Newton-seconds per square meter.) (From Ref. 2)

Constraints

- Results apply only to physical viscosity measured in centipoises; the value of the exponent k or the relationship between apparent viscosity and physical viscosity will be different if different units or definitions of viscosity are used.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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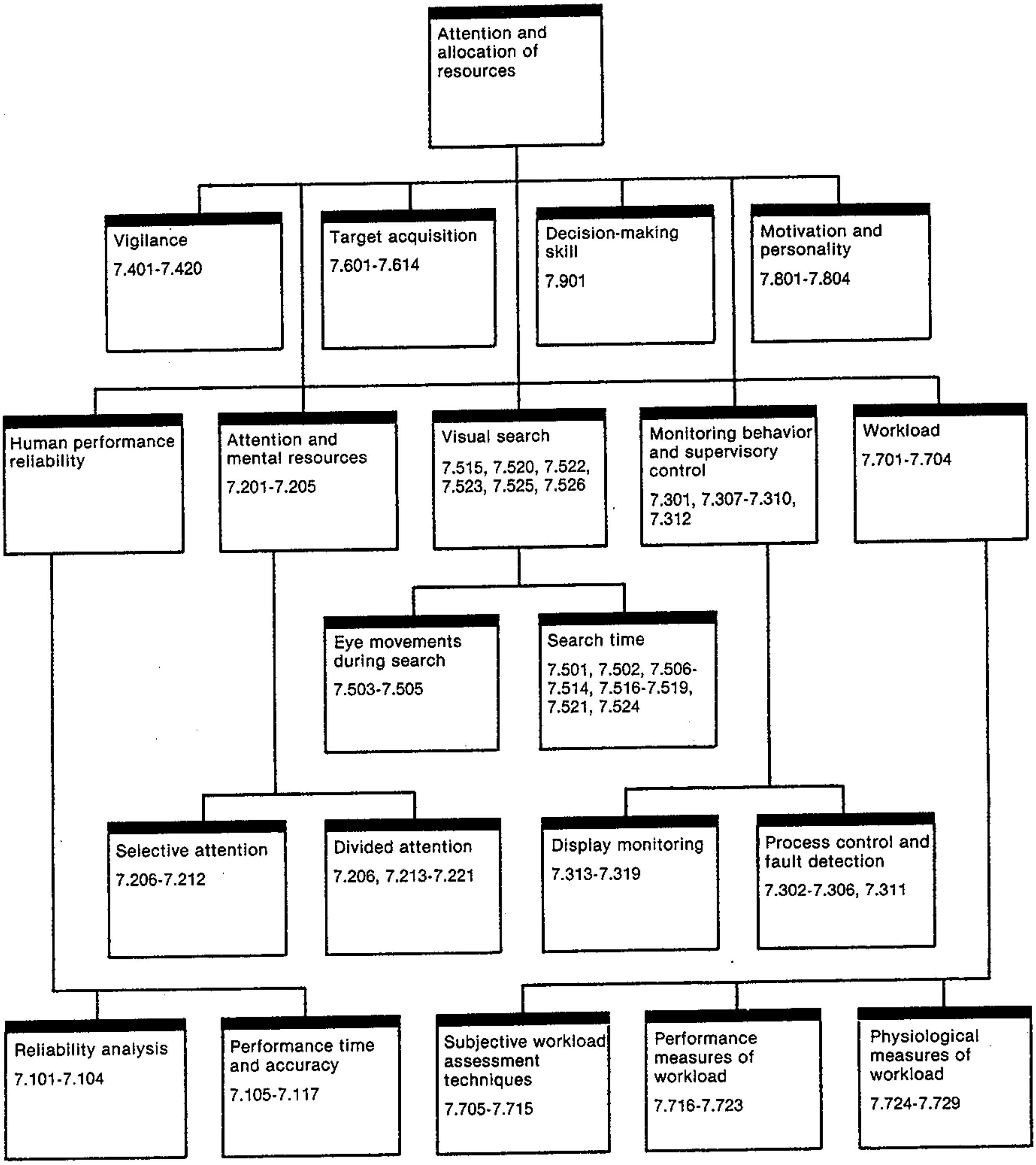
Cross References

6.607 Tactual discrimination of two-dimensional shape: effect of tactual mode

Notes

Organization of Entries



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Key Terms

Glossary

Accommodation. A change in the thickness of the lens of the eye (which changes the eye's focal length) to bring the image of an object into proper focus on the retina. (CRef. 1.222)

Arousal. Increased attention to and awareness of the environment, rendering the organism better prepared for mental or physical action.

Attention operating characteristic. A curve showing how performance on one task varies as a function of performance on a second task when the two are carried out concurrently and the allocation of attention between the two tasks is varied; that is, a performance trade-off function describing the improvement in the performance on one task due to any added resources released by lowering the level of performance on (by decreasing the level of attention to) another task with which it is time-shared.

Backward masking. Masking in which the masking stimulus occurs after the test stimulus. (*See* **masking**.)

Brain potential. Electrical voltage generated by the activity of nerve cells in the brain, usually measured from electrodes placed on the scalp or in contact with brain cells.

Compensatory tracking. Tracking in which the operator's display shows only the direction and magnitude of tracking error and does not independently present the command input and system position. The task is to compensate (correct) error.

Compound task. The combining of two or more component tasks in such a way that each trial consists of a single stimulus drawn randomly from one of the component tasks and a response, also from one of the component tasks.

Conjoint scaling. A technique that enables several variables to be combined such that the order of their joint effects is preserved by a composition rule (e.g., an additive rule) resulting from various axiom tests (e.g., transitivity, cancellation) specified by conjoint measurement theory. Conjoint scaling procedures are applied subsequent to the axiom testing, and specify actual numerical scale values for the joint effects that fit the combination rule derived from the conjoint measurement technique. When an additive combination rule is specified by the axiom tests, a number of scaling procedures can be applied to seek interval-scaled values for level of the variables based on the ordinal constraints imposed by the data.

Contrast attenuation. A reduction in contrast.

Divided attention. A task environment in which the observer or operator must attend to two or more stimuli, input channels, or mental operations that are active simultaneously, and must respond appropriately to each.

Dwell time. The length of time the eye is fixated on a given point.

Dynamometer. An instrument for measuring the force exerted by muscular contraction.

Electro-oculography. The recording and study of the changes in electrical potential across the front and back of the eyeball that occur during eye movements; generally measured using two electrodes placed on the skin at either side of the eye. The electrical potential is a function of eye position, and changes in the potential are caused by changes in the alignment of the resting potential of the eye with references to the electrodes.

Factorial design. An experimental design in which every level or state of each independent variable is presented in combination with every level or state of every other independent variable.

False alarm. In a detection task, a response of "signal present" when no signal occurred.

Gain. The ratio of output to input in a system; typically employed to specify, for example, the relation between control movement and display movement or system response. In the human describing function, it may also describe the relation between perceived error and controlled response.

Gaussian distribution. A probability density function that approximates the frequency distribution of many random variables in biological or other data (such as the proportion of outcomes taking a particular value in a large number of independent repetitions of an experiment where the probabilities remain constant from trial to trial). The distribution is symmetrical, with the greatest probability densities for values near the mean and decreasing densities at both larger and smaller values, and has the form

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where $f(x)$ is the probability density for the value x in the distribution, μ is the mean value, and σ is the standard deviation. Also called **normal distribution** or **normal probability distribution**.

Gaussian noise. Noise that is the result of random processes and whose spectral level (power density) is uniform over the frequency band where it occurs; also called **white noise.**

Inside-out display. A display (as of aircraft attitude) that uses the vehicle as a frame of reference, so that the display reflects the way the environment appears to the operator inside the vehicle looking out. For example, when the aircraft banks, the horizon in the attitude display tilts. (CRef. 9.529)

Interstimulus-onset interval. The time between the onset of one stimulus and the onset of a second stimulus. Also called **stimulus-onset interval.**

Landolt C. An incomplete ring, similar to the letter C in appearance, used as a test object for visual acuity. The thickness of the ring and the break in its continuity are each one-fifth of its overall diameter. The ring is rotated so that the gap appears in different positions and the observer is required to identify the location of the gap. Also called a **Landolt ring** or **Landolt C-ring.** (CRef. 1.602)

Liminal contrast threshold. The contrast associated with the minimum perceptible difference in luminance between two areas, often measured in terms of the luminance difference detectable on some specified proportion of trials (generally 0.50).

Masking. A decrease in the detectability of one stimulus (the test stimulus) due to the presence of another stimulus (the **mask**) that occurs simultaneously or close in time to the first.

Maxwellian view. A uniformly luminous field obtained when a light source is focused on the pupil of the eye. Very high luminances are achievable and the amount of light entering the eye is not affected by pupil size.

Monocular. Pertaining to, affecting, or impinging upon only one eye.

Monte Carlo method. A technique for obtaining a probabilistic approximation to the solution of problems in mathematics, science, and operations research by the use of random sampling.

Multidimensional scaling. A family of statistical techniques designed to uncover the underlying structure in data that consist of measures of relatedness among a set of objects (e.g., stimuli). Multidimensional scaling uses a matrix of proximities among the objects as input and produces an N-dimensional configuration or map of the objects as output. The configuration is so derived that the distances between the objects in the configuration match the original proximities as closely as possible. The locations of particular clusters of objects are said to reflect whatever dimensions might underlie the proximity measures.

Negative feedback servoloop. A feedback loop in which a signal from a part of the system following the control is fed back to the system input with a polarity opposite that of the control output, thus tending to decrease output and helping to stabilize the system by avoiding progressively increasing error.

Normal distribution. *See* **Gaussian distribution.**

Photopic. Pertaining to relatively high (daytime) levels of illumination at which the eye is light adapted and vision is mediated by the cone receptors. (CRef. 1.103)

Power spectrum. A graphical representation of mean square spectral density as a function of the logarithm of frequency.

Primary task. The principal task of the operator, whose performance is critical or most important. (*Compare* **secondary task.**)

Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).

ROC analysis. Signal detection theory maintains that performance in a detection task is a function of both the sensitivity or resolution of the operator's detection mechanism and the criterion or response bias adopted in responding to signals. A receiver operating characteristic (ROC) graphically depicts the joint effects of sensitivity and response bias on operator performance. It is defined by the locus of points on a graph obtained by plotting the probability of correct target detection (or "hits") versus the probability of false detections (or "false alarms") in a detection task. By requiring observers to vary their response criteria under identical stimulus conditions, points along a curve that represent equivalent sensitivity but different degrees of response bias can be generated. Given hit and false alarm rates from a detection experiment, ROCs can be plotted to compare the detection performance of observers under different conditions, and analyses conducted to specify the signal detection theory indices of sensitivity to the signal (d') and criterion or response bias (β).

Secondary task. A task the operator is asked to perform in addition to the primary task; performance on the secondary task provides an estimate of primary task workload. Secondary tasks may be "non-loading" (the operator attends to the secondary task when there is time) and "loading" (the operator must always attend to the secondary task).

Selective attention. A task environment in which the observer or operator must attend selectively to some stimuli or input channels while ignoring others that are active simultaneously.

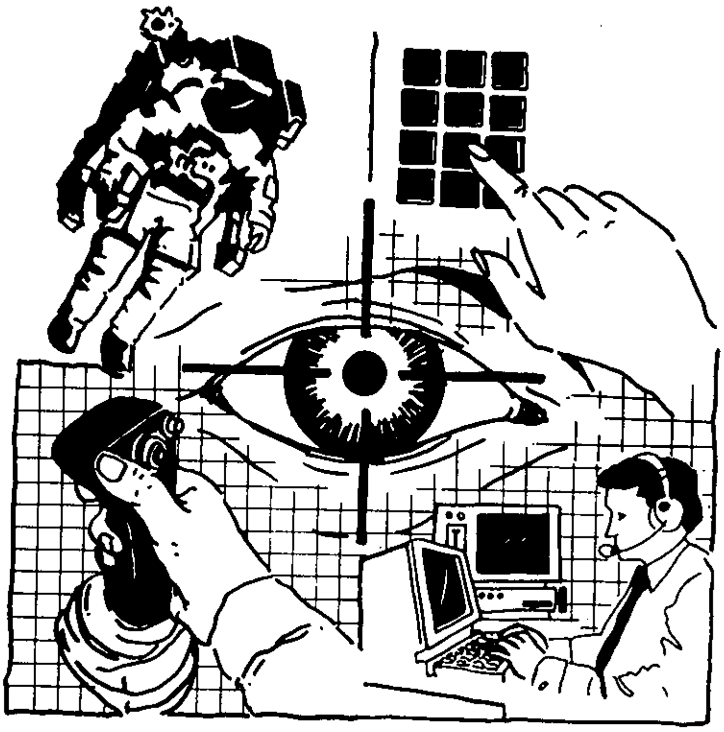
Sensation level. The amount (in decibels) by which the level of a sound exceeds the threshold of audibility of the sound for a given listener.

Sensitivity. In a general sense, the ability to detect stimulation; in psychophysical studies, refers in particular to the ability to be affected by and respond to low-intensity stimuli or to slight stimulus differences; commonly expressed as the reciprocal of measured threshold.

Spatial frequency. For a periodic target, such as a pattern of equally spaced bars, the reciprocal of the spacing between bars (i.e., the width of one cycle, or one light bar plus one dark bar), generally expressed in cycles per millimeter or cycles per degree of visual angle.

Standard deviation. The square root of the average squared deviations from the mean of the observations in a given sample. It is a measure of the scatter or dispersion of scores or observations in the sample.

Section 7.1 Human Performance Reliability



7.101 Error Classification and Analysis

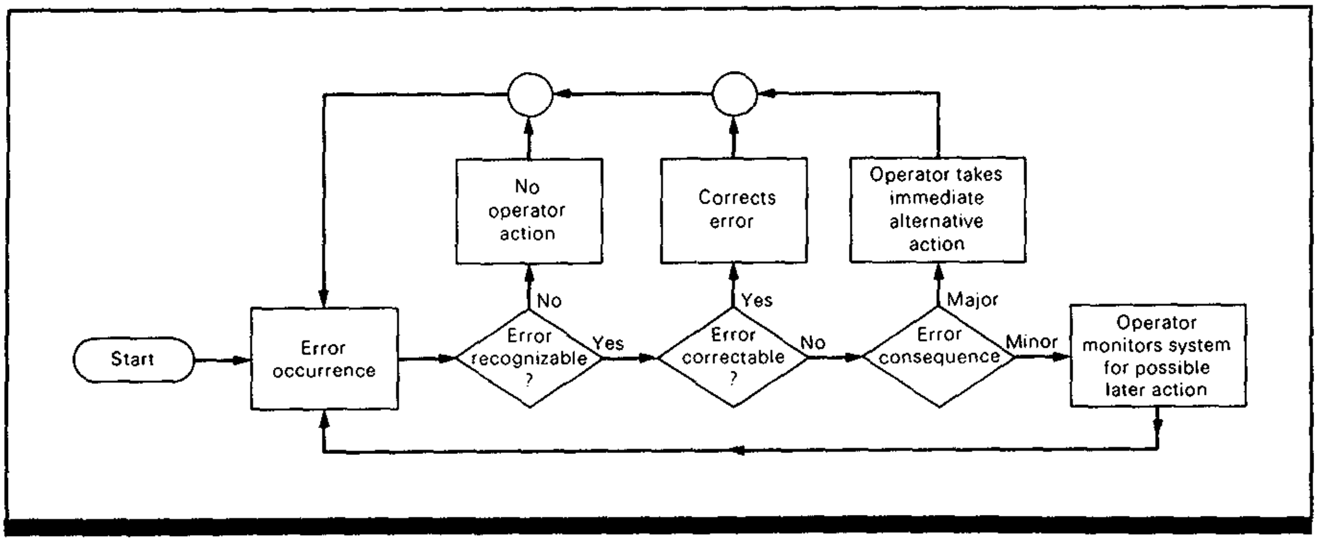


Figure 1. The effect of error visibility, correctability, and consequences.

Key Terms

Control errors; decision making; error probability; problem solving; tracking

General Description

An error is any action or failure to act that deviates from system requirements, that is not corrected, and that has an unacceptable effect on system output. System failures can occur as a result of error as well as from physical defects. During system development, performing an error analysis can help to anticipate errors that may occur and to facilitate system design to minimize those errors.

Errors can be classified in different ways (Refs. 1,3): e.g., in terms of equipment operated; step, task, or function performed; estimated error frequency; error consequences, etc. A detailed level of description is the most useful.

An initial classification of errors can be stated in terms of the operator functions (sensory/perceptual, estimating/tracking, decision-making/problem solving) with which the error is associated. More useful is an error classification stated in terms of system functions with which the error is associated, e.g., navigation, tracking, watchstanding, etc. Most useful, because of the level of detail, errors may be classified in terms of individual tasks performed incorrectly, e.g., failure to detect a signal on the radar scope, failure to input cost data to the computer correctly, etc. A variety of distinctions is possible, e.g., between failure to understand procedures, errors based on incorrect diagnosis of what should be done, and errors resulting from forgetting (Ref. 4).

Because categories of error/task classification are peculiar to individual systems in which the errors may occur, a taxonomy of such errors is beyond the scope of this entry.

Whenever possible, the error analyst should classify errors in terms of their task context, because this will suggest possible error causes. Although errors are made by people, they can often be traced to inadequate equipment design, procedures, technical data, training, workmanship, etc. Three extremely important aspects of an error are its visibility, its correctability, and its consequences, as seen by considering how the operator deals with error (Fig. 1). If an error is made, it may or may not be recognized by the operator as an error. If it is not recognized as an error, the operator will, of course, take no further action, and the system may be affected negatively. If the error is recognized, it may or may not be correctable. If it is correctable, the operator will correct the error and take no further action. If the error is not correctable, the operator must consider the consequences of the error, which may be major or minor. If error consequences are major, the operator must take immediate alternative and significant action. If error consequences are minor, the operator will continue to monitor system processes to see if further action is later required.

Error is important to the designer because one goal of system design should be to reduce error likelihood. Although "good" design would presumably eliminate all potential errors, real world design is rarely that "good." In any event, effective design requires an analysis of possible errors in terms of their salient dimensions and their relationships to task, equipment, software, procedural characteristics, and the operational environment.

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Applications

In performing an error analysis during system development, it is important to anticipate the kinds of errors that could occur. The goal is to design hardware, software, and procedures so that error likelihood is reduced. Good design requires that if an error does occur, it must be immediately recognizable as such, it must be correctable, and its consequences must be minor. An error analysis should contain the following: individual task to be performed, all errors that could occur in performing the task and that also have a reasonable probability of occurrence, system consequences of errors, possible causes of error, and potential system design actions.

Constraints

- For an error to be recognized, it must be defined unambiguously.
- To understand error consequences, the operator must have a detailed concept of system function.
- The error concepts described pertain primarily to discrete, procedural tasks rather than to continuous tracking tasks.

Key References

1. Altman, J. W. (1967). Classification of human error. In W. B. Askren (Ed.), *Symposium on reliability of human performance in work* (AMRL-TR-67-88). Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. (DTIC No. AD659140)

*2. Meister, D. (1984). Human reliability. In F. A. Muckler (Ed.), *Human factors review '84*. Santa Monica, CA: Human Factors Society.

*3. Meister, D. (1985). *Behavior analysis and measurement methods*. New York: Wiley.

*4. Swain, A. D., & Guttman, H. E. (1983). *Handbook of human reliability analysis with emphasis on nuclear power plant applications* (NUREG/CR-1278, SAND80-0200, RX, AN). Albuquerque, NM: Sandia National Laboratories.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.104 Human performance data and sources

7.102 Human Reliability Analysis

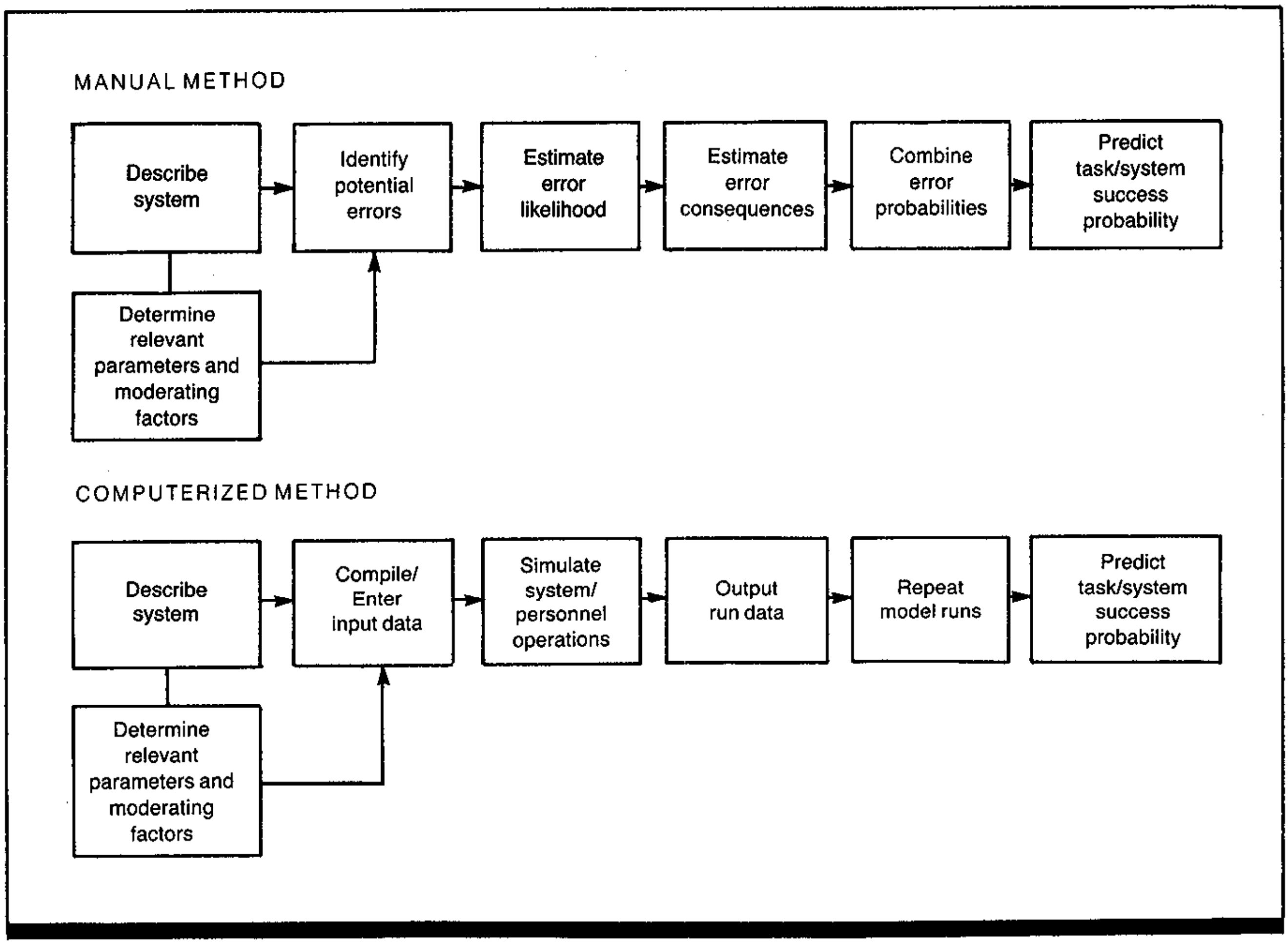

Figure 1. Manual and computerized methods of conducting human reliability analysis.

Key Terms

Error estimation; SAINT model; Siegel/Wolf stochastic models; THERP method

General Description

Human reliability analysis is the process of quantitatively predicting human error probability and task/system accomplishment. The manual and computerized methods depicted in the figure use different approaches. The manual method analyzes errors and their consequences. The computerized method simulates task performances on the basis of a system model.

Both techniques begin by describing the system whose performance is to be predicted. This is done by partitioning system operations into their individual tasks. Using the manual method, the analyst identifies potential errors in each task, estimates the likelihood of each error, and estimates error consequences. Error likelihood values are combined to construct two outputs: (1) individual task accomplishment probabilities, and (2) system success probability. Error probability is linked to task accomplishment because the latter is defined as 1.0 (errorless performance) minus error likelihood.

The computerized method models the system in terms of algorithms of task interrelationships. These simulate human/system operations by selecting, on a Monte Carlo basis, input distributions of task times and success probabilities. A simulated system operation is completed when the simulated operators use up their assigned work time or successfully complete all tasks. The simulation is repeated a number of times (e.g., 100-200 runs). Each time, the system either succeeds or fails in accomplishing its tasks. The percentage of runs on which the system succeeds is the system success probability.

Despite differences in approach, the two methods have certain similarities: the use of tasks as behavioral units, the use of probability mathematics, common assumptions such as the interdependence of tasks and task performances, and

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the modification of task performance probabilities by performance-shaping factors. The last are factors that influence personnel performance, such as stress and operator proficiency. In the Siegel/Wolf stochastic models (Ref. 2), the effect of certain degrees of stress is to reduce the task accomplishment probability. In the manual method, the analyst increases the error probability for a task if operator stress is assumed.

Empirical comparisons of the two methods have not been made so one cannot be recommended over the other. The computerized method requires development of model algorithms if these do not already exist. The manual method requires detailed molecular analysis of error tendencies and consequences. The latter is, however, advantageous for diagnosing system weaknesses. The manual method, known as Technique for Human Error Rate Prediction (THERP) (Ref. 3), has been used more frequently, particularly as part of the probabilistic risk assessment of new nuclear power plants. Of the two computerized methods that can be used for human reliability prediction, the Siegel/Wolf digital simulation models have been used many more times than SAINT (System Analysis of Integrated Network of Tasks) (Ref. 1) to predict human performance.

Applications

If quantitative human performance inputs are to be included in equipment/system design, the only formal way of doing so is by means of a human reliability analysis. Informal qualitative behavioral recommendations can be made, but these involve unacceptable subjectivity.

Empirical Validation

Validation of these methods has been both formal and informal. Formal validation of the Siegel/Wolf models has involved making a prediction of task/ system success based on exercising the model, then collecting empirical data of the operational system, and comparing the two values. These comparisons have shown fairly close correspondence between model predictions and empirical human reliability.

Informal validation, which is characteristic of THERP, involves applying the technique to practical problems and assessing its success as a design tool. Information about informal validations is largely lacking. Because of the scarcity of validation data, use of these techniques is justified primarily by their utility as design tools for improvement of system design.

Constraints

- Error probability data used as inputs to both techniques have great gaps that must be filled by an analyst's judgment.
- Both manual and computerized techniques involve some subjectivity.
- The number of interactive variables is very large and difficult to handle using the combinatorial mathematics required by the manual method.

Key References

1. Chubb, G. P. (1980, September). SAINT: A digital simulation language for the study of manned systems. *Proceedings, Conference on Manned Systems Design, New Methods and Equipment*. Freiburg, West Germany, 300-329.

*2. Department of the Navy (1977, December). *Human reliability prediction system user's manual.* Washington, DC: Sea Systems Command.

*3. Swain, A. D., & Guttman, H. E. (1983, August). *Handbook of human reliability analysis with emphasis on nuclear power plant applications*. (NUREG/CR-1278, SAND80-0200, RX, AN). Albuquerque, NM: Sandia National Laboratories.

Cross References

7.101 Error classification and analysis;

7.103 Technique for human error rate prediction (THERP);

7.104 Human performance data and sources

7.103 Technique for Human Error Rate Prediction (THERP)

Key Terms

Error estimation; sensitivity analysis; task analysis; task event tree; THERP method

General Description

The Technique for Human Error Rate Prediction (THERP) (Ref. 1) is the most frequently applied method of human reliability analysis. It involves a series of steps in which the analyst (1) describes system goals and functions, situations, and personnel characteristics, (2) describes jobs and tasks performed by personnel and analyzes them to identify error-likely situations, (3) estimates the likelihood of each potential error as well as the likelihood of its being undetected, (4) estimates the consequences of the undetected error, and (5) suggests and evaluates changes to the system to increase success probability.

The key steps are (3) and (4): measurement of (a) the probability(P_i) that an operation will lead to an error of class i, and (b) the probability that an error or class of errors will result in system failure (F_i).

These probabilities are depicted in the form of an event tree diagram shown in the figure. P_i is based on the error rate, which is the frequency of error occurring during an operation over some period of time. $1 - P_i$ is the probability that an operation will be performed without error. F_iP_i is the joint probability that an error will occur in an operation and that the error will lead to system failure. $1 - F_iP_i$ is the probability that an operation will be performed which does *not* lead to an error producing system failure. $Q_i = 1 - (1 - F_iP_i)^{n_i}$ is the probability of a failure condition existing as a result of class i errors occurring in n_i (independent) operations. Total system or subsystem failure rate resulting from human error is expressed as:

$$Q_t = 1 - \left[\prod_{k=1}^{n} (1 - Q_k)\right]$$

where Q_t is the probability that one or more failure conditions will result from errors in at least one of n classes and the quantity in brackets is $(1 - Q_1)(1 - Q_2)\ldots(1 - Q_n)$.

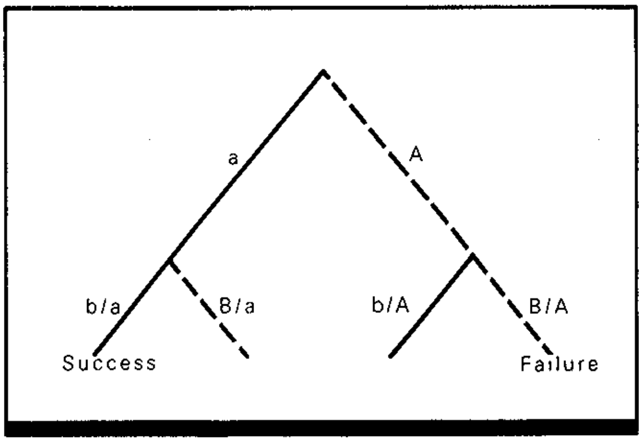

Figure 1. Task/event tree diagram (schematic form); solid lines represent success, dashed lines represent error. A = the first task; B = the second task; *a* = probability of successful performance of task A; *A* = probability of unsuccessful performance of task A; *b/a* = probability of successful performance of task B given *a*; *B/a* = probability of unsuccessful performance of task B given *a*; *b/A* = probability of successful performance of task B given *A*; *B/A* = probability of unsuccessful performance of task B given A. (From Ref. 1)

Applications

THERP is applied as follows:

(1) Task analysis: the procedure for operating and maintaining the system is partitioned into individual tasks; other relevant information, e.g., equipment acted upon, action required of personnel, and the limits of operator performance, is also documented.

(2) Error identification: the errors likely to be made in each task-step are identified. Non-significant errors (those with no important system consequences) are ignored.

(3) Development of event trees: each likely error is entered sequentially as the right limb in the binary branch of the event tree (Fig. 1). The first potential error starts from the highest point on the tree at the top of the page. Each left limb represents the probability of success in the task-step and each right limb represents its failure probability. To determine the probability of the task being performed without error, a complete-success path through the event tree is followed. Once an error has been made on any task, the system is presumed to have failed, unless the error is detected and corrected. The likelihood that an error will be detected and corrected must be taken into account by modifying the initial error probability.

(4) Assignment of error probabilities: the analyst estimates the probability of occurrence for each error, making use of all available data sources, formal data banks, subject matter experts, etc.

(5) Estimation of the relative effects of performance-shaping factors: error probabilities are modified to account for all conditions (e.g., stress, proficiency, experience) assumed to affect task performance significantly.

(6) Assessment of task dependence: except for the first branch of the event tree, all branches represent conditional probabilities, with task/event interdependence directly affecting success/failure probabilities. Thus, each task must be analyzed to determine its degree of dependency.

(7) Determination of success/failure probabilities: each end point of an event tree is labelled as a task success or failure, qualified probabilistically, and combined with other task probabilities to formulate total system success/failure probabilities. Failure probabilities are obtained by subtracting the task success probability from 1.0.

(8) Sensitivity analysis: the analyst may wish to determine the effects of manipulating the values of one or more of the task elements analyzed to determine effects of a design or procedure change before these changes are incorporated into system design.

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Constraints

• This procedure is applicable to discrete, procedural tasks or continuous tasks which can be categorized in discrete terms.
• Data necessary to derive error probabilities are frequently lacking.
• The effect of performance-shaping factors on task performance is not well known, at least quantitatively.
• The need to analyze and categorize *all* potential errors in a task takes considerable time and effort.

Key References

*1. Swain, A. D., & Guttman, H. E. (1983, August). *Handbook of human reliability analysis with emphasis on nuclear power plant* applications (NUREG/CR-1278, SAND800 200, RX, AN). Albuquerque, NM: Sandia National Laboratories.

Cross References

7.101 Error classification and analysis;

7.102 Human reliability analysis

7.104 Human Performance Data and Sources

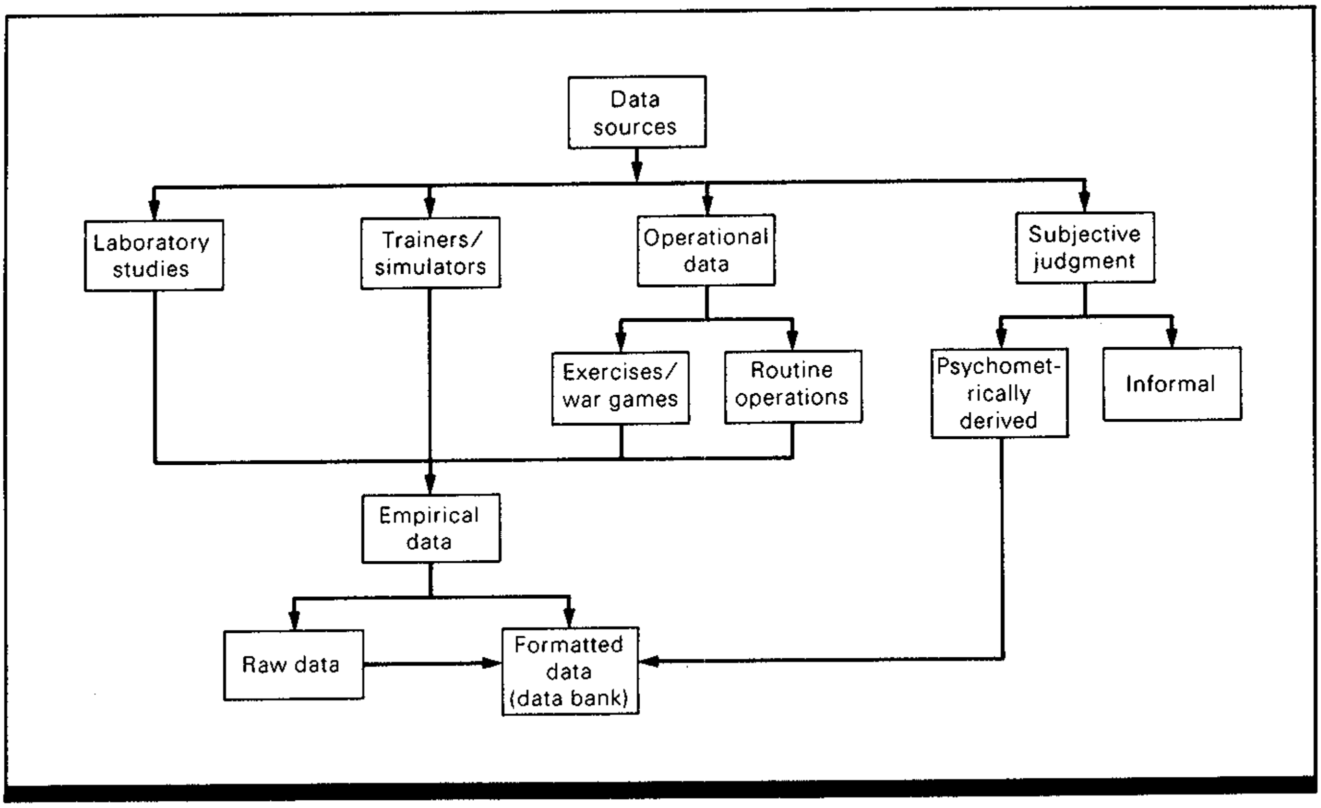

Figure 1. Human performance data sources and outputs.

Key Terms

Data taxonomy; error analysis; reaction time

General Description

Any analysis of human performance, such as the selection of the task probabilities required in human reliability analysis, requires supporting data in quantitative form. Objective human performance data take the form of time, error, frequency, and logistics measures. Time measures secured using instrumentation include reaction time from an initiating stimulus to task initiation, and task duration from initiating stimulus to task completion or failure. Errors include those of omission (failure to perform or complete required activities, failure to perform a required activity as expeditiously as possible or to satisfy a required criterion fully), commission (performance of non-required activities), and sequencing (performance of required activities out of sequence). Error data are produced by matching actual performance against an explicit or implicit set of requirements. Frequency data are produced by counting numbers of operator responses, errors, outputs, and events. Logistics measures are indirect measures of human performance; they reflect performance in terms of output, usually in terms of amount expended or accomplished. For example, one might measure a forklift operator's efficiency by the number of boxes moved in a specified time period. The most commonly used measures are errors, necessary in the manual method of performing human reliability analysis, and time, which is a critical requirement for the computerized methods of human reliability analysis (CRef. 7.102), since time is critical for stress determination and successful task accomplishment.

Several possible sources for these data are shown in the figure. Most human performance data are derived from laboratory studies; some data are developed using simulators; almost none come from operational sources (i.e., measurement of personnel performance on-the-job). However, operational data are most frequently requested by users. Laboratory data are most highly controlled, but because of this, often represent artificial situations and are difficult to apply meaningfully to real-world problems; it is difficult to generalize to other conditions. Simulator data are usually representative of operational situations and relatively well controlled, but they are not routinely collected for general prediction purposes. Operational data are most desirable, but usually are more heavily contaminated by extraneous, uncontrolled conditions. Moreover, there is almost no systematic effort to collect operational data.

Continuing efforts have been made to use human judgment ("expert opinion") to fill gaps in objective data. These efforts sometimes make use of formal psychometric meth-

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ods, such as the method of paired comparisons (Refs. 1, 3). However, they are more often applied informally when analysts adjust empirical data to satisfy special requirements of human performance prediction situations. Most empirical, objective data are in what one might call "raw" form, that is, data resident in an individual study which have not been extracted, combined with other data, or classified and formatted into "data banks." A data bank is a systematically organized and formatted compilation of data arranged according to a special taxonomic scheme to answer specific questions. There are relatively few data banks (Refs. 2, 4).

Applications

Human performance data can be used for prediction and evaluation of personnel performance, for diagnosing system inadequacies, and to specify system requirements. The data can be used both as indices of capability (e.g., operator response to a single discrete stimulus requires at least 200-300 msec), and as a standard (e.g., most personnel performing the specified task take *X* minutes to accomplish it). These data are of great potential use in system design because, as capabilities, they indicate the limits that can be expected of operator performance; design configurations must not exceed such limitations. Human performance data standards are used to evaluate the effectiveness of system personnel in performing their tasks. Data banks are used extensively to perform human reliability analyses and make human error rate predictions.

Constraints

- Data from laboratory studies are usually of comparatively little value for application to system design because they are molecular and artificial.
- The amount of empirical data formatted into data banks and derived from formal psychometric processes is limited.
- Few quantitative personnel performance standards exist.

Key References

1. Blanchard, R. E., Mitchell, M. B., & Smith, R. L. (1966, June). *Likelihood of accomplishment scale for a sample of man-machine activities*. Santa Monica, CA: Dunlap and Associates, Inc.

*2. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

3. Stillwell, W. G., Seaver, D. A., & Schwartz, J. P. (1982, May). *Expert estimation of human error probabilities in nuclear power plant operations: A review of probability assessment and scaling* (NUREG/CR-2255 and SAND81-740). Falls Church, VA: Decision Science Consortium.

*4. Topmiller, D. A., Eckel, J. S., & Kozinsky, E. J. (1982, December). *Human reliability data bank for nuclear power plant operations. Volume 1: A review of existing human error reliability data banks* (NUREG/CR-2744/1 of 2 and SAND82-7057/1 of 2, AN, RX). Dayton, OH: General Physics Corporation.

Cross References

7.101 Error classification and analysis;

7.102 Human reliability analysis;

7.103 Techniques for human error rate prediction (THERP)

7.105 Time and Accuracy in Monitoring Radar-Type Display Scopes

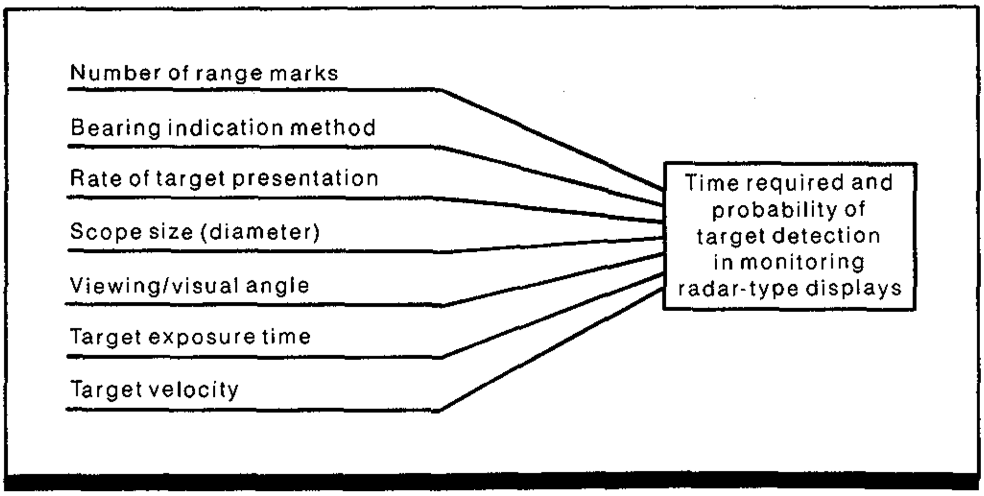


Figure 1. Characteristics affecting target detection probability and response duration in monitoring radar-type displays.

Key Terms

CRT displays; error prediction; monitoring; PPI sonar displays; radar; reaction time; target acquisition; target detection; vigilance; visual search

General Description

This entry describes response time and probability of target detection (Ref. 1), which vary as a function of the characteristics shown in Fig. 1 and Table 1. The displays are of the Plan Position Indicator (PPI) type used for radar/sonar applications, and the stimuli are "raw" video rather than alphanumeric and geometric symbols. In developing a human reliability measure of performance, the equipment/system must be analyzed to determine which of the characteristics in the figure are relevant. Then the probability value for each relevant display characteristic is extracted from the table and multiplied serially. Response times for each characteristic are extracted from the table and added to the base time value.

Applications

The data shown in the table can be used to perform human reliability analyses and make human error rate predictions.

Constraints

- It is unclear whether target classification is included in the data presented.
- Data were secured from laboratory-type situations which were somewhat artificial.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.104 Human performance data and sources;

7.402 Methods of measuring vigilance, monitoring, and search;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.512 Search time: effect of number of targets and target complexity;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.525 Target acquisition in real-world scenes;

11.214 Time and accuracy in reading circular scales

Table 1. Response time and probability of target detection in monitoring radar-type displays.

Base Time = 3.80 min.

Time Added	Human Reliability	Scopes
		1. Number of range marks
0.50	0.9980	a. 1 or 2
0	0.9997	b. 3-5
0	0.9999	c. 6-10
0.30	0.9990	d. 10-20
0.80	0.9983	e. 20 and up
		2. Bearing indication method
2.00	0.9975	a. Estimate (no aid)
1.00	0.9990	b. Use overlay
0.50	0.9995	c. Use cursor
		3. Rate of target presentation
3.50	0.9956	a. 10/hr
3.00	0.9971	b. 20/hr
2.00	0.9986	c. 30/hr
1.00	0.9990	d. 40/hr
0	0.9970	e. 1500/hr
		4. Scope size (diameter)
2.00	0.9990	a. 3 in.
0.75	0.9999	b. 4 in.
0	0.9999	c. 5-7 in. and up
		5. Visual angle (from operator to scope face)
0	0.9999	a. 0-45 deg
0.70	0.9995	b. 45-80 deg
		6. Target exposure time
0.75	0.9990	a. 3 sec
0.30	0.9995	b. 5 sec
0	0.9999	c. Over 5 sec
		7. Target velocity (inches per second)
0	0.9999	a. 0.75
2.00	0.9992	b. 1.75
3.00	0.9985	c. 3.25

7.106 Time and Accuracy in Responding to Discrete Indicator Lights

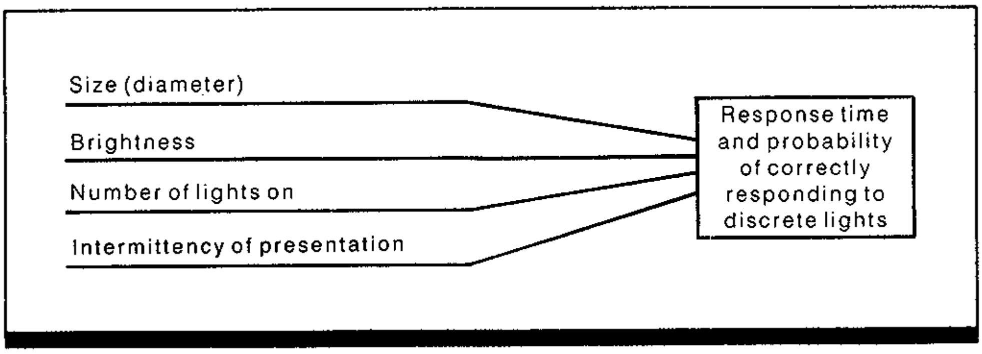


Figure 1. Characteristics affecting time and accuracy in responding to discrete lights.

Key Terms

Error prediction; indicators; reaction time

General Description

Response time and probability of correctly responding to discrete lights (based on error frequency per 10,000 observations, subtracted from errorless performance, 1.0) vary as a function of characteristics shown in Fig. 1 and Table 1. These are not transilluminated legend lights but are standard "jewel" type indicators that provide only limited information, e.g., on-off, danger, in or out of tolerance. To develop a human reliability measure of performance, the equipment/system must be analyzed to determine which characteristics in the figure are relevant. Probability values for all relevant indicator characteristics are extracted from the table and multiplied serially. Response times for each relevant characteristic are extracted from the table and added to the base time value.

Applications

The data in the table can be used to perform human reliability analyses and make human error rate predictions.

Constraints

- Serial multiplication of individual parameters probably underestimates actual probability of correctly responding.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.104 Human performance data and sources;

7.107 Probability of correctly responding to annunciators and discrete status lights;

11.214 Time and accuracy in reading circular scales

Table 1. Response time and probability of correctly responding to discrete lights.

Base Time = 0.25 Min		
Time Added	**Human Reliability**	**Lights**
		1. Size (diameter in inches)
0.30	0.9995	a. Less than 1/4
0.20	0.9997	b. 1/4-1/2
0	0.9999	c. 1/2-1
		2. Luminance
		a. Indicator
0	0.9999	(1) 10 x background
0	0.9997	(2) 2 x background
0.20	0.9995	(3) Less than 2 x background
		b. Caution and warning
0	0.9999	(1) 10 x indicator lights
0.20	0.9998	(2) 2 x indicator lights
1.20	0.9985	(3) Less than 2 x indicator lights
		3. Number of lights in visual field (lights ON)
0	0.9998	a. 1-2
1.20	0.9975	b. 3-4
2.40	0.9952	c. 5-7
3.50	0.9946	d. 8-10
		4. Presentation
0	0.9998	a. Intermittent (blinking)
0.20	0.9996	b. Continuous illumination

7.107 Probability of Correctly Responding to Annunciators and Discrete Status Lights

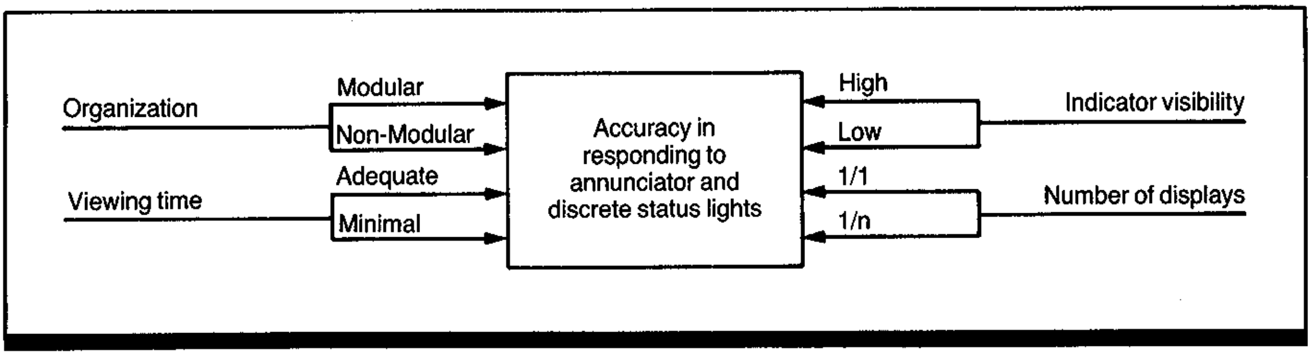


Figure 1. Characteristics affecting accuracy in responding to annunciator and discrete status lights.

Key Terms

Annuciator displays; attentional directors; error prediction; indicators; response probability; status lights; warnings

General Description

When a display consists of discrete indicators, e.g., legend (annunciator) or non-legend (jewel-type) lights, the operator's function is to recognize that an indicator has illuminated (or failed to illuminate when required) or that an illuminated indicator has extinguished (or failed to extinguish when required). This entry presents extrapolations and modifications of probabilities derived from Ref. 1. The figure shows that factors affecting responses to these displays are organization (modular rows and columns and non-modular), viewing time (adequate and minimal), display visibility (high and low), and display configuration (one light alone or 1/1; one out of four or 1/4; one out of eight 1/8, etc.). Data in the table are probabilities based on error frequency n per 10,000 observations subtracted from errorless performance (1.0): $P = 1-(n/10{,}000)$. Numbered conditions refer to combinations of parameters.

No multiplicative combination of parametric values is required because each probability already represents such a combination. In developing a human reliability measure of performance, the equipment/system must be analyzed to determine which characteristics in the figure are relevant. Probabilities associated with relevant characteristics are then taken from the table.

Based on an estimate of the contribution to error attributable to the number of identical indicators (18%), an initial estimate of performance under modular organization, adequate viewing time, and high visibility (Condition 1) was made using data from Ref. 1. The error effect of non-modular organization was also estimated at approximately 18%. The error effect of minimal viewing time was based on extrapolation from the data of Ref. 2. The error effect of low indicator visibility (e.g., poor resolution) was considered to be equivalent to the effect of minimal viewing time, and the same percent reduction in probability of correct performance was used for this factor.

Applications

Data in the table can be used to perform human reliability analyses and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resemble the conditions of the system being designed.

Constraints

- The values in the table are extrapolations of empirical data and therefore should be considered estimates only.
- Because of lack of data, the table does not take into account other performance-shaping factors.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

2. Nicholson, R. M. (1962). Maximum information handling rates for sequentially presented visual stimuli. *Human Factors, 4*, 367-373.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.106 Time and accuracy in responding to discrete indicator lights;

7.408 Effect of event rate on vigilance performance;

7.410 Maintenance of vigilance level by adaptive changes in signal detectability;

7.417 Effect of boredom on detection efficiency;

11.405 Visual warning signals: effect of visual field position and color;

11.408 Master warning signals: effect on detection of signals in the visual periphery

CONDITIONS	PARAMETERS: Organization: Modular	Organization: Non-Modular	Viewing Time: Adequate	Viewing Time: Minimal	Visibility: High	Visibility: Low	DISPLAY CONFIGURATION 1/1	1/4	1/8	2/4	2/8	4/4	4/8
(1)	●		●		●		.9998	.9975	.9952	.9943	.9933	.9923	.9909
(2)		●	●		●		.9998	.9971	.9943	.9933	.9921	.9909	.9893
(3)	●			●	●		.9990	.9850	.9800	.9764	.9721	.9671	.9600
(4)		●		●	●		.9990	.9823	.9764	.9721	.9671	.9612	.9558
(5)	●		●			●	.9990	.9850	.9800	.9764	.9721	.9671	.9600
(6)		●	●			●	.9990	.9823	.9764	.9721	.9671	.9612	.9558
(7)	●			●		●	.9982	.9698	.9648	.9585	.9570	.9419	.9291
(8)		●		●		●	.9980	.9644	.9585	.9510	.9422	.9324	.9163

Table 1. Probability of correct response to annunciator and discrete status lights.

7.108 Probability of Correctly Reading Meters

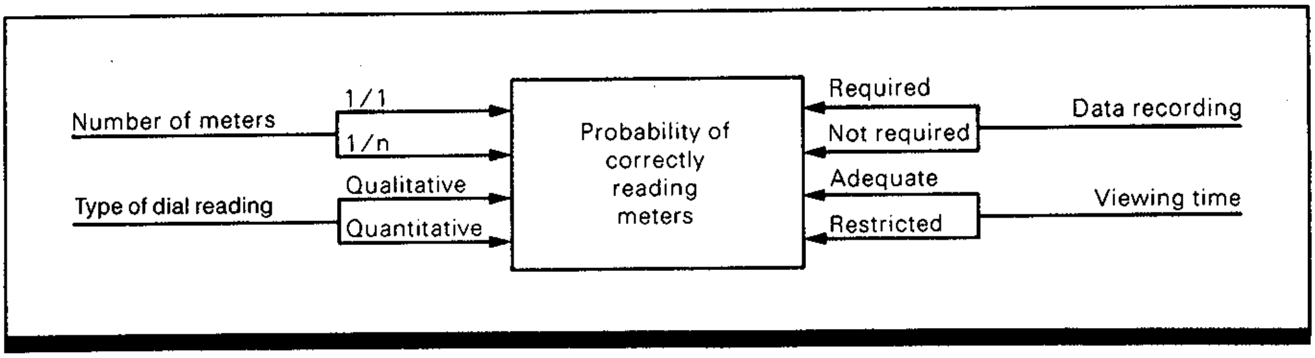


Figure 1. Characteristics affecting the probability of correctly reading meters.

Key Terms

Data recording; dial reading; error prediction; meter reading; response probability

General Description

When a display consists of a standard meter, the operator's function is to determine the value displayed by observing the meter. Estimates in Table 1 are probabilities of correct response (based on error frequency per 10,000 observations subtracted from errorless performance, 1.0) The estimates were taken from Ref. 1, but were checked against data from Refs. 2 and 3. Numbered conditions in the table refer to combinations of parameters. No multiplicative combination of parametric values is required. Factors affecting reading accuracy (see figure) are number of meters (one or several), type of dial reading (qualitative, quantitative), data recording (required and not-required), and visibility/viewing time (adequate and restricted). The definition of restricted viewing time is somewhat subjective. The original data of Refs. 2 and 3 are based on viewing times of 2.5 sec or less, but in the use of this table, any viewing requirement less than 10 sec should be considered restrictive. The effect of poor visibility is considered essentially the same as that of restricted viewing time and is therefore combined in the same category. When the operational condition includes both poor visibility and restricted viewing time, the probability estimate for this condition should be multiplied by itself. In developing a human reliability measure of performance, the equipment/system must be analyzed to determine which of the characteristics in the figure are relevant. Probabilities associated with these characteristics are then extracted from the table.

Applications

The data in the table can be used to perform human reliability analyses and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resemble the conditions of the system being designed.

Constraints

- Estimates are extrapolations of empirical data and therefore involve considerable judgment.
- Conditions are not precisely defined.
- Some relevant performance-shaping factors are not considered.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blanchard, R. E., Mitchell, M. B., & Smith, R. L. (1966, June 30). *Likelihood of accomplishment scale for a sample of man-machine activities*. Santa Monica, CA: Dunlap and Associates.

2. Dashevsky, S. G., & Oatman, L. C. (1963, December). *Combining check-reading accuracy and quantitative information in a space-saving display* (HEL-TM-17-63). Aberdeen Proving Ground, MD: Human Engineering Laboratory. (DTIC No. AD601575)

3. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

11.210 Time and accuracy in reading linear scales;

11.211 Scale divisions: reading to the nearest scale mark;

11.212 Scale divisions: straight scale interpolation;

11.214 Time and accuracy in reading circular scales;

11.215 Scale divisions: reading circular dials

	PARAMETERS								
CONDITIONS	No. of meters: One	No. of meters: Several	Reading: Qualitative	Reading: Quantitative	Visibility/Viewing Time: Adequate	Visibility/Viewing Time: Restricted	Data Recording: Not Required	Data Recording: Required	PROBABILITY ESTIMATE
(1)	●		●		●		●		.9994
(2)	●		●		●			●	.9990
(3)	●		●			●	●		.9965
(4)		●	●		●		●		.9973
(5)		●	●		●			●	.9952
(6)		●	●			●	●		.9873
(7)	●			●	●		●		.9977
(8)	●			●	●			●	.9955
(9)		●		●	●		●		.9865
(10)		●		●	●			●	.9825
(11)		●		●		●	●		.9685

Table 1. Probability of correctly reading meters.

7.109 Probability of Correctly Reading CRT or Large-Screen Projected Displays

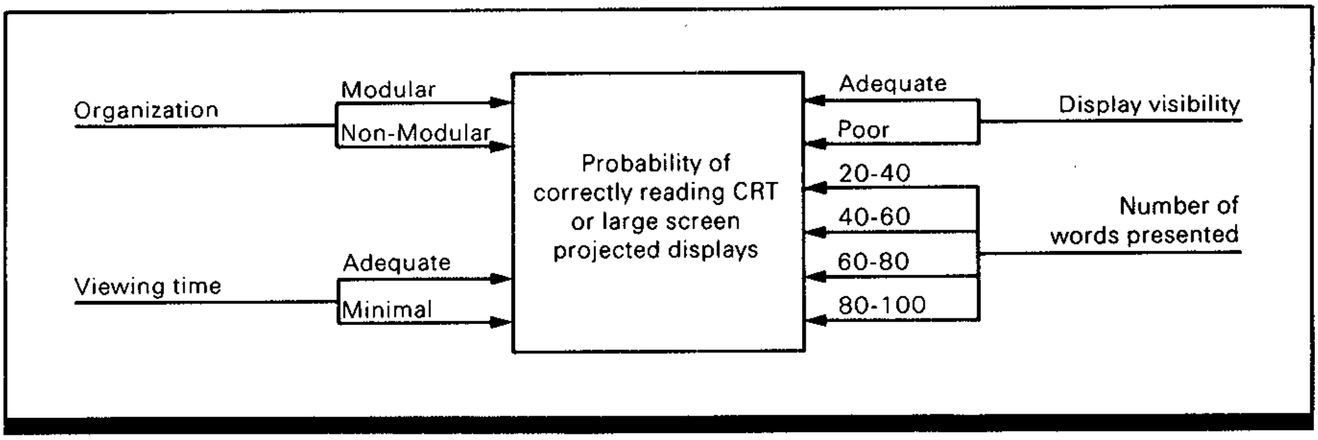


Figure 1. Characteristics affecting probability of correctly reading CRT or large-screen projected displays.

Key Terms

CRT displays; error prediction; information portrayal; response probability

General Description

With dynamic, projected displays (CRT and large screen), the operator's function is to read updated alphanumeric and geometric symbols. The estimates in Table 1 are probabilities of a correct response based on error frequencies (n) in 10,000 observations subtracted from errorless performance, (1.0): $P = 1-(n/10{,}000)$. Numbered conditions refer to combinations of parameters. No multiplicative combination of parametric values is required. The estimates were extrapolated from data in Refs. 2, 4, and 5. The figure shows factors affecting the probabilities: organization (modular and non-modular) viewing time (adequate and minimal) and display visibility (adequate and poor). The estimates for Condition 1, the optimal condition, were extrapolated from Ref. 1. Data for Condition 2 were taken from Ref. 2. Values for Condition 3 were taken (with slight extrapolation) from Ref. 5. To obtain values for the effect of non-modular organization, minimal viewing time and adequate visibility (Condition 4), the difference between Conditions 1 and 2 was subtracted from Condition 3. To obtain values for poor visibility, the values found in Ref. 4 were used. This produced a difference of 0.0319 in performance due to poor visibility; 0.0319 was therefore subtracted from each of the values in Condition 1 to secure the values for Condition 5. The same constant was subtracted to secure the values of Condition 6 (Condition 2 minus constant); Condition 7 (Condition 3 minus constant); and Condition 8 (Condition 4 minus constant). Use of the constant to represent poor visibility effects assumes that one can generalize from effects of poor resolution on 5-letter words to projected, formatted displays. The data for Conditions 9 and 10 were delivered from Ref. 3. The number of symbols presented were 24, one-third of them relevant to the criterion. Adequate viewing time in Ref. 3 was considered to range from 9 to 16 sec; restricted time was 2 sec. The criterion for minimal viewing time for this table, however, is any presentation time less than 10 sec. Word-type alphanumeric means that an alphanumeric appears as approximately a 5-character organized unit. Modular organization means that alphanumerics appear on the display in a tabular (row-by-column) format. Non-modular means they may appear in any position or configuration on the display.

Applications

The tabled data can be used to perform human reliability analyses and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resembles the conditions of the system being designed.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Probability estimates are based on a small number of studies.
- Conditions are not adequately defined.
- Some estimates are extrapolations and involve judgment.
- Some performance-shaping factors are not considered.

Key References

1. Dyer, W. R., & Christman, R. J. (1965, September). *Relative influence of time, complexity, and density on utilization of coded large-scale displays* (RADC-TR-65-325). Griffiss AFB, NY: Rome Air Development Center. (DTIC No. AD 622786)

2. Hammer, C. H., & Ringel. S. (1966). Information assimilation from updated alphanumeric displays. *Journal of Applied Psychology, 50*, 383-387.

3. Howell, W. C., & Tate, J. D. (1964, August). *Research on display variables* (RADC-TR-64-266). Griffiss AFB, NY: Rome Air Development Center. (DTIC No. AD606637)

4. Kosmider, G., Young, M., & Kinney, G. (1966, May). *Studies in display symbol legibility. Part VIII. Legibility of common five-letter words* (ESD-TR-65-385). Bedford, MA: Mitre Corporation. (DTIC No. AD633055)

5. Smith, S. L. (1963, August). *Display color coding for visual separability*. Bedford, MA: MITRE Corp.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

11.111 CRT symbol size and resolution: effect on legibility;

11.112 CRT symbol size and stroke width: effect on legibility;

11.121 CRT-image unsteadiness: effect on judged picture quality;

11.125 Effects on instrument reading performance: pointer, background, and panel lighting colors

CONDITIONS	PARAMETERS: Organization: Modular	Organization: Non-Modular	Viewing Time: Adequate	Viewing Time: Minimal	Visibility: Adequate	Visibility: Poor	NUMBER OF WORDS/SYMBOLS PRESENTED SIMULTANEOUSLY: 20-40	40-60	60-80	80-100
Word Type Alphanumerics										
(1)	●		●		●		.9995	.9940	.9910	.9821
(2)	●			●	●		.8600	.7600	.7000	.6200
(3)		●	●		●		.9780	.8955	.8350	.7745
(4)		●		●	●		.8385	.6615	.5440	.4124
(5)	●		●			●	.9676	.9621	.9591	.9502
(6)	●			●		●	.8281	.7281	.6681	.5881
(7)		●	●			●	.9461	.8636	.8031	.7426
(8)		●		●		●	.8066	.6296	.5121	.3805
Geometric Symbols										
(9)	●		●		●		.8000			
(10)	●			●	●		.6600			

Table 1. Probability of correctly reading CRT and large-screen projected displays.

7.110 Probability of Correctly Monitoring Multi-Channel Displays

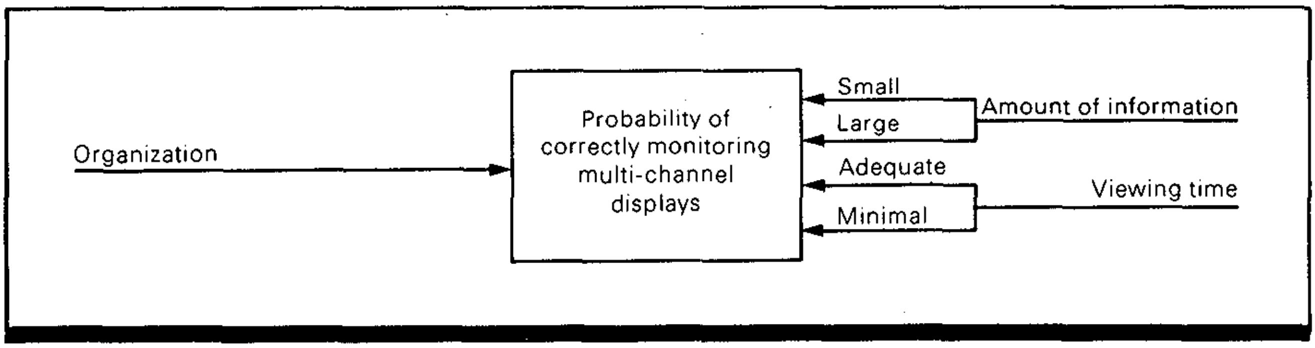


Figure 1. Factors affecting probability of correctly monitoring multi-channel displays.

Key Terms

Error prediction; multi-channel displays; response probability

General Description

Factors affecting accuracy in reading multi-channel displays of individual meters of indicators arranged in symmetrical rows and columns and displaying different values include: organization (modular); amount of information per channel (small, 2 levels; large, 8 levels); and viewing time (adequate, 10 sec; minimal, 5 sec or less). Probability values derived from Ref. 1 in the table are estimates based on error frequencies (n) per 10,000 observations subtracted from errorless performance, (1.0): $P = 1-(n/10{,}000)$. Numbered conditions refer to varying parametric combinations. No multiplicative combination of parametric values is required. Amount of information per channel is the number of information categories displayed in each channel. Monitoring is defined as continuous observation of a number of displays presented simultaneously to determine if a particular value has been reached or exceeded or if a specified value has been changed. Thus, the operator's function is similar to monitoring updated alphanumeric information in formatted displays.

Applications

The data in the table can be used to perform human reliability analysis and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resemble the conditions of the system being designed.

Constraints

- The conditions described are not precisely defined.

Key References

1. Gould, J. D., & Schaffer, A. (1966, June). Visual monitoring of multi-channel displays. *IEEE Transactions on Human Factors in Electronics, HFE-7*, 69-76.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.108 Probability of correctly reading meters

CONDITIONS	Amount of Information: Small	Amount of Information: Large	Viewing Time: Adequate (10 seconds)	Viewing Time: Minimal (5 seconds)	Viewing Time: Minimal (2.5 seconds)	NUMBER OF CHANNELS MONITORED: 8	12	16	24
(1)	●		●			.9750	.9625	.8750	.7687
(2)	●			●		.9187	.9062	.7812	.6375
(3)	●				●	.6875	.6562	.3937	.2875
(4)		●	●			.9687	.9750	.9062	.6687
(5)		●		●		.9375	.8500	.7937	.4937
(6)		●			●	.7187	.4812	.4250	.1750

Table 1. Probability of correctly monitoring multi-channel displays.

7.111 Probability of Correctly Activating a Discrete Control While Reading a Discrete Display

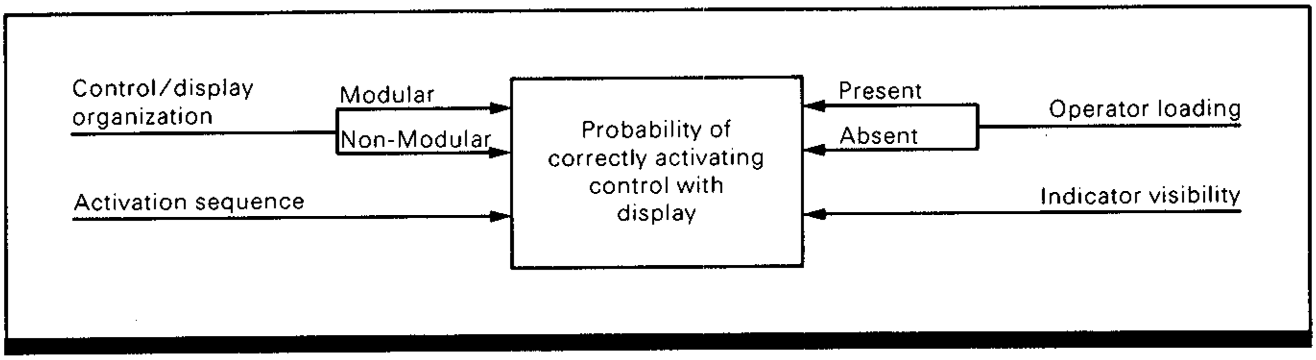


Figure 1. Factors affecting probability of correctly activating discrete control concurrently with observation of a discrete display.

Key Terms

Concurrent control; control errors; control/display activation; error prediction; response probability

General Description

Probability estimates in Table 1 were developed for two situations. In the first (control-display configuration 1/1), a single pushbutton or toggle switch is associated with a single indicator light. The operator's task is to activate the control and observe that the indicator has or has not been turned on; or to observe that the indicator has turned on and to activate the corresponding control. In the second situation (control/display configuration $1/n$), an indeterminate number of discrete controls (pushbuttons or toggle switches) are associated with a corresponding number of discrete displays (indicator lights). The operator's function is to operate one control and observe that the corresponding indicator has or has not turned on; or observe that a particular indicator has turned on and operate the corresponding control. The difference then is between one control and display, and several. Factors affecting accuracy in these situations (Fig. 1) are organization (modular and non-modular), operator loading (absent or present), activation sequence (variable for $1/n$ situation), and indicator visibility (adequate). The tabled probabilities are based on error frequencies (n) per 10,000 operations subtracted from errorless performance, (1.0): $P = 1 - (n/10{,}000)$. The probabilities were derived by multiplying estimates from Ref. 2 of correctly activating discrete controls (no displays) and from the table in CRef. 7.107 (estimates of correctly observing indicator lights, no controls). Estimates for Conditions 4 and 6 were derived from Ref. 1. Numbered conditions represent varying parametric combinations. No multiplicative combination of parametric values is required.

Applications

The data in the table can be used to perform human reliability analysis and make human error rate predictions. In using these data, the analyst will select from the table the combinations of parametric conditions that most closely resemble the conditions of the system being designed.

Constraints

- Data are extrapolations involving subjective judgment and should therefore be viewied as estimates only.
- Conditions are not precisely defined.
- Some parameters are not included in the table.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Chapanis, A., & Lockhead, G. R. (1965). A test of the effectiveness of sensor lines showing linkages between displays and controls. *Human Factors, 7,* 219-229.

2. Meister, D. (1982, December). Tables for predicting the operational performance of personnel. In D. A. Topmiller, J. S. Eckel, & E. J. Kozinsky, *Human reliability data bank for nuclear power plant operations. Vol. 1. A review of existing human reliability data banks* (NUREG/CR2744/1 of 2, SAND82-7057/2 of 2, RX, AN). Dayton, OH: General Physics Corporation.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.106 Time and accuracy in responding to discrete indicator lights;

7.107 Probability of correctly responding to annunciators and discrete status lights

CONDITIONS	PARAMETERS: Organization: Modular	PARAMETERS: Organization: Non-Modular	PARAMETERS: Operator Loading: Absent	PARAMETERS: Operator Loading: Present	CONTROL-DISPLAY CONFIGURATION: 1/1	CONTROL-DISPLAY CONFIGURATION: 1/n
(1)	●		●		.9997	
(2)	●			●	.9996	
(3)	●		●			.9966
(4)	●			●		.9936
(5)		●	●			.9959
(6)		●		●		.9413

Table 1. Probability of correctly activating a discrete control concurrently with observation of a discrete display.

7.112 Probability of Correctly Activating Discrete Controls While Reading a Meter or Other Dynamic Display

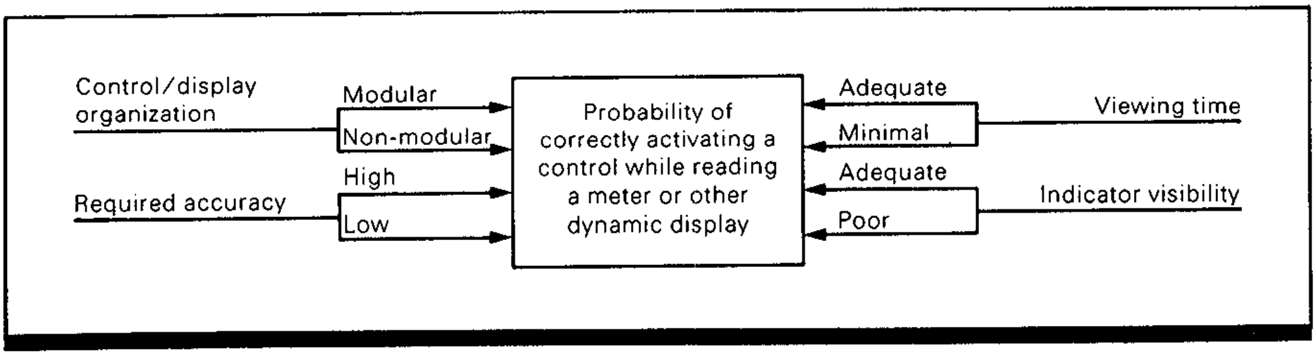


Figure 1. Factors affecting the probability of correctly activating a discrete control while reading a dynamic display.

Key Terms

Concurrent control; control/display activation; error prediction; meter reading; response probability

General Description

Two dynamic displays are considered. First, a single pushbutton or toggle switch is associated with a single meter or other dynamic display. The operator's function is to operate the control and read the meter to determine if an appropriate value has been achieved, or to read the meter and activate the control after a specified value has been reached. In the second situation, an indeterminate number of discrete controls are associated with the same number of continuous displays (e.g., meters). The operator's function is to operate one of the controls and read the corresponding display value, or to observe that one of the displays has reached a particular value and then activate the corresponding control.

The probability estimates in Table 1 are based on error frequency (n) per 10,000 operations subtracted from errorless performance, (1.0): $P = 1-(n/10{,}000)$. Factors affecting the probabilities (Fig. 1) include organization (modular, formatted, and non-modular), indicator visibility (adequate and poor), required accuracy (high, very precise values, and low, relatively gross values), and viewing time (adequate and minimal). Probability estimates, derived from Ref. 1, were modified by estimates from Ref. 2. A correction factor was applied for poor indicator visibility and minimal viewing time. Numbered conditions represent varying combinations of parameters. No multiplicative combination of parametric values is required.

Applications

The data in the table can be used to perform human reliability analysis and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resembles the conditions of the system being designed.

Constraints

- All factors affecting the probability estimates are not included because the data are not available.
- Data are extrapolations that involve considerable judgment and should therefore be considered as estimates only.
- The conditions involved are not well defined, nor are all of them included.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blanchard, R. E., Mitchell, M. B., & Smith, R. L. (1966, June). *Likelihood of accomplishment scale for a sample of man-machine activities*. Santa Monica, CA: Dunlap and Associates.

2. Meister, D. (1982, December). Tables for predicting the operational performance of personnel. In D. A. Topmiller, J. S. Eckel, & E. J. Kozinski, E. J. *Human reliability data bank for nuclear power plant operations. Vol. I. A review of existing human reliability data banks* (NUREG/CR-2744/1 of 2, SAND82-7057/1 of 2, AN, RX). Dayton, OH: General Physics Corporation.

3. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.108 Probability of correctly reading meters;

7.111 Probability of correctly activating a discrete control while reading a discrete display;

11.210 Time and accuracy in reading linear scales;

11.214 Time and accuracy in reading circular scales;

11.216 Time and accuracy in reading semi-circular scales

CONDITIONS	PARAMETERS: Organization: Modular	Organization: Non-Modular	Visibility: Adequate	Visibility: Poor	Required Accuracy: High	Required Accuracy: Low	Viewing Time: Adequate	Viewing Time: Minimal	CONTROL-DISPLAY CONFIGURATION 1/1	CONTROL-DISPLAY CONFIGURATION 1/n
(1)	●		●			●	●		.9995	.9970
(2)	●			●		●		●	.9960	.9838
(3)	●		●		●		●		.9976	.9862
(4)	●			●	●			●	.9750	.9710
(5)		●	●			●	●			.9968
(6)		●	●		●		●			.9860

Table 1. Probability of correctly activating a discrete control while reading a dynamic display.

7.113 Probability of Correctly Operating Continuous Controls While Monitoring Dynamic Displays

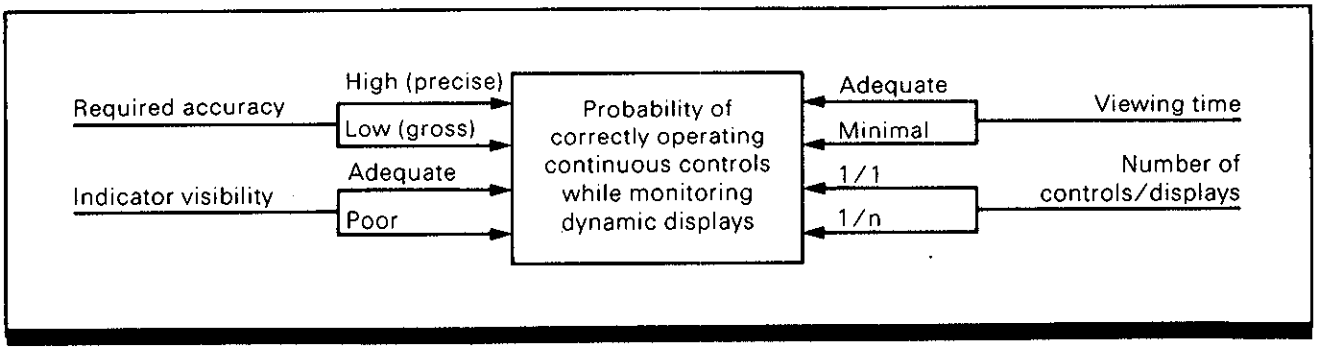


Figure 1. Factors affecting probability of correctly operating continuous controls while monitoring dynamic displays.

Key Terms

Control errors; control/display activation; error prediction; meter reading; monitoring; response probability

General Description

Table 1 indicates the probabilities of correctly operating a continuous control (e.g., a rotary switch) in a bank of such controls, while monitoring one of a number of associated dynamic displays (e.g., meters). The operator's function is to adjust one or more of the controls to predetermined positions and to read the display to check the accuracy of the switch position, or to read the display and adjust the corresponding switch to the position corresponding to the displayed reading. There are two situations: the first, with a single control and a single display; and a second, with a number of controls and a corresponding number of displays.

Factors affecting the probabilities (Fig. 1) include required accuracy (high, very precise values, and low, relatively gross values), indicator visibility (adequate and poor), viewing time (adequate and minimal), and number of controls and displays (1/1 and 1/*n*). Control/display organization is assumed to be formatted. The estimated probabilities are based on error frequency (*n*) per 10,000 operations subtracted from errorless performance (1.0): $P = 1 - (n/10{,}000)$. Data for the table were derived from Ref. 1 and from tables of continuous control activation (Ref. 2), as modified by correction factors for poor visibility and minimal viewing time (Ref. 3). Viewing time, in this case, refers to whether the display reading changes slowly (prolonged viewing) or changes frequently (minimal viewing). Numbered conditions represent combinations of parameters. No multiplicative combination of parametric values is required.

Applications

The data in the table can be used to perform human reliability analyses and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resembles the conditions of the system being designed.

Constraints

- Data are extrapolations that involve considerable judgment and should therefore be considered as estimates only.
- Conditions involved in the estimates are neither complete nor well defined.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blanchard, R. E., Mitchell, M. B., & Smith, R. L. (1966, June). *Likelihood of accomplishment scale for a sample of man-machine activities*. Santa Monica, CA: Dunlap and Associates.

2. Meister, D. (1982, December). Tables for predicting the operational performance of personnel. In D. A. Topmiller, J. S. Eckel, & E. J. Kozinsky. *Human reliability data bank for nuclear power plant operations. Vol. I. A review of existing human reliability data banks* (NUREG/CR2744/1 of 2, SAND82-7057/1 of 2, AN, RX). Dayton, OH: General Physics Corporation.

3. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* (AIR-C43-1/62-RP[1]). Pittsburgh, PA: American Institute for Research (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.112 Probability of correctly activating discrete controls while reading a meter or other dynamic display;

12.413 Rotary selector switches

CONDITIONS	PARAMETERS: Required Accuracy: Low	Required Accuracy: High	Visibility: Adequate	Visibility: Poor	Viewing Time: Adequate	Viewing Time: Minimal	CONTROL-DISPLAY CONFIGURATION: 1/1	1/n
(1)	●		●		●		.9971	.9727
(2)	●			●		●	.9946	.9577
(3)		●	●		●			.9562
(4)		●		●		●		.9412

Table 1. Probability of correctly operating continuous controls while monitoring continuous displays.

7.114 Probability of Correctly Operating Continuous Controls While Monitoring and Tracking Dynamic Displays

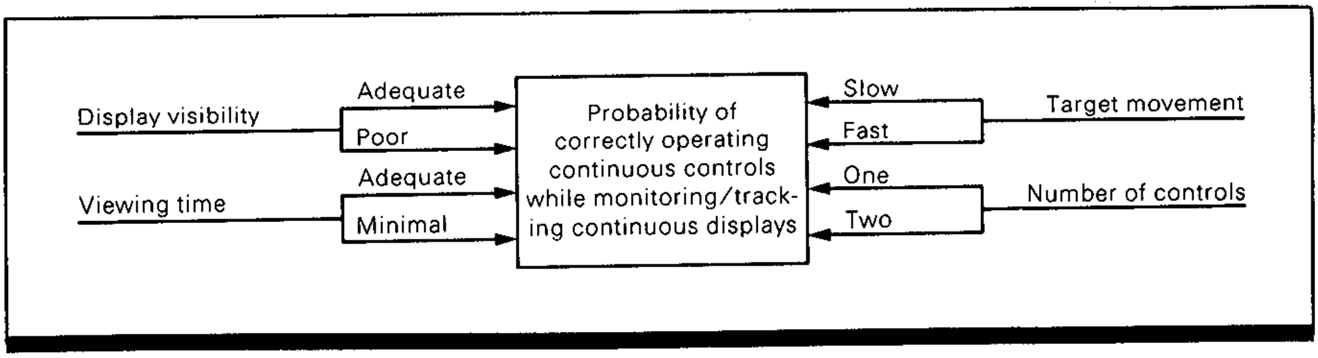


Figure 1. Factors affecting probability of correctly operating continuous controls while monitoring/tracking dynamic displays.

Key Terms

Error prediction; response probability; rotary selector switches; tracking

General Description

Table 1 describes the probability of correctly operating a continuous control, such as a rotary switch, while monitoring a dynamic (e.g., cathode ray tube or oscilloscope) but non-moving display. The operator's function is to adjust the rotary switch to change the displayed signal to a specified value. Table 2 also describes the probability of correctly operating continuous controls and dynamic displays. In addition, the task involves a tracking function, e.g., adjusting a joystick to align a cursor with a moving target signal presented on a CRT. Factors (Fig. 1) affecting the probability estimates in Table 1 include visibility (adequate and poor) and viewing time (adequate and minimal).

Visibility refers to signal resolution; viewing time refers to signal duration (before it changes characteristics). Factors affecting values in Table 2 (illustrated in Fig. 1) include target speed (stationary, moving slowly, or moving rapidly), display visibility (adequate and minimal), and number of controls (one and two). The probabilities estimated are based on error frequency (n) per 10,000 operations subtracted from errorless performance (1.0): $P = 1-(n/10{,}000)$.

Estimates in Table 1 were derived from Ref. 1. Condition 2 was derived from Ref. 3, taking the difference between high and low resolution in the identification of 5-letter words as a general measure of performance loss resulting from poor visibility; this difference (0.0319) was subtracted from the estimates of Condition 1 to provide an estimate for Condition 2. The effect of reduced viewing time (Condition 3) was determined by comparing performance estimates for high and moderate resolution in Refs. 2 and 3. This difference (0.0050) was subtracted from the estimates of Condition 1. The effect of combining poor visibility with minimal viewing time was determined again from Refs. 2 and 3 by comparing performance estimates for low resolution conditions with different time exposure conditions.

For the estimates in Table 2, Conditions 2, 3, and 6 were derived from Ref. 1. The estimates of Conditions 2 and 4 were those of Conditions 1 and 3, from which 0.0319 was subtracted to account for poor resolution; this constant was taken from Ref. 3. The estimate in Condition 5 was determined by subtracting the estimate for Condition 6 from that of Condition 3. This difference of 0.0153 (attributable to the effect of two versus one control) was subtracted from the estimate of Condition 1 for tracking a slowly moving target, since it is assumed that tracking with two controls is somewhat less accurate than tracking with one control (all other factors being equal). Estimates in Conditions 7 and 8 were those of Conditions 5 and 6, from which the 0.0319 constant derived from Ref. 3 was subtracted.

Numbered conditions in Tables 1 and 2 represent varying combinations of parameters. No multiplicative combination of parametric values is required.

Applications

Data in Tables 1 and 2 can be used to perform human reliability analyses and make human error rate predictions. In using these data, the analyst will select from the table the combination of parametric conditions that most closely resembles the conditions of the system being designed.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Estimates for Table 1 relate only to relatively structured stimuli (e.g., alphanumerics).
- Estimates for Table 2 greatly underestimate the difficulty of tracking a fast moving target.
- Data extrapolation and combination involve considerable subjectivity.
- Factors affecting performance are imprecisely defined and incompletely considered.

Key References

1. Blanchard, R. E., Mitchell, M. B., & Smith, R. L. (1966, June 30). *Likelihood of accomplishment scale for a sample of man-machine activities*. Santa Monica, CA: Dunlap and Associates.

2. Elias, M. F., Sandowsky, A. M., & Rizy, E. F. (1964, October). *The relation of number of scan lines per symbol height to recognition of televised alphanumerics* (RADC-TDR64-433). Griffiss AFB, NY: Rome Air Development Center. (DTIC No. AD608789)

3. Kosmider, G., Young, M., & Kinney, G. (1966, May). *Studies in display symbol legibility. Part VIII. Legibility of common five-letter words* (ESD-TR-65-385). Hanscom Field, MA: Electronic Systems Division. (DTIC No. AD 633055)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.113 Probability of correctly operating continuous controls while monitoring dynamic displays;

12.413 Rotary selector switches;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.416 Rotary controls: spacing, diameter, and orientation;

12.419 Rotary controls: effect of knob shape on blind-positioning accuracy

CONDITIONS	PARAMETERS: Visibility: Adequate	Visibility: Poor	Viewing Time: Adequate	Viewing Time: Minimal	PROBABILITY ESTIMATE
(1)	●		●		.9972
(2)		●	●		.9653
(3)	●			●	.9922
(4)		●		●	.8460

Table 1. Probability of correctly adjusting a continuous control while monitoring a dynamic display.

CONDITIONS	PARAMETERS: Target Movement: Stationary or Slow	Target Movement: Fast	Visibility: Adequate	Visibility: Low	One Control Adjustment	Two Control Adjustment	PROBABILITY ESTIMATE
(1)	●		●		●		.9964
(2)	●			●	●		.9645
(3)		●	●		●		.9841
(4)		●		●	●		.9522
(5)	●		●			●	.9888
(6)		●	●			●	.9688
(7)	●			●		●	.9569
(8)		●		●		●	.9369

Table 2. Probability of correctly adjusting a continuous control while tracking a dynamic target signal.

7.115 Error Probability in Responding to Annunciator Displays

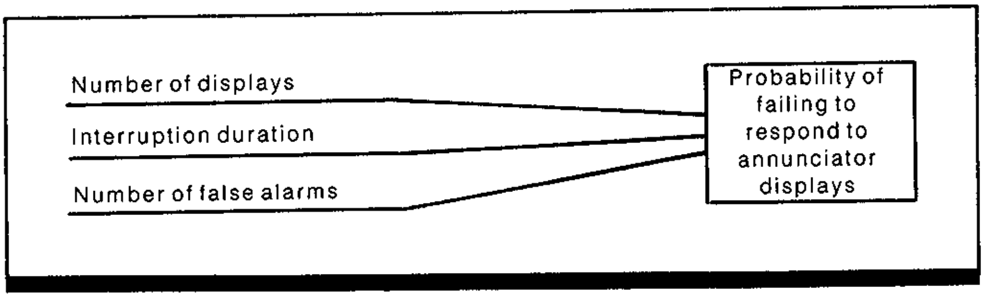


Figure 1. Factors affecting the probability of failing to respond to annunciator displays.

Key Terms

Annunciator displays; attention; monitoring

General Description

Tables 1 and 2 indicate the probability of *incorrectly* responding to one or more annunciator displays. The term "annunciator display" includes all visual indicators (e.g., legend lights or printouts) announced by compelling auditory signals. The correct response to such displays is to attend to the display and read the messaged information. An incorrect response is failure to respond at all or failure to read the message correctly.

Figure 1 shows factors affecting this response: number of displays, interruption duration, and number of false alarms. In Tables 1 and 2, the term "one annunciator" includes functional groups of annunciators (more than one annunciator; annunciators completely dependent on each other).

The probability estimates are based on error frequency. Error probabilities can be transformed to accuracy probabilities by subtracting them from 1.0. Values in parentheses are the limits of the range of error values for which the value outside parentheses is the median or nominal error probability. Note that as the number of annunciators (or functional groups of annunciators) sounding in a very brief interval increases, the probability of failure to respond to any one of them increases (Table 2). During performance of certain calibration or maintenance procedures, an alarm may sound a number of times as adjustments are made. The alarms, although anticipated by the operator, are "false alarms," and the operator may turn off the audio and visual signals without verifying the legend light. In such cases, the probability of failure to respond to an actual alarm is 0.001 (0.0001 to 0.01).

Applications

The data in Tables 1 and 2 can be used to perform human reliability analyses and make human error rate predictions.

Constraints

- Data were developed for application to nuclear power plant situations. Applicability to other situations is unknown, but data generalizability should be relatively high.
- Original sources of data are not given in Ref. 1, but may be assumed to be experiential.

Key References

1. Swain, A. D., & Guttman, H.E. (1983, August). *Handbook of human reliability analysis with emphasis on nuclear power plant applications* (NUREG/CR-1278, SAND80-0200, AN RX). Albuquerque, NM: Sandia Laboratories.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.107 Probability of correctly responding to annunciators and discrete status lights;

7.405 Application of signal detection theory (SDT) to vigilance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

11.406 Visual warning signals: effects of background color and luminance

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Probabilities of failing to respond to annunciated legend lights.

Task	Nominal Probability	Range
Respond to an annunciated legend light (one of one)	0.0001	(0.00005 to 0.001)
Reading the message (this figure includes the probability of reading the wrong legend light)	0.001	(0.0005 to 0.005)
Resume attention to a legend light within 1 min after an interruption (sound and blinking cancelled before interruption)	0.001	(0.0001 to 0.01)
Respond to a legend light if more than 1 min elapses after an interruption (sound and blinking cancelled before interruption)	0.95	(0.5 to 0.99)

Table 2. Probability of failing to respond to one randomly selected annunciator of several.

Number of Annunciators	Nominal Probability	Range
1	0.0001	(0.00005 to 0.001)
2	0.006	(0.0006 to 0.06)
3	0.001	(0.0001 to 0.01)
4	0.002	(0.0002 to 0.02)
5	0.003	(0.0003 to 0.03)
6	0.005	(0.0005 to 0.05)
7	0.009	(0.0009 to 0.09)
8	0.02	(0.002 to 0.2)
9	0.03	(0.003 to 0.3)
10	0.05	(0.005 to 0.5)
11-15	0.10	(0.02 to 0.999)
16-20	0.15	(0.015 to 0.999)
21-40	0.20	(0.02 to 0.999)
>40	0.25	(0.025 to 0.999)

7.116 Error Probability in Reading and Recording Information

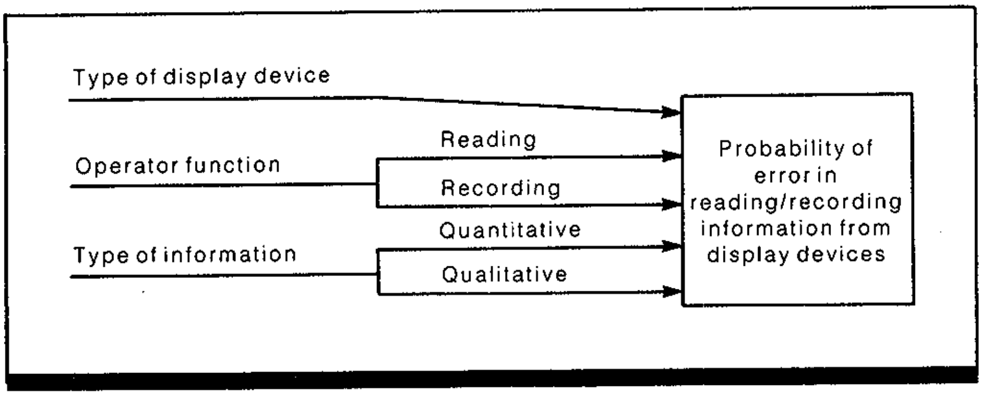


Figure 1. Factors affecting error probability in reading and recording information from various types of display devices.

Key Terms

Chart recorders; data recording; digital displays; error prediction; meter reading; reading error; response probability

General Description

Tables 1 and 2 indicate the probability of making various types of errors in reading quantitative and qualitative information from various display devices. Error probability is based on frequency of error. The error probability can be transformed into accuracy probability by subtracting error probability from errorless performance (1.0). Errors are categorized as errors of reading (Table 1) and of recording the values read (Table 2). The probability of error in check-reading displays for specific purposes is given in Table 2. The figure shows that major factors affecting the errors are type of display device, operator function performed (reading and recording), and type of information (quantitative and qualitative).

Applications

Data in the tables can be used to perform human reliability analyses and make error rate predictions.

Constraints

- Original source of estimates is not given in Ref. 1 but may be assumed to be experiential.
- Data were prepared for nuclear power plant situations. Applicability to other situations is unknown but data generalizability should be relatively high.
- Only a few performance-shaping factors are included in the data.

Key References

1. Swain, A. D., & Guttman, H. E. (1983, August). *Handbook of human reliability analysis with emphasis on nuclear power plant applications* (NUREG/CR-1278, SAND800200, RX, AN). Albuquerque, NM: Sandia Laboratories.

Cross References

7.101 Error classification and analysis

Table 1. Probabilities of errors in reading quantitative information from various types of display devices.

Reading Task	Nominal Probability	Range
Analog meter	0.003	(0.001 to 0.03)
Digital readout	0.001	(0.0005 to 0.01)
Chart recorder	0.006	(0.003 to 0.06)
Printing recorder with large number of parameters	0.05	(0.01 to 0.2)
Graphs	0.01	(0.005 to 0.05)
Values from indicator lamps that are used as quantitative displays	0.001	(0.0005 to 0.01)
Recognize that an instrument being read is jammed, if there are no indicators to alert the user	0.1	(0.01 to 0.2)

The probability that an entry will be recorded incorrectly is obtained by adding the reading error from Table 1 with the following:

Number of Digits to be Recorded	Nominal Probability	Range
Three or less	Negligible	
More than three	0.001	(0.005 to 0.01)

Table 2. Check-reading displays for specific purposes.

Check-Reading Task	Nominal Probability	Range
Digital indicators (these must be read; there is no true check-reading function)	0.001	(0.005 to 0.01)
Analog meters with easily seen limit marks	0.001	(0.0005 to 0.002)
Analog meters with difficult-to-see limit marks, such as scribed lines	0.002	(0.0005 to 0.003)
Analog meters without limit marks	0.003	(0.001 to 0.005)
Analog type chart recorders with limit marks	0.002	(0.0005 to 0.005)
Analog type chart recorders without limit marks	0.006	(0.003 to 0.01)
Confirming a status change on a status lamp	Negligible	
Checking the wrong indicator lamp (in an array of lamps)	0.003	(0.0005 to 0.01)
Misinterpreting the indication on the indicator lamps	0.001	(0.0001 to 0.01)

7.117 Probability of Failure to Detect in Periodic Scanning of Displays

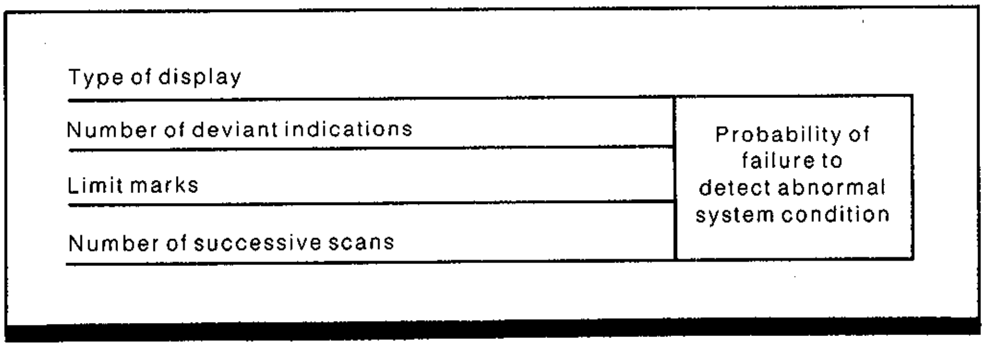


Figure 1. Factors affecting the probability of failure to detect an abnormal system condition.

Key Terms

Error prediction; errorless performance; monitoring; periodic inspection; target acquisition; target detection; unannunciated displays

General Description

Tables 1 and 2 indicate the probability of failing to detect and to respond to unannunciated displays presenting indications of an abnormal system condition. The failure probabilities are based on error frequencies; probabilities of detection can be determined by subtracting failure probabilities from errorless performance (1.0). Factors affecting failure probabilities (Fig. 1) include types of displays, number of deviant indications (1-5), presence or absence of limit marks, and number of successive scans or inspections. Table 1 describes the probability of failing to detect an abnormal system condition as a function of the number of deviant indications; failure probability decreases as the number of indications increases. Rules for developing the upper *and* lower bounds of the range of estimates are also provided. Table 2 describes the probability of failing to detect the abnormal system condition as a function of successive hourly scans. For analogue type displays, the failure probability increases with successive hourly inspections; with annunciator, legend, and indicator lights, the failure probability remains constant.

Applications

Data presented in Tables 1 and 2 can be used to perform human reliability analyses and make human error rate predictions.

Constraints

• Data were derived from a model using an exponential curve.
• Some relevant performance-shaping factors are not included.
• Data were prepared for nuclear power plant situations. Applicability to other situations is unknown but data generalizability should be relatively high.

Key References

1. Swain, A. D., & Guttman, H. E. (1983, August). *Handbook of human reliability analysis with emphasis on nuclear power plant applications* (NUREG/CR-1278, SAND800200, RX, AN). Albuquerque, NM: Sandia Laboratories.

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.107 Probability of correctly responding to annunciators and discrete status light;

7.402 Methods of measuring vigilance, monitoring, and search;

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

7.407 Effect of signal target location on visual search;

7.415 Effect of instruction on vigilance;

7.419 Intertask correlations in vigilance performance;

7.501 Factors affecting visual search with monochrome displays

Table 1. Probabilities of failure to detect at least one to five deviant indications as a function of the basic failure probability.

Human Error Probability (HEP)	Human Error Probabilities (HEP) as a Function of Number of Deviant Indications				
1	2	3	4	5	Uncertainty Bounds
0.99	0.985	0.98	0.975	0.97	For HEPs <0.5,
0.95	0.93	0.90	0.88	0.86	Lower bound = HEP × 0.2
0.90	0.85	0.81	0.77	0.73	Upper bound = HEP × 5
0.80	0.72	0.65	0.58	0.52	
0.70	0.59	0.51	0.43	0.37	
0.60	0.48	0.38	0.31	0.25	
0.50	0.37	0.28	0.21	0.16	For HEPs ≥ 0.5,
0.10	0.05	0.03	0.02	0.01	Lower Bound = 1 − 2 (1 − HEP)
0.05	0.03	0.01	0.007	0.004	Upper Bound = 1 − 0.2 (1 − HEP)
0.01	0.005	0.003	0.001	0.001	

Table 2. Probabilities of failure to detect one (of one) deviant unannunciated display* at each scan, when scanned hourly.

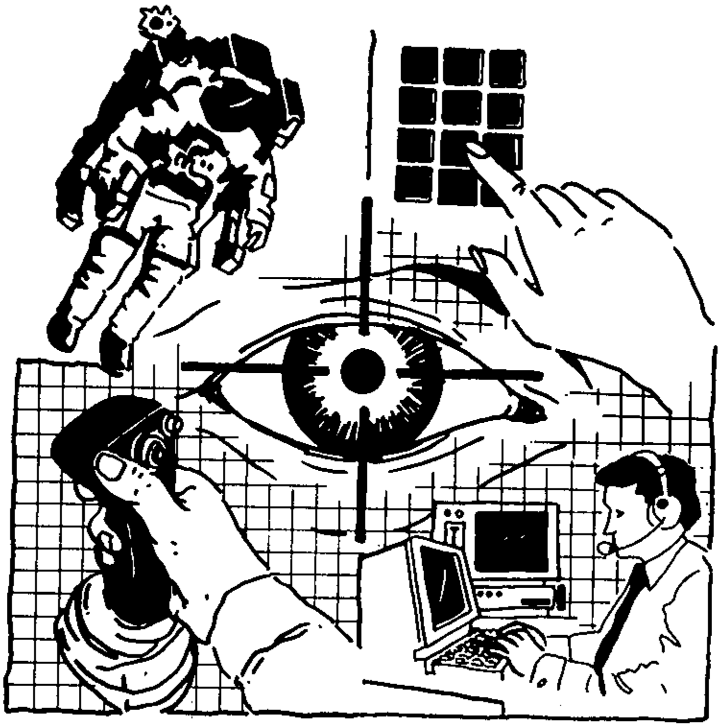
Display Type	Hourly Scans							
	1	2	3	4	5	6	7	8
Analog meter with limit marks	0.05	0.31	0.50	0.64	0.74	0.81	0.86	0.90**
Analog meter without limit marks	0.15	0.47	0.67	0.80	0.87	0.92	0.95	0.97
Analog-type chart recorders with limit marks	0.10	0.40	0.61	0.74	0.83	0.89	0.92	0.95
Chart recorders without limit marks	0.30	0.58	0.75	0.85	0.91	0.94	0.97	0.98
Annunciator light no longer annunciated	0.90	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Legend light other than annunciator light	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Indicator lamp	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

*One display refers to a single display or a group of completely dependent displays.

**For estimating uncertainty bounds, and for HEPs <0.5, lower bound = HEP × 0.2 and upper bound is HEP × 2. For HEPs ≥0.5, lower bound = 1 − 2 (1 − HEP) and upper bound is 1 − 0.2 (1 − HEP).

Notes

Section 7.2 Attention and Mental Resources



7.201 Contrasting Models of Attention: Undifferentiated Versus Differentiated Capacity

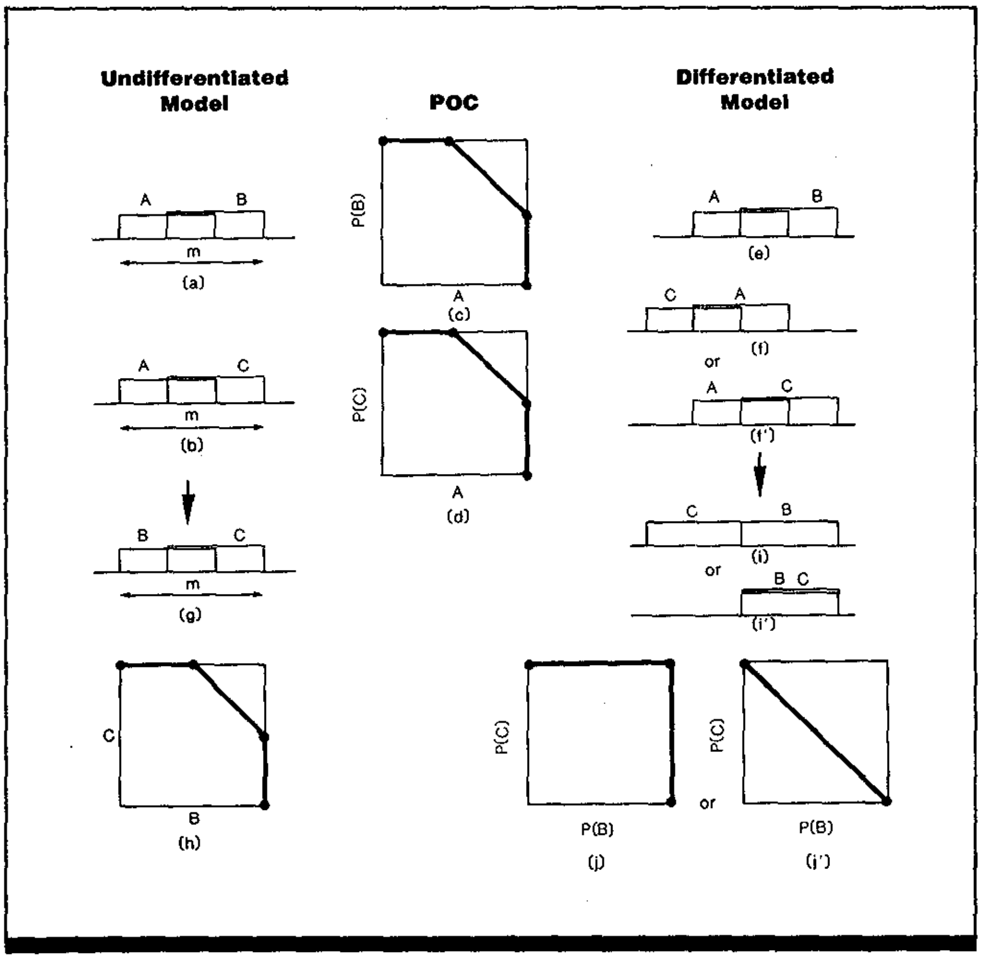


Figure 1. The undifferentiated and differentiated attentional models. The undifferentiated capacity model assumes a limit, *m*, on the total amount of resources, but assumes that the resources are interchangeable among Tasks A, B, and C. Each task is assumed to require an equal amount of resources, which is <*m* but >0.5 *m*. Panels (a) and (b) indicate two methods of allocating resources for Task Pairs (A, B) and (A, C) respectively. In both methods the tasks compete for some of the same resources, as indicated by the overlapping of curves. The attention operating characteristics (AOC) curves resulting from varying the proportion of A in Task Pairs (A, B) and (A, C) are shown in panels (c) and (d). When Task Pairs (A, B) and (A, C) produce the AOC curves in panels (c) and (d), then the undifferentiated capacity model requires that resources be allocated to Task Pair (B, C) as shown in panel (g) and the resulting AOC curve be that shown in panel (h). The differentiated model proposes that certain resources can be useful for some tasks, but not for others. For (e) and (f), Tasks B and C use different resources, and thus do not interfere with one another, as demonstrated by the AOC curve in panel (j). When Tasks B and C do draw on the same resources entirely, as in (e) and (f'), they maximally interfere with one another, as shown by the AOC curve in (j'). (From Ref. 3)

Key Terms

Attention operating characteristic; concurrent tasks; memory; mental models; mental resources; response selection; short-term memory

General Description

Two contrasting models of attention are the differentiated capacity hypothesis (Refs. 1, 2) and the structural or differentiated hypothesis (Ref. 4). Both models posit the existence of reservoirs, each with a finite capacity of mental resources. The first model emphasizes a single reservoir available for any and all tasks; the second model postulates that separate reservoirs are used for tasks requiring different, specialized processing structures. The first model predicts that two concurrent tasks will interfere with one another when their combined demand for resources exceeds the capacity of the single reservoir. When that occurs, performance will be less than optimal for either one or both tasks.

The second model predicts that interference occurs only when the two concurrent tasks make demands upon the same reservoir that exceed its capacity. If the two tasks make demands upon different reservoirs, because they require different, specialized processing structures, then performance on neither task would be adversely affected. The second model proposes reservoirs differentiated on the basis of stages of processing (e.g., encoding, decision, short-term memory, response selection, response emission), the two cerebral hemispheres, or sensory and motor modalities. Evidence has been cited for each possibility (Refs. 5, 6; CRef. 7.720).

According to the differentiated hypothesis, resources for a given reservoir (e.g., that for short-term memory) are used only when a given task (e.g., shadowing) specifically requires it. A structurally irrelevant task (e.g., visual search) would thus not deplete resources of the short-term memory reservoir.

The figure illustrates the two models, considering Tasks A, B, and C. The undifferentiated model claims that the resources of the single reservoir are interchangeable among the three tasks. The **attention operating characteristic** (AOC) curves plot the predicted performance on the two interdependent tasks. As more resources are allocated to Task A, performance on Task A improves, to the eventual detriment of Task B performance. According to the undifferentiated model, once the AOCs for Task Pairs (A, B) and for Task Pairs (A, C) have been measured, the AOC for the concurrent Tasks B and C is completely specified. The differentiated model does not make this last prediction. Rather, the figure shows two extremes in resource allocation and AOCs as stipulated by the second model. In one case, Tasks B and C each partially draw upon the same resources as Task A, but require different resources themselves, and thus Tasks B and C do not interfere with one another. In the other case, Tasks B and C again partially draw on the same resources as Task A, but also require identical resources for themselves, and, hence, interfere maximally with one another.

Empirical Validation

Experiments evaluating the two models collect performance data on two concurrent tasks and check for interference between them. Two tasks might be selected from among tracking, reaction time, visual search, mental arithmetic, short-term memory, and shadowing. Task conditions are made quite difficult to fully engage the subjects (to deplete mental resources).

Although nine studies show interference on performance in concurrent tasks, and hence support the undifferentiated capacity model, 27 studies demonstrate lack of interference on performance of two tasks and thus support the structural or differentiated model (Ref. 5). The latter set of studies seems to demonstrate that not all tasks draw upon the same reservoir for resources, but rather that separate reservoirs are linked to different specialized processing structures.

Constraints

- Many factors, such as specific stimulus dimensions, response categories, adaptation, and practice conditions, can influence each of the tasks cited previously; caution should be exercised in applying results to specific situations.

Key References

1. Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

2. Moray, N. (1969). *Listening and attention*. London: Penguin Books.

*3. Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception*. New York: Wiley.

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6. Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63-102). San Diego: Academic Press.

Cross References

7.202 Multiple-resources model;

7.204 Evidence for undifferentiated and differentiated attentional resources;

7.720 Choice of secondary task: application of a multiple-resources model

7.202 Multiple-Resources Model

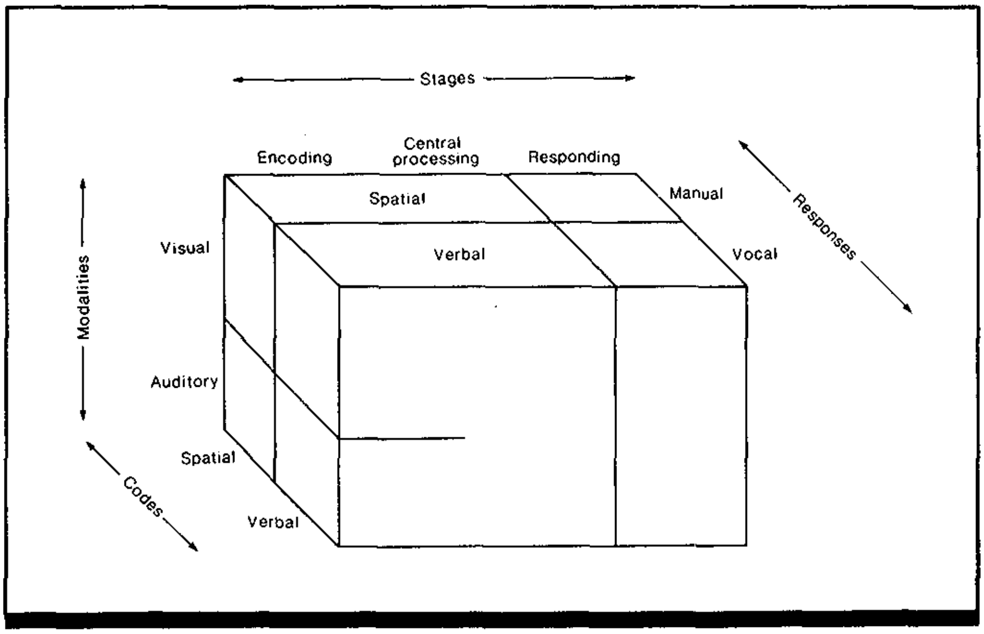

Figure 1. Proposed three-dimensional structure of human processing resources. Processing stages and perceptual modality are two dimensions; processing codes and response modalities are different ways of talking about the same dimension. (From Ref. 8)

Key Terms

Memory; mental models; multiple-resources model; P-300; secondary task; workload measurement

General Description

The multiple-resources model assumes that human operators possess independent, non-substitutable pools of resources for performing different task components. Application of this assumption entails identification of those dimensions defining separate resources. Three dimensions have been proposed (Ref. 8): (1) processing stage (perceptual versus central versus response), (2) perceptual modality (auditory versus visual), and (3) codes of information processing and response modality (spatial-manual versus verbal-vocal). Figure 1 depicts the structure of these resource dimensions. The model has implications for secondary-task methodology used in workload assessment (CRef. 7.720). To ensure sensitivity to workload associated with a particular primary task, the investigator must choose a secondary task that shares processing demands with the primary task (CRefs. 7.701, 7.702, 7.703). The model also implies that efficient task design will entail separation of resources in various task components.

Empirical Validation

Support for the proposed three dimensions of the multiple-resources model has come from both physiological and behavioral studies. The use of event-related brain potentials (CRef. 7.726) to index workload has supported the postulation of a processing-stage dimension. Amplitude of the P300 spike is influenced by manipulating display load of a concurrent task (Ref. 3), but not by imposing manual responses on subjects or by manipulating response frequency (Ref. 2). Display load presumably draws upon perceptual and central processing resources, whereas the latter manipulations draw upon response resources; hence the P300 spike indexed the workload at perceptual and central processing stages, but not at the response stage. A complex skill such as typing has been used to demonstrate that perceptual, central, and response processes all proceed in parallel without loss of efficiency at any stage, suggesting that resources applied to each stage are independent (Ref. 6).

Independence of processing codes is supported by work requiring subjects to concurrently process stimuli from the same or different modalities. Performance is impaired more when two spatial targets must be processed than when a spatial and verbal target must be processed (Ref. 5). Selective interference studies, in which a manual response will interfere more with spatial memory than a vocal response, and a vocal response interferes more with verbal memory than spatial memory, also support the independence of processing codes (Ref. 1).

Work with cross-modality input supports the proposal of a perceptual modality dimension. Cross-modal presentation in detection tasks produces more efficient detection than intramodal presentation (Ref. 7). This idea extends to response modality as well. Tracking and a concurrent vocal response produce greater efficiency than tracking combined with a manual response (Ref. 9).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Although perhaps the most recent approach, multiple resource theory is by no means the only description of operator resources. An alternative is to view operator capacity as composed of undifferentiated resources (Ref. 4); in this approach, tasks compete for the resources and for the structures used to carry out the tasks (e.g., encoding and response structures).

• In addition to accounting for the resources required by a particular task or design option, the design engineer must take into account priorities of resource allocation. This will generally be a problem, since demands increase for shared resources on concurrent tasks.

Key References

1. Brooks, L. R. (1968). Spatial and verbal components of the act of recall. *Canadian Journal of Psychology, 22*, 349-368.

2. Isreal, J. B., Chesney, G. L., Wickens, C. D., & Donchin, E. (1980). P300 and tracking difficulty: Evidence for multiple resources in dual-task performance. *Psychophysiology, 17*, 259-273.

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4. Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

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6. Shaffer, H. L. (1975). Multiple attention in continuous verbal tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 157-167). London: Academic Press.

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*8. Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention*. New York: Academic Press.

9. Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, control processing and output: Testing a model of complex performance. *Human Factors, 25*, 227-248.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.701 Criteria for selection of workload assessment techniques;

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.703 Diagnosticity in the choice of a workload assessment technique;

7.720 Choice of secondary task: application of a multiple-resources model;

7.726 Use of transient cortical evoked response in the primary task situation;

Handbook of perception and human performance, Ch. 42, Sect. 4.4

7.203 Method of Analyzing Multiple Resource Allocation

Key Terms

Capacity limitations; concurrent tasks; mental models; performance operating characteristic (POC); resource allocation; workload

General Description

Manipulation of both task difficulty and task priority can reveal the nature of the allocation of multiple resources. For example, dual-task performance of letter-typing and visual tracking shows performance tradeoffs as a function of the difficulty and the priority of letter typing, indicating that the two tasks compete for common resources. A significant interaction between difficulty and priority indicates there is only a partial overlap in demand on resources, and the performance operating characteristic (POC) curves suggest that the competition occurs at the level of response planning and organization.

Methods

Test Conditions

- Visual tracking display on CRT screen of ~18 deg visual angle
- Tracking task: target: 1.5-cm square in continuous random motion; pointer: 1.5-cm "x" moved by a hand-held acceleration controller
- Typing task: three sets of Hebrew letters varying in size and difficulty: four-letter set (easy), four-letter set (difficult-motor), 16-letter set (difficult-cognitive)
- 3-min trials of continuous performance

Experimental Procedure

- Within-subject design
- Independent variables: letter set, task priority, practice
- Dependent variables: tracking errors, letter typing response time
- Observer's task: Task 1: keep pointer positioned over target using right hand; Task 2: type code for letter shown inside target using left hand; visual feedback within trials; verbal feedback between trials
- Monetary rewards for good performance
- Six righthanded male subjects (ages 19-25), with some practice

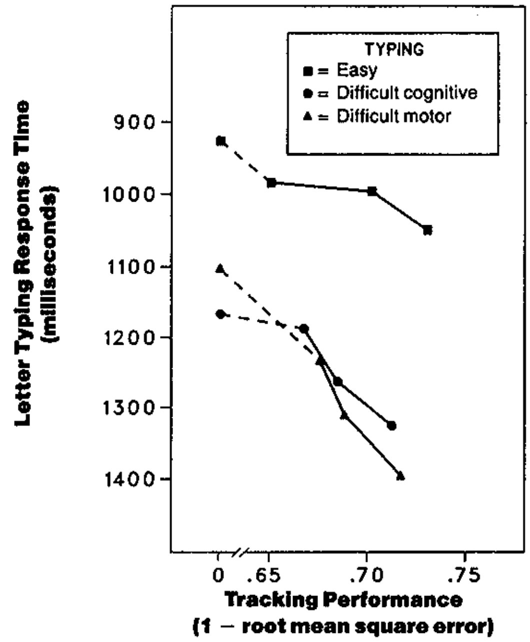

Figure 1. Performance operating characteristic (POC) curves depicting the tradeoffs between speed of letter-typing and accuracy of visual tracking as a function of the difficulty and priority of the typing task (the parameters for the curves). Dotted lines connect performance under dual-task conditions with single-task performance of typing (0 on x-axis). (From Ref. 1)

Experimental Results

- Resources were shared between letter typing and tracking: letter typing was significantly slower under dual-task than under single-task conditions, and when tracking had a higher priority than typing.
- POC curves (Fig. 1) show a change in slope from easy to difficult-motor, but not from easy to difficult-cognitive; this indicates that difficult-motor tasks compete for resources with tracking, whereas difficult-cognitive tasks do not.

Variability

No information on variability was given.

Constraints

- Acceleration controllers require complex tracking behavior (Ref. 2), whereas velocity or direction controllers do not; hence the observed interaction may not be found with them.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Gopher, D., Brickner, M., & Navon, D. (1982). Different difficulty manipulations interact differently with task emphasis: Evidence for multiple resources. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 146-157.

2. Wickens, D.C., & Gopher, D. (1977). Control theory measures of tracking as indices of attention allocation strategies. *Human Factors, 19,* 349-365.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.202 Multiple-resources model;

7.204 Evidence for undifferentiated and differentiated attentional resources;

7.701 Criteria for selection of workload assessment techniques;

7.704 Measurements used in workload assessment;

7.719 Major classes of secondary task;

7.720 Choice of secondary task: application of a multiple-resources model;

Handbook of perception and human performance, Ch. 41, Sect. 3.7

7.204 Evidence for Undifferentiated and Differentiated Attentional Resources

Table 1. Prevalence of structural alteration effects categorized by stage in which modality was altered for different pairs of tasks. (Adapted from Ref. 1)

	Stage Where Modality Altered							
	Encoding: Visual Versus Auditory		Memory: Spatial Versus Verbal		Response: Vocal Versus Manual		Total	
Paired task	Effect Present	Effect Absent	Effect Present	Effect Absent	Effect Present	Effect Absent	Effect Present	Effect Absent
Detection	3	2	1	1	–	–	4	3
Memory/reasoning	3	1	1	0	1	2	5	3
Reaction Time/shadowing	5	0	1	1	2	0	8	1
Tracking	3	2	2	0	5	0	10	2
Total	14	5	5	2	8	2	27	9

Each cell indicates number of reviewed studies in which effect was present or absent. Every instance of an effect supports the differentiated model.

Key Terms

Concurrent tasks; detection; memory; mental models; mental resources; reaction time; shadowing; tracking

General Description

Two models of attention that pertain to performance on two concurrent tasks are the undifferentiated capacity model and the structural or differentiated model (CRef. 7.201). The undifferentiated mental resources model posits a single reservoir of mental resources, used for any and all tasks, and predicts that as the difficulty of one of two concurrent tasks increases, performance on one or the other will eventually decline once the single reservoir has been depleted.

The empirical findings of the majority of 76 relevant experiments support the structural model, which proposes several reservoirs, each associated with a specialized processing structure used in a narrow set of performance tasks. This model proposes two ways to demonstrate differentiated resource structures: (1) by instances of insensitivity to task difficulty, which occur when an increase in the difficulty on one task does not affect performance on a concurrent task perhaps because the two draw from different resources; and (2) by instances of structural alteration effects, in which Tasks A and B, of equal difficulty, but involving different processing structures and hence different reservoirs, impair performance on concurrent Task C (paired either with Task A or B) to different degrees; the amount of interference is related to how much either Task A or B draws resources from the same reservoir used by Task C as well.

Research Paradigms

All published studies of concurrent task experiments were included in Table 1 with the following conditions. 1) the experimental task's modality of encoding, memory, or response of a task was changed (with task difficulty held constant) so that structural alteration effects could be evaluated, 2) the difficulty of one task was varied to determine if performance on a concurrent task was affected, i.e., if insensitivity to task difficulty occurred. Instances of structural alteration of insensitivity to task difficulty support the structural or differentiated model. Instances which do not show either effect support the undifferentiated capacity model.

Tasks

The following tasks were used in the various experiments: detection, memory, **reaction time**, shadowing, mental arithmetic, and tracking. In studies looking for structural alteration effects, modality is altered either by comparing visual and auditory stimulus presentations, or spatial and verbal memory, or vocal and manual responses.

Experimental Results

- The structural or differentiated model received strong support in 75% of relevant studies, i.e., structural alteration effects were found.
- Half (19 of 39) of the experiments that sought insensitivity to task difficulty between a tracking task and one of a number of other tasks, found evidence of it, supporting the differentiated model.
- Structural alteration effects were found for all methods of altering modality, whether it was sense of encoding, type of memory, or response category.

• Thirteen studies investigated insensitivity to task difficulty between a tracking task and a reaction time task; five of them found task insensitivity. Both tasks involved motor responses and hence used the same processing structures and the same reservoirs.
• Reaction time shadowing and tracking tasks were involved when cases of structural alteration were found (18 of 21 studies) compared to detection, memory, or reasoning tasks (9 of 15).
• Mental arithmetic and tracking, encoding and tracking, and vocal response and tracking can be carried on simultaneously without interfering with one another.

Constraints

• Many factors, such as specific stimulus dimensions, response categories, practice effects, and adaptation conditions, can influence each of the tasks.

Key References

*1. Wickens, C. D. (1980). The structure of attentional resources. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 239-255). Hillsdale, NJ: Erlbaum.

2. Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63-102). San Diego, CA: Academic Press.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.202 Multiple-resources model;

7.203 Method of analyzing multiple resource allocation;

7.720 Choice of secondary task: application of a multiple-resources model

7.205 Performance Operating Characteristic

Key Terms

Capacity limitations; concurrent tasks; mental effort; performance operating characteristic (POC); resource allocation; signal detection

General Description

The *performance operating characteristic* (POC) provides a description of dual task performance that is similar in some respects to the ROC (receiver operating characteristic) curve of signal detection analysis. The POC provides a useful framework in which to discuss the effects of capacity limitations on performance.

Figure 1 illustrates a hypothetical POC. The x-axis shows performance on Task B, and the y-axis performance on Task A. Single task performance on A and B separately is marked on each axis, and Point P represents joint performance of both tasks in the absence of any competition for processing resources. The box determined by the x-and y-axes and the dotted lines connecting signal task performance to Point P defines the POC space. The POC space represents all possible combinations of joint performance levels under dual task conditions. *Actual* performance levels will correspond to points that lie off the boundary to the degree that there is competition between A and B for the same resources.

Given a specified level of difficulty for Tasks A and B, performance will be represented by a curve in the POC space, corresponding to variations in dual task performance as a function of different strategies for *resource allocation.* Three points along one such curve are shown in Fig. 1. The POC curve yields simple definitions of the *efficiency* of dual task performance and of *bias* in the allocation of resources. Performance efficiency is measured as the distance from the POC curve to the boundaries defined by Point P. Bias in resource allocation is defined by whether the point representing a given level of performance lies closer to one axis or the other. The three points shown therefore represent equal levels of processing efficiency but different degrees of bias, with Point 1 biased toward Task A and Point 3 biased toward Task B.

With respect to workload assessment, the principal conclusion from the POC analysis in Fig. 1 concerns the interpretation of the effects of adding a second task to performance on a primary task. Consider the effects of adding Task B on the performance of A, the primary task. At Point 1, the addition of Task B causes a slight reduction in Task A performance, compared to the single task level. At Point 2, the addition causes a larger reduction, and at Point 3 the addition of B has reduced A to a low level. Thus, the disruptive effect of adding a secondary task to A depends on the way resources are allocated to the two tasks as well as on the resources required for either task.

It is also important to note that the POC curve does not intersect the axes at the level of single-task performance. The difference between the intersection of the curve for dual-task performance and the point of single-task performance is called the *concurrent cost* of the dual task. Concurrent costs do not arise from limitations in *central* processing resources, but from incompatabilities at the response or sensory level, such as the inability to tap two rhythms simultaneously with a single finger or to read two messages separated by 90 deg of visual angle.

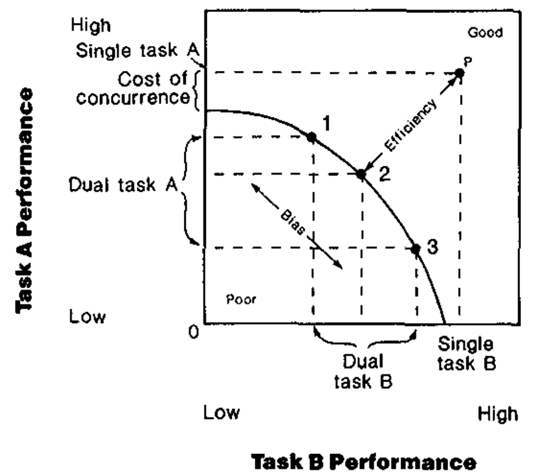

Figure 1. Hypothetical performance operating characteristic (POC) curve for dual task performance. Performance on one task, A, is plotted on the y-axis and performance on the other task, B, is plotted on the x-axis, with the levels of single task performance for each marked on the appropriate axis. Point P represents dual task performance that is equivalent to performance of either task separately, an outcome that can only occur if there is not competition for resources. Points 1, 2, and 3 represent three levels of joint performance that differ only in terms of the *bias* in resource allocation to one or the other task. Resource allocation is biased toward A for point 1 and toward B for point 3. Point 2 represents an unbiased resource allocation. Performance *efficiency* is the same for all three points, because they lie on the same POC curve. (From Ref. 8)

Empirical POCs are obtained by holding constant such variables as processing load and task difficulty while varying the relative emphasis on each task. Ideally, a family of POC curves can be obtained by measuring performance at several levels of emphasis for each of a number of levels of task difficulty.

Figure 2 illustrates, in quadrant I, three POCs obtained from manipulating the difficulty of Task A from easy (E) to medium (M) and difficult (D), while keeping the difficulty of Task B constant. The other three quadrants indicate how the POCs are a consequence of both the resource allocation policy, shown in quadrant III, and the functions relating resource allocation to performance for each task, shown in quadrants II and IV.

The principal point illustrated by Fig. 2 is that the effect of changing the difficulty of Task A on Task A performance

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

is greater when resources are more biased towards A. Thus, if most of the resources are devoted to Task B, as indicated by Point Y in quadrant III, manipulations of Task A difficulty will tend to have little impact on performance, whereas if most of the resources are devoted to A as indicated by Point X, it will have a large effect.

Applications

Measurement of the performance of operators in complex environments, such as aircraft pilots, radar tracking, sonar tracking, etc., will be more accurate if augmented by POC analysis.

Constraints

- Empirical application of POC analysis will not be possible for tasks in which appreciable changes in task emphasis may be catastrophic (such as flying aircraft).
- Interpretations of complex POC curves are likely to require supplementary data.
- Observers may learn specialized dual task strategies if given large amounts of practice and produce a distorted POC.

Key References

1. Gopher, D., Brickner, M., & Navon, D. (1982). Different difficulty manipulations interact differently with task emphasis: Evidence for multiple resources. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 146-157.

2. Gopher, D., & Sanders, A. F. (1984). S-Oh-R Oh stages, Oh resources. In W. Printz & A. F. Sanders (Eds.), *Cognition and motor processes.* New York: Springer-Verlag.

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Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.202 Multiple-resources model;

7.203 Method of analyzing multiple resource allocation;

7.701 Criteria for selection of workload assessment techniques;

7.720 Choice of secondary task: application of a multiple-resources model

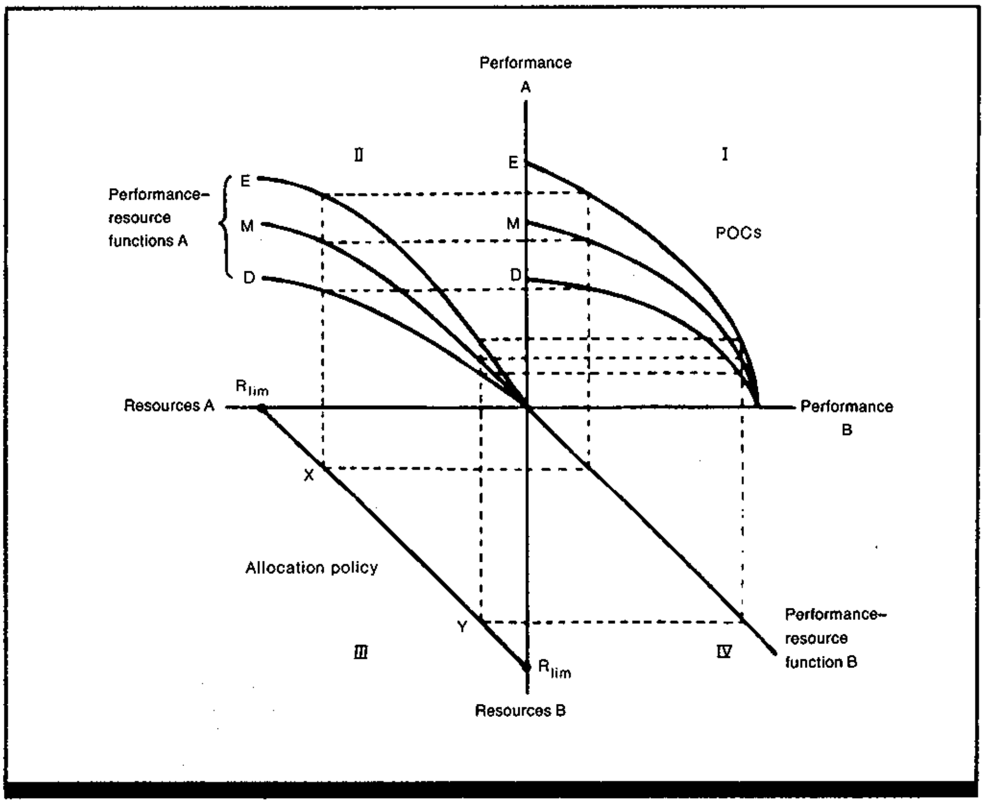

Figure 2. A family of hypothetical POC curves generated by manipulating the difficulty of task A is shown in quadrant I. Task A was easy (E), medium (M) or difficult (D), and Task B was held constant. The resource allocation policy is shown in quadrant III, and the functions relating resources to performance are shown in quadrants II and IV. The effects of task difficulty depend on the resource allocation policy, as indicated by the differences in the POC curves associated with the allocation of resources to A (point X) as compared to the allocation of resources to B (point Y). (From Ref. 2)

7.206 Divided Versus Selective Attention: Effect on Auditory Recognition Accuracy

Key Terms

Auditory attention; auditory recognition; backward masking; divided attention; letter recognition; loudness discrimination; masking; pitch discrimination; selective attention

General Description

Recognition accuracy for tones and letters decreases when the tone or letter is followed closely in time by a second stimulus in the same modality (known as *backward masking*). Recognition accuracy increases as the interval between the test stimulus and masking stimulus increases, until it reaches an asymptote at ~250 msec. When masked tones and letters are presented together, performance is better when subjects must report only the pitch of the tone or the identity of the letter (selective attention) than when they must report both tone pitch and letter identity (divided attention). When subjects must attend to different dimensions of a single stimulus, however, by identifying the loudness or the quality of a tone, performance is the same regardless of whether subjects must categorize the tone along only one of the two dimensions while ignoring the other, or along both simultaneously.

Applications

In conditions where there is rapid presentation of successive stimuli, slight delays between the stimuli will improve perceptibility of each. If the operator is required to report several properties of the stimulus situation, performance can be expected to be poorer for reports of stimuli from different modalities than for reports of different properties of a single stimulus.

Methods

Methodological details are given in Table 1.

Experimental Results

- In all studies, recognition accuracy improves as the interval between target and mask increases up to 250 msec ($p<0.001$).
- Both tone and letter recognition accuracy are worse when the subject must identify both tone and letter (divided attention) than when the subject must identify only one of the two (selective attention) ($p<0.05$) (Fig. 1).
- Tone recognition accuracy is impaired by simultaneous presentation of a letter (divided attention) relative to successive presentation (selective attention).
- Reporting both tone loudness and tone quality (divided attention) is as accurate as reporting just one of these dimensions (selective attention) (Fig. 2).
- For the poorest subjects, loudness judgments are easier than quality judgments at longer masking intervals (Fig. 2).
- Test tone duration does not affect performance.

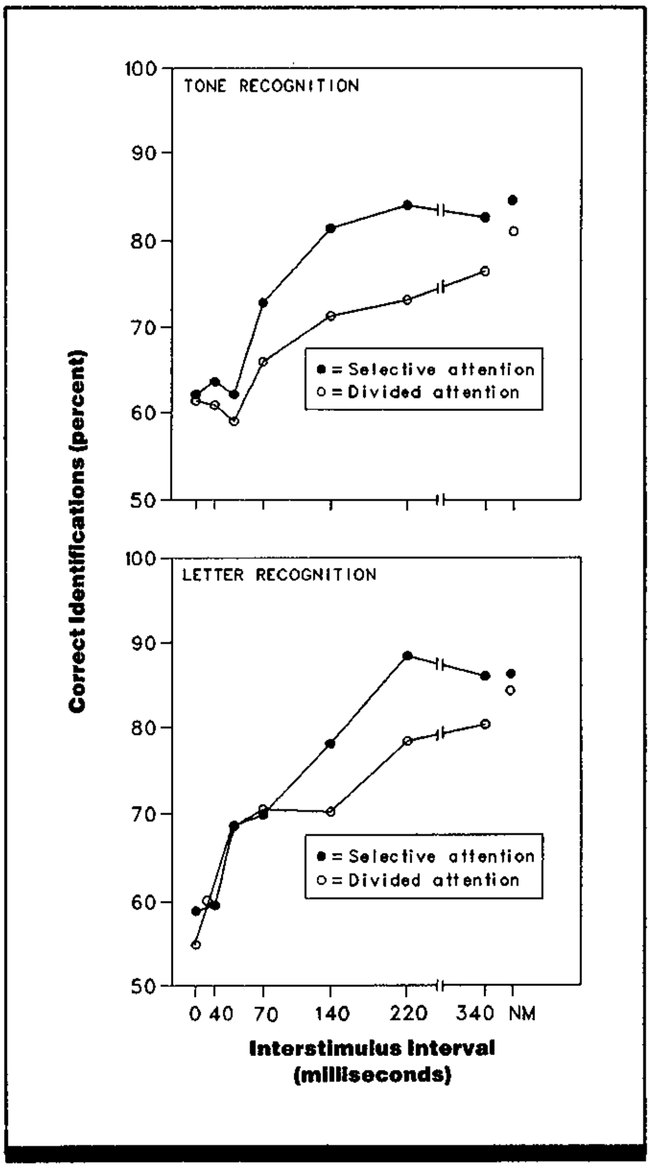

Figure 1. Recognition accuracy for tones and letters under backward masking as a function of interval between test stimulus and masking stimulus (Study 1). Subjects reported pitch of tone (high or low) and identity of letter (U or V) presented simultaneously. In selective attention condition, subjects made either pitch or letter identity judgment; in divided attention condition, subjects made both judgments. For comparison, performance with no masking stimulus (NM) is shown. (From Ref. 2)

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Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 2)	
Test tone and test letter simultaneously presented, followed by masking tone and masking letter Each trial preceded by 500-msec visual cue indicating what item(s) subject must identify: visual feedback after each trial 20-msec sine-wave test tone of 800 or 880 Hz; 20-msec square-wave masking tone of 840 Hz; both presented binaurally over headphones at 80-dB sound pressure level (SPL) in soundproof room 4-msec presentation of test letter (either U or V), followed by 3 msec of alternative letter followed by 4 msec of test letter; visual mask of alternating 2-msec presentations of letters U, V for 20 msec; test and masking letters subtended 50 deg in height, 38 deg in width, and were presented over light-emitting diodes Interval between target and mask of 0, 20, 40, 70, 140, 220, or 340 msec, with no masking stimuli presented on 1/8 trials	Backward masking, recognition Independent variables: type of attention (selective or divided), interval between target and mask, frequency of test tone, test letter Dependent variable: percentage of correct recognitions of test tone and letter Subject's task: identify which letter (U or V) and/or which tone (high or low) presented on each trial 500 trials/day for 4 days; 21 observations per subject per condition All 96 conditions (three attention conditions x two test tones x two test letters x eight masking conditions) completely randomized Subjects: 4 undergraduates, some practice
Study 2 (Ref. 3)	
Stimuli same as in Study 1 Test tone and test letter presented simultaneously (divided attention) or successively (selective attention), followed by masking tone and masking letter Each trial preceded by 500-msec visual cue indicating type of presentation (simultaneous or successive) and ended with visual feedback In sequential condition, test letter preceded test tone by 1500 msec; in simultaneous condition, test letter preceded test tone by 16 msec, but perceived as phenomenologically simultaneous Interval between target and mask of 25, 40, 70, 120, 180, 250, or 340 msec, with no masking stimuli presented on 1/8 trials Subjects: 12 young adults, some practice	Backward masking, recognition Independent variables: type of attention (selective or divided), interval between target and mask, frequency of test tone, test letter Dependent variable: percentage of correct recognitions of test tone and letter Subject's task: identify which letter (U or V) and which tone (high or low) presented on each trial 500 trials/day for 4 days; 21 observations per subject per condition All 64 conditions (two attention conditions x two test tones x two test letters x eight masking conditions) completely randomized
Study 3 (Ref. 3)	
Test tone and masking tone presented successively, binaurally over headphones in soundproof room Each trial preceded by visual cue indicating which sound dimension(s) must identify: loudness or quality (selective attention) or both (divided attention); visual cue remained on during 2-sec (selective attention) or 3-sec (divided attention) response period; visual feedback after each trial 855-Hz test tone, either loud (74.2 dB SPL) or soft (38.5 dB SPL) and either dull (pure sine wave) or sharp (pure triangle wave) 855-Hz, 120-msec masking tone consisted of six 20-msec square-wave segments with amplitudes of 67-75 dB SPL and steady-state SPL of 73 dB For 50% of subjects, 20-msec test tone followed by silent interval of 10, 20, 40, 70, 120, 200, 300, or 400 msec; for 50% of subjects, 40-msec test tone followed by silent interval of 10, 30, 50, 80, 130, 210, 300, or 410 msec	Backward masking, recognition Independent variables: type of attention (selective or divided); interval between target and mask; processing time, defined as test tone duration plus intertone interval; quality (shape) of test tone; loudness (amplitude) of test tone Dependent variable: percentage of correct identifications of test tone loudness and quality Subject's task: identify loudness (loud or soft) and/or quality (dull or sharp) of test tone on each trial 500 trials/day for 4 days; 21 observations per subject per condition All 96 conditions (three attention conditions x two test tone amplitudes x three test tone shapes x eight masking conditions) completely ramdomized Subjects: 20 undergraduates, much practice

Variability

The significance of independent variables and interactions was tested by analysis of variance.

Repeatability/Comparison with Other Studies

Many reaction-time experiments suggest that, for integral stimulus dimensions (such as loudness, pitch, and timbre), selective attention is impossible (i.e., all information is extracted simultaneously from the stimulus), while for separable dimensions (such as visual and auditory) selective attention is possible (Ref. 1). The results here are compatible with these findings: when tones and letters are presented together, forcing attention to separable dimensions appears to increase processing load (performance is worse for divided attention than for selective attention), but when integral dimensions of a tone must be identified, performance is no better with selective attention than with divided attention (processing load is equal under the two conditions).

Constraints

• Many factors affect performance under both selective and divided attention and must be considered in applying these results under different conditions (CRefs. 7.209, 7.213).

Key References

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*3. Moore, J. J., & Massaro, D. W. (1973). Attention and processing capacity in auditory recognition. *Journal of Experimental Psychology, 99*, 49-54.

Cross References

2.306 Factors affecting auditory sensitivity in the presence of masking noise;

7.209 Factors influencing performance in selective listening tasks;

7.213 Divided attention: factors influencing performance on auditory tasks;

Handbook of perception and human performance, Ch. 26, Sect. 2.2

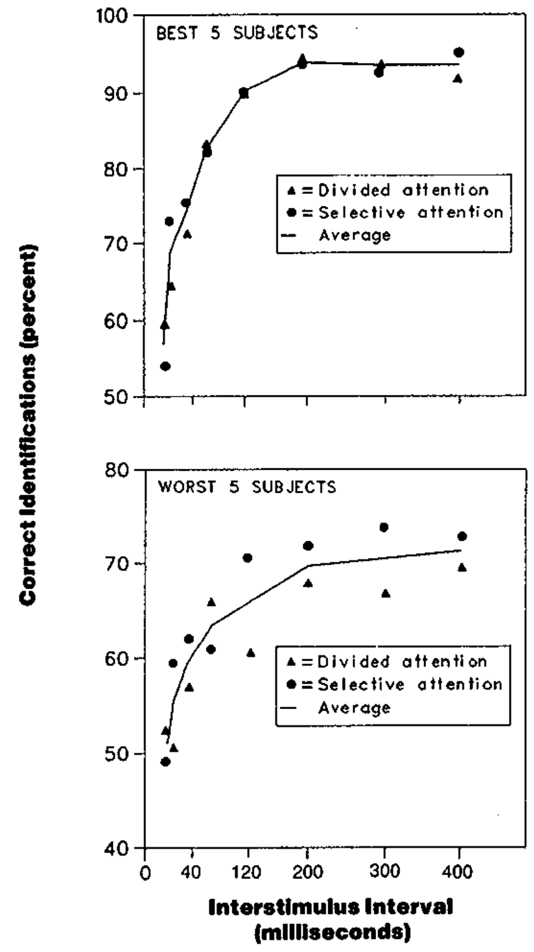

Figure 2. Recognition accuracy for the loudness of a masked tone as a function of interval between test stimulus and masking stimulus (Study 2). In selective attention condition, subjects reported whether a tone was loud or soft while ignoring its quality. In divided attention condition, subjects judged both loudness and quality (dull or sharp) of tone. Data are shown for 5 best and 5 worst subjects for 20-msec test tone. (From Ref. 3)

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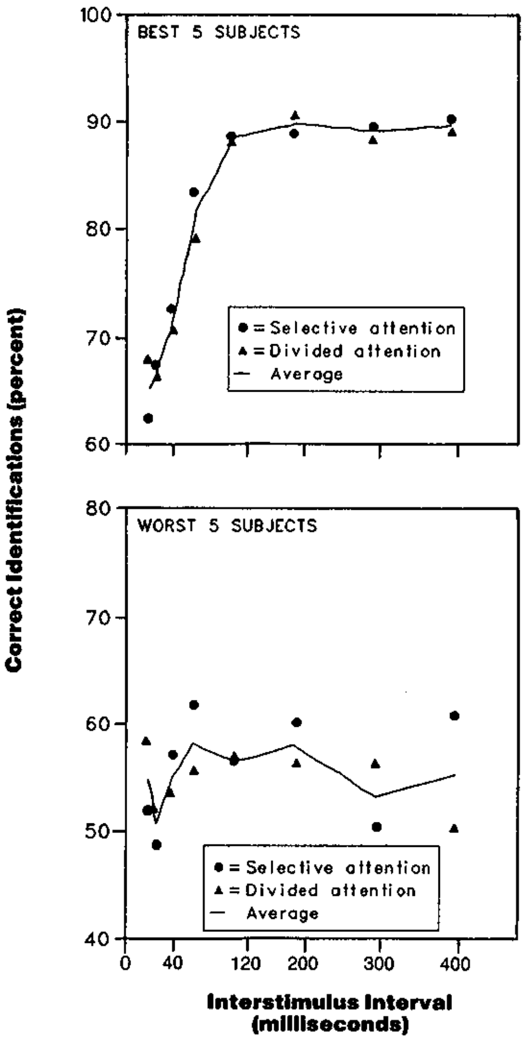

Figure 3. Recognition accuracy for the quality of a masked tone as a function of interval between test stimulus and masking stimulus (Study 3). In selective attention condition, subjects reported whether a tone was dull or sharp while ignoring its loudness. In divided attention conditions, subjects judged both quality and amplitude (loud or soft) of tone. Data are shown for 5 best and 5 worst subjects for 20-msec test tone. (From Ref. 3)

7.207 Auditory Shadowing and Secondary Task Performance: Evidence for the Multiple-Channel Model of Attention

Key Terms

Auditory recognition; auditory shadowing; concurrent tasks; divided attention; multi-channel models; selective listening; shadowing; workload

General Description

Models of attention posit that attention can be directed to only one input at a time (single-channel models) or simultaneously to multiple channels (multiple-channel models). To compare the two types of models, researchers often have subjects perform two concurrent (simultaneous) tasks: a primary task and a secondary task. Subjects are instructed that the primary task is the more important of the two tasks. Early studies used a shadowing task (the primary task) in which a subject repeats aloud (shadows) a message presented to one ear while another message is presented to the other ear; lack of recognition or recall of the unattended message supports the single-channel model. However, subjects can process information (e.g., pictures to be recognized later) without making errors in shadowing; accuracy on the picture recognition test is >90%.

This supports the multiple-channel model of attention. As the concurrent tasks become more similar (e.g., auditory shadowing and recognition of auditorily presented words), performance on the secondary task decreases.

Methods

Test Conditions

- In all conditions, 1-min prose passage to be shadowed, spoken by male voice presented to right ear
- In Exp. 1, concurrent presentation of words spoken by female voice to left ear, or words presented visually (subtending 7 deg visual angle), or presentation of photographs of complex scenes; in Exp. 2, concurrent presentation of musical scores
- In Exp. 1, subsequent recognition of concurrently presented material; in Exp. 2, concurrent sight reading of music scores

Experimental Procedure

- Within-groups design
- Independent variables: degree of difficulty of shadowing passage, type of input for concurrent tasks, degree of difficulty of music
- Dependent variables: number of errors in recognition, sight-reading, or shadowing
- Subject's task: shadow prose in all conditions; in Exp. 1, later recognize items that were presented concurrently with shadowed input; in Exp. 2, concurrently sight-read piano music
- Instructions stressed that the shadowing task was to be treated as the primary task
- In Exp. 1, 6 subjects, female undergraduates with extensive practice; in Exp. 2, 5 subjects, third-year music students

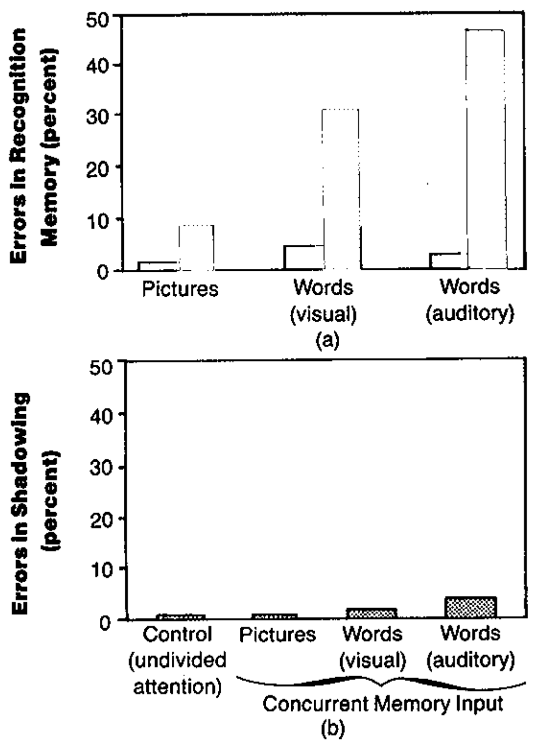

Figure 1. (a) Errors in recognition memory for different types of stimuli either with (shaded bars) or without (white bars) a concurrent auditory shadowing task. (b) Errors in shadowing with shadowing task alone (control) or concurrent with recognition input. (From Ref. 1)

Experimental Results

- Subjects make few errors in the shadowing task (Fig. 1b) and have varying degrees of proficiency in performing the other concurrent tasks. This provides support for the multiple-channel model.
- Experiment 1: there are few errors in recognition of pictures, a moderate number of errors in recognition of visual words, and chance performance in recognition of auditory words (Fig. 1a). Thus errors increase as stimulus similarity between the tasks increases.
- Experiment 2: performance on both the sight-reading task and the shadowing task in the concurrent condition is only slightly poorer than in the single task condition.

Variability

No information was reported for within-subject variability; in Exp. 2, large differences between subjects were not related to important variables.

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Constraints

- Shadowing performance is at a ceiling; this creates problems in giving models a thorough test.
- Results may not generalize to performance on pairs of tasks other than those used here, especially tasks that require more cognitive or motor resources.

Key References

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Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.202 Multiple-resources model;

7.204 Evidence for undifferentiated and differentiated attentional resources;

7.206 Divided versus selective attention: effect on auditory recognition accuracy;

7.208 Auditory shadowing: effect of message semantic and syntactic structure;

7.210 Selective listening: effect of the location of sound sources;

7.219 Division of attention among spatial locations;

7.220 Concurrent visual search;

7.221 Attentional and decision-making factors in component and compound tasks;

7.720 Choice of secondary task: application of a multiple-resources model;

7.721 Guidelines for the use of secondary task measures in workload assessment;

Handbook of perception and human performance, Ch. 2, Sect. 5.2

7.208 Auditory Shadowing: Effect of Message Semantic and Syntactic Structure

Key Terms

Communications; selective listening; semantic structure; shadowing; syntactic structure

General Description

In the shadowing paradigm, subjects repeat speech as they hear it. In shadowing at close latencies, listeners appear to use syntactic and semantic structure to guide their listening, correcting words with "errors" in the second or third syllable to be consistent with context.

Applications

In noisy listening situations, the redundancy provided by semantics and syntax may improve signal detection. Also, in noisy listening conditions, an unexpected target may be heard incorrectly, i.e., altered in accordance with expectation.

Methods

Test Conditions

- 120 pairs of normal sentences with one of each pair containing a trisyllabic target word
- 120 critical sentences divided into three groups: (1) target word unchanged (norm), (2) target word replaced by a trisyllabic semantically anomalous word (sem), (3) target word replaced by a trisyllabic syntactically anomalous target word (syn)
- Each group of 40 sentences divided into subgroups of 10 sentences. In each subgroup the target word was unchanged, or the first, second, or third syllable of the target word was altered to make it a nonsense word
- Sentences recorded in random order, at 160 words/min, with 3-sec pause between sentences

Experimental Procedure

- Independent variables: word context (normal, semantically anomalous, or syntactically anomalous), lexical accuracy of word (real word or nonsense word produced by error in first, second, or third syllable)
- Dependent variables: number of target words repeated correctly; shadowing (repetition) latency, as measured from the onset of the recorded word to onset of subject's output for that word
- Subject's task: repeat the spoken sentence as it is pronounced, as quickly and as accurately as possible
- 13 subjects with shadowing latencies of 250-750 msec

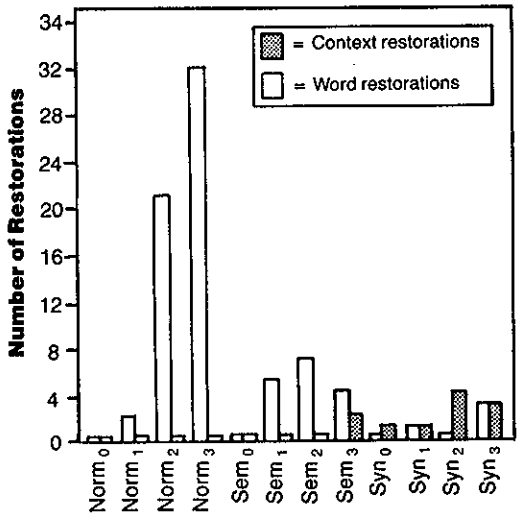


Figure 1. Distribution of word and context restorations by category. Norm = Normal, Sem = Semantic, Syn = Syntactic. The subscripts refer to the target-word syllable disrupted. (From Ref. 1)

Experimental Results

- Most frequent error (88% of all errors) is correcting a nonsense word from the passage to a real word (word restoration).
- Word restorations are most likely ($p<0.001$) when the restored word is syntactically and semantically appropriate to the sentence and when the deviation from the real word occurs in the second or third syllable ($Norm_2$, $Norm_3$ in Fig. 1).
- A few restorations replace a syntactically or semantically anomalous word with a sensible counterpart.
- Both types of restoration occur as frequently at short and long shadowing latencies.

Variability

Significance was determined by *t* tests.

Repeatability/Comparison with Other Studies

- Studies in Ref. 2 replicate these results; however, the interactive parallel processing model supported by these data contrasts with serial models of sentence processing (CRef. 8.128). The phenomenon of phonemic restoration is well described in the literature.

Constraints

- The shadowing task is very demanding and may employ other strategies than would be used in less demanding, more natural speech perception.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Marslen-Wilson, W. D. (1975). Sentence perception as an interactive parallel process. *Science, 189*, 226-228.

2. Marslen-Wilson, W.D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive Psychology, 10*, 29-63.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.206 Divided versus selective attention: effect on auditory recognition accuracy;

7.207 Auditory shadowing and secondary task performance: evidence for the multiple-channel model of attention;

7.209 Factors influencing performance in selective listening tasks;

7.210 Selective listening: effect of the location of sound sources;

7.212 Selective listening: effect of age;

7.213 Divided attention: factors influencing performance on auditory tasks;

8.128 Schema theory of memory for text

7.209 Factors Influencing Performance in Selective Listening Tasks

Factor	Manipulation	Effect	Source
Source location	Present signal and distractors from loudspeakers different distances apart	Easier to select signal message from distractor with greater separation	Ref. 3 CRef. 7.210
	Present signal and distractor to separate ears or the same ear	Easier when presented to separate ears	Refs. 4, 5 CRef. 7.211
Frequency band	Filter target and distractors to separate frequency bands	Easier than when presented at the same frequency	Refs. 1, 3 CRefs. 7.211, 8.306
	Present target and distractors in separate voices	Greater intelligibility for different voices, particularly male versus female, than for the same voice	Refs. 4, 5 CRef. 7.211
Intensity	Present signal and distractor in different intensities	The louder message is easier to hear, but there is a smaller disadvantage caused by a louder distractor than might be expected, since differentiating signal and distractor facilitates attention to the signal	Ref. 1 CRef. 8307
Semantic/syntactic structure	Target and distractor from two parts of the same novel or from different technical materials	Fewer errors if different types of material presented	Refs. 4, 5 CRef. 7.211
	Target and distractor in different or the same languages	Fewer errors if spoken in different language and with fewer intrusions	
	Target consisted of randomized words or fluent prose	Fewer errors if fluent prose	
Age of listener	Listeners of different ages asked to report precued members of dichotic pair	Ability to select declines with age between 25 and 72, particularly after 60	Ref. 2 CRef. 7.212

Key Terms

Auditory discrimination; intelligibility; selective attention; selective listening; semantic features; semantic structure; syntactic structure

General Description

In a selective-listening task, the listener is required to attend to an auditory message presented simultaneously with an auditory distraction, i.e., noise or other messages. The distraction can have two effects: a masking effect, where the target message is rendered harder to hear, and an interference effect, where the distractor is confused with the target. It is easier to listen selectively if the target message is physically distinct from the distractor, as when it occupies a different frequency band or emanates from a different perceived spatial location. Selective listening is also easier when the target and distractor are semantically less confusable, for example, when they contain different message content. Finally, ability to attend selectively diminishes with age. The table summarizes many of the factors that influence performance in selective listening tasks.

Applications

Signals presented in noisy channels, or in competition with other signals, may be more easily detected by manipulating the physical or cognitive properties of the signal with respect to the distractors.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Egan, J. P., Carterette, E. C., & Thwing, E. J. (1954). Some factors affecting multichannel listening. *Journal of the Acoustical Society of America, 26,* 774-782.

2. Panek, P. E., Barrett, G.V., Sterns, H. L., & Alexander, R. A. (1978). Age differences in perceptual style, selective attention, and perceptual-motor reaction time. *Experimental Aging Research, 4,* 377-387.

3. Spieth, W., Curtis, J. F., & Webster, J. C. (1954). Responding to one of two simultaneous messages. *Journal of the Acoustical Society of America, 26,* 391-396.

4. Treisman, A. M. (1964). The effect of irrelevant material on the efficiency of selective listening. *American Journal of Psychology, 77,* 533-546.

5. Treisman, A. M. (1964). Verbal cues, language, and meaning in selective attention. *American Journal of Psychology, 77,* 206-219.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.210 Selective listening: effect of the location of sound sources;

7.211 Selective listening: effect of message frequency spectrum;

7.212 Selective listening: effect of age;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

7.210 Selective Listening: Effect of the Location of Sound Sources

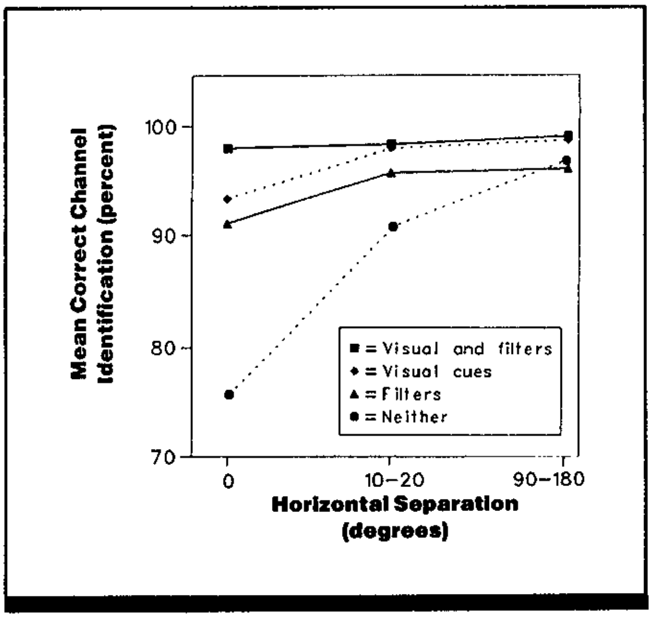


Figure 1. Mean correct identification of channel as function of frequency or spatial separation of message and distractor or visual precue of signal location. (From Ref. 1)

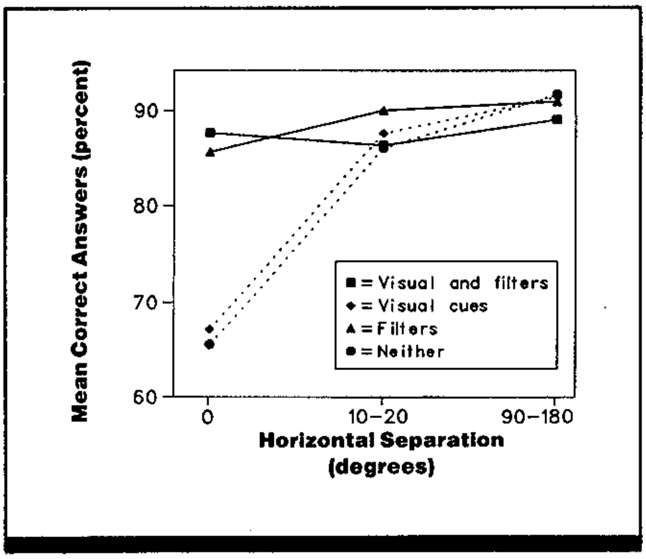


Figure 2. Mean correct answers as a function of frequency or spatial separation of signal and distractor or visual precue of location of signal. (From Ref. 1)

Key Terms

Communications; selective listening; speech intelligilibity

General Description

Accuracy in responding to one of two simultaneous auditory messages increases with spatial separation. Visually precueing the location from which any auditory message will be heard increases accuracy, particularly at small spatial separations.

Applications

Intelligibility and efficiency in receiving audio-only messages, when there are potentially distracting messages, may be enhanced by assigning each channel a unique location and unique frequency band.

Methods

Test Conditions

- Messages consisted of two-syllable code name (e.g., "Oboe"), a channel name (Abel, Baker, Charlie), a talker number (1, 2, 3, or 4), and a question about a visual display in front of the listener (e.g., "What figure is in the upper left Box 1?")
- Pair of ~4 sec messages presented simultaneously at regular intervals
- Distractors were of the same format, except that they contained a one-syllable name (e.g., "King") instead of two-syllable name. (On one trial the subject might hear "Oboe, this is Able 2, where in Box 5 is the triangle, over" simultaneously with "King, this is Baker 1, what box contains two circles, over?"
- Three-track magnetic film playback providing two of three channels of recorded messages on each trial
- Messages either presented as is, or with one filtered by a 1600-Hz, low-pass filter and the other through a 1600-Hz, high-pass filter
- Channels presented either through the same loudspeaker (no spatial separation) or through loudspeakers 10, 20, 90, or 180 deg apart with respect to the listener
- Sound level set at 75 dB; overall noise level of ~51 dB
- Three lamps on subject's station which could signal location of message

Experimental Procedure

- Within-subject design
- Independent variables: spatial separation of channels, separated or not separated in frequency, visually cued or not cued in location of relevant channel
- Dependent variable: accuracy of identifying channel and talker, and answering question
- Subject's task: respond to talker and answer question, e.g., "Able 2, triangle is in upper left of box 5"
- Subjects were 20 paid inexperienced undergraduates of both sexes

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Channel identification is 75% accurate without the benefits of spatial separation, filtering, or precueing.
- Spatial separation of 10-20 deg increases channel identification accuracy to 90%, and further separation boosts accuracy to >95%.
- Precueing the channels increases channel identification accuracy to >90% without spatial separation; with spatial separation and precueing, there are additional small increments in accuracy.
- Filtering the messages to separate frequency bands increases channel identification accuracy to >90%, with small additional increase when there is also spatial separation.
- Precueing and filtering together produced nearly perfect channel identification at all spatial separations.
- Comparable results occur for each condition when correct answers rather than channel identification is the independent variable.

Constraints

- The messages appeared at regular intervals, so that the subject might have anticipated them. An additional cue was that the message channel was constantly phonetically distinct from the distractor channel (two- versus one-syllable code names).

Key References

*1. Spieth, W, Curtis, J. F., & Webster, J. C. (1954). Responding to one of two simultaneous messages. *Journal of the Acoustical Society of America, 26*, 391-396.

Cross References

2.801 Sound localization;

2.812 Precision of localization (minimum audible angle);

7.209 Factors influencing performance in selective listening tasks;

7.211 Selective listening: effect of message frequency spectrum;

7.212 Selective listening: effect of age;

7.213 Dividend attention: factors influencing performance on auditory tasks;

7.215 Divided attention: effect of mixed modalities;

7.216 Auditory divided attention: effect of practice

7.211 Selective Listening: Effect of Message Frequency Spectrum

Table 1. Accuracy of report, intrusion errors and standard errors on shadowing task as a function of type of distractor message. (From Refs. 1, 2)

	Man's Voice, Same Novel	Man's Voice, with Latin	Same Voice, Same Novel	Same Voice, Technical English	Same Voice, Reversed English	Same Voice, Foreign Language (for silent Ss)
Mean % Correct	73.7	73.9	31.0	39.8	45.9	42.2
SE	2.5	3.1	2.4	3.3	2.3	2.8
Mean % Intrusions	<1	<1	19.5	12.3	<1	<1
SE			2.1	2.1		

Key Terms

Communications; dichotic listening; message frequency; selective listening; shadowing

General Description

When auditory messages are simultaneously perceived, usually only one may be attended to at a time. Attention to the relevant message may be facilitated if the messages are

- grammatically coherent;
- presented from different perceived spatial locations;
- in different voices;
- in different frequency bands;
- on different topics.

Applications

In noisy listening conditions, attention to physical and semantic structure of signal relative to noise may enhance reception of signal.

Methods

Test Conditions

Study 1 (Ref. 1)

- Message to be shadowed was 150-word passage from a novel, recorded in a female voice on one track of two-channel tape
- Irrelevant messages (distractors) recorded on other track, starting a few words after the first, and were (1) from the same novel but recorded in five different languages in male or female voice, (2) from technical material in same or different language, (3) from same novel but in a male voice (4) the target played backwards, or (5) randomized English strings where sentences were randomized by word or by two, four, six, eight, or twelve words

Study 2 (Ref. 2)

- Passages of novel (150 words in length) presented: two messages presented, one to each ear; or three messages presented, one to each of the two ears and one to both ears
- Apparent loudness controlled over conditions
- Relevant message presented to right ear

Experimental Procedure

Study 1

- Shadowing task
- Independent variables: voice of irrelevant message, language of irrelevant message, syntactic coherence of irrelevant message (passage from novel, technical passage, passage in reversed English)
- Dependent variables: percentage of words correct, intrusions from distractor, errors, and omissions
- Subject's task: to shadow (repeat back continuously) message which started first
- 42 college students, self-rated as fluent in the relevant foreign language, having some knowledge of the language, or having no knowledge of it

Study 2

- Shadowing task
- Independent variables: number of irrelevant messages, number of irrelevant channels (the two irrelevant messages were separate or mixed on one channel), spatial localization of irrelevant messages
- Dependent variables: number of words correctly repeated, number of omissions, number of errors
- Subject's task: to repeat back the relevant message continuously and fluently
- 47 college students

Experimental Results

- Shadowing accuracy is greater when the distractor message is in a different voice from the target message than if it is in the same voice.
- Shadowing accuracy is greater if the distractor and target message are semantically dissimilar than if they are similar.
- Shadowing accuracy is greater if the distractor message is nonsense or a foreign language than if it is words of the same language.
- Shadowing accuracy is excellent if the distractor message is in a different spatial location from the target.
- Shadowing accuracy is poorer if there are two distractor messages to separate locations from the target than if both are in the same channel with the target in a different one.
- Intrusions from the irrelevant channel occur only if they are in the same voice and language as the target.
- Shadowing accuracy is poor if the target message is not syntactically well-formed and intrusions from well-formed distractors are frequent.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Separate or Different Ear from Target	Binaural Distractor & Cue to Other Ear	2 Binaural Distractors	Coherent Prose with Target Randomized Sentences (Word-by-word Randomized)	Coherent Prose with Target Randomized Sentences (Randomized by 12 Words)
94	79	94	10.6	28.5
1.1	2.8	1.5	1.2	2.3
			40.6	24.8
			2.6	2.2

Constraints

- The shadowing task is highly demanding; repeating back creates distractors.

Key References

*1. Treisman, A. M. (1964). Verbal cues, language, and meaning in selective attention. *American Journal of Psychology, 77*, 206-219.

*2. Treisman, A. M. (1964). The effect of irrelevant material on the efficiency of selective listening. *American Journal of Psychology, 77*, 533-546.

Cross References

7.201 Contrasting models of attention: undifferentiated versus differentiated capacity;

7.207 Auditory shadowing and secondary task performance: evidence for the multiple-channel model of attention;

7.209 Factors influencing performance in selective listening tasks;

7.210 Selective listening: effect of the location of sound sources;

7.212 Selective listening: effect of age;

7.213 Divided attention: factors influencing performance on auditory tasks

7.212 Selective Listening: Effect of Age

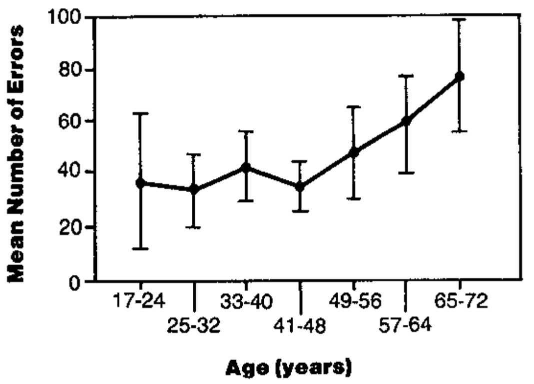


Figure 1. Accuracy of performance of dichotic listening task as a function of age. (Adapted from Ref. 1)

Key Terms

Communications; dichotic listening; lateralization; selective listening

General Description

In a dichotic selective listening task (different messages presented simultaneously to each ear, one message to be reported), performance errors increase as a function of increasing age. Around age 60 the ability to correctly report one of two dichotic messages declines markedly. Hence, in noisy listening conditions, older subjects may be more adversely affected by distractors than younger ones.

Methods

Test Conditions

- 24 dichotic messages, consisting of letters or digits (0-9), presented two items per sec
- Each message segment consisted of 16 letter/digit pairs; preceded by tone to one ear
- Tone indicated that subject should report items presented to that ear

Experimental Procedure

- Within-subjects design
- Independent variable: age of subject
- Dependent variable: number of errors
- Subject's task: after tone, report all digits heard in the relevant ear immediately upon hearing them
- 25 female subjects each in age groups 17-24, 25-32, 33-40, 41-48, 49-56, 57-64, 65-72, all screened for normal health and hearing; within each age group, the most common education level was high school graduate

Experimental Results

- Ability to selectively attend to messages declines with age ($p<0.001$), particularly in the 60's ($p<0.05$).

Variability

Bars in Fig. 1 represent standard deviation. Significance was determined by a multivariate analysis and Newman-Keuls analysis.

Repeatability/Comparison with Other Studies

Other studies generally have shown that selective attention ability declines in the 60's. In this study other abilities were examined in the same subjects, and the oldest group deviated from the others on an embedded figures test, complex reaction-time test, and rod-and-frame test.

Constraints

- Because this study involved a one-time measurement of subjects in various age groups, individual abilities as affected by age were not measured. A study in which measures are taken over the lifetime of a group of subjects is needed to assess the effects of age.
- Only female subjects tested.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Panek, P. E., Barrett, G.V., Sterns, H. L., & Alexander, R.A. (1978). Age differences in perceptual style, selective attention, and perceptual-motor reaction time. *Experimental Aging Research, 4*, 377-387.

Cross References

7.209 Factors influencing performance in selective listening tasks;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

7.213 Divided Attention: Factors Influencing Performance on Auditory Tasks

Key Terms

Auditory discrimination; communications; selective listening; semantic features; signal detection

General Description

When listeners are required to divide attention among simultaneous messages, they perceive a message less accurately or at higher thresholds than when the message is presented alone, particularly if they must report the occurrence of the competing message (divided attention). The performance decrement decreases in divided attention as the competing messages become more discrepant. Furthermore, performance may improve with practice, and may be better for younger listeners than for older listeners. Table 1 summarizes the effects of several factors on performance of auditory divided attention tasks.

Applications

Designs in natural signal detection situations, where an observer is likely to be monitoring for occurrence of several possible signals at the same time (such as a voice giving instructions together with a visible change on an oscilloscope), perhaps under noisy conditions.

Key References

1. Inglis, J., & Caird, W. K. (1963). Age differences in successive responses to simultaneous stimulation. *Canadian Journal of Psychology, 17*, 98-105.

2. Long, J. (1975). Reduced efficiency and capacity limitations in multidimension signal recognition. *Quarterly Journal of Experimental Psychology, 27*, 599-614.

3. Massaro, D. W., & Warner, D. S. (1977). Dividing attention between auditory and visual perception. *Perception & Psychophysics, 21*, 569-574.

4. Moore, J. J., & Massaro, D. W. (1973). Attention and processing capacity in auditory recognition. *Journal of Experimental Psychology, 99*, 49-54.

5. Ostry, D., Moray, N., & Marks, G. (1976). Attention, practice, and semantic targets. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 326-336.

6. Pohlman, L. D., & Sorkin, R. D. (1976). Simultaneous three-channel signal detection: Performance and criterion as a function of order of report. *Perception & Psychophysics, 20*, 179-186.

7. Sorkin, R. D., & Pohlman, L. D. (1973). Some models of observer behavior in two-channel auditory signal detection. *Perception & Psychophysics, 14*, 101-109.

Cross References

7.206 Divided versus selective attention: effect on auditory recognition accuracy;

7.208 Auditory shadowing: effect of message semantic and syntactic structure;

7.212 Selective listening: effect of age;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

Factor	Conditions Tested	Effect	References
Discriminability	Subjects asked to forced-choice identify one of two signal tones alone or together with one of two light intensities. In one condition, the tones and lights were very close in values, and in one very disparate	The presence of a signal in another dimension decreased performance for difficult discriminations only	Ref. 2
Age of subject (11-70 years)	Memory for digits presented dichotically where the numbers of digits were 2, 4, 6, 8, 10, 12	Memory for first-reported member of each dichotic pair not affected by age, while accuracy for second-reported member declines with age	Ref. 1 CRef. 7.212
Selected versus divided attention to visual and auditory dimensions	Tones and letters presented in backward masking paradigm, with subject asked to report one or both when the two are simultaneously presented, or report both when the two are either simultaneously or successively presented	Dividing attention between letters and tone by reporting both when both have been presented simultaneously diminishes recognition accuracy	Ref. 3 CRef. 7.206

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Factor	Conditions Tested	Effect	References
Selected versus divided attention to auditory dimensions of one stimulus	A tone varying in loudness and timbre presented in a backward masking paradigm with subject asked to report both loudness and timbre or just one dimension	No effect of dividing attention between integral dimensions of stimulus	Ref. 4 CRef. 7.206
Selected versus divided attention to semantic feature of a stimulus in the presence of semantic distractors	Letter and number names or animal names and other nouns were presented dichotically with subjects instructed to monitor for the letter or animal name in both ears (divided attention) or in only one. Subjects practiced divided attention for days	It is more difficult to detect a target if another target is also present in another channel. Sensitivity to targets increases markedly with practice	Ref. 5 CRef. 7.208
Detection of single frequency versus detection of three frequencies in noise	One of 500-, 810-, or 1320-Hz frequencies presented in noise for yes-no detection in single condition. In multiple condition, three separate yes-no responses required, one for each frequency. Responses made by button press with six buttons in multiple-channel conditions. Simultaneous monaural presentation of signal(s) and noise	Performance inversely related to the number of targets presented on each trial	Ref. 6 CRef. 8.307
Detection of two frequencies in which one, the other, or neither was presented monaurally or to opposite ears	In the monaural condition either a 630- or 140-Hz tone or neither would occur on the left with noise. In the dichotic condition, the 630-Hz tone could only occur on the left and the 1400-Hz tone on the right	No difference between one and two-channel monitoring, perhaps because of frequency separation	Ref. 7

7.214 Auditory Divided Attention: Signal Detection Across Two Channels

Key Terms

Communications; signal detection; target detection

General Description

Poorer signal detection performance may be expected from an observer monitoring several sources of input for the same targets than from monitoring only one source. In divided attention between two channels, detection of a target on one channel is more likely if in the competing channel the target is absent or is not detected. If the probability is high that the targets may appear simultaneously on more than one channel, it may be advantageous to have separate observers for each channel.

Methods

Methodological details are given in Table 1.

Experimental Results

- Detection performance is greater when only one channel is monitored at a time.
- Performance in divided attention depends on the perceived or actual presence of a target in the other channel; if there is no target or if it is missed, performance is better than if it is perceived.
- Detection accuracy in a channel decreases with an increase in the number of signals present on competing channels and as signals become closer in frequency.
- In Fig. 1, data are collapsed across days.

Repeatability/Comparison with Other Studies

Reference 1 reports variability with practice but replicates itself with new stimuli. Reference 2 shows separate data for each subject and indicates the same general findings across subjects. Together the studies show comparable effects for pure tones, relatively meaningless speech, and meaningful words.

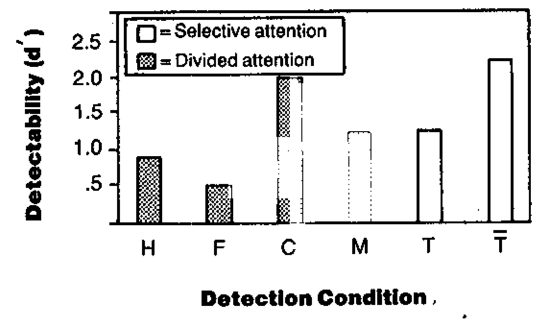


Figure 1. Target detectability (d') in one channel (ear) as a function of stimulus and response conditions in the second channel (other ear) (Study 1). Target could occur in either channel. In divided attention, listener attended to both channels simultaneously. Ordinate shows target detectability in one channel when subject's response for second channel was a hit (H), false alarm (F), correct rejection (C), or miss (M). In selective attention, listener attended to one channel and ignored the other. Detectability of target in attended channel is shown when unattended (off) channel contained a target (T) or did not contain a target ($\bar{T}$). (Adapted from Ref. 1)

Constraints

- Both studies require a complex set of button-press responses rather than meaningful responses.
- Study 2 measures the effects of divided attention where signals are presented amid high noise levels.
- Only 3 subjects were tested for Study 2.

Key References

*1. Ostry, D., Moray, N., & Marks, G. (1976). Attention, practice, and semantic targets. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 326-336.

*2. Pohlman, L. D., & Sorkin, R. D. (1976). Simultaneous three-channel signal detection: Performance and criterion as a function of order of report. *Perception & Psychophysics, 20*, 179-186.

Cross References

7.209 Factors influencing performance in selective listening tasks;

7.213 Divided attention: factors influencing performance on auditory tasks;

7.216 Auditory divided attention: effect of practice;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 1)	
Selective and divided attention studied Letter targets: 10 lists of 180 dichotic pairs of digits with letters inserted in digit streams such that half occurred simultaneously with a letter in the other channel and half did not Word targets: 10 lists of 100 pairs of monosyllabic words, where target words were animal names (70) and nontarget words, other nouns Messages presented (two pairs of signals per sec) dichotically via headphones accompanied by binaural white noise, with speech level of 70 dB sound pressure level (SPL) and signal-to-noise ratio −6 dB; subjects in sound-proof cubicle 200 trials/day/subject	Method of signal detection, within-subjects design Independent variables: type of attention (selective or divided), target on other channel(s) (presence or absence) Dependent variable: target detectability, measured as *d'* Subject's task: press button to indicate where target heard For letters, 8 student subjects tested 1 hr/day for 11 days; for words, 5 student subjects tested for 1 hr/day for 7 days
Study 2 (Ref. 2)	
Selective attention only studied Monaural presentation of 100-msec, 500-, 810-, and/or 1320-Hz sinusoidal signal in broadband Gaussian noise at overall level of 62 dB SPL over headphones to subjects in soundproof cubicle Interval was simultaneously marked visually, while subject selected three buttons, one yes/no pair for each frequency, and received feedback 600-800 trials per day per subject after practice	Method of signal detection within-subjects design Independent variable: frequency of signal Dependent variable: target detectability, measured as *d'* Subject's task: press "yes" or "no" response button 3 subjects, female students, tested after 20 hr of practice

7.215 Divided Attention: Effect of Mixed Modalities

Key Terms

Auditory recognition; backward masking; communications; masking; multi-sensory stimulation

General Description

A tone presented in a **backward masking** paradigm is recognized more accurately when presented alone (selective attention) than when it is paired with a visual presentation of a letter (divided attention), whether or not identification of the letter is also required. Letter recognition is also hampered by simultaneous tone presentation, but not to such great extent. For both visual and auditory recognition tasks, accuracy is greater as the interval between the target and mask increases.

Applications

Signal detection may be enhanced by minimizing distracting stimuli in all modalities, not just in the modality of the signal.

Methods

Test Conditions

- Binaural presentation via headphone of 20-msec, 800- (low) or 880- (high) Hz sine-wave test tones; 20-msec, 840-Hz, square-wave mask presented at 80-dB sound pressure level
- 4-msec LED-presentation of letters U or V which subtended a visual angle of 50 min arc in height and 38 min arc in width; visual mask consisted of alternating 2-msec presentations of the letters U or V for a total of 20 msec
- Masking intervals of 0, 20, 40, 70, 140, 220, or 340 msec; no mask presented on 1/8 trials
- Cue indicated whether tone, letter, or tone and letter were to be identified or the order of the stimuli on the trial
- On trials where visual and auditory stimuli were successive, intersignal interval was 1500 msec

Experimental Procedure

- Backward recognition masking with tone (and mask) presented simultaneously with letter (and mask); variation in which the letter and tone were presented successively
- Within-subjects design
- Independent variables: masking interval, simultaneous versus successive presentation of signals (divided or selective attention), report of both letter and tone (divided attention) versus report of only one (selective attention)
- Dependent variable: accuracy of report
- Subject's task: identify tone as high or low and/or identify letter; feedback provided
- 16 subjects, college students with some practice

Experimental Results

- Increasing the interval between signal and mask increases accuracy in all conditions.
- Both tone and letter recognition accuracy are worse when both must be reported (divided attention) than when only one of two is reported (selective attention) (Fig. 1).
- Tone recognition accuracy is impaired by simultaneous presentation of a letter (divided attention), relative to successive presentation (selective attention). Letter recognition accuracy is also impaired by simultaneous presentation, relative to successive presentation, but not to so great an extent (Fig. 2).

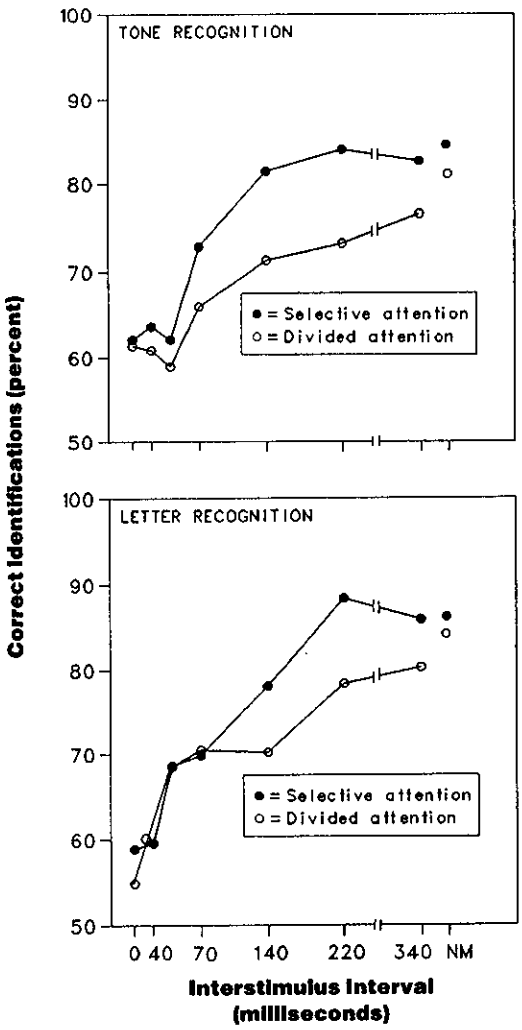


Figure 1. Recognition accuracy for tones and letters under backward masking as a function of interval between test stimulus and masking stimulus. Subjects reported pitch of tone (high or low) and identity of letter (U or V) presented simultaneously. In selective attention condition, subjects made either pitch or letter identity judgment; in divided attention condition, subjects made both judgments. For comparison, performance with no masking stimulus (NM) is shown. (From Ref. 1)

Repeatability/Comparison with Other Studies

Results are comparable to those of an earlier study in which subjects identified tone, timbre, and letter duration.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Only one type of auditory and visual signal tested.

Key References

*1. Massaro, D. W., & Warner, D. S. (1977). Dividing attention between auditory and visual perception. *Perception & Psychophysics, 21*, 569-574.

Cross References

7.206 Divided versus selective attention: effect on auditory recognition accuracy;

7.213 Divided attention: factors influencing performance on auditory tasks;

7.214 Auditory divided attention: signal detection across two channels;

7.221 Attentional and decision-making factors in component and compound tasks;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.421 Integration of visual and auditory alerts in warning systems

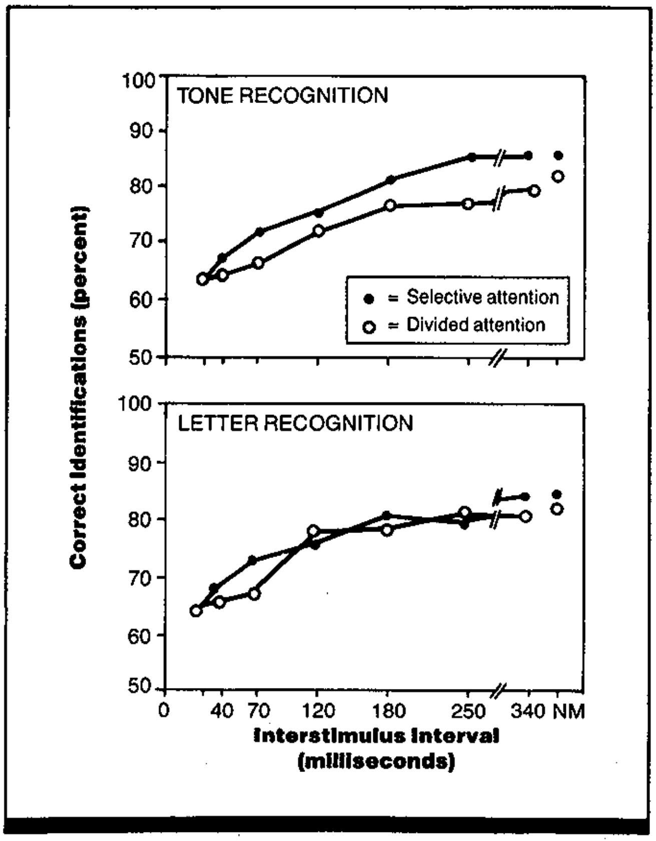


Figure 2. Recognition accuracy for times and letters under backward masking as a function of interval between test stimulus and masking stimulus. Subjects reported both pitch of tone and identity of letter after simultaneous presentation (divided attention condition) or successive presentation (selective attention condition) of the signals. NM = no mask condition. (From Ref. 1)

7.216 Auditory Divided Attention: Effect of Practice

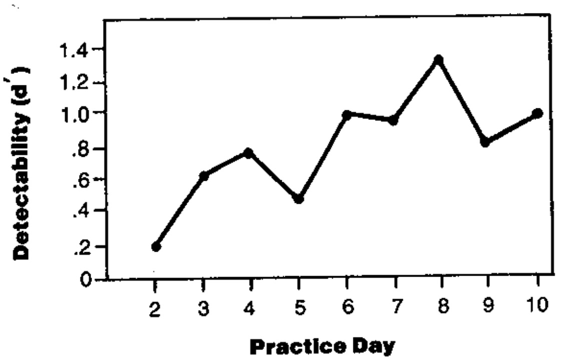


Figure 1. Detectability as a function of practice on a divided attention task. (From Ref. 1)

Key Terms

Communications; dichotic listening; practice; signal detection

General Description

When listeners are required to monitor a target on more than one channel (divided attention), detection improves with practice for 4-5 days (10,000 trials) and then reaches an asymptote. Performance never reaches the level obtained for selective attention.

Applications

Designs for which there is a high probability of targets occurring simultaneously on two channels.

Methods

Test Conditions

- Ten lists of dichotic pairs of digits, with letters inserted into the digit stream such that half the digits were heard simultaneously with a letter via the other channel and half were not
- Message rate: two pairs of signals per sec
- Messages presented through binaural white noise with speech level of 70 dB sound pressure level and signal-to-noise ratio of 6 dB
- Lists presented on eleventh day with instructions to monitor one ear only

Experimental Procedure

- Within-subjects design
- Independent variables: target in competing channel (presence or absence), type of attention (divided or selective), amount of practice
- Dependent variable: target detectability, measured as d'
- Subject's task: press appropriate button when target detected
- 8 student subjects tested 1 hr/day

Experimental Results

- Detection performance improves markedly for first 4-5 days and then levels off.
- Selective attention performance is much greater than even the most practiced divided attention performance.
- In Fig. 1, data are collapsed across conditions over days.

Repeatability/Comparison with Other Studies

In a similar design with different stimuli, authors tested new observers for 6 days, after the asymptote was reached (Ref. 1). The results of practice are not reported, so presumably they are comparable.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Ostry, D., Moray, N., & Marks, G. (1976). Attention, practice, and semantic targets. *Journal of Experimental Psychology: Human Perception and Performance*, 2, 326-336.

Cross References

7.209 Factors influencing performance in selective listening tasks;

7.213 Divided attention: factors influencing performance on auditory tasks;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask

7.217 Divided Attention: Effect of Age

Key Terms

Multi-sensory stimulation; short-term memory

General Description

Divided attention, measured in terms of the ability to report both members of *dichotically* presented pairs of digits, or to switch from auditory to visual tasks, or to attend to both auditory and visual stimuli simultaneously, declines with age, particularly between 40 and 50. However, there is an increase in performance around age 20. The dichotic task reported here can also be considered a short-term memory task because digits are usually grouped for report by ear of presentation (e.g., the digits heard in the right ear followed by the digits heard in the left ear). Thus all previously presented digits must be remembered during subsequent presentations, and the second group of digits (e.g., those from the left ear) must remain in memory while the first group (e.g., those from the right ear) are reported. Only the second group shows the decline. Physical exercise, perhaps because it increases cerebrovascular activity, may improve attention in older subjects (Ref. 2).

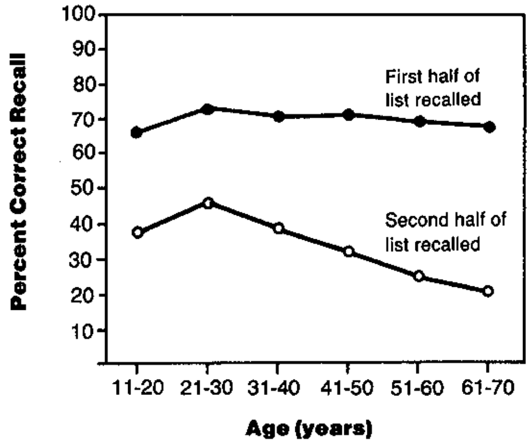


Figure 1. Percentage recall averaged across list lengths for first and second members of dichotic digit pairs as a function of subject's age (Study 1). (Adapted from Ref. 1)

Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 1)	
Groups of digits (1-6 digits per ear) dichotically presented as simultaneous pairs (e.g., "5" to left ear and "1" to right ear) through headphones at three digits per 2 sec Four trials per list length per subject; total of 24 trials per subject	Within-subjects design Independent variables: age of subject, number of dichotic pairs in list Dependent variable: recall accuracy, defined as average number of correct responses for digits presented to each ear Subject's task: recall digits presented Subjects: 10 males and 10 females in each of 6 age groups (11-20, 21-30, 31-40, 41-50, 51-60, 61-70); subject groups matched for mean orthodox digit-span scores
Study 2 (Ref. 2)	
Two Hebrew letters, presented on cathode ray tube in dimly illuminated cubicle; letter subtended visual angle of 3 deg in width and 4 deg in height 820- or 1200-Hz at 81 dB, presented through headphones Attentional flexibility; auditory or visual stimuli presented alone or in rapid alternation (auditory-visual combined condition), with each trial beginning 50 msec after subject's response to previous trial Time-sharing: stimuli presented alone or simultaneously (auditory-visual combined condition), with auditory task treated as primary, followed by 1000-msec silence, 500-msec visual warning cue, and 500-msec empty interval Feedback on accuracy after each block of trials 24 trials/subject for visual and auditory stimuli alone, 48 trials per subject for two combined conditions; 8 practice trials per subject per condition	Within-subjects design Independent variables: age of subject, perceptual mode condition Dependent variables: mean reaction time, percentage of errors in identification task; both for last three of five days of testing only Subject's task: press one or two of four piano-type response keys to indicate stimuli presented, responding to auditory stimulus first in simultaneous condition Subjects: 5 males and 9 females, average 27.5 yrs, 2 whose data were discarded due to equipment malfunction; 4 males and 10 females, average 68.0 yrs.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

In tasks requiring divided attention, poorer performance should be expected for older observers than for younger. An exercise program may enhance performance of older observers.

Methods

Methodological details are given in Table 1.

Experimental Results

- Subjects rarely report more than three digits per digit group (those digits presented to each ear), even for longer lists.
- Across age groups, accuracy in reporting the second group of digits decreases sharply for four or more dichotic pairs.
- For nearly all list lengths (number of dichotic pairs), performance is poorer for age group 11-20 than for 21-30.
- For all list lengths, accuracy for first group of digits reported does not change with age, whereas accuracy for second group reported declines with age (Fig. 1).
- Older subjects have longer reaction times than young subjects for all tasks, for stimulus combinations than for a single stimulus and for visual stimuli than for auditory stimuli in all comparable conditions (Fig. 2).

Variability

Standard deviations and percentages of error are reported in Refs. 1 and 2 but are not reproduced here.

Repeatability/Comparison with Other Studies

Decline in attention performance with age is commonly reported, at least for subjects >60 yrs. Older subjects show decreased reaction time for most tasks after participating in an aquatics exercise program; however, control subjects who do not exercise between testing periods also improve (Ref. 2).

Constraints

- Dichotic listening tasks used in divided-attention studies usually ask subjects to shadow (orally repeat) one of two simultaneously presented messages; thus they are strictly attention tasks that do not depend on short-time memory.
- Dichotic digit study suffers from floor effects for the second group of digits reported for long lists. Because *all* subjects got close to 0 correct here, it is impossible to determine age effects. In the average data displayed (Fig. 1), this problem is not apparent.
- Difference in visual and auditory reaction times for time-sharing task is confounded by instructions for subjects to report auditory stimulus first and, therefore, with less delay. However these instructions were not given for attentional flexibility task, yet results are similar.

Key References

*1. Inglis, J., & Caird, W. K. (1963). Age differences in successive responses to simultaneous stimulation. *Canadian Journal of Psychology, 17,* 98-105.

*2. Hawkins, H. L., & Capaldi, D. (1983). *Aging, exercise, and attentional capacity.* Unpublished manuscript, University of Oregon.

Cross References

7.212 Selective listening: effect of age;

8.301 Effect of type of test material on speech intelligibility;

8.315 Noise masking of speech: effect of interaural phase relations for listeners of different ages;

8.401 Effect of age on perception of altered and unaltered speech

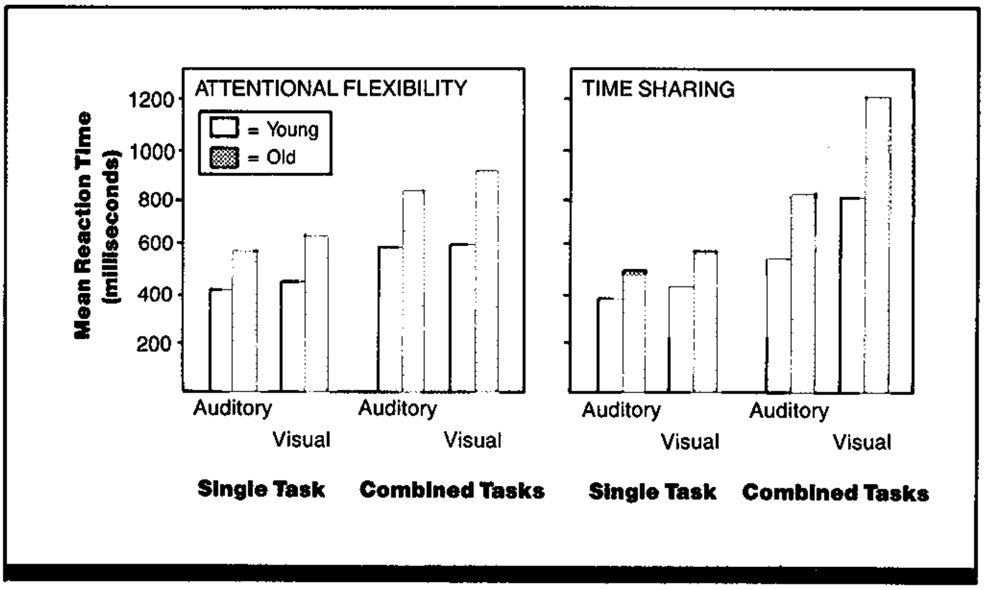


Figure 2. Mean reaction time for auditory and visual stimuli presented alone or together in time-sharing and attentional flexibility tasks for young and old subjects (Study 2). (Adapted from Ref. 2)

7.218 Visual Attention Switching Without Eye Movements

Key Terms

Eye movements; memory; monitoring; visual displays; visual search

General Description

Attention can be shifted to different locations in a visual display without moving the eyes. The attentional shift is continuous between two locations; that is, attention is directed toward intermediate points as attention shifts from the first location to the second. The time it takes to switch from element to element in a visual display is equivalent to the time it takes to switch from element to element in memory.

Applications

Situations in which operators must detect and respond manually to a visual signal when more than one location must be monitored, especially when expectation for a signal in one location is greater than in other locations.

Methods

Test Conditions

Study 1 (Ref. 1)

- Vertical fixation line through center of a box ~3 deg visual angle
- Warning cue was plus sign or arrow pointing left or right; each cueing condition occurred on a third of trials; plus sign cued random occurrence of target to left or right of fixation; arrow cue indicated 0.8 probability of target occurrence on indicated side (thus valid 80% of the time)
- Target stimulus was an "X" appearing 1 deg below warning cue and 0.5 deg left or right of fixation; interval between warning cue and target was 0, 50, 150, 300, 500, or 1000 msec

Study 2 (Ref. 3)

- Cross displayed at central fixation point on CRT screen for 500 msec cued target stimulus presentation consisting of one of four lights on a bar across the CRT screen, 8 or 18 deg left or right of fixation
- Arrow (cue) displayed at fixation point 500 msec after offset of cross, pointing left or right to indicate that farther light (18 deg) had 0.7 probability of occurrence (thus valid 70% of the time)
- Interval between cue and target was 50, 100, 150, 200, 350, or 500 msec for Exp. 1, and 75, 150, 225, 375, 575, or 800 msec for Exp. 2; 800-msec intertrial interval
- 15% of trials had no target presentation and observer had to withhold response

Experimental Procedure

Study 1

- Simple reaction time (RT)
- Within-subjects design
- Independent variables: target position uncertainty, occurrence of anticipatory eye movements, determined by electro-oculographic technique; interval between warning cue and target presentation
- Dependent variable: RT
- Observer's task: indicate detection of target by making manual response; feedback provided
- 8 observers with unknown amount of practice

Study 2

- Simple RT
- Within-subjects design
- Independent variables: target position uncertainty, interval between onsets of cue and target
- Dependent variable: RT
- Observer's task: indicate detection of target by pressing a button (same button for all lights)
- Observer told to attend to farther light on cued side but to fixate at center
- Central fixation monitored by electro-oculogram; trials on which eye movements occurred were repeated
- 9 observers with some practice

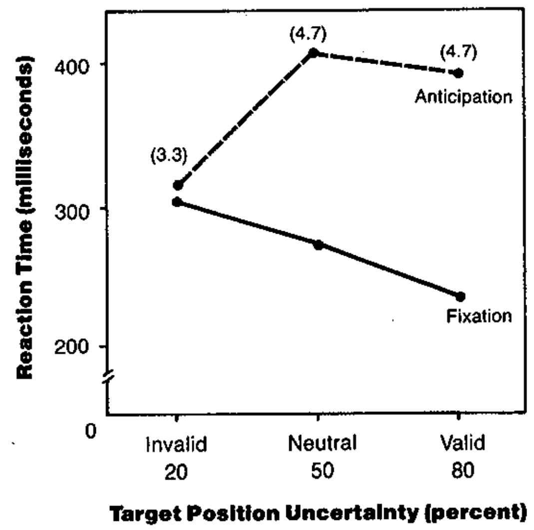


Figure 1. Response times for trials in which fixation was maintained (solid line) and in which anticipatory eye movements occurred (dashed line) (Study 1). Abscissa represents validity of cues in indicating location of target stimulus. Numbers in parentheses are percentage of anticipatory eye movements for each value of target position uncertainty. (From Ref. 1)

Experimental Results

- In Study 1, RTs for trials in which eye movements occurred are longer than RTs for trials during which fixation is maintained (Fig 1). These results imply that attention can be switched to various locations without shifting eye fixation, suggesting that a central system controls attention independent of overt eye movements.
- Response time decreases as validity of positional cue increases when fixation is maintained (Fig. 1).
- After presentation of a valid cue in Study 2, the difference between the RTs for near (an intermediate location between fixation and far light) and far lights is greater at an intermediate interval between onsets of cue and light (150 msec) than at much shorter and much longer intervals. There is no similar pattern of facilitation for the unexpected near light (i.e., when there is an invalid directional cue). This implies that attention "moves through" intermediate locations before reaching its destination, proceeding continuously between locations rather than in discrete jumps.
- In a related study, time to switch from one element to another in a visual display is about the same as the time to switch from one element to another in memory (Ref. 4). This further supports the action of a central system that controls attentional switching (Ref. 4).

Variability

No information on variability was given.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Repeatability/Comparison with Other Studies

The decrease in manual reaction time with increase in certainty of stimulus location is a very consistent finding. However, eye response times are less strongly affected by increase in position expectancy (Ref. 1). In addition, other studies have shown that subjects are able to share attention between two locations instead of switching back and forth between locations (Ref. 2).

Constraints

- Size of displays used here was fairly small (maximum of 18 deg from fixation). Larger displays may cause attentional switching to operate in a different fashion.

Key References

*1. Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), *Modes of perceiving and processing information*. Hillsdale, NJ: Erlbaum.

2. Shaw, M. L. (1982). Attending to multiple sources of information: I. The integration of information in decision making. *Cognitive Psychology, 14*, 353-409.

*3. Shulman, G. L., Remington, R. W., & McLean, J. P. (1979). Moving attention through visual space. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 522-526.

4. Sternberg, S. (1967, April). *Scanning a persisting visual image versus a memorized list*. Paper presented at the meeting of the Eastern Psychological Association, Boston, MA.

Cross References

4.103 Memory search rates;

7.110 Probability of correctly monitoring multi-channel displays;

7.219 Division of attention among spatial locations;

7.508 Visual search rates without eye movements

Table 1. Reaction time for the intermediate point subtracted from that for the far expected point, as a function of interstimulus-onset interval (Study 2). (From Ref. 3)

	Interstimulus-Onset Interval (milliseconds)											
	Experiment 1						Experiment 2					
Item	50	100	150	200	350	500	75	150	225	375	575	800
Far expected – intermediate	9	6	23	23	15	12	6	20	14	10	10	13

7.219 Division of Attention Among Spatial Locations

Key Terms

Cognitive complexity

General Description

Dividing attention among several spatial locations produces more deleterious effects upon detection of letters than upon detection of white spots. With letters as targets, detection performance drops significantly as the number of possible locations increases. With white spots as targets, no large decrease in performance occurs. Performance differences between **compound tasks**, with many target locations, and component tasks, with fewer target locations, are small for simple stimuli, but large for complex stimuli. These findings are taken as evidence that letters involve more capacity limitations in their coding than do white spots, which are only slightly affected by decision uncertainty.

Methods

Test Conditions

- Fixation point in middle of visual display; targets could appear at each of four corners
- Targets either letters or white spots
- For letter condition, specific letter designation as target, other letters distractors; for white spot condition, target involved brightening of one or more corners
- On two-location trials, either zero, one, or two targets could appear; on four-location trials, either zero, one, two, three, or four targets could appear

Experimental Procedure

- Independent variables: number of possible locations, type of target
- Dependent variable: probability of correct detection
- Observer's task: for letters, judge location(s) of target letter in array; for white spots, judge brightened location(s)
- 6 well-practiced observers

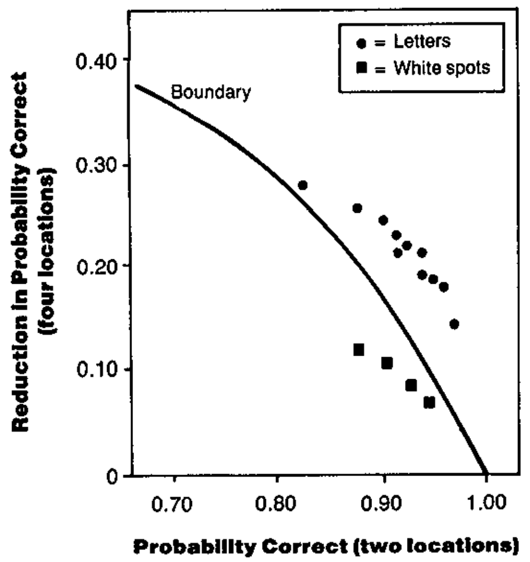


Figure 1. Reduction in probability of correct detection as the number of possible locations increases from two to four, for letters and white spots. Boundary line indicates theoretically derived distribution-free curve, above which capacity limitations in coding are involved because of divided attention processes. (From Ref. 2, based on data from Ref. 1)

Experimental Results

- For observers detecting a white spot, probability of a correct detection decreases by <10% as the number of possible target locations increases from two to four.
- For detection of letters, there is a reduction of 15-30% in detection performance as the number of possible locations increases from two to four.
- The obtained performance drop in detection of white spots with increasing number of possible locations is well below the boundary above which divided attention or stimulus coding would be implicated (CRef. 7.221). Instead, this slight drop in performance can be accounted for by decision uncertainty.
- The performance drop for detection of letters with increasing number of locations is considered large enough to involve divided attention processes and cannot be explained entirely by decision uncertainty (CRef. 7.221).

Variability

For both letters and white spots, the standard errors were <0.015; no interobserver differences were reported.

Constraints

- Results cannot be extended to differences between complex patterns such as letters, numbers, and other symbols.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Shaw, M. L. (1980). Identifying attentional and decision making components in information processing. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 277-296). Hillsdale, NJ: Erlbaum.

2. Shaw, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma (Ed.), *Attention and performance X* (pp. 109-121), Hillsdale, NJ: Erlbaum.

Cross References

7.220 Concurrent visual search;

7.221 Attentional and decision-making factors in component and compound tasks;

7.508 Visual search rates without eye movements

7.220 Concurrent Visual Search

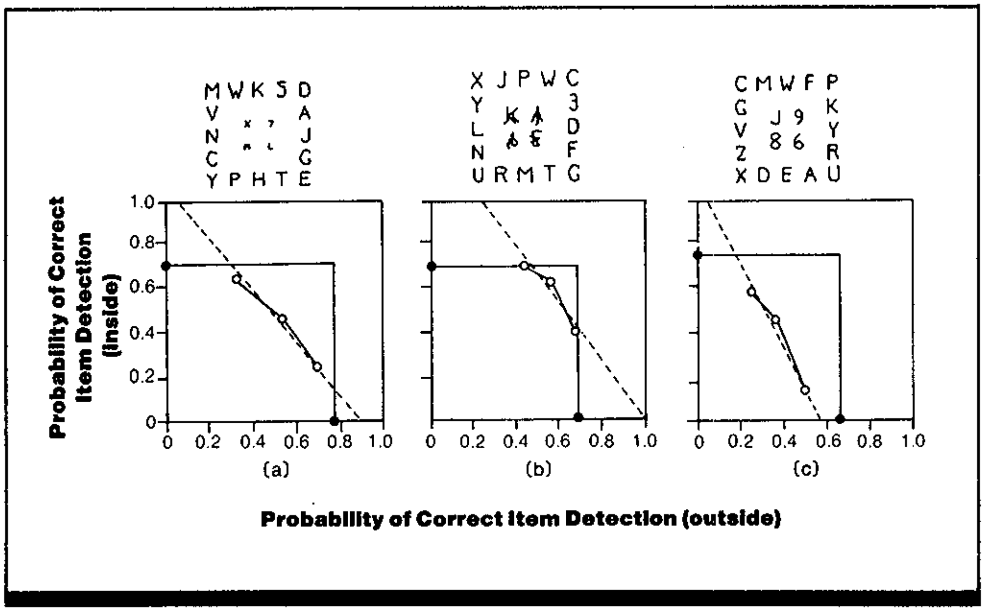


Figure 1. Stimulus configurations and the empirical attention operating characteristic (AOC) curves (lines connecting open circles) for three pairs of concurrent tasks. (a) A large (outside) and small (inside) numerical target appear concurrently for independent detection. Abscissa and ordinate indicate the percent of correct identifications of the outside target and inside target, respectively. Isolated control conditions are shown as filled circles on the coordinate axes. The intersection of the perpendiculars drawn through the control points defines the independence point for each pair of tasks. Concurrent performance is indicated by open circles. Attention conditions (open circles) ordered from upper left to lower right, respectively, are 90% to inside, equal, and 90% to outside, with each point representing the average of two or three blocks of trials. The heavy line connecting the data points is the empirical AOC curve. The broken line represents the best fitting straight line. (b) Same as (a) except the inside task is detection of a noise-obscured numeral target of same size as the outside target. (c) Same conditions as (a) except the concurrent inside task is detection of a letter target among three numerical distractors. (From Ref. 1)

Key Terms

Attention operating characteristic; concurrent tasks; visual search

General Description

An experimental technique to examine the effects of **divided attention** presents an observer with two tasks of equal difficulty; the observer is instructed to allocate a specified portion of attention toward each task (e.g., 90% to one task and 10% to the other). Data are collected under different attention allocation schedules and are plotted as **attention operating characteristic** (AOC) curves. The concurrent visual search methodology generates compensatory performance; as performance on one task improves, performance on the other worsens.

Applications

Allocation of attention studies within a single sensory modality; situation where an observer must search for more than one target in a specified visual location, such as for targets on a radar screen.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Concurrent visual search task with attention divided between inside and outside array
- Observer instructed to allocate attention in one of three ways: 90% to inside array and 10% to outside array, 90% to outside array and 10% to inside array, or 50% to each array
- Three types of inside arrays: three to four small letters, three to four noise-obscured letters, or three to four numbers (for detection of letters among numbers for the inside array)
- Each display of 20 alphanumeric characters was arranged in two concentric squares with 16 characters forming the perimeter of the outside square and 4 characters forming the corners of the inside square (Fig. 1); for numbers among letters, all characters were letters except on critical arrays, which had one randomly chosen digit on outside array and one randomly chosen digit on inside array; all but two characters were digits for search of letters among numbers
- Critical array presented after 7-12 noncritical arrays and followed by another set of at least 12 noncritical arrays; new array presented every 240 msec
- In control conditions, observers reported only outside target and ignored inside target, or vice versa

Experimental Procedure

- Within-subjects design
- Independent variables: attention-allocation instructions, composition of inside array, target category
- Dependent variables: percent correct identification of inside and outside targets
- Observer's task: state the identity and location of targets and indicate confidence level for each response
- 2 observers

Experimental Results

- The AOC curves have slopes of about − 1, indicating that better performance on one task (because of greater attention allocation) results in poorer performance on the other task.
- The three inside tasks are not equally compatible (more compatibility implies less interference) with the search for a number in the outside array of letters: searching for an inside letter target is least compatible, searching for an inside number target is more compatible, and searching for an inside noise-obscured number target is most compatible. As compatibility increases, the two search tasks become more independent (i.e., they have less mutual interference).

Variability

Inter- and intra-observer variabilities were not reported but, in general, they are not large for observers with extensive practice in visual search tasks.

Constraints

- Factors such as presentation rate, array size, target type, target size, and number of confidence levels can affect performance; therefore generalization of these results is limited.

Key References

*1. Sperling, G., & Melchner, M. J. (1978). The attention operating characteristic: Some examples from visual search. *Science, 202,* 315-318.

2. Sperling, G., & Melchner, M. J. (1978). Visual search, visual attention and the attention operating characteristic. In J. Requin (Ed.), *Attention and performance VII*. Hillsdale, NJ: Earlbaum.

Cross References

7.218 Visual attention switching without eye movements;

7.512 Search time: effect of number of targets and target complexity;

7.517 Search time: effect of number of background characters and display density;

7.524 Visual search for multiple targets;

7.525 Target acquisition in real-world scenes;

Handbook of perception and human performance, Ch. 2, Sect. 5.3

7.221 Attentional and Decision-Making Factors in Component and Compound Tasks

Key Terms

Concurrent tasks; decision making; uncertainty; visual search

General Description

Research on attention compares performance on a compound task with performance on a simpler, component task to determine if a performance difference can be attributed to changes in stimulus coding or to decision uncertainty. A compound task requires divided attention over several stimulus alternatives, typically at least four, whereas a component task allows for focused attention on a smaller number of alternatives. Figure 1 illustrates several stimulus configurations used in these paradigms. As indicated, attention can be divided spatially (over different regions in the visual field) or temporally. The empirical finding is that observers perform better on component tasks than on compound tasks; performance deteriorates with increasing uncertainty, i.e., with an increasing number of stimulus and response alternatives. A theoretical explanation by Shaw (Refs. 1, 2) provides a method to test the two theories of performance decline with uncertainty or divided attention. The stimulus-coding theory claims that dividing attention through compound tasks results in each alternative receiving less stimulus coding than in component tasks. Poorer coding ultimately lends to poorer task performance. The decision uncertainty theory argues that the greater number of alternatives in compound tasks creates problems in the decision process which leads to poorer performance. Shaw's model provides a distribution-free prediction of the maximum drop in performance that can be attributed solely to decision uncertainty. Greater decline can be attributed to other factors, such as reduced coding.

Applications

Tasks in which spatial and/or temporal uncertainty are varied; tasks involving divided attention between two sensory modalities.

Empirical Validation

Experimental results have been compared for a compound task versus a component task. One study used either white spots or letters with either two or four alternatives. Performance dropped sharply with increasing uncertainty for letters, but not for white spots. Shaw's model indicates that both decision uncertainty and stimulus coding are involved in performance decline with letters, whereas only decision uncertainty produced the slight decline for white spots.

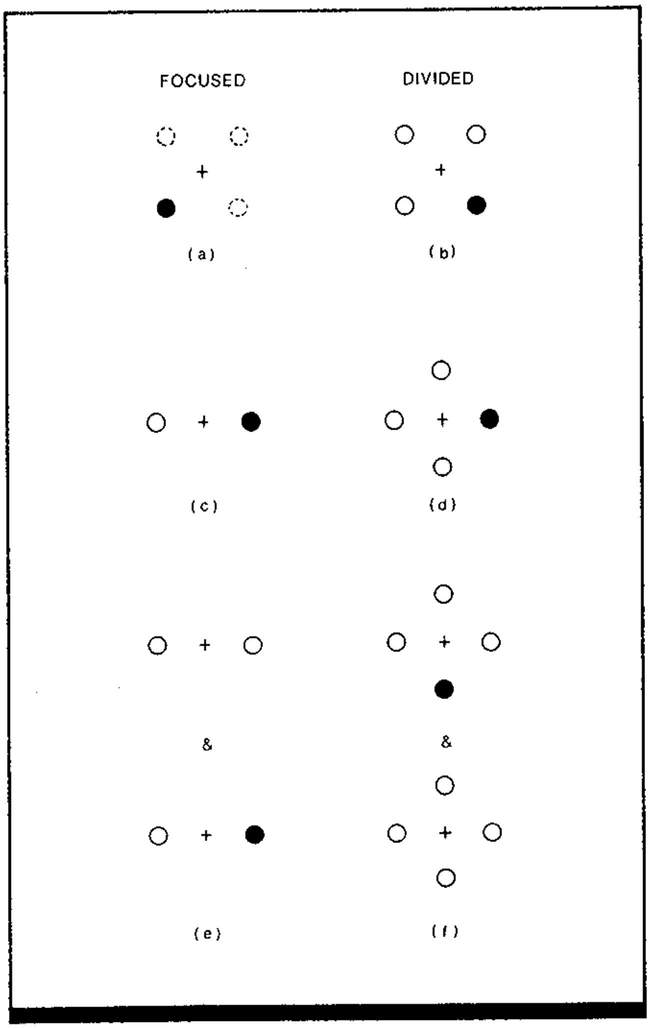


Figure 1. Stimulus configurations used in studying attention. Each panel illustrates a particular, potential stimulus. A cross indicates the fixation point; filled circle, a target; and open circle, a noise or non-target stimulus. (a) Yes/No detection: stimuli for focused attention in component tasks, targets would occur only in the particular location selected by the observer; the dashed circles indicate that other locations were displayed, nonetheless. (b) In divided attention of compound tasks, the target could occur in one of four possible locations, shown here in the southeast location. (c, d) Forced-choice location: the target occurs in one of two locations, panel (c), or one of four locations, panel (d). (e, f) Two-interval forced-choice: two temporal intervals (separated by and in panels) within which target can occur are defined for observer. (From Ref. 3)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Validation used very simple and very complex stimuli, and extensions of the model to stimuli of intermediate complexity are not obvious.
• The model does not apply to stimuli of the same degree of complexity and should not be used to compare complex stimuli, such as letters, words, or other symbols.
• The model does not specify other attentional processes that could produce drops in performance.
• Many factors have been found to affect attention, such as amount of practice, fatigue, drugs, range and number of alternatives, and payoff matrices, so that caution should be exercised in using the model to explain declines in performance in dividend attention tasks.

Key References

*1. Shaw, M. L. (1980). Identifying attentional and decision making components in information processing. In R. S. Nickerson (Ed.), *Attention and performance VIII*. Hillsdale, NJ: Erlbaum.

2. Shaw, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma (Ed.), *Attention and performance X*. Hillsdale, NJ: Erlbaum.

3. Sperling, G. (1984). A unified theory of attention and signal detection. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention*. New York: Academic Press.

4. Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in human information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance. Vol. I: Sensory processes and perception*. New York: Wiley.

Cross References

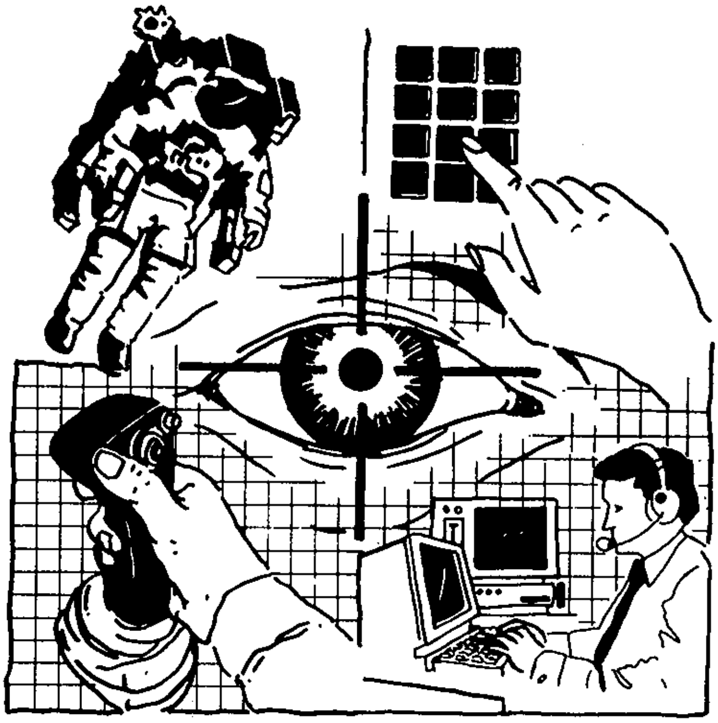
7.219 Division of attention among spatial locations;

7.220 Concurrent visual search;

7.524 Visual search for multiple targets

Notes

Section 7.3 Monitoring Behavior and Supervisory Control



7.301 Monitoring and Supervisory Control

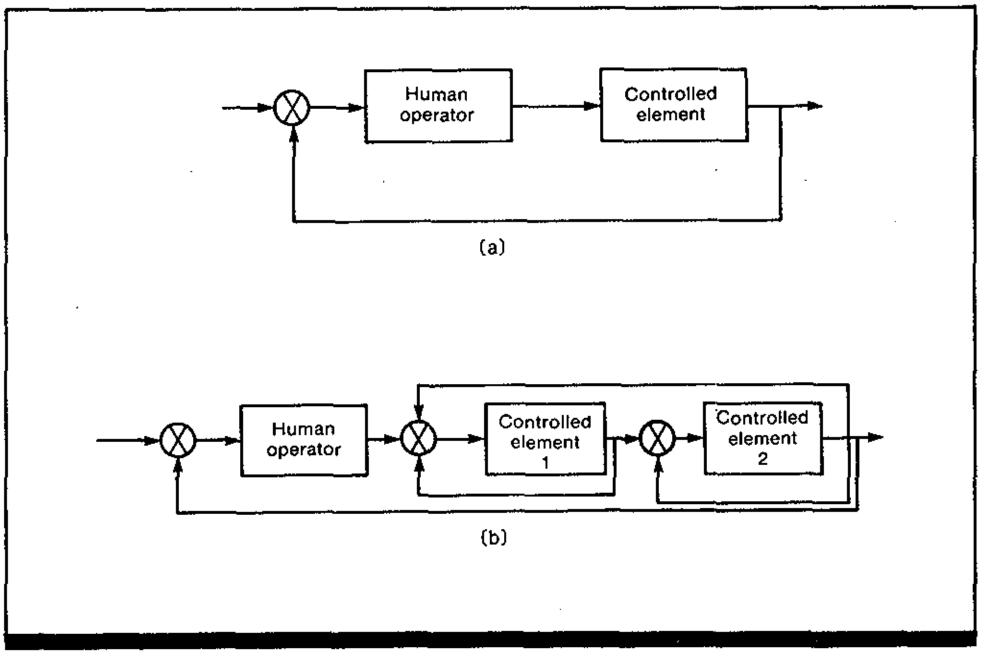


Figure 1. General models of (a) manual control and (b) supervisory control processes. (From Ref. 1)

Key Terms

Control strategy; control theory; decision making; failure detection; function allocation; human-computer interface; human operator models; instrument monitoring; man-machine models; manual control; monitoring; optimal control; planning; supervisory control; visual displays; workload

General Description

Monitoring is the process of sampling displayed status information to decide if a system is in a normal state and under control. Monitoring is a necessary but not sufficient condition for exercising supervisory control.

Manual control or direct control (Fig. 1a) means that a human directly maintains or changes the state of a system (via manual, electrical, electromagnetic, or hydraulic techniques). It can be modeled as a simple, single degree of freedom, closed-loop servosystem. Monitoring of displayed error status is necessary to determine when—and how much—action is needed, as shown by the feedback loop on the model.

Supervisory control is a hierarchical control scheme whereby the status of a system (Controlled element 2) is remotely monitored by a human (Fig. 1b). However, control is exercised through the mediation of an "intelligent" controller (Controlled element 1), capable of autonomous decisions and controlling actions, rather than by the supervisor's direct action. Some outer control loops are closed through the operator, other autonomous inner loops only through the mediating controller. Monitoring is necessary to determine when Controlled element 1 requires adjustment or must be overridden. Although this intermediary controller could be another human, only those situations where a computer performs this role are considered here.

A simple example of monitoring is looking at an automobile's gas gauge to determine fuel status. An example of manual control is maintaining speed and trajectory via an automobile's accelerator pedal and steering wheel, while monitoring the speedometer and the outside scene through the windshield to determine needed corrections. Examples of supervisory control include (1) driving a car equipped with automatic speed control and effecting speed changes, as required, through the automatic controller; (2) flying an aircraft by means of an onboard computer that optimizes the route and operates the control surfaces; and (3) controlling a nuclear power plant by programming a control computer.

The human can be considered a single-channel processor of rather limited capacity, who samples and thinks about only one thing at a time. Eight aspects of human information processing that are highly relevant to supervisory control are shown in Table 1. Since information processing, cannot be observed, it is important to determine various operator behaviors that *can* be observed, measured, and predicted using supervisory control models.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Some of the observable behaviors related to the eight information processing tasks are also noted in Table 1. These include (1) how long it takes the operator to begin some process (latency), (2) how long it takes for task completion (duration), (3) the number and direction of visual links made between displays, (4) the smallest change that can be detected by the operator (difference threshold), (5) number of errors of omission (missed signals), and (6) number of errors of commission (false alarms, incorrect time of response, incorrect response, number of corrections required, etc.).

Numerous models have been proposed to describe the process of supervisory control. These draw on well-established modeling techniques based on concepts such as manual control theory, optical control theory, optimal estimation theory, queuing theory, and decision theory. Several of these models are included in this section. Models directly useful for making *predictions* (especially useful in designing supervisory control systems) are noted as cross references in Table 1. Other models included in this section are primarily *descriptive*—useful for understanding and explaining various aspects of supervisory control systems (CRefs. 7.303, 7.308, 7.309, 7.312, 7.316).

Several advantages of supervisory control are listed in Table 2. Generally, these can be characterized as ways a computer can take over tasks to save the human's effort for other purposes (and perhaps improve efficiency).

During supervisory control, time constants of outer loops are always longer than those for inner loops, and increase in a geometric progression through the loops. If the loops contain integrators (a common type of control), system response speed decreases at least as fast as a geometric progression of ratio 0.8. Effectively, the operator need not work so rapidly and has time to control more loops—that is to control more complex systems.

On the other hand, there are disadvantages to supervisory control. Increasing time constants slows down the system's response to control signals and this makes the task harder. Observations of error signals must be integrated over time, and this imposes a heavy mental load. The requirement for fast-control responses (the bandwidth for control) may be lower, but the task may not be easier; instead of performing continuously, the operator will make discrete control movements from time to time, and then wait to see what happens. Finally, when an emergency requires the operator to reenter the inner control loop, unfamiliarity with the system will make the task much more difficult (CRef. 7.304).

Table 1. Human information processing aspects of supervisory control, related human parameters that can be measured or predicted, and relevant entries in this section.

Information Processing Tasks	Measurable Parameters	Cross References
Scheduling: Deciding the moment to sample each variable	Latency period (time to begin) Eye movements (links) between displays: frequency, direction	7.302, 7.314, 7.315, 7.318, 7.319
Sampling: Examining a display that is a source of data on a variable	Dwell time (duration of fixation) Detection threshold	7.302, 7.312, 7.314, 7.315, 7.318, 7.319
Data acquisition: Obtaining data through the sense organs from the sampled source	Dwell time (duration of fixation) Errors: missed signals, false alarms, wrong value	7.302, 7.304, 7.305, 7.312, 7.314, 7.315, 7.318, 7.319
Combining information: Making use of data from several sources to get a better estimate	Eye movements (links) between displays: frequency, direction Time to correlate information (duration)	7.302, 7.304, 7.305, 7.312, 7.314, 7.318, 7.319
Decision making: Deciding whether an abnormal state exists and if intervention is needed	Latency period (time to begin) Time to reach conclusion (duration) Errors: missed signals, false alarms	7.304, 7.305, 7.306, 7.307, 7.310, 7.312, 7.315
Diagnosis: Determining the system's true state and how to deal with the problem	Errors: missed signals, false alarms, wrong response time, wrong value	7.304, 7.305, 7.306, 7.312
Execution: Performing the appropriate actions to maintain the desired states	Latency period (time to begin) Time to complete action (duration) Errors: wrong response time; incorrect force, magnitude, or direction Corrections: quantity needed, time to correct	7.304, 7.305
Function allocation: Allocating decisions and control between operator and computer	Latency period (time to begin) Errors: missed signals, incorrect actions	7.304, 7.307

Key References

1. Moray N. (1986). Monitoring behavior and supervisory control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.) *Handbook of perception and performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

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Cross References

7.302 Sampling behavior during process-control monitoring;

7.303 Hierarchically structured control models;

7.304 Fault detection and response with different levels of automation;

7.305 Time required to detect, diagnose, and repair faults;

7.306 Training of operators for supervisory control;

7.307 Allocation of decisions between human and computer;

7.308 Sharing of knowledge and control between supervisor and computer;

7.309 General model of supervisory control;

7.310 Optimal estimation model;

7.311 Application of optimal control theory to monitoring performance;

7.312 Comparison of different research settings for study of supervisory control;

7.313 Eye fixations and eye movements during display monitoring;

7.314 Factors affecting monitoring performance;

7.315 Effect of display size on visual fixation;

7.316 Models of observer monitoring performance;

7.317 Senders' periodic sampling model of display monitoring;

7.318 Markov model for eye transitions during display monitoring;

7.319 Queuing model of display monitoring;

7.901 Characteristics of humans as decision makers;

9.512 Modeling of the human operator: the optimal control model;

Table 2. Advantages of supervisory control over manual control of systems and the information processing tasks affected by these advantages.

Supervisory Control Advantage	Information Processing Tasks	
Workload reduction for operator; performance of dull or fatiguing tasks by computer	Scheduling Sampling Data acquisition Combining information	Decision making Diagnosis Execution Allocation
Overall performance improvement, with computer doing some control tasks while operator concentrates on other tasks	Scheduling Sampling Data Acquisition Combining information	Decision making Diagnosis Execution
Nearer optimum speed, smoothness, power from computer, once taught	Scheduling Sampling Data acquisition Combining information	Decision making Diagnosis Execution
Task planning improvement by provision of online simulation, predictor displays, etc.	Scheduling Combining information	Decision making Execution
Fail-soft* capability when operator response time is not adequate or monitoring displays fail	Scheduling Sampling Combining information	Decision making Diagnosis Execution
System failure monitoring, detection, and diagnosis aided	Sampling Data acquisition Combining information	Decision making Diagnosis
Easier direct control by operator, when needed, via display and control aids	Sampling Data acquisition	Decision making Execution
Performance of tasks operator can specify, but not perform, due to time or space remoteness, noise, time delay, etc.	Sampling Data acquisition	Diagnosis Execution
Hazardous environment cost reduction for life support systems, plus saved lives, by eliminating need for operators there	Sampling Data acquisition	Diagnosis Execution

*Fail-soft procedures allow a system to fail at a rate that prevents catastrophic shocks to its components, operators, and the public, when failure cannot be prevented.

Notes

7.302 Sampling Behavior During Process-Control Monitoring

Table 1. Variables affecting sampling behavior. (Adapted from Ref. 1)

Variable	Effect on Sampling Behavior
Random process variations ("noise")	Once a process has been correctly adjusted so that there is no residual drift due to control setting errors, the operator's background sampling rate is dependent on the highest frequency variation that causes excursions outside allowed tolerance limits.
Uncertainty introduced by errors in operator control actions	When the controlled variable is within the allowable range but is drifting due to an error in control setting, the sampling rate is dependent on the rate of drift and rises when the variable is near a tolerance range limit.
System lag in response to major control changes made by operator	When a variable is outside of its tolerance range and the operator makes a control change to correct it, a sample is taken at a time nearly equal to 80% of the lag in system response to control change; if this sample does not result in a further control change, one or two additional samples are taken at similar intervals.
Observation of unusual happenings	Whenever anything unusual is noted about the system or its surroundings, there is a rise in the sampling rate.
Practice effects on rate of change estimates	The rate of change of a variable is initially estimated by prolonged observation during one sample; with practice, the more efficient procedure of noting the differences between successive readings is adopted; in general, no attempt is made to estimate higher derivatives.

Key Terms

Attention; monitoring; process control; Shannon-Wiener sampling theorem; uncertainty; vigilance

General Description

An operator's behavior during controlling or monitoring tasks shows short-term fluctuations in sampling rate (i.e., how often relevant displays are viewed). The durations of the intervals between samples (display views) are based on the way data gained in the sample reduces the operator's uncertainty about the behavior of the process(es) being sampled.

For example, when an operator is dividing attention between two activities, the operator does not simultaneously attend to both activities (e.g., reading a newspaper while also monitoring and controlling a Process A, which must be kept within certain bounds or a penalty is incurred). Assume that the operator has just observed that Process A is right on specification and diverts attention to the newspaper. As time passes, the operator's uncertainty regarding the state of Process A progressively increases. Accordingly, the operator becomes more and more uneasy due to the increased probability of Process A being outside permissible limits and the concomitant risk of incurring a penalty. However, any time the operator samples Process A, this will "cost" something, at least the time taken away from reading the newspaper. As uncertainty continues to increase with time, the operator mentally estimates the expected sampling payoff, which is the difference between the gain (reduction of uncertainty) and the loss (the sampling "cost"). Whenever the expected payoff becomes positive, the operator will take a sample. This causes uncertainty to decrease to zero and the cycle begins again (Ref. 1).

Thus Crossman et al. (Ref. 1) propose that the length of the sampling interval is determined jointly by (1) the rate of growth of uncertainty, (2) the penalties for process errors, and (3) the sampling costs. The first factor (rate of growth of uncertainty) was examined in several studies. Field studies were conducted examining a machine operator's task of controlling the basis weight of paper being made in a paper mill; laboratory studies realistically simulated the task of water-bath control in a chemical plant. The experimental studies were designed to examine the detailed relationships between sampling interval and system state.

For these studies, the Shannon-Wiener sampling theorem as applied in Ref. 2 (i.e., that the operator's minimum sampling rate is determined by the process bandwidth) successfully predicted operator's behavior when process bandwidth was defined in terms of "the highest frequency component of random fluctuation having a peak amplitude greater than the assigned tolerance" (Ref. 1). However, Crossman et al. note that the sampling behaviors could not be explained in terms of information theory (the sampling theory) alone, but also depend upon other factors in the more general problem of control: required accuracy; error costs; operator's knowledge of system structure, degree, type, and predictability of disturbances; response lag effects; and the effects of forgetting.

Table 1 lists several empirical generalizations specifying how some of these factors influence sampling behavior.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Design of displays so that efficient scanning patterns are encouraged or even enforced by the display itself.

Constraints

• Additional highly detailed analysis of contributors to operator uncertainty, such as rate of growth over time, effects of sampling costs, and forgetting, is needed before even moderately accurate estimates of sampling rates can be made.

• The quantitative performance data needed for design applications will require additional detailed study on: (1) the pattern of attention to displays recorded over long periods of time; (2) the accuracy of time estimation and its relation to sampling behavior; and (3) the effects of operator uncertainty about the nature of the system's response to control actions.

Key References

*1. Crossman, E. R. F. W., Cooke, J. E., & Beishon, R. J. (1974). Visual attention and sampling of displayed information in process control. In E. Edwards & F. P. Lees (Eds.), *The human operator in process control* (pp. 25-50). London: Taylor & Francis.

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Cross References

7.301 Monitoring and supervisory control;

7.309 General model of supervisory control;

7.313 Eye fixations and eye movements during display monitoring;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

7.317 Senders' periodic sampling model of display monitoring

7.303 Hierarchically Structured Control Models

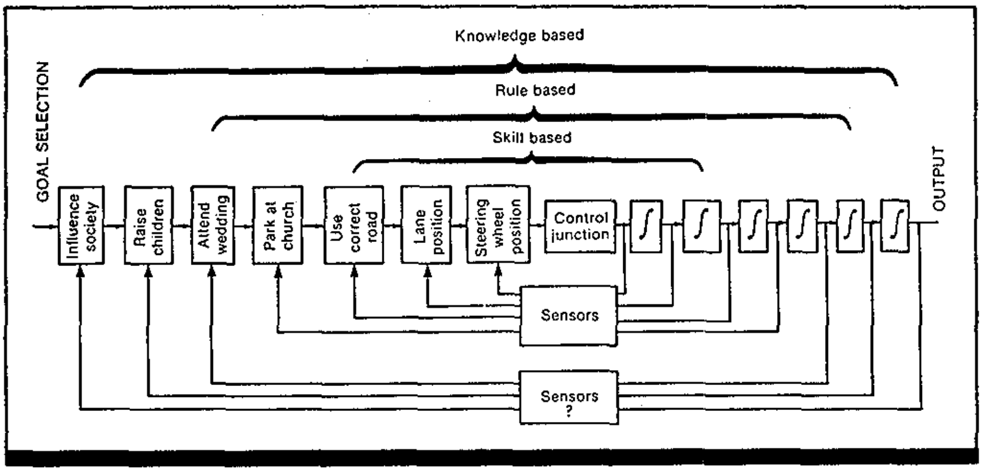

Figure 1. Hierarchically structured model for human supervisory control behavior in a complex system. *(From Handbook of perception and human performance)*

Key Terms

Decision making; expert systems; human operator models; manual control; model hierarchies; monitoring; optimal control; optimal estimation; process control; supervisory control

General Description

Monitoring and control of complex systems by human operators can be modeled as a hierarchical, multi-looped structure with an organizing taxonomy based on three levels of operator activity or behavior: skill-based, rule-based, and knowledge-based. Figure 1 illustrates this taxonomy, using the example of an automobile journey to a wedding, plus subsequent events (time scale is not constant).

The innermost loops represent continuous manual control of the car using largely automatic, skill-based behavior. Sensors are the eyes, ears, and vestibular and kinesthetic receptors. Stimuli are referred to as "signals": continuous, quantitative, sensed information about the time-space behavior of the environment. These loops are appropriately represented by optimal control theory (OCT) (CRef. 9.512).

The middle loops represent estimating and rule-based behavior, as the driver processes the noisy visual information necessary to get to the desired location. "Error signals" invoke rule-based programs that result in appropriate control actions. Stimuli are perceived as "signs": indications of the state of the environment (usually labeled by a name) for which convention or prior experience provides rules of behavior. Optimal estimation theory (OET) can be used to model these loops (CRef. 7.310).

The outermost loops represent goal-driven, knowledge-based procedures (raising children, influencing society). Reaching such general goals requires all three levels of behavior, with "error signals" a function of how the goal is interpreted, and "sensors," per se, not directly involved in recognizing goal achievement. Information is perceived as "symbols": internal representations (models) for abstract concepts tied to objects, functions, properties, relationships, etc., and used for reasoning and computations.

Figure 2 expands on this idea, relating behavior level to how frequently an event occurs and to the potential loss or the cost of failures. Events that occur frequently and have

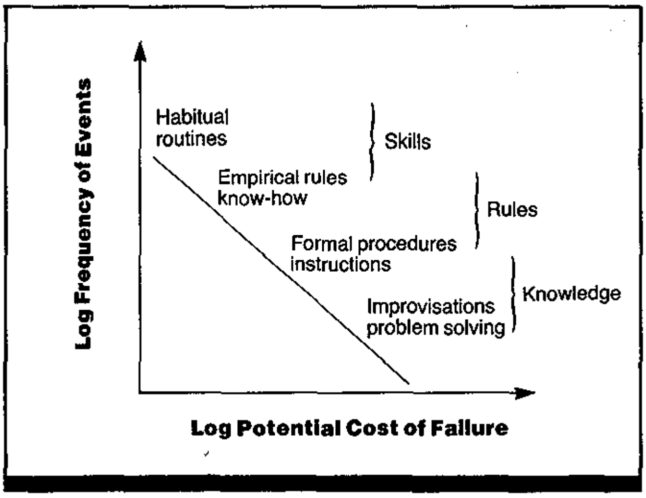

Figure 2. Model of expected human behaviors and behavior levels, as related to event frequency and to potential cost of error or failure. (From *Handbook of perception and human performance*)

small costs for failures (errors) provide the opportunity to acquire habitual, automatic, skilled behaviors. In contrast, rare (often unforeseen) events with high cost of errors do not usually invoke automatic behaviors; rather, knowledge-based, problem-solving procedures are used.

Figure 3 hypothesizes an "operator surface" that encloses a space in which the human can solve control problems without computer aiding. The surface is defined along axes representing (1) the frequency with which the events occur, (2) the potential cost of error or failure, and (3) the amount of time available for operator response. The nature of the operator response (automatic, rule-based, or decision-making) and the consequences for system design are determined (to some degree) by where the event lies within the shell. For example, computer aiding will be provided in a well-designed system so that an operator will not be expected to respond rapidly to a rare event with potential high cost for failure.

Table 1 summarizes the characteristics of events and human behaviors for each of the three hierarchical control levels, as represented by inner, intermediate, and outer loops in various OCT, OET, and other model structures.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Primarily useful as a framework for discussion of human behavior. *Potentially* useful for function, task, and workload analyses, to assist in categorizing types of behaviors during the enumerating and cataloging process; for developing models of microprocesses under control of a system executive; and for modeling human processes during development of artificial intelligence algorithms, especially for expert systems.

Constraints

- The hierarchical model is intended to be strictly descriptive and qualitative; attempts to convert it to be predictive or to yield quantitative results may not be appropriate.
- Models based on OCT and OET should not be overextended; experienced human controllers exhibit many nonlinearities and often-unexpected adaptive behavior.
- Complex systems are comprised of variables that are time varying, non-random, and not independent, but instead are coupled through feedback loops and other processes.
- Operators have different kinds of mental models for inner-loop and outer-loop control, but usually are unable to express these models in words or pictures.
- The boundaries between the three levels of behavior are unclear; each researcher must determine these for the tasks under consideration.

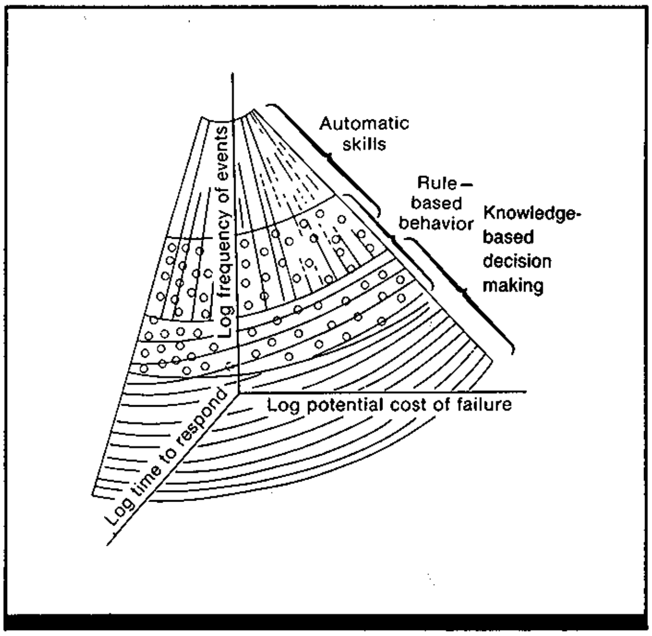

Figure 3. Relationship of expected human behavior levels to three parameters: event frequency, cost of error or failure, and response time available. (From *Handbook of perception and human performance*)

Key References

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*5. Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics, 13*, 257-266.

Cross References

7.301 Monitoring and supervisory control;

7.304 Fault detection and response with different levels of automation;

7.309 General model of supervisory control;

7.310 Optimal estimation model;

7.311 Application of optimal control theory to monitoring performance;

7.316 Models of observer monitoring performance;

9.512 Modeling of the human operator: the optimal control model;

Handbook of perception and human performance, Ch. 40, Sect. 6

Table 1. Characteristics of inner, intermediate, and outer loops in hierarchically structured control models.

	Control Loop		
Characteristic	**Inner**	**Intermediate**	**Outer**
Goal	System equilibrium	Problem solving	Decision execution
Event frequency	Frequent	Occasional	Possibly rare
Cost of failure	Relatively low	Medium	Relatively high
Event time scale	Fairly immediate	Relatively long	Possibly very long
Allowable response time	Short	Variable	Relatively long
Nature of stimuli	Continuous signals*	Name-labeled signs*	Symbols* for concepts
Error signals	Direct sensory inputs	Cognitive perceptions	Goal-determined
Behavior level	Skill-based, automatic	Rule-based	Knowledge-based
Nature of control	Manual, servo, closed-loop	Monitoring, supervision	Open-loop feed-forward
Appropriate model	OCT, Information theory	OET, Decision theory	Artificial intelligence

*See text for definitions.

7.304 Fault Detection and Response with Different Levels of Automation

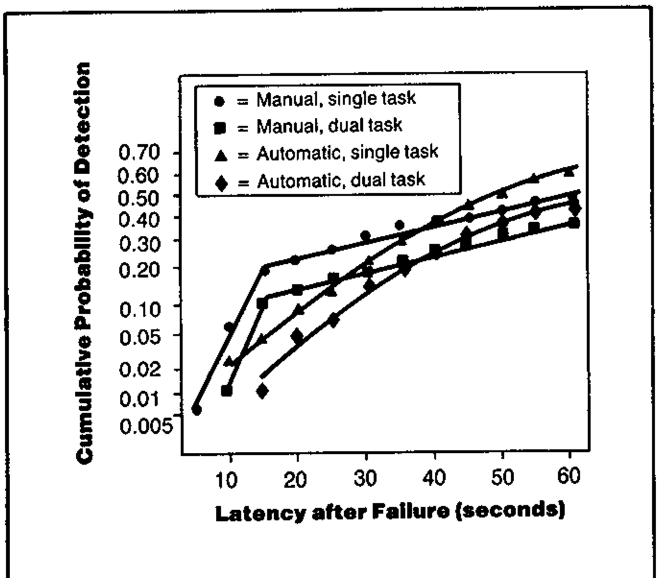

Figure 1. Cumulative probability of detection of a system failure for a tracking task as a function of time between failure and response. Tracking tasks were either manually controlled or automated. In the single-task situation, observers performed (or monitored) only a simple tracking task. For the dual-task situation, observers concurrently performed a second (more difficult) tracking task. (From C. Wickens & C. Kessel, The effects of participatory mode and task workloads on the detection of dynamic system failures, *IEEE Transactions on Systems, Man & Cybernetics, SMC-9*. Copyright © 1979 IEEE. Reprinted with permission.)

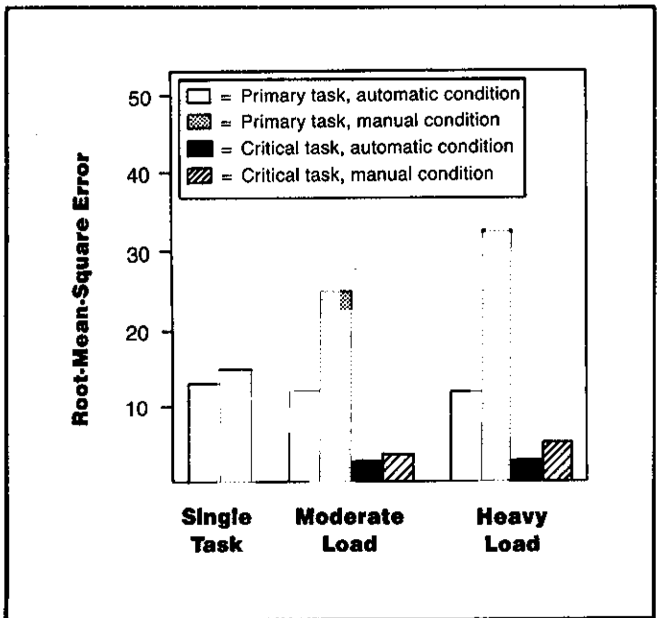

Figure 2. Response (root-mean-square) errors to system failures for manual control conditions and automatic control conditions for a tracking task, as a function of task difficulty (workload level). The single task (also the primary task) was as described in Fig. 1. The critical task was an additional tracking task for loading purposes that was presented at moderate and at high difficulty levels. Observers were instructed to give primary attention to the critical task, so that workload effect on the primary task could be evaluated. (From C. Wickens & C. Kessel, The effects of participatory mode and task workloads on the detection of dynamic system failures, *IEEE Transactions on Systems, Man & Cybernetics, SMC-9*. Copyright © 1979 IEEE. Reprinted with permission.)

Key Terms

Automation; decision making; failure detection; function allocation; human-computer interface: human operator models; man-machine models; manual control; monitoring; process control models; proprioceptive input; simulation; supervisory control; tracking; visual displays; workload

General Description

An operator directly controlling a system is said to be "in the control loop"; when only monitoring is performed, terms such as "not in the loop" and "out of the loop" are used (CRef. 7.303). One major effect of automation is to remove the operator from the control loop, while keeping the operator responsible for detection of and response to system malfunctions. Allowing the operator to have actual manual control of a system or process results in better monitoring and response to failures for three reasons (Ref. 5):

1. The operator develops a better mental model of the system or process—how it can fail, and how it is controlled.
2. The operator receives proprioceptive input, in addition to visual input, on the effect of control commands.
3. The operator has the ability to introduce "test" signals to observe the subsequent response when a failure is suspected.

On the other hand, automation yields better failure detection and diagnosis for two reasons:

1. There is a reduction of overall operator workload, leaving more cognitive resources available for monitoring, diagnosis, and decision making.
2. The operator is unable to compensate for and adapt to system failure, through slight control actions, without awareness of doing so.

Various levels of automation are possible (CRef. 7.307). One approach uses four levels of description: (1) the human has full manual control (manual); (2) a computer is available as an aid or tool (computer-aided); (3) a "computer assistant" results in a semiautomatic system (semiautomated); and (4) the computer operates as an "autonomous agent" — until it breaks down (automated).

Whether automation enhances or degrades the operator's ability to respond to failures quickly and accurately depends on:

- the level of automation;
- the nature of the operator's monitoring and control tasks, before and after failures;
- the nature of a failure;
- the overall level of the operator's workload;
- the degree to which loading tasks interfere with the ability to monitor for failures; and
- the accuracy of the operator's model of system operation and control.

For example, for skilled operators performing a high workload tracking task (such as simulated control of an aircraft flight path), where a failure is a gradual (ramp) change in aircraft direction or attitude, *automation* or *semi-automation* of control of aircraft course and attitude results in faster, more accurate detection of and response to computer failures (Refs. 1, 2). Under these conditions, the value of automation increases as workload levels increase.

On the other hand, for a simple tracking task where a failure is a step change in direction, speed, or acceleration of a cursor, *manual* control of the process by the operator results in faster failure detection (Refs. 4, 6). As is shown in Fig. 1, this effect is most marked in the first few seconds after a failure. If the operators have been provided a good internal model of the process, responses also are considerably more accurate (Ref. 5). Increasing the workload results in more errors in manual control (Fig. 2); this is especially true if the loading tasks interfere with monitoring and decision-making ability.

When the tasks are more complex (such as in supervisory control of a number of controllers or of the operation of a simulated plant), the operator's ability to detect and correct failures is considerably enhanced if *computer aiding* is provided or if the operator can allocate tasks to the computer as desired (Ref. 3). As is shown in Fig. 3, simple monitoring of an automatic or semiautomatic process results in a longer time to gain control, more control manipulations, and more incorrect control actions.

If an operator has been trained exclusively for outer-loop (knowledge-based) control (CRef. 7.303) such as required by automated systems, and suddenly is required to perform the inner-loop (skill-based) control actions required by manual control, the operator will not be able to quickly and appropriately deal with system behavior. Expectations of the time scale of effects of actions will be inappropriate, and internalized mental models of input-output relationships will not be available. Training only for inner-loop behavior is equally disastrous. When faced with outer-loop decisions where knowledge-based, discrete, slow behavior is appropriate, such an operator will inject high-frequency noise into the system by trimming it too often rather than letting it settle.

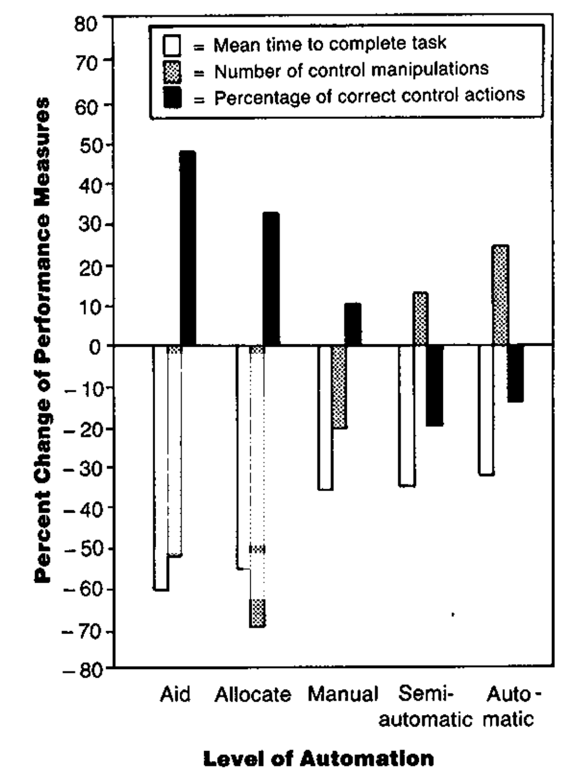

Figure 3. Percent change of performance measures as a function of the level of automation for a complex supervisory-control process. The five participatory modes studied are ordered here according to completion time for detecting and diagnosing failures. (From Ref. 3)

Table 1 summarizes the results of several studies investigating the effect of "in-the-loop" versus "out-of-the-loop" control on failure detection.

Applications

Useful in determining whether automation of a function or set of tasks is appropriate, and, if so, the best level of automation. Potentially useful for developing comprehensive models of human-computer function allocation; for specifying whether inner-loop or outer-loop training is needed for operators of a given system; for modeling human and computer processes during development of artificial-intelligence algorithms, especially for expert systems and decision support systems; and for determining areas of needed research when and where automation is appropriate for supervisory-control systems.

Table 1. Summary of data on the effects of "in-the-loop" versus "out-of-the-loop" supervision on detecting and correcting failures.

Conditions	Task	Variables	Results	Source
Ground simulation of low-visibility landing approaches in commercial jet transports; 15 professional airline pilots; no warnings; 90 approaches each with lateral and longitudinal failures; four levels of pilot participation: passive monitoring, yaw manual, pitch manual, full manual; three workload levels; three failure conditions: none, yaw axis, pitch axis; manual control and workload required much attention to steering displays	Detect failure in yaw axis (subtle 1.25 deg lateral deviation from desired course) or pitch axis (0.35 deg deviation from desired attitude) and report verbally	Independent: pilot's participation; workload; failure condition Dependent: time to detect and report (verbally) system failure; fraction of unreported failures	More failures went unreported under manual control, especially with high workloads (up to 35.7%); no failures were missed when only monitoring system; much longer failure detection times occurred under manual control (40-65 sec) than under automatic control (15-45 sec)	Ref. 1
Simulated control of pulp and paper mill; 10 well-trained controllers, 12-15 min trials; five levels of operator participation: manual, computer aiding, semi-automatic, automatic, allocation of functions by operator; control actions simulated pump adjustments, valve adjustments, sampling the levels of tanks, and allocating functions to the computer	Monitor CRT display of "tanks," "mixtures," etc., to keep process under control; detect computer failure resulting in out-of-tolerance flow rates and component mixtures; use light pen to simulate return of system to equilibrium	Independent: degree of operator participation Dependent: time to complete task after failure; number of control manipulations; number of correct manipulations	Operators responded better to failures that occurred in computer-aiding mode and when operators themselves allocated the computer functions; strictly manual control was next best; worst performance resulted from semi-automatic participation levels; results were consistent over all performance measures (see Fig. 3)	Ref. 3
Pursuit tracking task to match a cursor with a moving dot on a CRT, using a joystick; loading task (some conditions) of another tracking task with other hand; trigger on joystick to signal failure detection; 5 well-trained controllers; eight 150-sec trials; two levels of operator participation: manual, automatic; three workload levels: single task, moderate, heavy; step change in cursor dynamics represented a failure	Monitor signal for changed dynamics; press trigger to signal failure detection and diagnosis of nature of change	Independent: degree of operator participation; workload Dependent: number of correct detections; number of false alarms; time to respond (latency)	Manual control resulted in markedly faster detections, especially during first 1.5 sec, before proprioceptive signals decayed; automatic control resulted in slightly more accurate responses, especially at higher workload levels (see Figs. 1 and 2)	Ref. 4
Compensatory tracking task on CRT, using joystick; well-trained controllers indicated failure detection via button release; three levels of operator participation: active controller, "inactive" controller (tracking, but stick not coupled), passive monitor; step change in cursor dynamics represented a failure; no additional loading of controllers	Monitor signal for changed dynamics; release button to signal failure detection; attempt to restabilize system	Independent: degree of operator participation Dependent: time to detect and report failure	Active controllers detected failures in $\sim$1 sec; "inactive" controllers detected in $\sim$2 sec; passive monitors took 3-5 sec to detect failures	Ref. 6

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Constraints

• This model assumes that the main task of the operator in supervisory control is to detect system abnormalities and faults; as computer pattern recognition and fault diagnosis capabilities increase, this assumption may no longer hold; instead, the human may be needed primarily to come up with "non-linear" solutions that cannot be predicted in advance (after the computer determines it needs help).
• Failure detection is considered a "fragile" capability, like other monitoring/detection tasks; when it becomes more difficult, cognitive resources cannot be "borrowed" from those being used for tracking tasks; the converse is not true, however; failure detection performance deteriorates when tracking demand is increased.
• No single factor (nature of task, failure type, workload, etc.) can be considered in isolation when determining an appropriate level of automation for a given process; the interactions among factors should be considered when making decisions about automating processes.
• Piecemeal automation of a process often automates tasks that operators perform well unaided, and leaves complex activities that are not understood for the operator to perform; manual workload may be reduced, but at the expense of vastly increased monitoring and information processing demands.
• Identification of appropriate tasks to automate must be based on the reconfigured "improved" human/system environment, not on the one being replaced; human performance in a new system seldom can be predicted from that in an old one because of human adaptability.
• Complex systems consist of non-random variables that vary across time, and that are coupled through feedback loops and other processes (i.e., they are non-independent). Thus, simple non-dynamic models may be inappropriate; functions and tasks may need to be distributed dynamically as conditions change with time.
• Designing or automating a human-machine system rarely produces an acceptable result without extensive searches through alternative designs plus experimentation to evaluate overall system performance; there are no shortcuts to success.
• The field of artificial intelligence is developing rapidly, especially in the area of expert systems; the relationships between supervisory control and artificial intelligence have not been systematically studied, and no widely accepted models for this relationship are available at present.
• These models of operator performance apply to well-trained, highly motivated monitors and controllers; the effects of fatigue and stress are not considered.
• The effect of operator boredom is not considered in these studies; vigilance decreases when failures are rare, so that they are often missed when they do occur.
• The role of individual differences is especially important in operation of complex systems; generalities from "average" performance measures may not be useful.
• Operators frequently are able to control a system even when they have only very imperfect conscious knowledge of the system; they often describe how they intend to control a system and then behave in a different way; thus, an operator's verbal description of his or her mental model of the system may not be useful.
• With heavy cognitive workloads, flight crews make an error approximately every 5 min (mostly detected and corrected); such errors are not random, but are linked to knowledge and understanding of the aircraft systems; specific training in fault diagnosis, in addition to normal operation, is required for efficient overall system operation.
• Operators trade off speed and accuracy in making decisions and correcting failures; thus one measure should not be considered without the other when judging performance.

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Cross References

7.301 Monitoring and supervisory control;

7.302 Sampling behavior during process-control monitoring;

7.303 Hierarchically structured control models;

7.307 Allocation of decisions between human and computer;

7.308 Sharing of knowledge and control between supervisor and computer;

7.309 General model of supervisory control;

7.310 Optimal estimation model;

7.311 Application of optimal control theory to monitoring performance;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

7.901 Characteristics of humans as decision makers;

9.512 Modeling of the human operator: the optimal control model;

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7.305 Time Required to Detect, Diagnose, and Repair Faults

Key Terms

Cognitive control; control strategy; maintainability; manual control; monitoring; reaction time; simulation; supervisory control; visual displays

General Description

The processes of observing, diagnosing, and repairing faults (failures) can be described using a hierarchical model of control based on loops (CRef .7.303); inner-loop processes are lower-level automated processes and outer-loop processes are those processes requiring more cognitive control.

Observing that a failure has occurred or that a fault exists can be considered an inner-loop process, since it is usually skill-based, fairly automatic, and relies on direct sensory inputs. When a team of operators is monitoring a bank of displays in a simulator, cumulative probability of fault detection versus time-to-detect fits a lognormal distribution curve (Fig. 1), with more than 50% of faults detected within 100 sec (Ref. 1). The same task performed under real-world conditions can be expected to take about ten times longer.

As a rule of thumb, the halving or doubling of a parameter (as observed on one constantly monitored display) will be detected in 10 sec for processes that are typical of manual control (Ref. 3). If the display is driven by a zero-mean Gaussian bandlimited signal, a change of two standard deviations will always be detected; changes of one standard deviation or less take longer to detect, and may go undetected (Ref. 4). An increase is usually spotted more quickly than a decrease.

Once detected, fault diagnosis and fault repair usually are either intermediate-loop or outer-loop processes. The former process relies on problem-solving, rule-based behavior; a large proportion of military equipment failures fit this model, and will be repaired in less than 2 hr. An outer-loop process requires decision execution and knowledge-based behavior, and equipment repairs requiring this process can be expected to take more than 2 hr (Ref. 5).

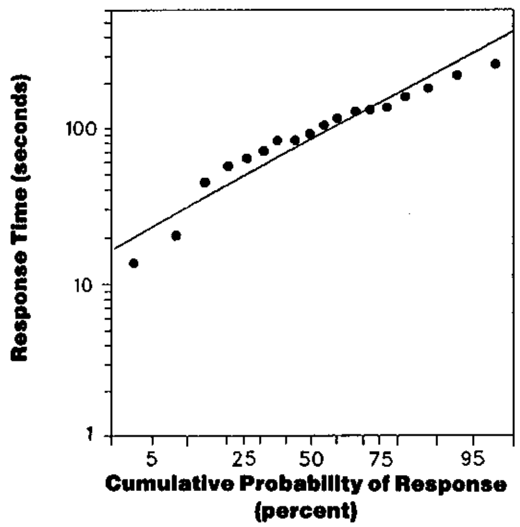

Figure 1. Cumulative probability of operator (team) detection of and response to a nuclear power plant mainstream relief valve failure (Study 1). Response time versus cumulative probability is plotted as lognormal distribution. Line was fit after transformations of data to units with equal-interval properties. (From Ref. 1)

Diagnosis and repair times obtained under laboratory conditions are exponentially distributed. For repairs made in the field, the family of Weibull distributions (Ref. 2) provides a reasonable fit for combined diagnosis and repair data (Fig. 2); the different values of Weibull parameters required to model rule-based and knowledge-based supervisory control processes are reflected in the different slopes for the two parts of the curve.

The results of several empirical studies of fault detection, diagnosis, and repair are summarized in Table 1.

Applications

Has been used in setting time-response design criteria for nuclear power plant safety standards (Ref. 1). Useful in modeling and in obtaining performance estimates for human failure detection performance (Ref. 3). Provides a direct basis for predicting both the mean active repair time for military equipment and also the "tail" of the cumulative frequency distribution (Ref. 5). Potential application in determining when an alerting system is needed; when computer aiding will be of value in speeding fault detection, diagnosis, and repair; and for assessment of various training techniques to determine if maintenance times will be improved.

Constraints

Study 1 (Ref. 1)

- There is presently no generally accepted model of nuclear power plant operator response behavior; performance measures and critical performance shaping factors (such as experience) needed for such a model have not yet been identified.
- Responses were made by the first member of a three- or four-member team who diagnosed the problem and formulated a plan of action for response; the probability that at least one team member will be above average is ~0.94 for a four person team; extrapolation of the data to individual operators must be done with caution.

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• Team capability varies widely; variation in response time from one team to another was large, with more experienced teams responding faster and more accurately.
• Response time is highly task-dependent, making it difficult to predict performance on other tasks from the data discussed here.

Study 2 (Ref. 3)

• Observers monitored a single display, with no auxiliary tasks.
• Observers were allowed 30 sec to view each display, then a forced choice was required to determine the presence or absence of a failure; thus, maximum detection time was 30 sec.

Study 3 (Ref. 4)

• Observers were performing a simple tracking task where displayed information and control tasks are especially well coupled.
• Although the signal change was a discrete one, the task was continuous; results may not apply to discrete tasks occurring over long periods of time.

Study 4 (Ref. 5)

• Diagnostic interpretation time (time between successive tests) is assumed to include cognition, hypothesis development, analysis, and action selection; its increase over time probably occurs because of the technician's tendency to do the easiest tasks with highest probability of success first, leaving difficult, lengthy tasks until last; these assumptions may not hold for all diagnosis and repair tasks.
• Military equipment repaired in this study represents 1950s technology; a separate study of 1970s technology aircraft equipment repair indicates that the "break point" between rule-based and knowledge-based diagnosis is ~0.3 hr instead of 2 hr; a combination of improved test equipment and increased equipment complexity may account for the change.

Table 1. Summary of data on fault detection, diagnosis, and repair times.

Study	Conditions	Task	Variables	Results
Study 1 (Ref. 1)	Nuclear power plant control room crews (twenty-four 4-5 person teams), during scheduled training exercises in full scope, high-fidelity training simulator	Detect and respond to faults as indicated via gauges, lights, alarms, and charts during ten malfunction scenarios; response was usually a switch setting action	Independent: nature of fault requiring response (ten abnormal events) Dependent: time to initiate response action	Average response time ranged from 6.9-185 sec, depending on the malfunction (geometric means, since log-normal distribution assumed); individual response time ranged from ~2-390 sec (see also Fig. 1)
Study 2 (Ref. 3)	Uniformly distributed zero-mean white noise (smoothed) used to drive oscilloscope display; 16 trained graduate students, in two 40-min sessions	Detect and respond to increase or decrease in signal frequency (band-width or period), damping, or gain (variance); two response switches (for increase or decrease)	Independent: increase or decrease in stimulus level (ratios from ±0.0005 to ±0.8) Dependent: time to initiate response action	Observers reliably distinguished between increases and decreases; increases detected more rapidly; frequency changes detected most rapidly, damping next, gain slowest; response times ranged from ~3-30 sec; doubled or halved values detected in ~10 sec
Study 3 (Ref. 4)	Zero-mean Gaussian-band-limited noise used to drive a trace on a CRT; well-trained subjects performed a 2-min tracking task with a joystick, to keep a dot on a reference line; an audio alarm signaled a change in system dynamics under some conditions	Detect a change (reversed polarity) in system dynamics and revise tracking strategy accordingly	Independent: alarm/no alarm condition; step change in system dynamics (six treatments, 0-3 standard deviation change) Dependent: time to initiate appropriate tracking response to changed polarity	Alerting signal significantly improved response time for changes of one standard deviation; alarm did not improve performance for changes of more than two standard deviations (alerting signal was redundant)
Study 4 (Ref. 5)	Field diagnosis and repair of military aircraft sensors, computers, and navigation equipment by specially selected, motivated maintenance personnel; only active repair time included in the data; total of 983 repairs on seven kinds of equipment	Detect, diagnose, and repair failed equipment	Independent: types of equipment, labeled A-G Dependent: time to diagnose fault and complete repair	Personnel completed 60-80% of repairs in less than 2 hr; arithmetic mean-time-to-repair was 2-6 hr; Weibull distributions fit repair time data; longer repair times were due to fault diagnosis difficulty (see Fig. 2)

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Cross References

7.301 Monitoring and supervisory control;

7.303 Hierarchically structured control models;

7.304 Fault detection and response with different levels of automation;

7.309 General model of supervisory control;

7.316 Models of observer monitoring performance;

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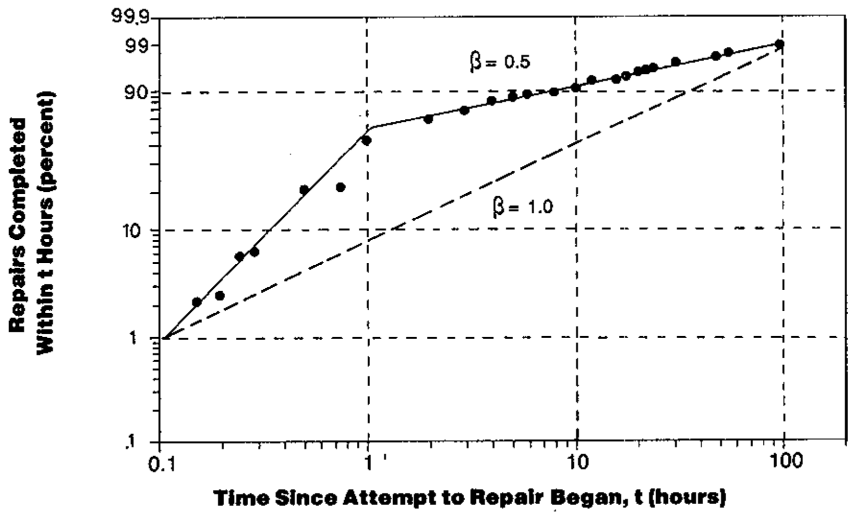

Figure 2. Cumulative diagnosis and repair time for one typical kind of military equipment (based on 257 repairs) (Study 4). Percent of repairs completed versus time to complete the repair is plotted as a Weibull distribution (Ref. 2) with $\beta > 1.0$ (an accelerating process) for repairs taking 1 hr. or less, and $\beta < 1.0$ (a decelerating process) for those taking > 1 hr. The dashed line represents an exponential distribution ($\beta = 1.0$). (From J.G. Wohl, Maintainability prediction revisited: Diagnostic behavior, system complexity, and repair time, *IEEE Transactions on Systems, Man, & Cybernetics, SME-12*. Copyright © 1982 IEEE. Reprinted with permission.)

Notes

7.306 Training of Operators for Supervisory Control

Key Terms

Diagnosis strategies; failure diagnosis; manual control; monitoring; simulation; supervisory control; training

General Description

Operators must be trained for the outer loop (knowledge-based) behavior during normal system function (CRef. 7.303) that is required by supervisory control; operators also require the intermediate loop (rule-based) ability to detect abnormalities and to diagnose them. When these types of knowledge are immediately available, operators can take appropriate action including, when necessary, using innerloop (skill-based) control (i.e., manual control). When the goal is transfer of training to solution of new problems, this process is facilitated by providing training in heuristic rule-based behavior.

Frequent hands-on manual-control practice (such as in a simulator) enables a supervisory operator to retain an accurate mental model of an automated process he or she normally monitors. Such manual-control practice should keep the entire range of knowledge-based, rule-based, and skill-based behaviors available for use when needed. In addition, rule-based training (specific to the tasks to be performed) can be designed to maximize transfer from the particular problems used during training to effective behavior when confronted with totally new problems.

In one study, three equivalent groups were given initial fault diagnosis training sessions, using specific examples (Ref. 1). One group then received additional training via further examples ("no story" group). The second group was given a lecture on the physics of the process represented ("theory" group) to further knowledge-based behavior. The third group was given a set of general heuristics for trouble shooting, which included directions for locating and recognizing failures ("rules" group). As illustrated in Fig. 1, all groups performed about equally well on diagnosing faults they had observed during training. However, when the groups were tested with problems not previously seen, the "rules" group diagnosed the faults significantly better than the other two groups.

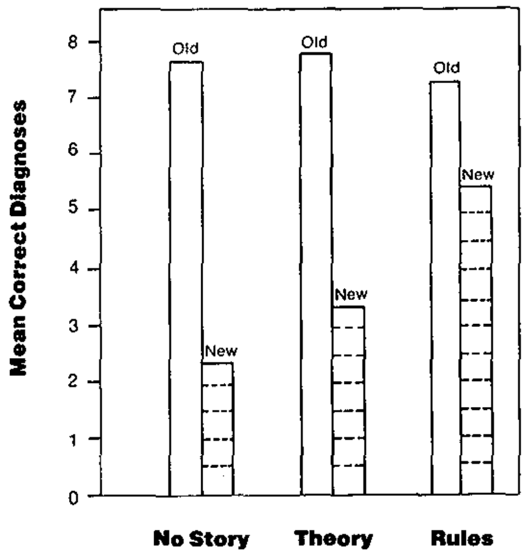

Figure 1. Effects of three kinds of training on fault diagnosis skills: "no story" group received examples only; "theory" group received explanation of physics of the process; and "rules" group received trouble-shooting heuristics. "Old" and "new" indicate whether faults to be diagnosed had been seen during training. (From Ref. 1)

Applications

Designing training programs for fault diagnosis and similar supervisory-control tasks. Potentially useful in modeling human processes during development of artificial intelligence algorithms, especially for expert systems such as decision support and diagnostic systems.

Constraints

- The study reported assumed that supervisors are motivated observers who desire to make correct diagnoses; effects of fatigue, stress, lack of motivation, or emergency conditions were not considered.
- The study considered only fault diagnosis tasks; training for other supervisory control tasks (such as overall system planning or decision execution) may or may not demonstrate similar results, because experienced human controllers exhibit many nonlinearities and often-unexpected adaptive behavior.
- Experimental groups usually receive only limited training for the tasks tested; really extensive theoretical training might result in even better training transfer than does training in heuristic rules.
- The boundaries between the three levels of behavior are very fuzzy; each researcher must determine where these should be for the tasks under consideration.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

7.301 Monitoring and supervisory control;

7.303 Hierarchically structured control models;

7.304 Fault detection and response with different levels of automation;

7.305 Time required to detect, diagnose, and repair faults;

7.309 General model of supervisory control;

9.512 Modeling of the human operator: the optimal control model;

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7.307 Allocation of Decisions Between Human and Computer

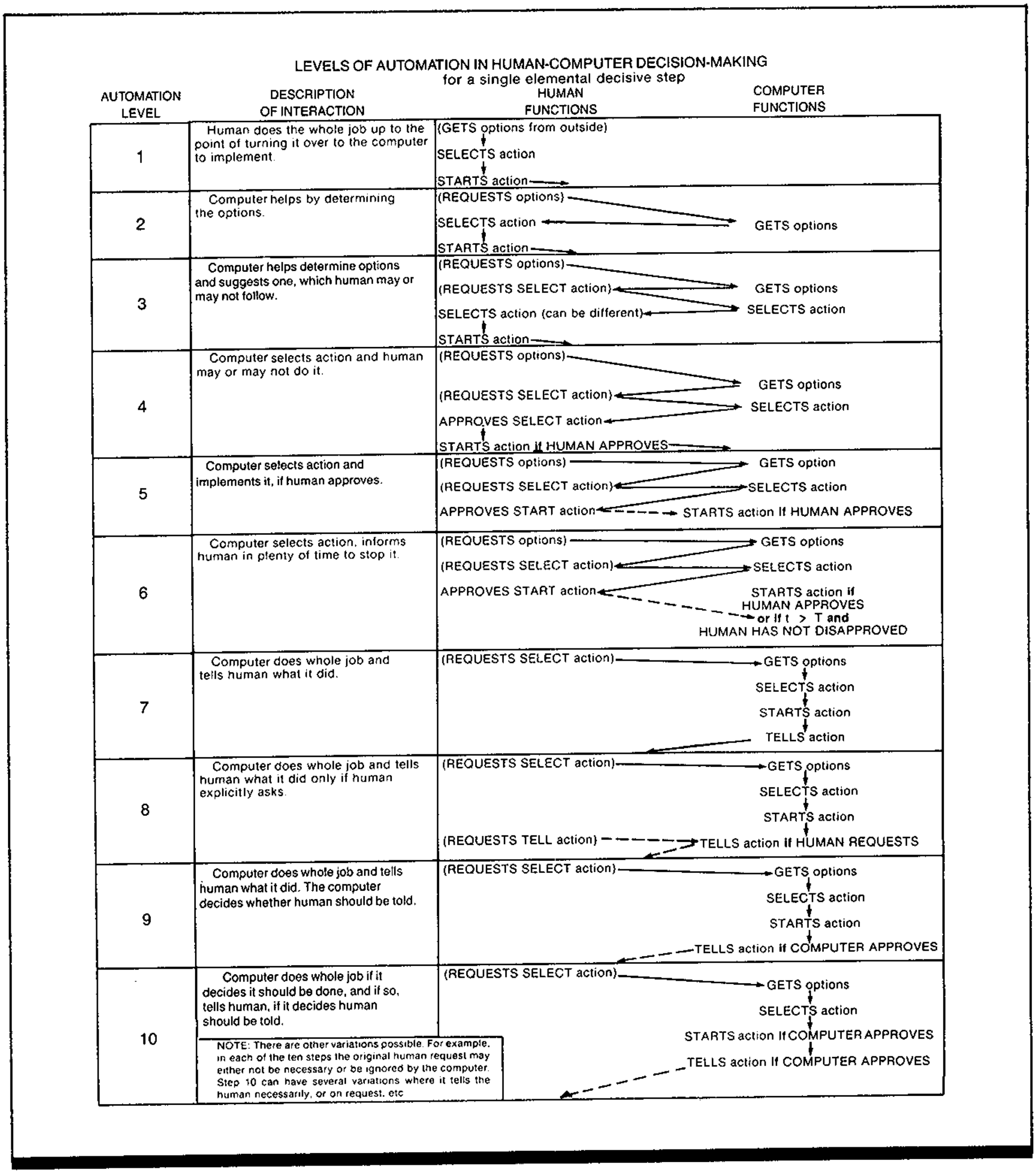

Figure 1. Sheridan's model of possible levels of allocation of decision-making tasks between humans and computers. Other variations are possible; for example, in each of the ten levels, the original human request may not be necessary or may be ignored by the computer. (From Ref. 1)

Key Terms

Automation; decision aiding; decision making; expert systems; function allocation; goal setting; hierarchical models; human-computer interface; human operator models; manual control; planning; process control; supervisory control; workload

General Description

One taxonomy of human-computer decision-related interactions (Ref. 1) is based on concepts introduced in a general model of supervisory control (CRef. 7.309). The taxonomy describes ten levels of automation (ways human and computer may cooperate), ranging from the situation where the human makes virtually all decisions and carries them out, to the opposite situation where the computer decides whether a task must be done and only informs the human if it determines that to be appropriate.

Six behavioral elements (functions) are used in the figure to characterize the decision process. These functions are possible activities of the human or computer during decision making:

- "Requests" asks the other party for something;
- "Gets" fetches what is requested or is necessary;
- "Selects" chooses from among options for intended action;
- "Approves" agrees or disagrees with a particular decision;
- "Starts" initiates implementation; and
- "Tells" informs the other party of what was done.

Moving down the figure, the computer assumes more and more responsibility. It progresses from the role of tool (Levels 2 and 3), to that of assistant (Levels 4 to 6), to a full associate of the human (Levels 7 and 8), and finally to the role of autonomous agent (Levels 9 and 10).

As a tool, the computer predicts the consequences of well-defined options, and can be considered a *decision aid*. The term *decision support system* includes both tool and assistant levels, while *decision augmentation system* is an all-inclusive term for all four roles (Ref. 2).

Determination of the appropriate level of automation for a given supervisory control system is linked with the *allocation of decision functions* between human and computer (Ref. 3). Five general, high-level cognitive and computational functions are:

- Goal definition or resolution;
- Situation assessment;
- Resource and action assessment;
- Consideration of decision impact on situations outside the present context; and
- Decision evaluation.

Currently, goal definition and decision evaluation are usually reserved for the human, while the other functions are shared. However, various factors may change this "standard allocation." These include overall *human-computer reliability* (CRef. 7.304), the *decision situation*, and the *cognitive capabilities* of human and computer.

Decisions are made in the context of *decision situations*, which fall into five categories ranging from calculations to nightmares, as shown in Table 1 (Ref. 3). The category of a decision is determined by how many of the following *characteristics* are known and how many are unknown.

- Goals: ultimate desired states against which outcomes will be judged.
- Knowledge: representations of real-world information (situations and resources) used to generate action options.
- Action options: possible manipulations of the current state of the world.
- Action outcomes: states of the world that result from implementing action options.
- Desirability functions: rules that determine the degree to which specific action outcomes meet objectives.

Automation of decisions is feasible only within decision situations where all or nearly all decision characteristics are known. Attempts to automate situations classed as problems, dilemmas, and nightmares are inappropriate. For each supervisory-control process, the *cognitive* abilities of human and computer to perform required decision and computational functions must be assessed before defining an automation level and allocating functions. While human cognitive capabilities are relatively fixed, those of computers are increasing rapidly. For example, although presently one of the human's main functions is to detect system failures, computer capability soon will surpass humans in this area. This is due to improvements in artificial pattern recognition algorithms, and to the vast amount of cheap "brute force" computation becoming available.

Applications

Primarily useful for considering the appropriate allocation of functions between computers and humans for a given supervisory control process. Potentially useful for function, task, and workload analyses; for developing models of microprocesses under control of a system executive; and for modeling human processes during development of artificial intelligence algorithms, especially for expert systems.

Constraints

- At present, the model is strictly descriptive and qualitative; attempts to make it predictive or to make it yield quantitative results may not be appropriate.
- Complex systems are comprised of non-random variables that vary across time, and that are coupled through feedback loops and other processes (i.e., they are non-independent). Thus, simple non-dynamic models may be inappropriate; functions and tasks may need to be distributed dynamically as conditions change with time.
- Designing or automating a human-machine system rarely produces an acceptable result without extensive searches through alternative designs plus experimentation to evaluate overall system performance; there are no shortcuts to success.
- Piecemeal automation of a process often automates tasks that operators perform well unaided, and leaves complex activities that are not understood for the operator to perform; manual workload may be reduced, but at the expense of vastly increased monitoring and information processing demands.

• Identification of appropriate tasks to automate must be based on the reconfigured "improved" human/system environment, not on the one being replaced; human performance in a new system seldom can be predicted from that in an old one because of human adaptability.
• The communication interface between human and intelligent computer is the weakest link in symbiotic human-computer systems, due to limited knowledge about what constitutes fruitful communications and how to engineer them.
• The field of artificial intelligence is developing rapidly, especially in the area of expert systems; the relationships between supervisory control and artificial intelligence have not been systematically studied, and no widely accepted models for this relationship are available at present.

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Cross References

7.301 Monitoring and supervisory control;

7.303 Hierarchically structured control models;

7.304 Fault detection and response with different levels of automation;

7.306 Training of operators for supervisory control;

7.308 Sharing of knowledge and control between supervisor and computer;

7.309 General model of supervisory control;

7.901 Characteristics of humans as decision makers;

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Table 1. Definitions of five decision situations, based on known and unknown characteristics of each decision. (From Ref. 3)

Decision Situation	Known Characteristics	Unknown or Uncertain	Automation Level*
Calculation	Goals Knowledge Action options Action outcomes Desirabilities		6, 7, 8, 9, 10
Decision	Goals Knowledge Action options	Action outcomes Desirabilities	2, 3, 4, 5
Problem	Goals Knowledge	Action options Action outcomes Desirabilities	1
Dilemma	Goals	Knowledge Action options Action outcomes Desirabilities	1
Nightmare		Goals Knowledge Action options Action outcomes Desirabilities	1

*See Fig. 1 for description of automation levels.

Notes

7.308 Sharing of Knowledge and Control Between Supervisor and Computer

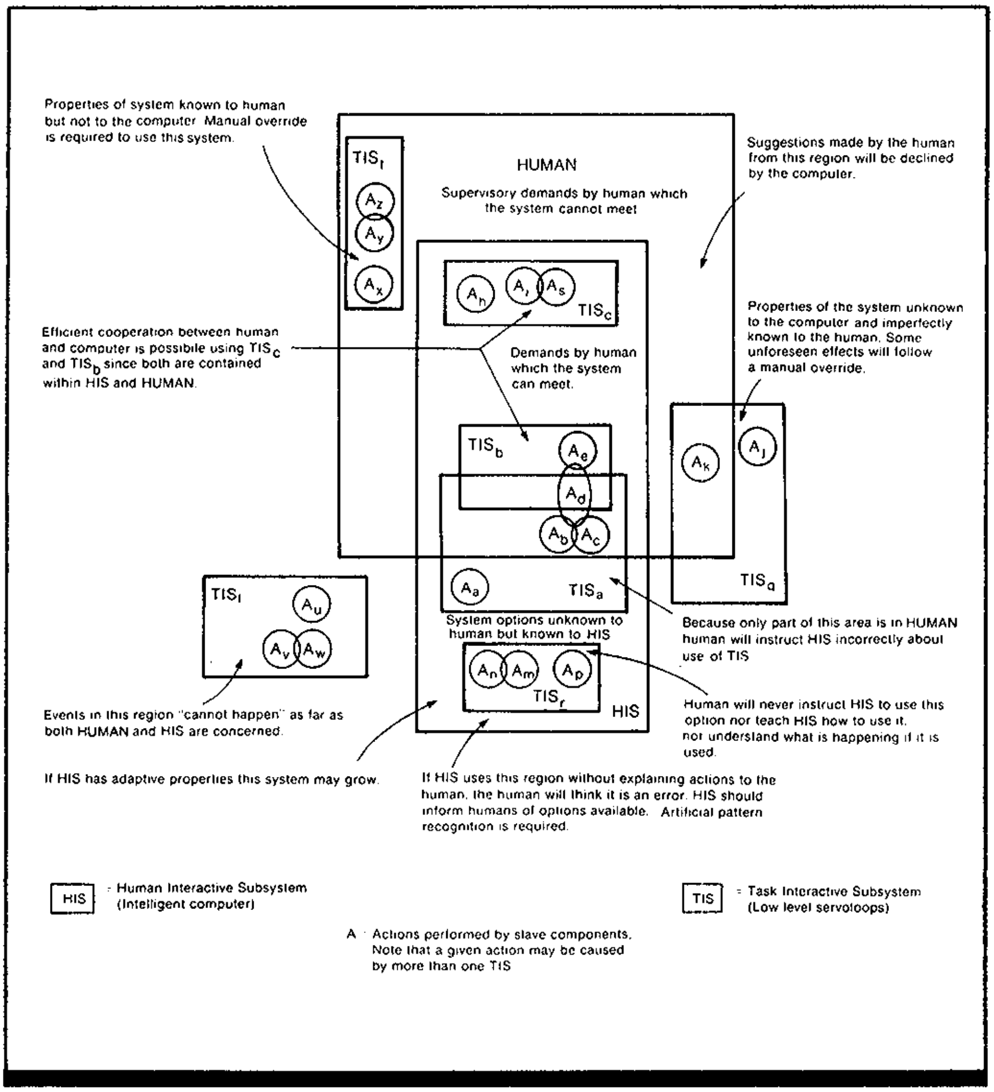

Figure 1. Moray's Venn diagram summarizing degrees of the sharing of system knowledge and system control among a human supervisor, intelligent computer (Human Interactive System), semi-automatic subsystem (Task Interactive System), and the controlled elements of the system. Not all possible cases are included on this diagram. (From Ref. 1)

Key Terms

Automation; expert systems; function allocation; hierarchical models; human-computer interface; human operator models; process control; supervisory control; task interactive system; workload

General Description

Moray's model of human-computer relationships (Ref. 1) is based on Sheridan's hierarchical four-level schema for describing the supervisory control process (Ref. 2; CRef. 7.309). The model provides a framework or starting place for study and development of a comprehensive, quantitative theory of supervisory control.

The model, as illustrated in the figure, considers ways in which knowledge and control may be distributed among three system components:

HUMAN: a human operator or supervisor;

HIS: the Human Interactive System, an intelligent computer that can carry out plans chosen by the human; and

$TIS_a, \ldots, TIS_t$: the Task Interactive Systems, "dumb" or semi-intelligent "slave systems" in charge of actual task performance or system control.

$A_a, \ldots, A_z$ are actions, controlled elements, or tasks to be performed.

The degree of overlap between the sets (boxes) in the figure represents the extent to which knowledge of system proper-

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ties is shared among the components. In the ideal supervisory system, actions affecting the task would be completely nested, ensuring reliable communications among all levels. All of the actions (A_a, A_b, etc.) would be within some TIS, all TIS areas within the HIS box, and the HIS completely within the area representing the HUMAN.

Figure 1 represents the more common situation. It is not possible, in general, for a designer to enumerate all possible system states and all interactions. All complex systems have properties that are unexpected. The extent to which the areas representing the HUMAN and the HIS overlap indicates the extent to which the human supervisor understands the properties of the intelligent computer; in the illustrated example, understanding is not complete. Similarly, the extent to which the HIS includes all boxes labeled TIS is an indication of the degree of its understanding of and control over the TIS.

Although the areas labeled TIS_b and TIS_c conform to the ideal (completely nested) situation, the box labeled TIS_f represents the extreme case of incomplete knowledge. Here, actions A_u, A_v, and A_w occur without knowledge of either the HUMAN or the HIS. Other cases of incomplete knowledge are represented by TIS_t (actions known only to the HUMAN) and TIS_r (actions known only to HIS). In area TIS_a, the HIS is always aware of TIS actions, but the HUMAN is aware of only some actions. And in TIS_q, the HIS is unaware of TIS actions, and the HUMAN only partly aware of them—resulting in unforeseen effects following a manual override.

Finally, the effects of interacting actions must be considered, as illustrated by A_z and A_y, and by A_n and A_m. Indeed, in some cases, actions may both interact (overlap) and be under the control of more than one TIS (A_d)—a situation which extensively increases the probability of "misunderstandings" among the various levels.

Applications

Primarily useful as a framework for discussion and for model development for supervisory-control processes and for time-shared computer systems. In the latter situation, the HIS represents a computer operating system in use by the human; the TISs are the local terminals and their hardware; and the actions, A_s, are the events the user sees at the terminal or printer. Potentially useful for studying the role of training and learning (both for the human supervisor and intelligent computer) in developing "well-nested" hierarchies; for function, task, and workload analyses, to assist in allocating tasks among the four model levels; for developing models of microprocesses under control of a system executive; and for modeling human processes during development of artificial intelligence algorithms, especially for expert systems.

Constraints

- The model at present is strictly descriptive and qualitative; attempts to make it predictive or to make it yield quantitative results may not be appropriate.
- Complex systems are comprised of non-random variables that vary across time and that are coupled through feedback loops and other processes (i.e., they are non-independent). Thus, a simple non-dynamic model may not always hold.
- Designing or automating a human-machine system rarely produces an acceptable result without extensive searches through alternative designs plus experimentation to evaluate overall system performance; there are no shortcuts to success.
- Piecemeal automation of a process often removes from operators the tasks that they perform well unaided, and leaves complex activities that are not understood for the operator to perform; manual workload may be reduced, but at the expense of vastly increased monitoring and information-processing demands.
- Identification of appropriate tasks to automate must be based on the reconfigured "improved" human/system environment, rather than on the environment being replaced; human performance in a new system seldom can be predicted from that in an old one, because of human adaptability.
- The communication interface between human and intelligent computer is the weakest link in symbiotic human-computer systems, due to limited knowledge about what constitutes fruitful communications and how to engineer them.

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Cross References

6.605 Perceived roughness: effect of shear force;

7.301 Monitoring and supervisory control;

7.304 Fault detection and response with different levels of automation;

7.307 Allocation of decisions between human and computer;

7.309 General model of supervisory control;

7.312 Comparison of different research settings for study of supervisory control;

7.316 Models of observer monitoring performance;

7.901 Characteristics of humans as decision makers

7.309 General Model of Supervisory Control

Key Terms

Automation; failure detection; function allocation; goal setting; hierarchical models; human-computer interface; human operator models; monitoring; planning; process control; supervisory control; task interactive system; training; visual displays; workload

General Description

One schema (Ref. 3) for supervisory control is a four-level, hierarchical, descriptive model that considers the relationships among (1) a series of tasks to be performed, (2) a "slave system" or Controlled Element 2 (CRef. 7.301), (3) an "intelligent" computer or Controlled Element 1, and (4) a human operator.

At the lowest level are the basic controlled elements—the actual physical plant and materials, such as propellers, engines, pumps, switches, and valves. This level is called the *task*, which can be considered as a set of physical variables to be controlled.

The second level consists in part of "dumb" controllers such as thermostats, gyrocompass autopilots, and governors. These are all **negative-feedback servoloops** (i.e., systems in which a deviation from a preset state causes an opposite control action to be applied to bring the system back to the preset state) integrated into a semi-intelligent computerized system called the *Task Interactive System* (TIS). The TIS can, for example, trim a system to a set point, but cannot choose set points for itself.

The third level is an "intelligent" computer that interfaces between the human operator and the lower level controllers — the *Human Interactive System* (HIS). It receives commands from the operator and autonomously imposes tactics on the lower level servoloops. It also feeds back information about the state of the system to the operator. The HIS can change setpoints, but its "goals" are set by the human operator (e.g., to minimize the system's operating cost, to maximize its efficiency, to optimize comfort, etc.).

The fourth or highest level in the hierarchy is the *human operator*, who monitors the system as a whole but who normally does not exercise manual control. The operator sets the "goals" for the intelligent computer, HIS.

The numbered paths in Fig. 1 show possible interactions among the levels.

1. Task is observed directly by the operator.
2. Task is observed indirectly through sensors, computers, and displays. This TIS feedback interacts with the HIS feedback.
3. Task is controlled within the TIS automatic mode.
4. Task is affected by the process of being sensed.
5. Task affects actuators and, in turn, is affected.
6. Operator directly affects task.
7. Operator affects task indirectly through controls, HIS computers, and actuators. This control interacts with that from TIS.
8. Operator gets feedback from HIS.
9. Operator adjusts control parameters.
10. Operator adjusts display parameters.

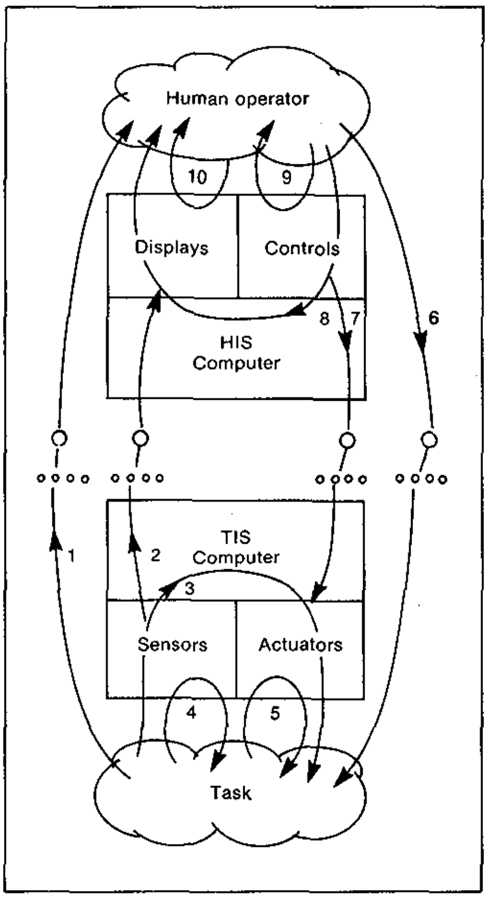

Figure 1. Sheridan's multi-loop interaction model for describing the supervisory control process. The numbered paths show possible interactions among the levels (see text). (From *Handbook of perception and human performance*)

The allocation of cognitive and computational tasks among the three intelligent or semi-intelligent levels is central to supervisory control. If the tasks are described using Rasmussen's categories of knowledge-based, rule-based, and skill-based behavior (CRef. 7.303), the operator usually assigns rule-based tasks (e.g., pattern recognition, running predictive models, organizing) to HIS. Skill-based tasks (filtering information, generating displays, servocontrol) are assigned to TIS. Meanwhile, the operator concentrates on (1) *planning* what to do next, (2) *teaching* or on-line programming of computers, (3) *monitoring* the automatic behavior of the system for abnormalities, (4) *intervening* when necessary to make adjustments, and (5) *learning* from experience.

The associations between the human operator and the HIS have been described as "man-computer symbiosis" (Ref. 2). Instead of human-machine systems merely provid-

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ing a mechanical extension of the human, human brains and computing systems can be coupled in a close cooperative partnership to perform intellectual operations. The computer acts as the human's assistant, as its computational capability facilitates human formulative thinking. The human assesses the validity of automated processing, incorporates heuristics into the process, provides novel information, and performs abstract problem-solving tasks.

A similar concept is that of "distributed intelligence" systems (Ref. 1), human-machine systems capable of goal-directed cooperative work in complex real-time environments. The computer is no longer merely a tool, but becomes an intelligent partner or co-worker cooperating much as another human would. Intelligence is considered to be distributed among all entities in the system, with performance judged by how well all components interact to produce system-wide intelligence behavior. In this view, the computer becomes a full associate of the human. At this point, the boundary between supervisory control models and artificial intelligence models is not well defined.

Applications

Primarily useful as a description of the supervisory control process and as a framework for its discussion. *Potentially* useful for function, task, and workload analyses, to assist in allocating tasks among the four model levels; for developing models of microprocesses under control of a system executive; and for modeling human processes during development of artificial intelligence algorithms, especially for expert systems.

Constraints

- The model is intended to be strictly descriptive and qualitative; attempts to make it predictive or to make it yield quantitative results may not be appropriate.
- Complex systems are comprised of variables that are time varying, non-random, and not independent; instead, the variables are coupled through feedback loops and other processes. Consequently, a simple non-dynamic model may not always hold.
- The boundaries between Rasmussen's three levels of behavior are very fuzzy; each researcher must determine where these should be for the tasks under consideration.
- The communication interface between human and intelligent computer is the weakest link in symbiotic human-computer systems, due to limited knowledge about what constitutes fruitful communications and how to engineer them.

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Cross References

7.301 Monitoring and supervisory control;

7.303 Hierarchically structured control models;

7.305 Time required to detect, diagnose, and repair faults;

7.306 Training of operators for supervisory control;

7.307 Allocation of decisions between human and computer;

7.312 Comparison of different research settings for study of supervisory control;

7.316 Models of observer monitoring performance;

7.901 Characteristics of humans as decision makers;

Handbook of perception and human performance, Ch. 40, Sect. 1.

7.310 Optimal Estimation Model

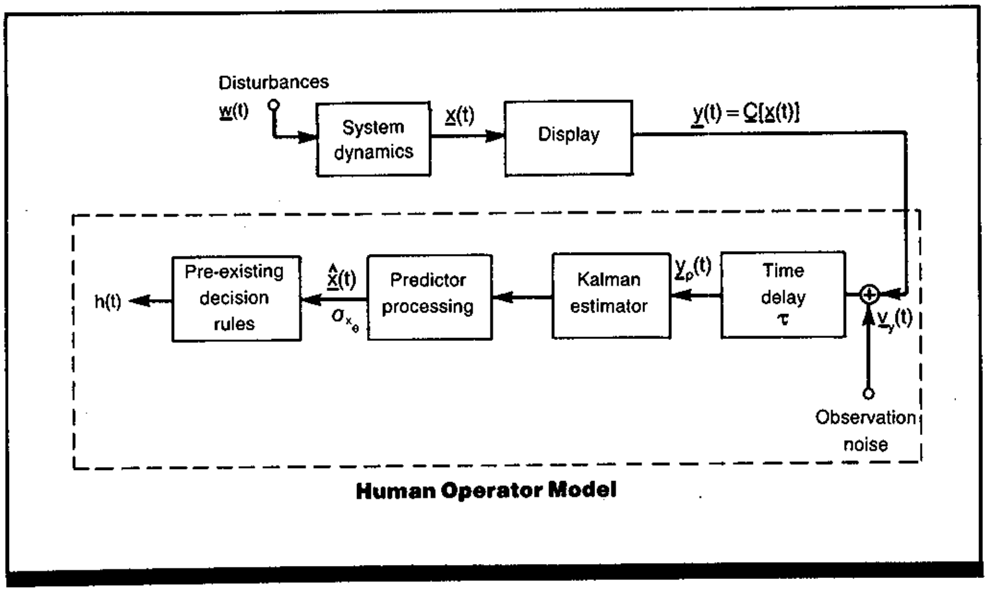

Figure 1. Optimal estimation model of a monitored system and the human observer who is making estimations and decisions based on observations. Matrix and vector variables are underlined. (After Ref. 2)

Key Terms

Decision making; estimation strategy; instrument monitoring; Kalman estimator; mental models; optimal estimation; workload

General Description

Optimal estimation theory (OET) is derived from optimal control theory (CRef. 9.512). It provides a general model of how the human obtains a best estimate of the state of a system when the displayed variables are corrupted (either by exogenous noise due to physical limitations, poor instrument design, or endogenous noise in the human observation system) so that it is impossible to measure exactly the true values of displayed system parameters.

Model parameters are as follows:

$\underline{w}(t)$ is a set (vector) of disturbances that affect the system dynamics at time t.

$\underline{x}(t)$ is the vector of values representing the system state variables at time t.

$\underline{y}(t)$ is the vector of displayed values of the state variables—equivalent to a vector of constants times the values themselves, $\underline{C}(\underline{x}[t])$

$\underline{v}_y(t)$ is an observation noise vector (associated with variable vector $\underline{y}$), considered to have a zero-mean Gaussian distribution

$\underline{y}_p(t)$ is the perceived vector of signal values (now inside the human operator model), following a perceptual time delay, τ

$\underline{x}(t)$ is the vector of estimated values for the state of the system, following optimal (i.e., *Kalman estimator*) and human predictor processing of the perceived information; σ_{x_e} is the **standard deviation** of the estimation error

$h(t)$ is the resulting hypothesis about the system state, based on the estimated values and on pre-existing decision rules about the system

The observed process is dynamic, and a new estimate must be obtained at each instant, based on the whole past history of observations. The goal is to minimize the error of the estimate. At each instant there are two sources of information: the running best estimate (the more accurate source if measurements are known to be noisy) and the current observation (the best when measurements are relatively noise-free). The model's Kalman filter (estimator), with its associated Kalman gain matrix, provides the best (statistically optimal) multipliers for the two information sources, since it behaves as if it were proportional to estimate uncertainty and inversely proportional to uncertainty due to noise.

The OET model assumes that (1) a well-trained, well-motivated observer behaves optimally in some sense, subject to inherent psychophysical limitations, such as randomness due to underlying multiplicative noise sources; (2) observation noise distributions are linearly independent of one another and of display-related noise; (3) the power density level of each noise term is proportional to the variance of the corresponding perceptual variable, with a known constant of proportionality (termed the noise/signal

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ratio); (4) the noise/signal ratio varies inversely with attention; (5) the observer has a fixed amount of information-processing capability (or attention) allocated optimally among the various observation tasks; and (6) the time delay for mental processing is a known constant.

The model is used to predict human decision performance in a multiple-task situation by (1) defining a total performance measure that is to be minimized (usually a weighted sum of decision errors such as misses and false alarms), (2) obtaining theoretical curves relating decision errors to the model's noise/signal parameter, and (3) using an iteration technique to find the noise/signal ratio associated with each task which minimizes decision errors, subject to the constraint of the human's fixed amount of information processing capability. Predicted values then may be obtained for total-task performance, component-task performance, and allocation of attention among the tasks (Ref. 2).

Applications

Has been used for (1) modeling failure detection and tolerance-band monitoring, including prediction of eye movements, failure detection times, and the probability of error; (2) the design of optimal displays; (3) predicting decision-making accuracy; (4) analysis of human monitoring behavior; (5) prediction of supervisory performance with slowly responding process control systems; and (6) analysis of the idea of the human operator's internal model. *Potential* application to (1) reliability assessment, (2) modeling workload, and (3) modeling process supervision in a nuclear power control room.

Empirical Validation

The OET model was tested in single-decision-task and multiple-decision-task studies using four engineering students (Ref. 2). The tasks simulated a pilot's task of deciding if the aircraft is within a landing window using a glide-slope indicator and displayed region of acceptable glide-slope error during airport approach. Agreement between model and empirical values was good; for both single and multiple decisions, predicted error scores were within 10% of observed scores.

Constraints

- The model applies to well-trained, highly motivated observers who have mental models of the process being monitored; different observers may have different models.
- The model implies that observers are performing complex, detailed mathematical operations; it may not be plausible for humans to perform such calculations in their heads, in real time. Alternate theories propose that humans use verbal plans based on cognitive, non-mathematical diagnoses of system states.
- Constants or known distributions must be specified for the time delay, τ, and noise/signal ratio. Values of 0.2 sec and -20 dB were used in model validation (Ref. 2), but may not be appropriate for other kinds of tasks.
- Considerable experience in using the model is necessary to apply it with confidence.
- Considerable computation resources/programming effort are required for model implementation.

Key References

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Cross References

9.512 Modeling of the human operator: the optimal control model;

Handbook of perception and human performance, Ch. 40, Sect. 4.

7.311 Application of Optimal Control Theory to Monitoring Performance

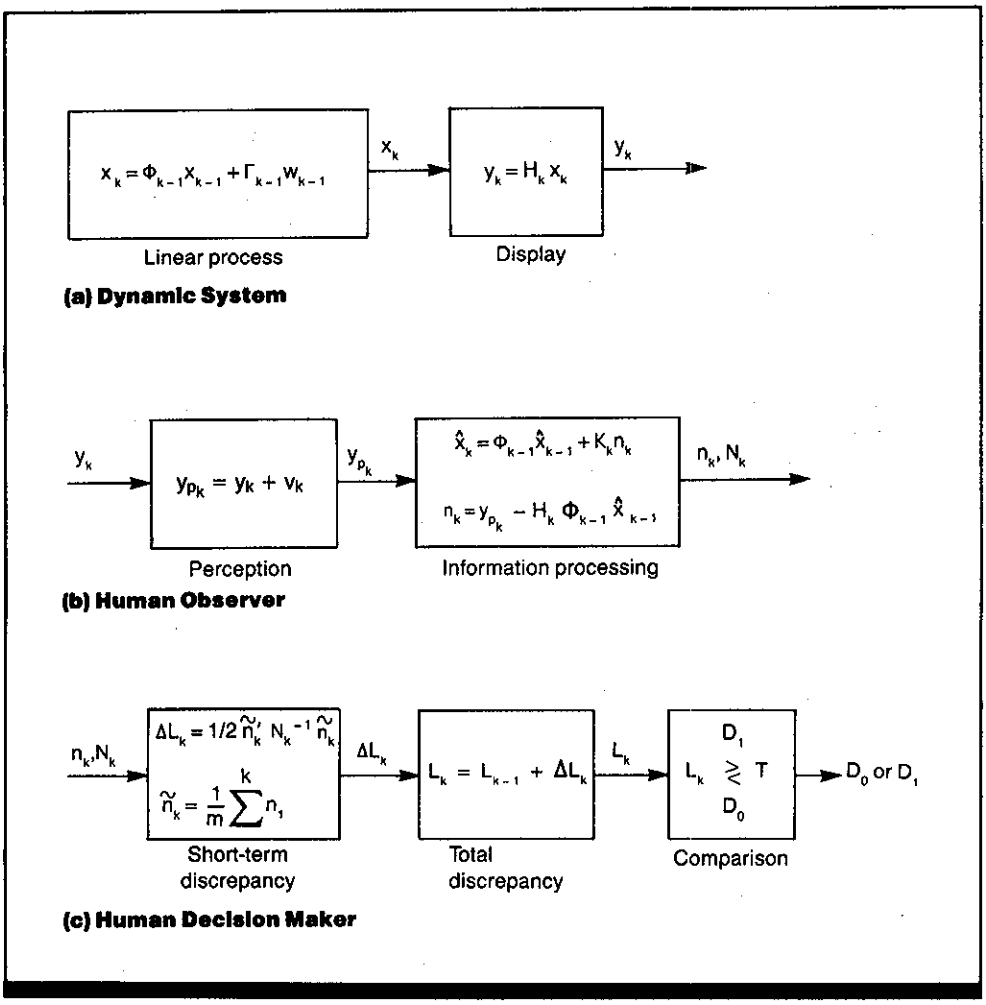

Figure 1. Model of the human decision maker observing a dynamic process for failures. The output of (a) a dynamic system is input to (b) a human observer who is (c) a decision maker. (From Ref. 4)

Key Terms

Decision making; failure detection; Kalman estimator; monitoring; optimal control; reaction time; visual displays; Wald decision rule; workload

General Description

Wewerinke's model of human detection and decision making (Ref. 4) is a monitoring model developed within the framework of optimal control theory (Ref. 1) and classical sequential decision theory (Ref. 3). The model consists of three submodels: a dynamic system (Fig. 1a), a human observer (Fig. 1b), and the observer as a decision maker (Fig. 1c).

The observer's's task is assumed to be detection of failures in one or more systems, as indicated via displays. Each system is considered linear and dynamic, representable by a Gauss-Markov random sequence with zero mean when operating normally. The observer perceives displayed outputs and processes the perceived information about the system state.

The observer keeps a running estimate of the mean and variance of the displayed output values. The estimate is updated with each observation via a Kalman estimator (the best estimate of the true value, given observation noise in the nervous system), and is used to form a likelihood ratio (which is a ratio of measure of the probability of obtaining that estimate, given that the process is in an abnormal state, to the probability of obtaining that estimate, given that the process is in a normal state). These ratios are cumulated and

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used to move sequentially toward a decision. When a decision threshold is reached (the observer decides that the mean is non-zero), a failed condition is detected in a system.

Parameters of the dynamic system submodel include:

- x_k — Vector of state variables at time k
- ϕ_{k-1} — State transition matrix at time $k-1$
- Γ_{k-1} — Noise distribution matrix
- w_{k-1} — Vector of linear independent, zero-mean Gaussian random sequence with covariance W_k
- y_k — Information values derived from the display
- H_k — Observation matrix

Additional parameters for the human observation submodel are:

- y_{pk} — Perceived value of displayed information
- v_k — Vector of linear independent Gaussian random noise sequence with covariance $V_k = P_o E(y_k^2)$; P_o represents the human "full attention" noise ratio
- $\hat{x}_k$ — Best estimate of system state at time k (generated by a Kalman estimator)
- K_k — Kalman filter gain: ratio between uncertainty in the system state (in terms of an estimation error with covariance P_k) and reliability of incoming information
- n_k — Vector of new information ("innovative sequence") about the system state, obtained from the displays; in the unfailed mode, there is a zero-mean Gaussian random sequence with covariance $N_k = H_k P_{k/k-1} H'_k + V_k$

The human decision-maker submodel also requires as parameters:

- L_k — Likelihood ratio at time k (the probability of the present observed value, given a failed state, divided by its probability, given an unfailed state)
- ΔL_k — Change in likelihood ratio since the last observation
- $\tilde{n}_k$ — Observer's estimate of the mean of n based on m observations
- $\tilde{n}'_k$ — Observer's estimate of rate of change of mean of n, based on m observations
- D_1 — Decision that alternative hypothesis H_1 is true and a failure exists (failure state)
- D_0 — Decision that null hypothesis H_0 is true and no failure exists (normal state)
- T — Threshold value based on utilities of the two states (U_0 and U_1) and probabilities of their occurrences or, equivalently, on the probabilities of a missed failure and a false alarm (P_m and P_f); that is,

$$T = U_0 P(H_0)/U_1 P(H_1) = (1 - P_m)/P_f$$

From this model Wewerinke has derived an equation for the average failure detection time, n, given that a failure state exists:

$$n = (2P_f T \ln T)/(E[\overline{\tilde{n}' N^{-1} \tilde{n}}]) = (2P_f T \ln T)/E_t(\tilde{n}_e^2)$$

where $E_t(\tilde{n}_e^2)$ is the expected value of the estimate of the running average of the mean, $\tilde{n}$, based on the values, the display, and the sequence.

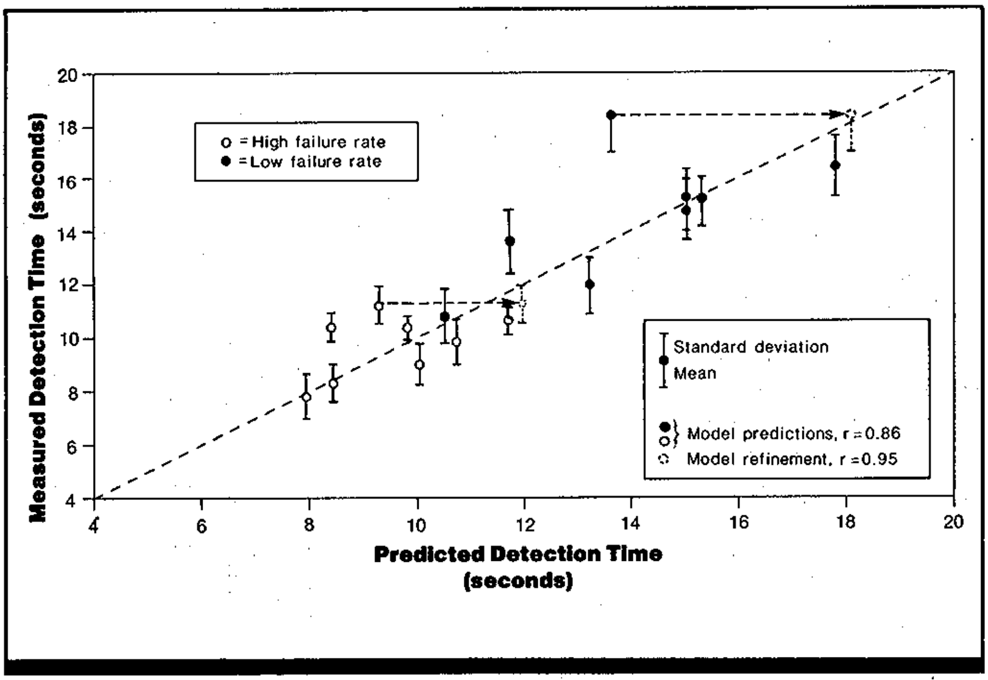

Figure 2. Comparison of observed time to detect failures with predictions from Wewerinke's model, for up to four displays, two failure rates, and eight configurations (based on 2 observers). The dashed line indicates the line of perfect correlation. See text for discussion of points identified as "Model refinement." (From Ref. 4)

Applications

Prediction of the average time it will take observers to detect system failures, under a variety of system and display conditions. May also be used to predict transitional probabilities **(link values)** of eye movements, proportion of time spent on the various instruments, and the amount of interference caused by correlated signals.

Empirical Validation

For model validation, Wewerinke used the following values for various system, display, and human parameters:

high bandwidth signal = 1.2 radian/sec (0.7 damping)

low bandwidth signal = 1.2 radian/sec (0.7 damping) + 4 sec time constant first-order filter

system failure rate 1 = 0.13 deg/sec (0.1 standard deviation of display position per sec)

system failure rate 2 = 0.26 deg/sec (0.2 standard deviation of display position per sec)

observer distance from displays = 0.55m

$E(\tilde{n}) = 0.01$ deg (0.6 arc min) visual angle (expected human threshold for observing display position)

$E(\tilde{n}') = 0.02$ deg visual angle per sec (expected human threshold for observing display position)

$P_f = P_m = 0.05$ (probability of false alarm and miss)

$P_0 = 0.01\ \pi$; equivalent to -20 dB (level of attention—a typical value)

$m = 4.0$ sec (moving average window size—typical span of short-term memory for visual stimuli)

Wewerinke tested the model using three experienced general aviation pilots, with 12 replications per experimental condition per pilot. Eight display configurations were used, with up to four oscilloscope displays per configuration: two displayed identical high bandwidth variables representative of aircraft attitude signal frequencies and two had identical low bandwidth variables similar to aircraft trajectory signal frequencies. Failures consisted of system failures and display failures. Two failure rates were tested: 0.13 deg/sec and 0.26 deg/sec. Failures were reported by depressing a button; a second depression indicated that failure diagnosis had been made. Figure 2 and Table 1 compare the experimental results with predicted values for two observers who used similar detection strategies (the third used a different strategy, as discussed under Constraints). Points labeled "Model refinement" show the result of taking into account the observers' inaccurate model of system dynamics with one set of display configurations, due to prior knowledge of impending system failure. When predictions are corrected for this factor, excellent agreement is shown between predicted and observed failure detection times.

Constraints

- Considerable experience with the model is necessary to use it with confidence.
- The model applies in monitoring tasks for a well-trained, highly motivated observer; although workload effects are included, the effects of fatigue and stress are not considered.
- The observer's time is assumed to be filled with display reading and failure diagnosis; no other tasks are included during model operation.
- The model assumes a constant level of attention and an equal division of attention between display position (reading) and display velocity (rate of reading change); these assumptions may be in considerable error for some conditions and display types.
- Two distinctly different failure detection strategies were observed with the 3 observers in the model validation; one required detection times ~40% longer that the others, with no false alarms at all during nearly 200 runs (the other two had a 5% false alarm rate); in the real world, various tradeoffs between speed and risk must be expected.
- Heart rate and variability measurements made during experimental validation indicated that the level of attention increases significantly with the number of uncorrelated displays. A constant level of attention was assumed for the model's predictions, resulting in overly long predicted detection times for the four-display configurations.
- The model deals only with steady-state, non-emergency conditions; in the real world, lights and alarms may demand attention; behavior will change with alarm states.
- Modern aircraft crewstations now use head-up and multifunction CRT displays in place of fixed, dedicated instruments; the applicability of this model to such displays is uncertain.
- Constants or known distributions must be specified for many of the model parameters; those used during model validation may not apply for other tasks and other user environments.

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Cross References

7.301 Monitoring and supervisory control;

7.302 Sampling behavior during process-control monitoring;

7.304 Fault detection and response with different levels of automation;

7.305 Time required to detect, diagnose, and repair faults;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

9.512 Modeling of the human operator: the optimal control model;

Handbook of perception and human performance, Ch 40, Sect. 2.2

Table 1. Comparison of model predictions with experimental results for five task variables. (From Ref. 4)

	Observed		Predicted	
Variable Producing Effect	**Mean**	**SD**	**Mean**	**SD**
Bandwidth (low/high)	1.01	0.12	1.00	0.08
Information correlation (correlated/ uncorrelated)	0.76	0.06	0.77	0.07
Information interference (high/low)	1.11	0.05	1.24	0.05
Failure type (system/display)	1.43	0.33	1.24 (1.37)	0.06 (0.21)
Failure rate	0.67	0.05	0.69	0.07

Each table entry represents the mean and standard deviation (SD) for the ratio of the values found under the two noted conditions for each variable; that is, the ratio of low to high bandwidth is predicted to be 1.00 and observed to be 1.01 (no effect of bandwidth on detection time). The values in parentheses reflect the two model refinement points discussed in the text.

7.312 Comparison of Different Research Settings for Study of Supervisory Control

Table 1. Factors in selecting settings in supervisory control or for evaluating data. (After Ref. 2)

Factors for Consideration	Real-World Studies	High-Fidelity Simulation	Low-Fidelity Simulation	Laboratory Experiment
Nature of system	Large, complex; multi-loop coupling of components	Moderate size, complex; some component coupling	Small, simple; some component coupling	Small; one or few independent components
System stability with time	Dynamic variables, depending on time and previous actions	Dynamic, much like real world	Generally static	Generally static
Research	Practical (positive as well as negative)	Practical; training	Tryout of conceptual ideas in "near real-world"	Test of conceptions
Experimental design	Very difficult	Difficult	Easy	Easy
Tasks	Inferred by operator; controlled by operator; time-varying; meaningful and coherent	Specified, but not well defined; time-varying; somewhat meaningful	Specific, fairly stable,fairly well defined; often not meaningful	Specific, stable, well defined; usually not meaningful
Experimental variables	Usually many; seldom independent	May be many; difficult to maintain independence	Usually few; usually independent	Seldom more than three; independence maintained
Trials, events	Not independent; interrelationships usually meaningful	Seldom independent; interrelationships usually meaningful	Statistically independent; some pattern	Statistically independent; no coherent pattern
Operator experience	Highly trained	Fairly well trained	Only enough training to reach plateau	Minimal training; often still climbing curve
Operator strategies	Self-selected, based on experience	Self-selected or provided by experimenter	Dictated by tasks or by experimenter	Dictated by tasks or by experimenter
Operator payoffs	Real-world costs, benefits, risks; often life and death	Artificial; moderate value; low risk	Artificial; low value; no risk	Artificial; low value; no risk
Performance measures	Productivity; efficiency; internal goals met	Control strategy; information processing; problem solving	Error corrections; decision correctness; procedure following	Response latency; completion time; error rate
Effects of operator responses	Determine scenario from start to end	Determine scenario except for initial conditions, manipulated variables	Little or no effect on what occurs next	Little or no effect on what occurs next
Ease of collection	Very difficult	Difficult	Moderately easy	Easy
Data assessment	Very difficult; time series analysis, operator ratings, decision analysis	Difficult; time series analysis, operator ratings, decision analysis	Difficult; analysis of variance, operator ratings	Easy; analysis of variance
Cost of research	Very costly	Very costly	Costly	Low cost
Application of results	Directly applicable to that specific system; cannot always be generalized	Usually applicable to a specific system; can generalize to similar systems	Can be generalized but does not apply well to any given system	Can be generalized but does not apply well to any given system
Transfer of research to new designs	High	High	Possible	Not direct

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Automation; human-computer interface; human operator models; monitoring; operator strategy; simulation; supervisory control

General Description

Human supervisory control behavior and performance are often investigated in research settings that differ in many ways from real-life settings. These differences must be recognized and considered if such research is to serve its two intended purposes: (1) to develop behavioral principles, causal relationships, or detailed models that can serve as a basis for design; and (2) to evaluate specific models or design solutions. Empirical data on supervisory control behavior can be obtained from analysis of incidents, events, and activities as observed in four major types of research.

- Actual real-world systems (monitoring everyday, complicated tasks and situations)
- High-fidelity simulation in the field or laboratory (attempting to re-create the work environment of interest)
- Low-fidelity simulations in the field or laboratory (abstracting the critical elements into a generalized work environment)
- Laboratory studies (using simplified experimental paradigms in a general, context-free environment for parametric studies, in which various levels of a treatment can be manipulated across a known range)

Real systems are the source of the problem set and the final proving ground for design and procedural concepts developed in other research contexts. Yet all four of the research settings can be used. For example, the basic properties of supervisory control can be initially established using approximations and simple systems in the laboratory. Once these basic properties are determined, it is easier to design those critical experiments that require expensive simulation or real facilities.

The four levels of research can be considered in the light of Rasmussen's three-level hierarchy of control behavior (CRef. 7.303). In the laboratory and in low-fidelity simulations, often the researcher can examine any of the three levels, skill-based, rule-based, *or* knowledge-based performance, as desired. In high-fidelity simulations and real-life situations, however, the three performance levels seldom can be separated; performance is along a continuum of behaviors.

Table 1 summarizes the differences between laboratory, simulation, and real-world settings for experimentation and other forms of data gathering. These factors should be considered when choosing a setting for research, and also when evaluating the results of studies to determine their applicability to a given situation.

Applications

Determination of the appropriate research setting for investigation of a given system, either for design or for evaluation.

Key References

1. Rasmussen, J. (1979). Reflection on the concept of operator workload. In N. Moray (Ed.), *Mental workload: Theory and measurement* (pp. 41-78). New York: Plenum Press.

*2. Sheridan, T. B., & Hennessy, R. T. (Eds.) (1984). *Research and modeling of supervisory control behavior: Report of a workshop.* Washington, DC: National Academy Press.

Cross References

7.301 Monitoring and supervisory control;

7.303 Hierarchically structured control models;

7.307 Allocation of decisions between human and computer;

7.309 General model of supervisory control;

7.316 Models of observer monitoring performance;

Handbook of perception and human performance, Ch. 40, Sect. 6.2

7.313 Eye Fixations and Eye Movements During Display Monitoring

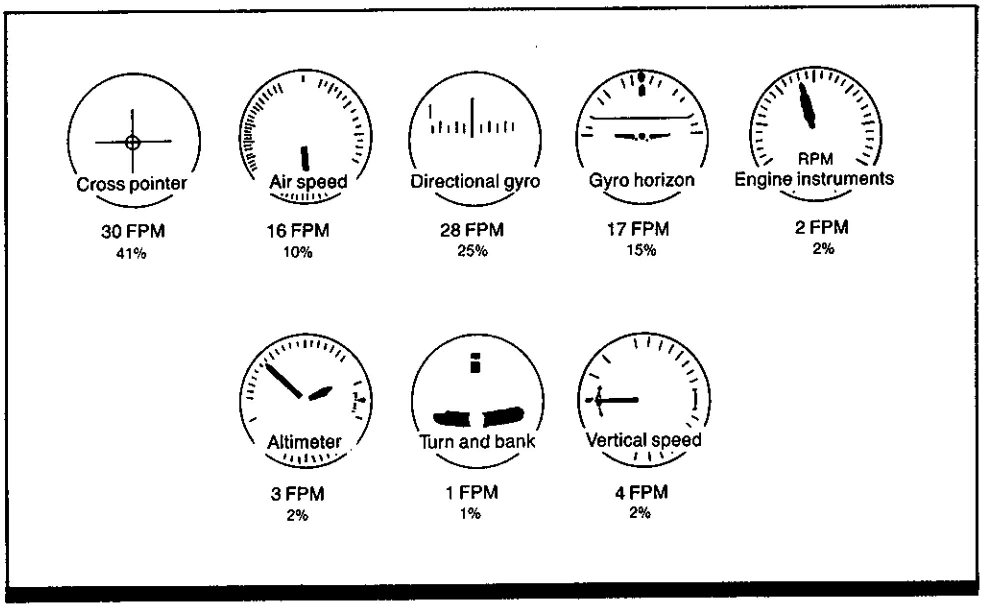

Figure 1. Schematic layout of cockpit instruments for Study 1. FPM is the number of eye fixations per min; the numerical value is the number of FPMs for that instrument during instrument-landing approaches. The percentage is the relative amount of time spent looking at that instrument. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Key Terms

Eye movements; instrument layout; instrument panels; monitoring; simulation; visual fixation

General Description

Visual **dwell time**, the time a pilot spends looking at an instrument, is a function of the individual pilot and of the instrument type. The frequency of eye fixations appears to be a function of the importance of the information provided (e.g., aircraft attitude is considered extremely important), and the duration of the fixations appears to be a function of the difficulty of reading the instrument and of interpreting data from it (e.g., extraction of general information versus the specific value). Changing the flight situation (e.g., from instrument low approach to ground control approach) changes the pilot's pattern of eye movements (e.g., the cross pointer drops from the most-often-scanned instrument to the least-often-scanned instrument).

Applications

Designing, arranging, and evaluating aircraft instruments so that the most used displays are most convenient, length of eye movements between fixations is minimized, and ease of reading and data interpretation is maximized.

Methods

Details of the experimental methods are provided in Table 1.

Experimental Results

- Mean eye fixation duration for all aircraft instruments is 0.6 sec, with a standard deviation of 0.12 sec.
- Range of instrument fixation durations is 0.4-1.4 sec for instrument landings (Study 1), and 0.1-4.0 sec for combined climb, holding, and approach maneuvers (Study 2).
- For the instrument arrangement shown in Fig. 1 (Study 1), the greatest eye-movement link values (Fig. 2) are between the cross-pointer attitude indicator and the directional gyro (29% of links). Link values are relatively large between attitude and air-speed indicators (16%), attitude and gyro-horizon indicators (10%), air-speed and directional-

gyro indicators (11%), and directional-gyro and gyro-horizon indicators (15%). The pattern of eye movements dramatically changes for ground-control approaches.

- Digital displays (which must be read) require longer interpretation time than do analog displays (usually just glanced at to determine that the moving needle is in a safe range) (Study 2).
- Using the data shown in Fig. 3a, Study 2 classifies the nine instruments used in the study into three categories: Type 0 (Fig. 3b), Type 1 (Fig. 3c), and Type 2 (Fig. 3d).
- The attitude indicator (the only Type 0 instrument) receives the longest dwell times (0.5-2.0 sec) and the highest percentage of eye fixation time (30-70%).
- The altimeter, directional gyro, course-deviation indicator, and glideslope/localizer are in the Type 1 category (Fig. 3b), with each instrument receiving brief fixations (0.5 sec) over a fair percentage of the time (2-35%). The directional gyro compass receives the second highest percentage of fixation time (up to 35%), with shorter dwell times (0.3-1.0 sec).
- The airspeed, engine-speed, turn-and-bank, and vertical-speed indicators are in the Type 2 category (Fig. 3c), which is characterized by small percentages of fixation time (1-10%) and a bimodal distribution of dwell times (0.10.2-sec "global checks" and 0.4-4.0-sec "information extraction" dwells).

Variability

Study 1 found a 13% difference in mean fixation duration for different landing-approach system types. Significant intersubject differences also were found (mean fixation time per min ranging from 0.4-1.0 sec). Study 2 found significant differences between attitude indicator dwell times ($p < 10\%$) and dwell percentages ($p < 5\%$), for climbing (1.2 sec, 57%), holding (1.1 sec, 49%), and approach (1.0 sec, 45%) maneuvers.

Repeatability/Comparison with Other Studies

The data are very typical of findings of both laboratory and field studies on dynamic display monitoring. Reference 3 reported mean dwell times of 0.73 sec (standard deviation 0.11) on radar watching tasks. Reference 4 reported mean dwell times of 0.37 sec (standard deviation 0.10) for laboratory meter-reading tasks. These results suggest 0.5 sec as the approximate shortest dwell times in "real life" tasks.

Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 1)	
• C-45 aircraft equipped with standard instruments • 35-mm motion picture camera (8 frames per sec) behind pilot photographing eyes as reflected in mirror in center of instrument panel • Translucent hood giving unrestricted view of instrument panel but preventing vision outside cockpit • Instrument layout as shown in Figs. 1, 2 • Eight 30-sec eye-movement records on each pilot: two records of two approaches, each with Instrument Low Approach System (ILAS) and radar Ground Controlled Approach (GCA) system	• Independent variables: instrument design, instrument placement • Dependent variables: instrument fixated, fixation time, number of fixations per min, eye-movement links between instruments • Observer's task: perform normal instrument scanning while making approach • 40 experienced Air Force pilots (ages 23-37 yrs)
Study 2 (Ref. 2)	
• Fixed-base simulator cockpit equipped with normal general aviation aircraft instruments and controls • Control Data Cyber 175 computer (32 iterations/sec) for real-time sequencing and data collection • Electro-optical oculometer recording reflected infrared light from observer's eyes • Simulation of climb, holding pattern, and approach maneuvers; seven times each per observer	• Independent variables: instrument designs, flight maneuver type • Dependent variables: instrument fixated, fixation time, percent of total fixation time per instrument • Observer's task: perform normal instrument scanning while performing flight maneuvers • 28 eye movement recordings per observer • 4 experienced instrument-rated private pilots

Constraints

- Only skilled aircraft pilots were used in both studies.
- Different instruments are checked with different frequencies (>10:1); combining numerical values about them may not be meaningful.
- Different instruments require different amounts of time to check (>2:1); average checking times may not be useful.
- Little time is spent not looking at any instrument; thus, reducing the number of displays may not reduce the number of fixations per minute.
- Design improvements intended to reduce workload (fixations required) may lead to unpredictable qualitative changes in work pattern.
- Modern aircraft crewstations now use head-up and multifunction CRT displays in place of many of the instruments discussed here; the applicability of results of these two studies to such displays has low validity.

Key References

*1. Fitts, P. M., Jones, R. E., & Milton, J. L. (1950). Eye movements of aircraft pilots during instrument-landing approaches. *Aeronautical Engineering Review, 9*(2), 24-29.

*2. Harris, R. L., & Christhilf, D. M. (1980). What do pilots see in displays? *Proceedings of the Human Factors Society—24th Annual Meeting* (pp. 22-26). Los Angeles, CA: Human Factors Society.

3. Moray, N., Neil, G., & Brophy, C. (1983). *The behavior and selection of fighter controllers* (Tech. Rep.). London: Ministry of Defense.

4. Senders, J. W., Elkind, J. I., Grignetti, M. C., & Smallwood, R. (1964). *An investigation of the visual sampling behavior of human observers* (NASA CR-434). Cambridge, MA: Bolt, Beranek & Newman, Inc.

Cross References

7.302 Sampling behavior during process-control monitoring;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

7.317 Senders' periodic sampling model of display monitoring;

7.318 Markov model for eye transitions during display monitoring;

7.319 Queuing model of display monitoring;

Handbook of perception and human performance, Ch. 39, Sect. 2.8; Ch. 40, Sect. 2.1

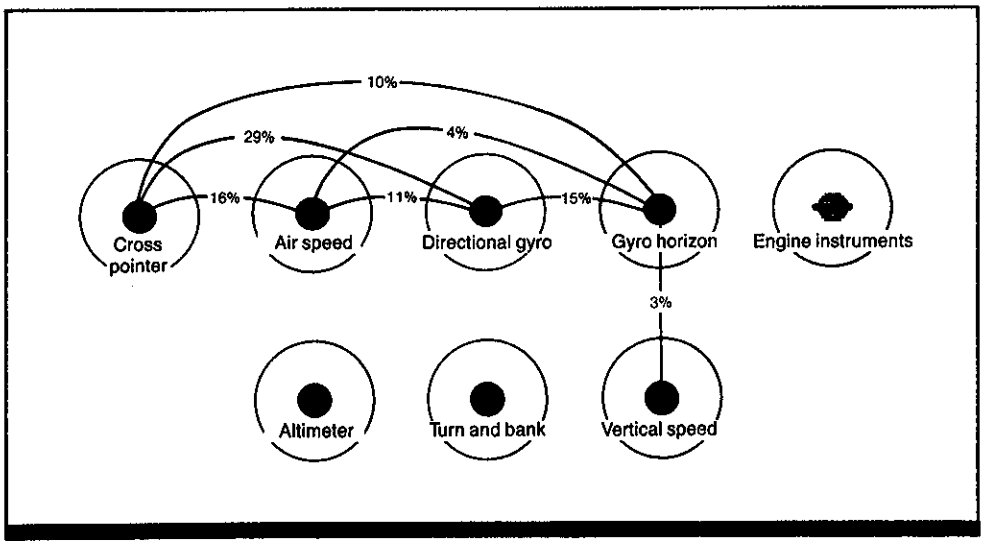

Figure 2. Eye-movement link values between aircraft instruments under the same conditions as Fig. 1 (Study 1). Link values represent the percentage of all eye transitions that were made between the two instruments indicated. Values <2% are omitted. (From *Handbook of perception and human performance*, adapted from Ref. 1)

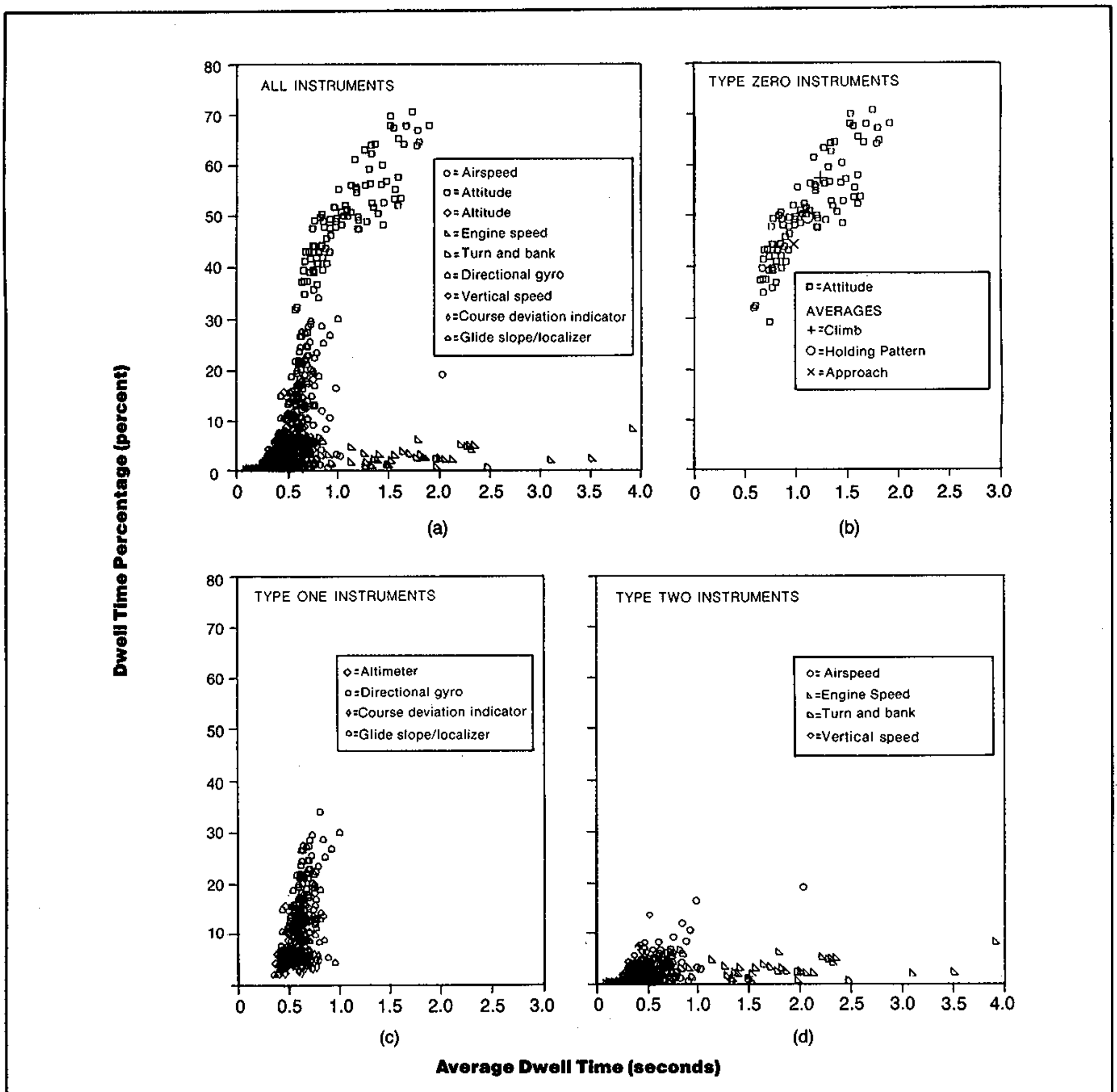

Figure 3. Average fixation dwell time and percent of time fixated on particular instruments (Study 2). (a) Data for all instruments; (b) data for Type 0 instrument (for three kinds of flight maneuvers); (c) data for Type 1 instruments; and (d) data for Type 2 instruments. (From Ref. 2)

7.314 Factors Affecting Monitoring Performance

Factor	Effect on Monitoring Performance	Sources
Signal bandwidth	Sampling rate is proportional to the bandwidth of the monitored process; below 2.5 Hz the signal is "oversampled" due to endogenous uncertainty generated by forgetting; above 2.5 Hz "undersampling" occurs because the observer is able to estimate instantaneous velocity	CRefs. 7.311, 7.317
Intercorrelations of monitored process	Observers use intercorrelations of displays to reduce the number of observations required for effective monitoring	CRef. 7.316
Accuracy of the display	"Noisy," hard-to-read displays (with low signal-to-noise ratios) require longer sampling durations	CRefs. 7.313, 7.317
Monitoring of multiple displays	Sampling allocations, durations, transitions, and rates are proportional to relative bandwidths, error rates, and/or importance of multiple displays	CRefs. 7.313, 7.318
Observer overload and/or stress	Overload/stress degrades failure-detection performance	CRefs. 7.313
Overall monitoring strategy chosen by observer to optimize behavior	There is a strong interaction between task demands, process statistical structure, and the observer's strategy. Under heavy task loads the observer narrows the range of monitoring (number of processes sampled), based on the relative priorities of task demands and the statistical structure of the monitored processes	CRef. 7.309 Ref. 2
System tolerance limit L and its violation cost	Sampling frequency increases as a process gets nearer to the limit *L* (which the process must not exceed) and is a positive function of the threshold violation cost; when the sampled value of a process is close to *L*, the process is given priority to pre-empt the queue of processes to be sampled	CRefs. 7.302, 7.319 Ref. 2
Payoff matrix relating costs of monitoring errors (missed critical events) to costs of making observations	When several process are monitored simultaneously, sampling frequency is a positive function of error cost and a negative function of sampling cost.	Ref. 3
Amount of practice	Inexperienced observers who must think consciously about monitored signal statistics and related decisions perform sub-optimally, whereas experienced observers who have developed an internal model of the signal process respond automatically in as optimal manner as innate human limitations permit	CRef. 7.316; Ref. 3
Human limitations	Experienced observers operate in the realm of constrained optimality (i.e., behavior is optimal, given the limitations of perceptual, memory, cognitive, and motor systems). Since severe forgetting occurs after 15 sec and fixation eye movements seldom exceed 2/sec, not more than 30-40 independent displays can be effectively monitored by one observer	CRef. 7.316
Automation assists	Monitoring in monotonous situations can be aided by automated alarms and alerts	Ref. 3

Key Terms

Automation; monitoring; process control; stress; training; warnings; workload

General Description

Monitoring and supervisory control entails information assimilation and processing in meaningful and useful ways from one or more controlled processes (CRefs. 7.301, 7.309). Monitoring may sometimes entail continuous and exclusive sampling as in tracking of a high-bandwidth (quickly varying) signal, such as in aircraft or missile control (CRefs. 7.313, 7.317, 7.318). Conversely, several

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

slowly changing processes may be monitored simultaneously, with the observer allocating sampling among the different slow-data-rate signals using a strategy that maximizes payoff (and/or minimizes risk or cost); this is typical of supervisory control of nuclear power plant operations (CRefs. 7.302, 7.311). In either case, the assimilation of information during monitoring inherently entails sampling and data-processing functions by the observer. Those functions have been modeled, in many cases, with high predictive accuracy by researchers using a variety of approaches that usually depend on the particular demands of the monitoring task(s) involved (CRef. 7.316). The table summarizes the effects of many of the factors that have a strong influence on observer strategy and success in monitoring tasks.

Constraints

- A model's ability to predict an observer's performance depends on the observer's extent of practice; in the early stages of practice, when observers are thinking consciously of process statistics, costs, and related decisions, there are large individual differences.
- Other factors (e.g., boredom) may influence monitoring behavior for very slow systems (e.g., in process control).
- The experimental validation of many early performance-predicting models entailed a small number of displays with low bandwidths imposing relatively light monitoring workloads on the observers. In many actual systems bandwidths are high, displays are numerous, and delays may be involved in choosing which displays to view; under such conditions there will be significant interactions between the operator's display scheduling and data acquisition algorithms.
- For highly complex systems having many displays and many variables, the observer has a problem of integrating information, in both time and space, into a coherent perception of the overall system's state. This problem requires careful study and analysis of individual operator workloads, development of coordinated multiple observer actions as required, and creation of automated monitoring aids, as critical situations may warrant.

Key References

1. Carbonell, J. R. (1966). A queuing model for many-instrument visual sampling. *IEEE Transactions on Human Factors in Electronics, 7,* 157-164.

2. Kleinman, D.L., Krishna-Rao, P., Ephrath, A.R. (1980, October). From OCU to ODU: An Optimal Decision Model of Human Task Sequencing Performance. In *Proceedings of International Conference in Cybernetics and Society,* Boston, MA: Institute of Electrical and Electronics Engineers.

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5. Sheridan, T. B. (1970). On how often the supervisor should sample. *IEEE Transactions on System Science and Cybernetics, 6,* 140-145.

6. Wewerinke, P. (1981). *A model of human decision maker observing a dynamic system* (Tech. Rep. NLR TR 81062 L). Netherlands: Nationaal Luchten Ruimtevaor Laboratorium.

Cross References

7.301 Monitoring and supervisory control;

7.302 Sampling behavior during process-control monitoring;

7.309 General model of supervisory control;

7.311 Application of optimal control theory to monitoring performance;

7.313 Eye fixations and eye movements during display monitoring;

7.316 Models of observer monitoring performance;

7.317 Senders's periodic sampling model of display monitoring;

7.318 Markov model for eye transitions during display monitoring;

7.319 Queuing model of display monitoring

7.315 Effect of Display Size on Visual Fixation

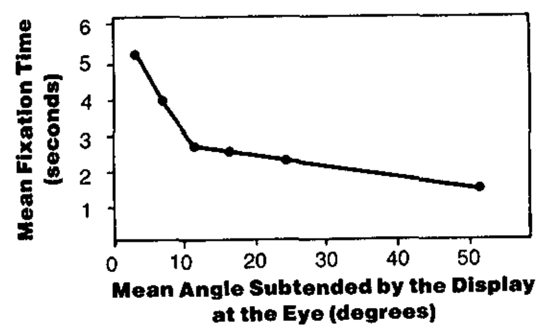

Figure 1. Mean duration of fixation as a function of visual angle subtended by display. (From Ref. 1)

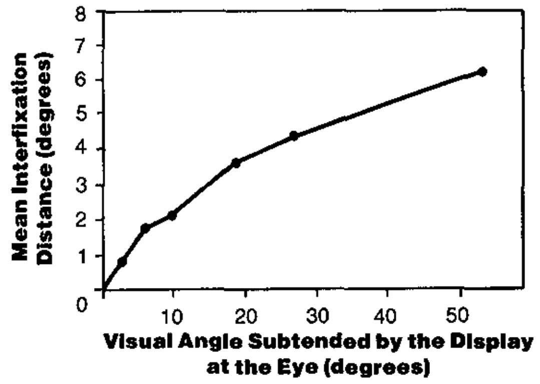

Figure 2. Mean interfixation distance as a function of visual angle subtended by the display. (From Ref. 1)

Key Terms

Display size; monitoring; vigilance; visual fixation; visual fixation duration

General Description

As the size of a visual display increases, the average duration of each eye fixation decreases (Fig. 1) and the average interfixation distance increases (Fig. 2). The optimum size of a static display subtends 9 deg of visual angle at the eye. When viewing a display <9 deg in diameter, observer efficiency (defined as the percentage of fixations made within the display area) decreases; although some fixations are made in the center of the display, many occur outside the display (Fig. 3). In larger displays, the tendency to concentrate fixations in the center of the display results in a loss of peripheral information; the larger the display, the more peripheral information may be lost.

Methods

Test Conditions

- Seven 22.86 x 22.86 cm (9 x 9 in.) aerial maps, each presented for 30 sec, containing regions of white, black, and five shades of gray; maps equated for contrast and content
- Target detail in maps was a **Landolt "C"**, subtending 5 min arc of visual angle, placed on areas of uniform density at least 1 deg in diameter and located in zones of approximately equal weight
- Gray paper masks covered maps; openings of 3-, 6-, 9-, 18-, or 24-deg diameter centered on map; one map, left unmasked, subtended 51 deg 18 min on the diagonal
- Luminance level for white areas was 205.56 cd/m² (60 fL); luminance of masks equal to median gray in maps

Experimental Procedure

- Eye fixation recorded by modified ophthalmograph; repeated measures design
- Independent variable: display size, defined as diameter of opening in mask
- Dependent variables: eye fixation duration in sec; efficiency, defined as percentage of fixations falling within display area; interfixation distance, measured in deg of visual angle
- Observer's task: indicate presence or absence of Landolt "C" on map by making manual response
- Observer's head held in place by bite bar and head rest
- 12 observers, with uncorrected 20/20 visual acuity, ages 20-35, some practice

Experimental Results

- As display size increases, duration of fixations decreases (Fig. 1), and average interfixation distance increases (Fig. 2). There is a sharp break in the duration function at 9 deg, implying a change in search mode at this display size. Increasing display size over 9 deg has little effect on search behavior.
- When viewing a display <9 deg in diameter, percentage of eye fixations falling outside the display markedly increases (Fig. 3). This implies that if display size is to be limited to <9 deg by an overlay technique, the limiting grid should leave surrounding areas visible.
- Peripheral information in displays >9 deg is lost because fixations are concentrated in the center of the display. Larger displays entail a lower probability that peripherally located objects will be detected.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The finding of nonuniform eye fixations across visual displays is consistently reported in other studies. However, the pattern of eye fixations has been shown to be dependent upon the observer's search strategy, type of material scanned, and distribution of detail within the visual display (Ref. 2; CRefs. 7.516, 11.403.)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- No information provided on how maps were equated for contrast and content.
- The largest display used here (51 deg 18 min) should be considered separately from the others, since keeping head position fixed with displays this large would prevent efficient display use.
- Search strategies may differ if target detail is not uniformly distributed into equally weighted zones (Ref. 2).
- Search strategies employed with static displays used here should not be assumed to generalize to dynamic displays.
- For displays of territory, for target images to be of adequate size to be found, territory coverage would be so small that most targets would never appear on the display.

Key References

*1. Enoch, J. M. (1959). Effect of the size of a complex display upon visual search. *Journal of the Optical Society of America, 49*, 280-286.

2. Yarbus, A. L. (1967). *Eye movements and vision*. New York: Plenum.

Cross References

1.913 Visual fixation: relationship between head and eye movements;

1.914 Monocular fixation on stationary targets;

1.915 Effects of target characteristics on eye movements and fixation;

1.916 Visual fixation on dimly illuminated targets;

7.313 Eye fixations and eye movements during display monitoring;

7.314 Factors affecting monitoring performance;

7.516 Target acquisition in distractor target arrays

7.524 Visual search for multiple targets;

11.403 Target coding: effect on search time

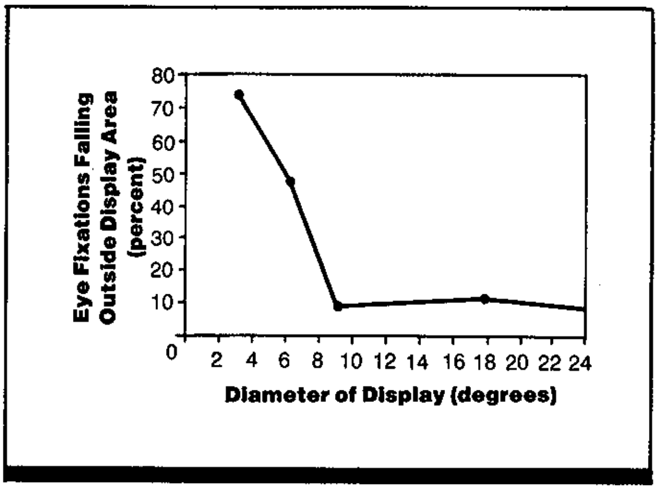

Figure 3. Percentage of eye fixations falling outside display area as a function of visual angle subtended by display. (From Ref. 1)

7.316 Models of Observer Monitoring Performance

Table 1. Summary of monitoring models.

Model	Evaluation	Advantages	Disadvantages	Predictions	Where Applicable	References
Senders' periodic sampler method	Good for moderate band-width signals; consistent with other studies	Simple to use; only two para-meters needed	Many assump-tions; limited applicability, especially below 0.1-Hz band-widths	Sampling fre-quency; dwell time	Multi-instrument panel layout; in-strument ease-of-use evaluation	CRef. 7.317
Senders' Markov model	Good agreement with empirical studies	Simple to use; re-quired data easy to obtain	Many assump-tions; limited applicability	Transition probabilities	Multi-instrument panel layout	CRef. 7.318
Senders' aperiodic sampler models	Model has not been validated; unlikely to apply to low bandwidths	More realistic assumptions in-crease usefulness	Calculations more compli-cated; parameters harder to obtain	Expected time of next observation	Multi-instrument panel layout	Refs. 4, 5
Carbonell's queueing model	Excellent agree-ment with em-pirical studies	Provides predic-tions not yielded by other models; useful for low bandwidths	Requires com-puter program and simulation	Sampling fre-quency; prob-ability of obser-vation at a given time; "cost" of an observation	Multi-instrument panel layout; evaluation	CRef. 7.319
Kvalseth's infor-mation theory model of sampling	Validation was limited; results seem reasonable	The only model dealing with discrete (digital) signals	Calculations somewhat com-plicated; predic-tions are limited	Expected time between obser-vations on digital displays	Design and layout of digital displays	Ref. 1
Moray's model of radar operator eye movements	Predictions reasonably accurate	The only model dealing with im-aging displays	Markov analysis required to ob-tain results	Dwell time; ex-pected time between obser-vations	Design of imag-ing and sym-bolic displays	Refs. 2, 3, 5
Wewerinke's op-timal control theory model	Excellent agree-ment with em-pirical studies, when corrected for observer strategy and inter-nal model	Comprehensive model, taking many factors into account; useful for high bandwidths	Model applica-tion is extremely difficult	Time to detect failures; transi-tion probabilities of eye move-ments; dwell time; interfer-ence from corre-lated signals	Design of displays for failure detection	CRef. 7.311

Key Terms

Digital displays; eye movements; failure detection; imaging displays; information theory; link values; Markov model; monitoring; optimal control theory; queuing model; radar; reaction time; visual displays; visual fixation; workload

General Description

No single model describes human monitoring behavior under all conditions; such a model would be too complex to employ. Instead, numerous models have been developed, each addressing a specific situation in the simplest possible terms that allow accurate predictions. The practical problem for a designer of a user-machine system is to decide which model to use in the situation of interest. Table 1 provides a summary of seven models that permit predictions of several measures of human monitoring behavior under various conditions. Included are brief statements indicating what a given model can predict, what systems it may be used for, how good its predictions usually are, and its advantages and disadvantages. Most of these models are discussed in detail in this section, and additional information about them may be found in the entries indicated in the cross references. Literature references are provided for models mentioned in the table that are not included in the cross-referenced entries.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Selection of the appropriate model for predicting monitoring performance, as needed for a new system under design or development. *Potential* use for determining areas where models do not presently exist or need improvement.

Empirical Validation

General results of empirical validations are shown in Table 1; more detailed discussions are provided in the individual entries.

Constraints

- These models apply in monitoring tasks for a well-trained, highly motivated observer; the effects of fatigue and stress are not considered.
- The models deal only with steady-state, non-emergency conditions. In the real world, lights and alarms may sound to demand attention; behavior will change under such alarm states.
- The human operator does not fit any single model in all cases; even within a given task on a specified system, more than one model will be appropriate over time.
- Modern aircraft crewstations now use head-up and multifunction CRT displays in place of many of the instruments considered in these models; model applicability to such displays is uncertain.
- The degree to which monitoring models predict performance of observers is strongly dependent on the extent to which observers are practiced.
- Most of the experimental work used to validate these models used a small number of displays with low bandwidths; thus, workloads were not generally heavy; in real systems, observers have much more difficulty in scheduling "looks" at displays and in assimilating information from them; integrating information into a single, unified view of the state of the system becomes a problem.
- An operator's memory for an observation becomes seriously deficient in ~15 sec; eye movements seldom exceed two per second; thus, not more than 30-40 displays can be efficiently monitored by a single observer.

Key References

1. Moray, N. (1986). Monitoring behavior and supervisory control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance. Vol. II: Cognitive processes and performance.* New York: Wiley.

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Cross References

7.311 Application of optimal control theory to monitoring performance;

7.317 Senders's periodic sampling model of display monitoring;

7.318 Markov model for eye transitions during display monitoring;

7.319 Queuing model of display monitoring;

7.317 Senders' Periodic Sampling Model of Display Monitoring

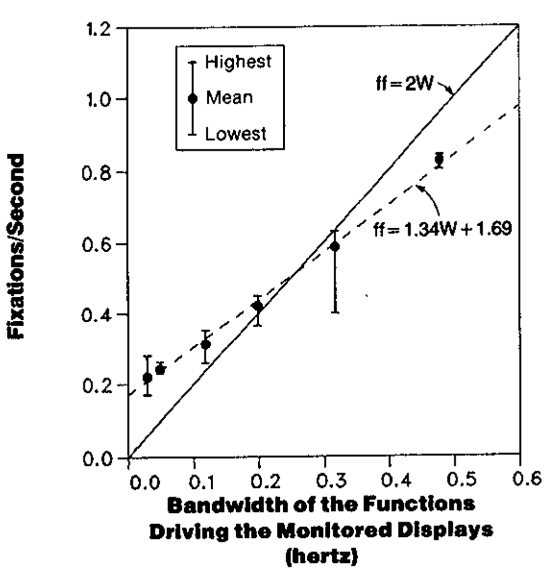

Figure 1. Eye fixation frequency as function of signal bandwidth. The solid diagonal line represents the theoretical value of fixation frequency (*ff*), which is twice the bandwidth, *W*. The dashed diagonal line represents the function for the empirically observed *ff* values. (From Ref. 3, adapted from Ref. 5)

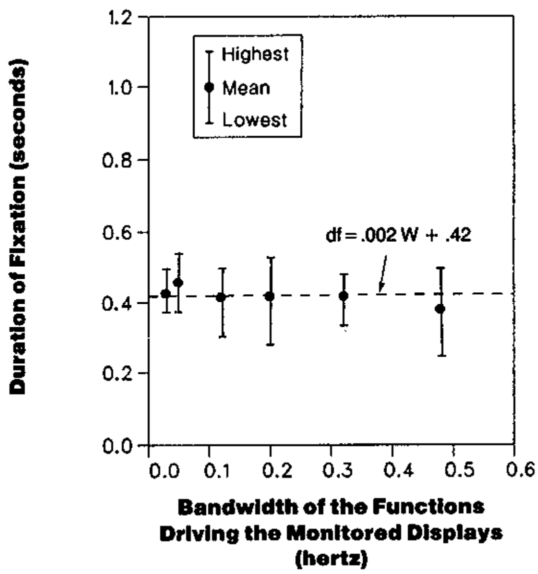

Figure 2. Fixation dwell time as a function of signal bandwidth, *W*. Observed values of duration of fixation (*df*) have been corrected for the probability of consecutive glances at the same instrument. (From Ref. 3, adapted from Ref. 5)

Key Terms

Aircraft instruments; eye movements; information theory; monitoring; Nyquist Theorem; Senders' model; uncertainty; visual fixation

General Description

Senders' periodic sampler model of many-instrument visual sampling assumes that the **power spectrum** of the displayed signal is the only determinant of the observer's monitoring behavior. The model applies mainly to displays with bandwidths above 0.05 Hz, that is, to displays that sample the condition of some system and change readings at least once each 20 sec.

For each display or instrument, the observer monitors a random signal with a limited bandwidth of W Hz. The Sampling Theorem or Nyquist Theorem states that it is necessary and sufficient that a signal be sampled at a rate of $2W$ Hz. It follows that an ideal observer can reconstruct the signal if observations are taken each $1/2W$ sec ($1/2W$ is referred to as the Nyquist interval). For example, if $W = 0.2$ Hz (i.e., a display changes at least every 5 sec), then sampling at a rate of $2W = 0.4$ Hz means observations are spaced $1/2W = 2.5$ sec apart. Observations at this frequency allow an observer to accurately evaluate the system's condition.

According to information theory, information generated by display i, defined in bits/sec, would be the important variable. Information is given by

$$\overline{H}_i = \text{Log}_2\,(A_i/E_i)^2 \qquad (1)$$

where A_i is the root mean square (rms) amplitude of a continuous, bandlimited Gaussian function of time, $f_i(t)$, for system and instrument i; and E_i is the tolerable rms error.

According to Senders' model, visual **dwell time** (fixation duration) is proportional to the average information rate defined in bits/sample, which is

$$\overline{H} = \text{Log}_2\,(A_i/E_i) \qquad (2)$$

when the observer samples the display $2W$ times/sec.

Assumptions of the model include:

1. Tasks are demanding, meaningful, and have well-defined goals, but the values read on the displays are of no consequence.

2. Observers are motivated, alert, highly practiced, ideal, identical, and have perfect recall.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

3. Humans are "uncertainty-reducing machines" who direct their behavior toward ordering and interpreting chaotic information.

4. Attention to a display is driven by subjective uncertainty about the state of a variable or of the world. Sampling behavior is driven only by the need to sample frequently enough to reconstruct the signal represented by the display, and signal reconstruction via successive looks is the observer's goal.

5. The observer always looks at something, and chooses that display about which he has maximum uncertainty; an instrument that varies rapidly and requires precise readouts will be read more often, but still is a random "draw from an urn" (although it has more "markers" in the urn).

6. Three or more instruments are being monitored; the signals that drive the instruments are statistically independent and are uncorrelated with each other.

Applications

For multi-instrument monitoring, the model can be used for panel layouts and instrument design, and for instrument ease-of-use evaluation. Boundary estimates also may be obtained for workload levels related to monitoring tasks. The model can also be used in situations where information is supplied globally, rather than via displays, such as in automobile driving, or where displays are unchanging but the observer's attention to detail changes with time, as when viewing a painting.

Empirical Validation

Experimental studies indicate a strong positive, monotonic relationship between frequency of fixation on an instrument and the bandwidth of the signal presented on that instrument (Fig. 1). Three to five well-practiced observers monitored banks of six instruments with bandwidths of 0.03-0.48 Hz. Instruments were zero-centered ammeters, each subtending a visual angle of 6 deg, separated by 12 deg, and arranged in two rows of three instruments. Observer's task was to press a button when any pointer exceeded a specified limit on its scale. Each instrument fixation and the duration of each fixation was recorded for 11-min periods.

When the data are compared with the theoretical values generated by the Sampling Theorem (Fig. 1), the high-bandwidth signals are undersampled and the low-bandwidth signals are oversampled. The undersampling of higher bandwidths can be accounted for by Fogel's Extended Sampling Theorem (Ref. 1): the appropriate sampling rate should be W Hz, not $2W$ Hz, if the observer can detect both instantaneous pointer position and instantaneous velocity. Oversampling of the lower bandwidths can be attributed to forgetting, an important factor as the interval between samplings increases with decreasing bandwidth (Ref. 2).

Because the ratio of A to E in Eq. 2 is the same for all bandwidths, average eye fixation duration is nearly constant at ~0.4 sec for all bandwidths studied (Fig. 2). This finding is consistent with other studies on eye fixation durations (CRefs. 7.313, 7.319).

Constraints

- The model applies in monitoring tasks for a well-trained, highly motivated observer who desires to reconstruct the represented signal from the display; the effects of fatigue and stress are not considered.
- The model deals only with steady-state, non-emergency conditions; in the real world, lights and alarms may sound to demand attention; behavior will change under such alarm states.
- In the real world, displays are rarely all of the same importance; degree of criticality of the information displayed also is expected to influence fixation frequency.
- Sampling periodicity is assumed, so no estimates of variance of either period or duration are provided by this model, nor are link values between glances at the various instruments considered.
- The human operator does not fit any signal model in all cases; even within a given task on a specified system, more than one model will be appropriate over time.
- The assumption of statistical independence between signals is unrealistic in real systems; this is especially true for aircraft instruments.
- Modern aircraft crewstations now use head-up and multifunction CRT displays in place of many of the instruments considered here; the applicability of this model to such displays is uncertain.

Key References

1. Fogel, L. A. (1956). A note on the sampling theorem. *Transactions of IRE Professional Group on Information Theory, 12*, 47-48.

2. Moray, N. (1981). The role of attention in the detection of errors and the diagnosis of failures in man-machine systems. In J. Rasmussen & W. B. Rouse (Eds.), *Human detection and diagnosis of system failures*. New York: Plenum Press.

3. Moray, N. (1986). Monitoring behavior and supervisory control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II: Cognitive processes and performance*. New York: Wiley.

*4. Senders, J. W. (1983). *Visual scanning processes*. Netherlands: University of Tilburg Press.

*5. Senders, J. W., Elkind, J. E., Grignetti, M. C., & Smallwood, R. P. (1964). *An investigation of the visual sampling behavior of human observers* (NASA-CR-434). Cambridge, MA: Bolt, Beranek, & Newman.

Cross References

7.311 Application of optimal control theory to monitoring performance;

7.313 Eye fixations and eye movements during display monitoring;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

7.318 Markov model for eye transitions during display monitoring;

7.319 Queuing model of display monitoring

7.318 Markov Model for Eye Transitions During Display Monitoring

Key Terms

Aircraft instruments; eye movements; link values; Markov model; monitoring

General Description

A simple Markov model based on probability and queuing theories may be used to predict the probability of an observer shifting attention from one instrument to another in a multi-instrument setting.

Over the long run, each of N instruments will receive a certain proportion of the total number of eye fixations, P_1, $P_2, \ldots, P_n$. The model says that the next instrument will be chosen with a probability equal to the proportion of fixations it obtains overall.

The probability that the observer is looking at instrument a is P_a, and the corresponding probability is P_b for instrument b. Assuming independence between fixations, the probability that a transition will be made between instruments a and b at time t is the probability that a is being fixated multiplied by the probability that b is fixated next: P_aP_b. For the simplest example, that of two instruments with equal probability of fixation, this gives a transition probability of $(0.5 \times 0.5) = 0.25$. Since the probability of a transition between instrument a and instrument b is the same as the probability of a transition from b to a, the probability of a transition in either direction is

$$P_{\overline{ab}} = 2P_aP_b$$

Two successive fixations may not be observable if they happen to be on the same instrument; this likelihood is not constant, but rather increases with greater signal bandwidths (CRef. 7.317). A pair of observations on instrument a (constituting an unobservable transition) occurs with probability $P_a{}^2$. Therefore, the equation must be corrected to obtain the probability of an *observable transition* between a and b. The resulting equation is

$$P_{\overline{oab}} = 2P_aP_b/[1 - \sum_{i=1}^{N} P_i^2]$$

For two instruments with equi-probable fixations, $P_{\overline{ab}}$ is 0.5 and $P_{\overline{oab}} = 1$. For banks of four and six instruments, each with equal fixation probabilities, $P_{\overline{ab}}$ is 0.125 and 0.0556, respectively, and $P_{\overline{oab}}$ is 0.1667 and 0.0667—slightly higher than the simple transition probability.

The model is based on several assumptions: (1) The observation of one instrument delays the observation of other instruments (the queuing concept) (CRef. 7.319). (2) The likelihood of a transition to any instrument in the future depends only on the instrument presently being fixated, not on any past history of fixations (the Markov property). (3) The signals that drive the instruments—and also visual transitions from instrument to instrument—are statistically independent and uncorrelated with each other. Finally, (4) the proportion of time each instrument is fixated is a known constant.

Senders has recently developed this model further so that dwell times, fixation frequencies, and transition probabilities may be generated (Ref. 2).

Table 1. Validation of Senders' Markov model for display transitions. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Transition	Predicted Probability	Observed Probabilities
$P_{1,2}$	0.117	0.112
$P_{1,3}$	0.042	0.040
$P_{1,4}$	0.203	0.297
$P_{2,3}$	0.052	0.051
$P_{2,4}$	0.364	0.324
$P_{3,4}$	0.131	0.133

Predicted and observed values of $P_{i,j}$ are shown for all six possible transition links between pairs for the four displays.

Applications

Design of instrument panels so that visual transitions between instruments that usually are read successively are facilitated, and length of eye movements between fixations is minimized.

Empirical Validation

Five well-practiced observers monitored banks of four instruments that sampled signals with bandwidths of 0.08, 0.15, 0.32, and 0.64 Hz. Instruments were zero-centered ammeters, each subtending a visual angle of 6 deg and placed at the corners of a 23-deg square. The observer's task was to press a button when any pointer exceeded a specified limit on the scale. Fixations on each instrument and transitions between instruments were recorded for 3-min periods. Table 1 compares these data values for transitions with values predicted for observable transitions ($P_{\overline{oab}}$) using Senders' Markov model. There is good agreement between model and empirical values.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Pilots and others who read complex banks of displays may or may not set up scanning patterns; thus the assumption that past history of fixations has no effect on future transitions may not always hold. In fact, pilots and other instrument observers do set up quasi-regular scanning patterns, invalidating the assumption.

• The assumption of statistical independence between displayed signals is unrealistic in real systems; this is especially true for aircraft instruments.

• Modern aircraft crewstations now use multi-function displays combining information from several aircraft systems, rather than individual instruments as considered here; the applicability of this model to such displays is uncertain.

Key References

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3. Senders, J. W., Elkind, J. E., Grignetti, M. C., & Smallwood, R. P. (1964). *An investigation of the visual sampling behavior of human observers* (NASA-CR-434). Cambridge, MA: Bolt, Beranek, & Newman, Inc.

Cross References

7.302 Sampling behavior during process-control monitoring;

7.311 Application of optimal control theory to monitoring performance;

7.313 Eye fixations and eye movements during display monitoring;

7.314 Factors affecting monitoring performance;

7.316 Models of observer monitoring performance;

7.317 Senders' periodic sampling model of display monitoring;

7.319 Queuing model of display monitoring;

Handbook of perception and human performance, Ch. 40, Sect. 2.2

7.319 Queuing Model of Display Monitoring

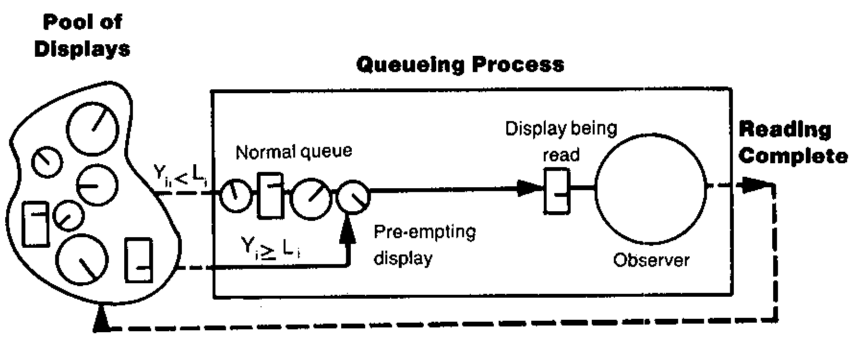


Figure 1. Queuing model for tasks related to display monitoring. Y_i is the current reading and L_i is the critical-limit reading for instruments.

Key Terms

Carbonell's model; monitoring; risk minimization

General Description

Carbonell's many-instrument visual sampling model is structured within a framework of queuing theory. Monitoring instruments can be considered a queuing process (Fig. 1), with each instrument joining a queue to await service (to be read). However, an instrument may preempt the queue if there is a high probability that the value of its reading will exceed some predetermined high-risk or critical level (L, which is time-varying, based on the last-noted reading of that instrument). A constant cost, C_i, is incurred when instrument i exceeds its critical level. The model may be used to predict the cost of looking at a specific instrument or of not looking at any instrument; the model can also predict the probability of an instrument having a critical-level reading at a given time. The following notation is used in the equations:

M is the number of instruments to be monitored,

t is the moment at which an observation is made,

t_o is the time of the last observation,

$y_i(t)$ is the value shown by instrument i,

$YO_i(t)$ is the last reading of instrument i before time t,

$P_i[y_i(t)]$ is the probability of instrument i showing value $y_i(t)$

L_i is the critical-level reading value for instrument i,

C_i is the cost incurred when instrument i exceeds L_i,

$C(t)$ is the total cost of not looking at any instrument at time t,

$C_j^*(t)$ is the cost of looking at some particular instrument j at time t,

$P_i(t)$ is the probability that instrument i will exceed L_i at time t,

Δ_i is the length of time (before time t) since instrument i was read,

and,

σ_i is the standard deviation of a Gaussian distribution, with mean $\exp[-(t - t_o)K_i]$.

The probability that instrument i will exceed its limit at time t can be described as

$$P_i(t) = P\{y_i(t) \geqslant L_i \mid y_i[t-\Delta_i(t)] = YO_i(t)\}.$$

The overall probability that Y_i is the value of the ith instrument at time t, given its value as observed at t_o, is

$$P_i[y_i(t) = Y_i \mid y_i(t_o) = YO_i] =$$

$$\frac{1}{\{2\pi[\sigma_i(t-t_o)]^2\}^{0.5}} \cdot \exp\left[\frac{-\{y_i - YO_i\exp[-(t-t_o)K_i]\}^2}{-2[\sigma_i(t-t_o)]^2}\right]$$

The cost of not looking at any instrument at time t is

$$C(t) = \sum_{i=1}^{m} \{C_iP_i(t)/[1-P_i(t)]\}.$$

Thus the cost of looking at any particular instrument j is

$$C_j^*(t) = C(t) - C_jP_j(t).$$

The model assumes that (1) the observation of one instrument delays the observation of other instruments (the queuing concept), (2) allowing some system to exceed its permissible limit (as indicated by an instrument) is associated with a cost, (3) the observer makes intelligent, deterministic decisions that reduce risk and cost, (4) only control actions will return a system to equilibrium, (5) if control is not exerted, divergence from the desired values will increase with time, and (6) if the observer exerts control, concern will be with variation from the last reading rather than from some absolute reading.

Carbonell used computer simulation to implement the

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

model. Initial inputs required for each run are (1) the number of instruments, M; (2) a threshold for not considering any instrument in the queue; and, for each instrument; (3) standard deviation of random fluctuations, σ_i; (4) autocorrelation decay constant, K_i; (5) threshold of risk, L_i; (6) threshold of accident, L'_i; (7) unitary cost; (8) divergence constant; and (9) control decay constant. Runs of 70 or more "decisions" (to read an instrument) are used to simulate monitoring of some specified number of instruments. For each instrument, the program outputs the time it was "read" (the sample number) and the interval between consecutive readings for the total number of decision samples (eye fixations). From these, the user can calculate the probability that a given instrument will be monitored at time t.

Applications

For multi-display monitoring, predicting the probability that an observer will not have enough time to scan all displays and that one or more will indicate a critical value that goes unnoticed. Also can be used to predict a cost for looking at a specific display (since others must be neglected while that one is read) and, similarly, the cost of not looking at any of the displays. *Potential* application in design of display layouts, to predict whether display-reading tasks can be performed in the allotted time.

Empirical Validation

The computer simulation model was tested using three experienced pilots flying a simulated airport approach in a Link trainer (Ref. 2). Data values were collected (eye movements recorded) for the number and times of eye fixations on each of six flight instruments, during descent, turn, and runway approach. Table 1 shows the correlation between these empirical data and the values predicted by Carbonell's queuing theory model and by Senders' Nyquist interval model (CRef. 7.317). Carbonell's model correlates better with the data.

Constraints

- The model applies to monitoring tasks for a well-trained, highly motivated observer who tries to minimize risk.
- The constants needed to run the model must be determined by analysis of the signals being used (their cutoff frequency and the mean square or variance of the corrected signal) and from questionnaires administered to experts on the system and the mission being studied (to ascertain critical-level readings for instruments, the cost of exceeding a limit, and rate of growth of risk with time between readings).
- Considerable experience with the model is necessary to apply it with confidence.
- The model requires tuning to particular observers and the particular tasks being performed.
- The model applies to tasks where each display is read for a fixed amount of time that is constant for all displays (0.4 sec assumed during validation); longer fixations are considered consecutive selections of the same display (in 0.4-sec quanta of time).
- The observer is assumed to fill all of his or her time with display reading; no other tasks are included during actual model operation.
- A non-zero mean Gaussian distribution is assumed for the probability of the value of the ith instrument at time t, with a mean of $\exp[-(t - t_0)K_i]$; for a zero-mean process, variance due to the autocorrelation function is used: $\rho_i(t - t_0)$. In this form, the probability of exceeding L never decreases unless a new observation is made.

Key References

*1. Carbonell, J. R. (1966). A queuing model for many instrument visual sampling. *IEEE Transactions on Human Factors in Electronics, HFE-4*, 157-164.

2. Carbonell, J. R., Ward, J. L., Senders, J. W. (1968). A queuing model of visual sampling: Experimental validation. *IEEE Transactions on Man-Machine Systems, MMS-9*, 82-87.

Cross References

7.302 Sampling behavior during process-control monitoring;

7.317 Senders's periodic sampling model of display monitoring;

Handbook of perception and human performance, Ch. 40, Sect. 2.2

Table 1. Validation of Carbonell's queuing model.

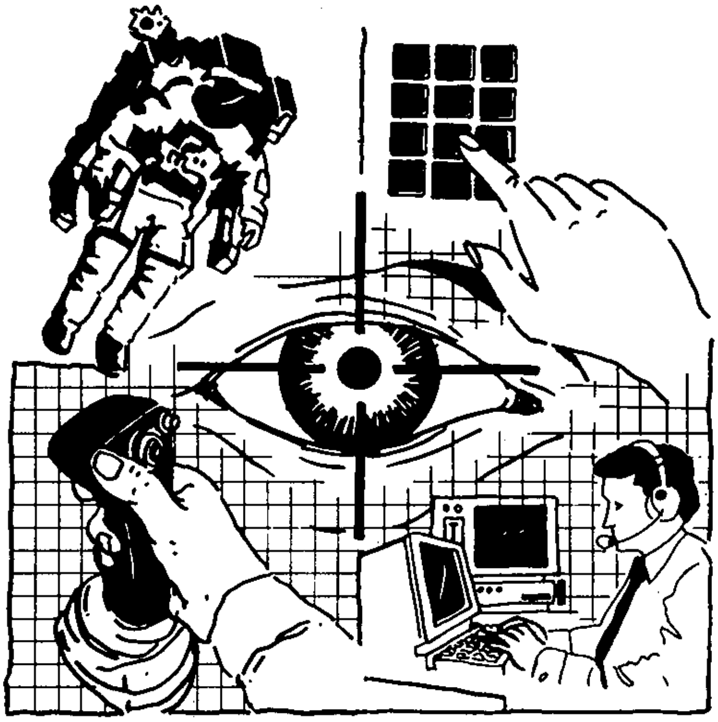
	Mission Phase					
	Descent		Turn		Approach	
Pilot	Senders Model	Carbonell Model	Senders Model	Carbonell Model	Senders Model	Carbonell Model
1	0.905	0.966	0.730	0.874	—	—
2	0.190	0.944	0.940	0.983	0.653	0.917
3	—	—	0.903	0.984	−0.263	0.837

Correlation coefficients are shown for correlation of the observed eye-fixation data with the values predicted by Senders' Nyquist interval model and by Carbonell's queuing model.

From J. R. Carbonell, J. L. Ward, & J. W. Senders, A queuing model of visual sampling: Experimental validation, *IEEE Transactions on Man-Machine Systems, MMS-9*. Copyright 1968 IEEE. Reprinted with permission.

Notes

Section 7.4 Vigilance



7.401 Vigilance

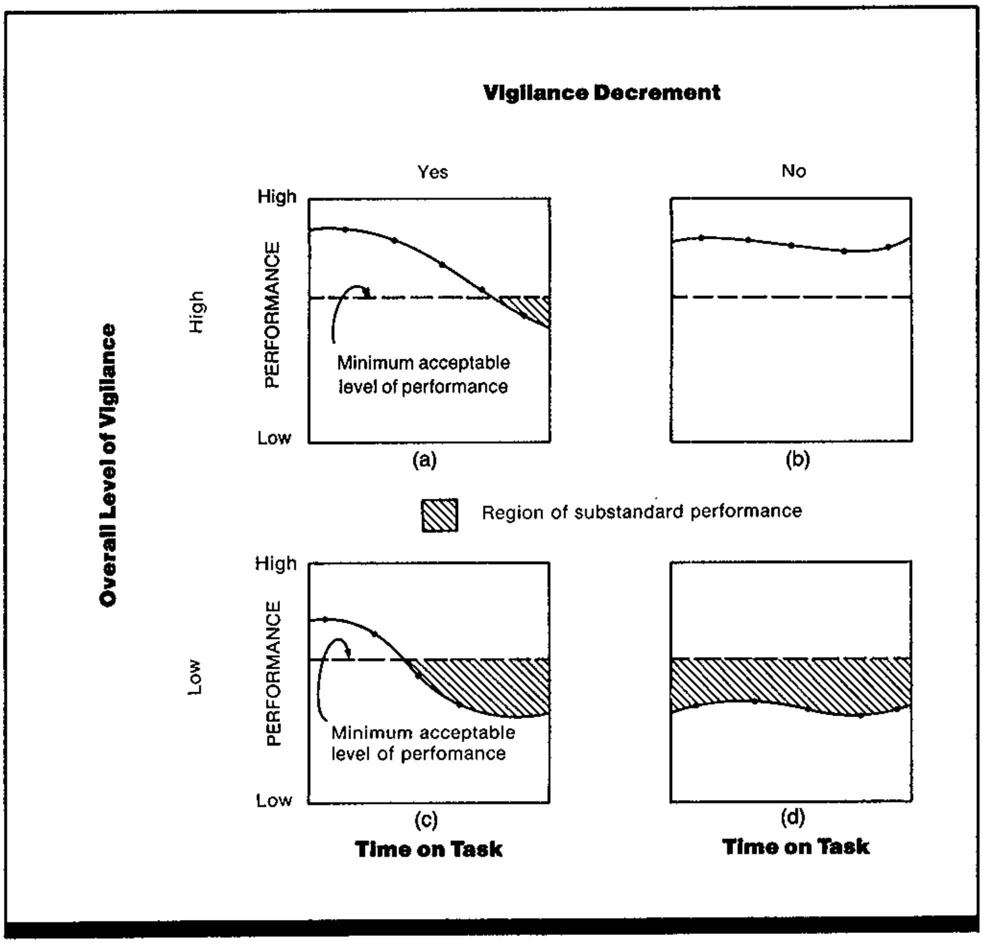


Figure 1. Vigilance performance profiles with overall levels of vigilance (high/low) and level of performance (high/low) as a function of the presence of a vigilance decrement (yes/no) and time on task. (a) Decrement with little significance; (b) continual excellent performance; (c) decrement that quickly yields unacceptable performance; and (d) continual unacceptable performance. (From Ref. 4)

Key Terms

Arousal; attention; monitoring; sustained attention; vigilance decrement; visual search

General Description

Vigilance tasks involve detecting infrequent, simple signals over prolonged periods of time without rest. Vigilance, then, is a state of readiness to detect these signals and involves sustained attention. For single-source events, vigilance is simply this long-term attentive behavior, but in multiple-source or time-shared tasks, **selective attention** and the orienting of attention to visual space are additional important determinants of performance. In more complex tasks, the operator may use many other mental processes.

A certain level of arousal is necessary for vigilance, but the two are not synonymous. **Arousal** is a general physiological state varying from coma and drowsiness to alertness and frantic excitement. Arousal level affects a person's ability to carry out various tasks (functions of attention), such as maintaining vigilance, monitoring the environment, and searching for objects. Each kind of task can be defined separately, but the elements of each may be found in combination in operational settings.

Vigilance tasks have relatively simple, specified, unchanging signals, usually infrequently presented via a single source at unpredictable times. Search tasks involve signals that have high spatial uncertainty, but little or no temporal uncertainty. Signals in simple search tasks are readily discriminable and the resolution of spatial uncertainty is the key to detecting the signal (although in complex search tasks other sources of uncertainty may affect performance).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Monitoring tasks require the detection of signals having both temporal and spatial uncertainty. In some monitoring tasks, the signal is not precisely specified, but must be inferred and may change over time.

Origin of Vigilance Research

Vigilance research began as an attempt to solve a serious practical problem: potential U-boat contacts were being missed in World War II, apparently because of overstrain among radar operators on antisubmarine patrol. Mackworth set up laboratory experiments to determine the optimal length of watch for radar operators and found that vigilance performance deteriorated after 30 min on watch. He named this decline in the frequency of correct detections the "vigilance decrement." Understanding the factors responsible for this decrement has been the primary concern of vigilance research; attention has also been directed toward finding methods for preventing the decrement.

Performance on vigilance tasks shows considerable individual variation, and seems to be sensitive to the effects of environmental stressors and pharmacological agents. In some cases, there is no vigilance decrement. Consequently, research efforts have also been directed to the factors that affect the absolute level of efficiency in vigilance tasks: both the overall vigilance level and the vigilance decrement contribute to the efficiency of vigilance performance. A high level of performance that shows some decrement (Fig. 1a) may be more efficient than a low level that shows no decrement (Fig. 1d).

Although research on vigilance, monitoring, and search arose in response to pressing practical concerns, it subsequently turned to more theoretical concerns, an orientation that received an impetus from a resurgence of interest in the psychology of attention in the 1950s. Other methods for measuring vigilance performance were developed, factors underlying performance were isolated, and performance on more complex tasks was studied.

The application of signal-detection theory (CRef. 7.420) to vigilance performance made possible the separation of factors affecting the sensitivity of the observer and the bias (criterion) of the observer, (i.e., the observer's rule for deciding whether a given stimulus is a target). This allowed a re-examination of factors affecting vigilance performance.

As machines and equipment have become more complex and increasingly automated, and with the advent of microprocessor control, the role of the human operator has changed from that of an active controller to a decision maker and manager (a shift from active to supervisory control). In highly automated systems, targets may be detected by instruments and control executed by machine; yet the same problems of vigilance and monitoring occur when the automated system malfunctions or some unusual but infrequent condition occurs.

Current research reflects two trends: (1) a return to consideration of practical problems of human performance in human-machine systems following several years of consolidation of basic research; and (2) a growing interest in human performance problems in industrial and medical systems.

Industrial applications have come increasingly to the fore. In most such complex task situations, the functions of vigilance, monitoring, and search are supplemented by a number of other demands on the human operator, including signal interpretation, high-level decision making, task scheduling, resource allocation, and other tasks. The interaction of these other tasks with basic factors of vigilance performance is a current focus of research.

Methods

See Entry 7.402 for a discussion of methods used to study vigilance, monitoring, and search.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.420 Signal detection theory

7.402 Methods of Measuring Vigilance, Monitoring, and Search

Key Terms

Fatigue; mental workload; monitoring; reaction time; response bias; target detection; vigilance decrement; visual search

General Description

Vigilance tasks require detecting infrequent, simple signals over prolonged periods of time without rest. Monitoring involves more complex signals and/or more than one source for signals and/or continuous rather than discrete events. In search tasks, the temporal uncertainty of vigilance is replaced by spatial uncertainty. Two aspects of vigilance performance are of interest: the vigilance level and the vigilance decrement over time on task. The table lists the most common methods of measuring level and/or decrement in vigilance, monitoring, and search tasks, briefly explains what they measure, when they are used, their limits, and cites entries or sources of more information.

Method	Explanation	Measures
1. Detection rate	Number of correct detections (hits) averaged for blocks of time (can be analyzed signal-by-signal)	Accuracy of detection; level and decrement
2. Incorrect detection rate	Number of incorrect detections (false alarms) averaged for blocks of time (also called errors of commission)	Accuracy of detection only in combination with hit rate; level and decrement; possibly learning
3. Reaction time	Time from signal onset to beginning of response; also called mean response latency (any task), detection latency (vigilance tasks), search time (search tasks)	Speed of detection; level and decrement
Variance of reaction time	Measures variance or standard deviation of reaction times	Decrement
4. Signal-detection theory analysis	Also called decision theory; uses hits and false alarms expressed as probabilities (or response latencies converted into hits and false alarms) to estimate and differentiate criterion from sensitivity	Placement of decision criterion (β) and changes in sensitivity (d'); accuracy of detection; level and decrement
Receiver operating characteristic curve (ROC curve)	Graphic representation of signal-detection theory results, using confidence ratings for responses or repeated experiments varying a payoff matrix to develop ROC curve	Same things as signal-detection theory, but with greater confidence in parameter estimation (CRef. 7.205)
5. Adaptive measures	Detection rate is held in a steady range by varying some parameter of the signal	Decrement; accuracy of detection
6. Mental workload	Performance on a second or subsidiary task is measured to evaluate performance on main task	Estimated accuracy on primary task; decrement
7. Self-report	Questionnaires tapping arousal, boredom, distractability, temperament etc., are used in correlational studies with some measure of vigilance performance and sometimes also physiological measures	Correlations of reportable state or individual differences with vigilance performance
8. Physiological	Brain waves and event-related potentials from EEGs, pupil size, skin conductance, skin potential, skin resistance, mean heart rate or heart rate variability, adrenalin and noradrenalin levels, respiration rate, and/or muscle tension are recorded during vigilance task	Correlations of physiological state or change of state or individual differences with vigilance performance

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

7.205 Performance operating characteristic;

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

7.404 Reaction time patterns in vigilance performance;

7.408 Effect of signal discriminability on vigilance performance;

7.410 Maintenance of vigilance level by adaptive changes in signal detectability;

7.414 Effect of practice on vigilance;

7.416 Effects of different training methods on vigilance;

7.420 Signal detection theory;

Handbook of perception and human performance, Chs. 40, 42, 44, Overview Sect. VII

Use	Limitations	Source
On simple vigilance tasks where only one button is used to respond to target	Incomplete error data; when subtracted from signal rate yields omission-type errors only; cannot distinguish effects of criterion from sensitivity	CRef. 7.403
With hit rate on tasks with one response button	Not useful alone except as indication of learning	CRefs. 7.414, 7.416
On search tasks; as supplement to hit rate; when hit rate is at asymptote (i.e., 100%); for unlimited-hold, self-paced, free-response tasks	No measure of accuracy when used alone; RT should not be used when hit rate is very low	Refs. 1, 4, 5
When mean RT shows no decrement; to measure differential effects of stressors	No measure of accuracy when used alone	CRef. 7.404
In many paradigms, but mostly where both "yes" and "no" responses are employed	Can give most complete analysis of vigilance performance, but validity outside highly controlled laboratory settings is questionable	CRefs. 7.405, 7.420
In paradigms using confidence rating responses or payoff matrix variations		CRef. 7.408
In training research and manual control tasks	Results depend on method of calculating signal changes	CRef. 7.410
For continuous, complex monitoring tasks; for tasks that overload the operator	Assumes common pool of mental capacity for both tasks	CRef. Handbook, Chs. 40, 42, Overview Sect. VII
To find measure that will differentiate individuals who perform better in vigilance tasks	Although correlations have been found, they may not be strong, may not be repeatable, and/or the relevance of the measure to vigilance may be questioned	CRef. 7.404 Refs. 2, 3
To assess effect of stressors on vigilance performance; to find measure that will differentiate individuals who perform better on vigilance tasks	Only a few of the measures listed correlate with vigilance performance, and some contradictory correlations have been found	Refs. 2, 3; CRef. Handbook, Ch. 44

7.403 Decline in Rate of Correct Detection of Signals Over Time (Vigilance Decrement)

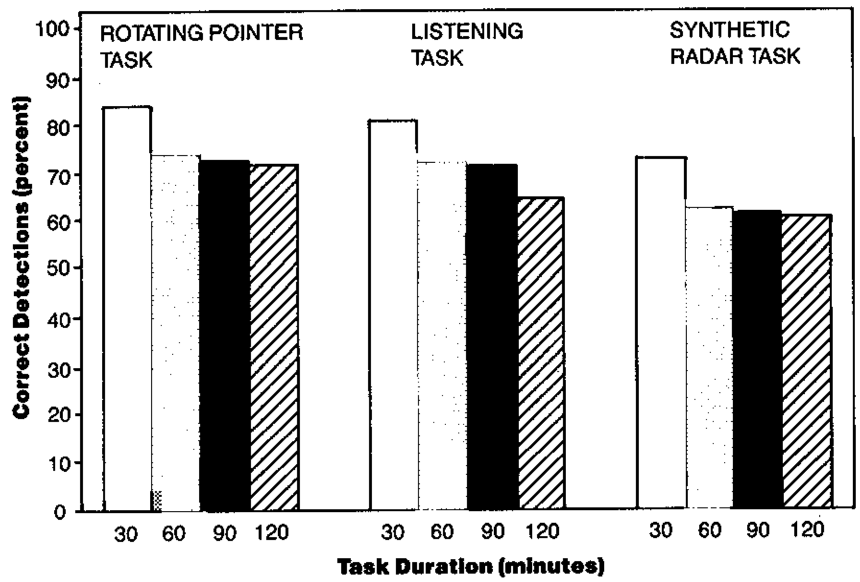

Figure 1. Vigilance decrement as a function of task duration for the rotating pointer task described in the text. For comparison, results are shown for two other vigilance tasks. (Data from Ref. 3)

Key Terms

Target detection; vigilance decrement

General Description

The correct detection of signals (hit rate) in most simple vigilance tasks shows a decrement over time. When hit rate is averaged for blocks of time (e.g., 30 min) in a 2-hr task, the vigilance decrement is greatest between the first and second blocks. A signal-by-signal analysis indicates that the blocks chosen may disguise either the magnitude of the decrement or when it occurs.

Applications

Method can be used to determine most efficient placement of rest breaks.

Methods

Test Conditions

- Black pointer 15.24 cm long rotating in discrete steps one per second on blank white background (the Mackworth clock test); tip of pointer traced out a circle 25.4 cm in diameter; width of pointer was 8 min visual angle at tip and 16 min visual angle at broad end
- Signal target was 1.5-cm (24 min visual angle) double step; nonsignal target was 0.76-cm (12 min visual angle) step
- Twelve signals at intervals of 0.75, 0.75, 1.5, 2, 2, 1, 5, 1, 1, 2, and 3 min; signal schedule repeated each 30 min of 2-hr task
- Viewing distance 2.15 m; response switch immediately below display directly in front of observer
- Response within 8 sec of pointer double jump considered a hit; if no response after 8 sec trial was scored as a miss

Experimental Procedure

- Independent variable: change in pointer movement from 0.76-cm single step to 1.5-cm double step
- Dependent variable: correct detection of signals
- Observer's task: press switch to indicate detection of double step of pointer
- 25 Royal Air Force cadets, with extensive practice

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Experimental Results

• When averaged over 30-min blocks, correct detection (hit) rate shows greatest drop between first and second blocks, declining slightly thereafter (Fig. 1).
• When analyzed signal-by-signal, the greatest decline in hit rate occurs within the first block (Fig. 2).

Variability

Large performance differences between observers were mentioned but not specified.

Repeatability/Comparison with Other Studies

Occurrence of vigilance decrement was replicated (Ref. 3) on synthetic radar and listening tasks; although scores vary, decrements follow similar pattern (see Fig. 1). Replication of pointer test for signal-by-signal analysis (Ref. 1) shows same pattern when averaged by blocks (see Fig. 2).

Constraints

• Although it is not clear that observers were told task length, observers in these studies served in several experiments; knowledge that the task is long contributes to an early and steep vigilance decrement.

• Incorrect detections were not analyzed and part of the decline in correct detections might be associated with shifts in decision criteria toward greater accuracy.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.411 Characteristics of the task that affect vigilance, monitoring and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

7.414 Effect of practice on vigilance

Handbook of perception and human performance, Ch. 43, Sect. 3.1

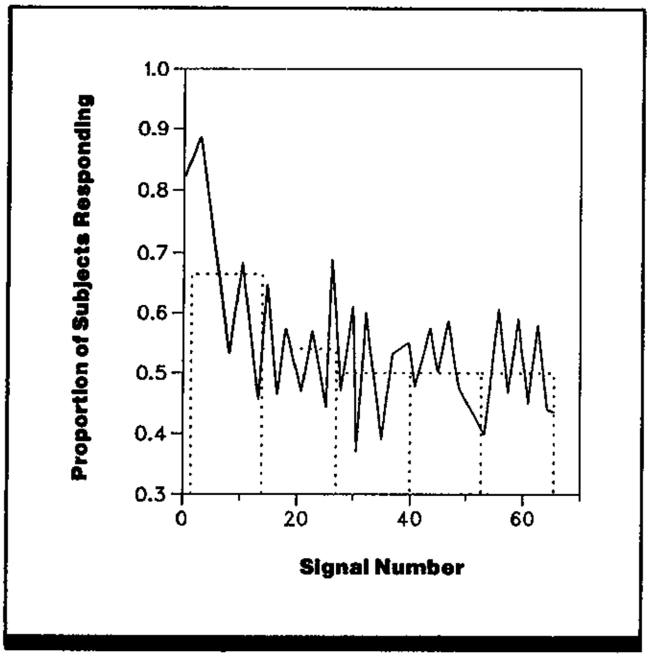

Figure 2. Proportion of subjects correctly responding to each individual signal for rotating pointer (Mackworth clock) task similar to that discussed in the text (87 subjects in four experiments). Dotted lines show a block-by-block analysis that does not capture the full extent of the vigilance decrement; the largest decrement occurs within the first block (first 27 min of experiment). (From *Handbook of perception and human performance*, after Ref. 1)

7.404 Reaction Time Patterns in Vigilance Performance

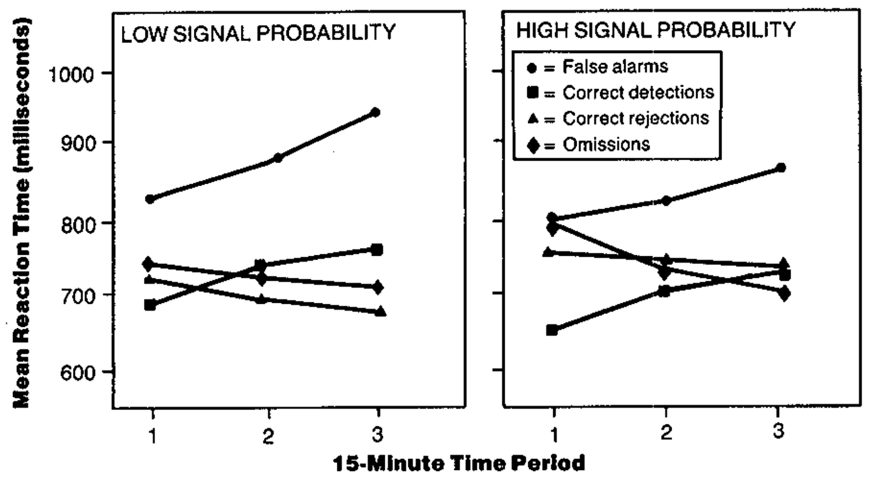

Figure 1. Mean reaction times for a vigilance task with (a) low-signal probability and (b) high-signal probability. Data points are mean values for 15-min blocks of time. (From Ref. 3)

Key Terms

Decision criteria; reaction time; signal probability; vigilance decrement

General Description

Although differences in factors such as signal probability and event rates influence observers' reaction times for vigilance tasks, three response patterns are the same across the different conditions: (1) false alarms (incorrect "yes" responses) are always slower than hits (correct "yes" responses), misses (incorrect "no" responses), and correct rejections (correct "no" responses); (2) positive responses (hits and false alarms) become slower as time on task increases (i.e., observers take longer to report a "yes" response); and (3) negative responses (misses and correct rejections) become faster as time on task increases (i.e., observers are quicker to report a "no" response).

Methods

Test Conditions

- Series of circular light flashes (luminance not given); series of target flashes (signals) were dimmed by 9.2 cd/m^2
- Signal probability (Exp. 1) governed by presentations of 24 target series per 45 min (low) or 45 target series per 45 min (high); higher signal rate of 3.73 signals per minute used in Exp. 2
- Rate of event presentation was 15 series per min (Exp. 1) or either 15 or 30 series per min (Exp. 2)
- Intersignal interval was irregular (randomized within each 5 min) for Exp. 1 or either regular or irregular for Exp. 2
- Separate "yes" and "no" response buttons; observer responded to each series
- For Exp. 2, one 45-min session at the same time of day on the same day of four successive weeks (randomized order)

Experimental Procedure

- Two-alternative forced-choice response; Exp. 1 had between-observer conditions; Exp. 2 was within-observer
- Independent variables: luminance of light flash, signal probability, event rate, intersignal interval
- Dependent variables: reaction times for all responses, decision criterion β (a ratio of the height of the signal-plus-noise distribution to the height of the noise distribution at a given point of overlap), sensitivity d' (the distance between the mean of the noise distribution and the mean of the signal-plus-noise distribution)
- Observer's task: respond to each series of flashes by pressing "no" button for nontarget or "yes" button for target
- For signal probability variation (Exp. 1), 20 males (ages 17-25), with normal uncorrected vision and hearing and with some practice; for Exp. 2, 10 males (ages 18-25), with normal, uncorrected vision and hearing and with some practice

Experimental Results

- As time-on-task increases, reaction times for positive responses (hits and false alarms) increase and reaction times for negative responses (correct rejections and omissions) decrease or remain unchanged (Figs. 1, 2).
- Reaction times for "yes" responses decrease for a higher signal probability, but reaction times for correct rejections increase. (The decrease for misses [omissions] did not reach significance at $p < 0.05$.)
- Changes in mean reaction times with increase of time on task or with reduced signal probabilities are associated with a stricter criterion (β).
- A higher event rate has no significant effect on reaction times for false alarms and correct rejections, but yields longer reaction times for correct detections and shorter reaction times for misses (omissions) (Fig. 2).

• Regular intersignal intervals yield faster reaction times for hits (correct detections).
• Changes in mean reaction times with variations in intersignal interval and time on task are associated with a stricter criterion.
• Changes in mean reaction times for high event rate and time-on-task represent a decrease in sensitivity (d'), as well as a stricter criterion.

Variability

Analyses of variance were used to test significance.

Repeatability/Comparison with Other Studies

Increases in mean reaction time for correct detection over time have been reported often (see Ref. 2). On a complex monitoring task, increases of 1 sec over a 3-hr period were found for mean reaction time (Ref. 1).

Constraints

• Mean response latencies for the four types of responses (hits, false alarms, correct rejections, and omissions) are not similar in number of observations per type: there were as few as eight errors in any 15-min period, but as many as 202 correct responses for the same period.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.408 Effect of signal discriminability on vigilance performance;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.420 Signal detection theory;

Handbook of perception and human performance, Ch. 43

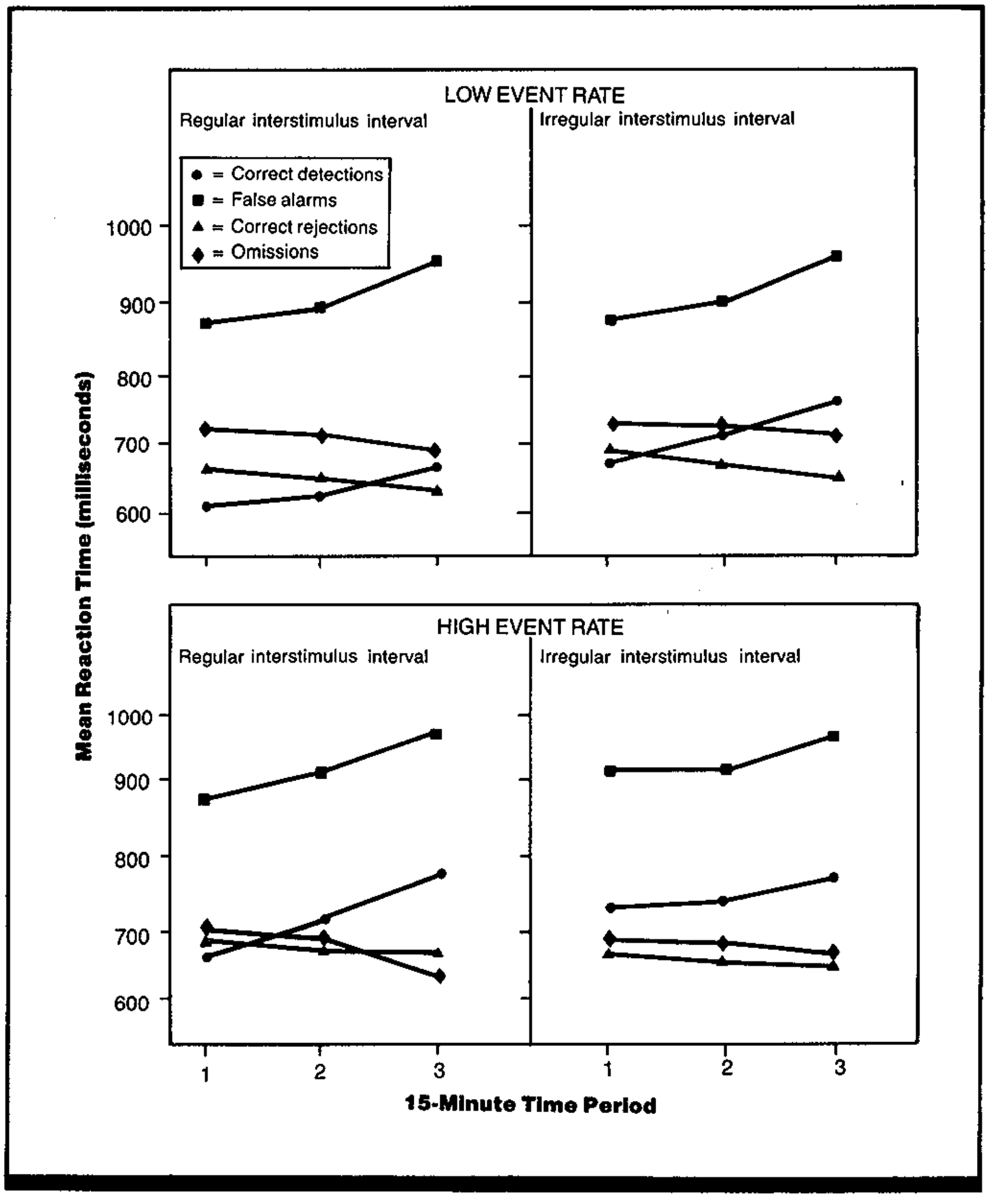

Figure 2. Mean reaction times for a vigilance task with low or high event rates and regular or irregular intersignal intervals. Data points are mean values for 15-min blocks of time. (From Ref. 3)

7.405 Application of Signal Detection Theory to Vigilance

Key Terms

Decision criteria; receiver operating characteristics; signal detection theory

General Description

In the early years of vigilance research, correct detection (hit) rate was used as the measure of vigilance performance. There are two problems with using hit rate as the only measure of vigilance.

1. The same percent of hits can be paired with either a low or a high rate of incorrect detections, so that total efficiency is not measured.
2. The hit rate reflects both the detectability of the signal (or observer **sensitivity**) and the response bias (or decision criterion) of the observer.

The use of signal detection theory (CRef. 7.420) permits the behavior underlying vigilance performance to be analyzed in ways that the use of hit rate alone does not allow. The advantages of signal detection theory include:

- Efficiency can be specified in terms of both hits and false alarms (incorrect detections);
- Factors affecting sensitivity can be separated from those affecting bias; and
- Performance on complex monitoring tasks, or tasks with unlimited-hold or easily discriminable signals, as well as standard vigilance tasks, can be analyzed within the same framework.

Signal detection theory assumes that there is a signal-plus-noise (SN) distribution that overlaps the distribution of noise (N) alone. There are two theoretical parameters, a detectability or sensitivity index (d') and a decision criterion (β) that are based on the conditional probability of hits, p (yes|SN), and false alarms, p (yes|N). The detectability index (d') is the difference between the means of the two distributions, scaled in units of the standard deviation of the noise distribution:

$$d' = (\mu_{SN} - \mu_N)/\sigma_N = Z_N - Z_{SN},$$

where μ indicates the mean of the N or SN distributions, and σ_N indicates the standard deviation of the noise distribution. Z is the standard score for the indicated distribution. The decision criterion (β) is a ratio that defines the degree of bias toward responding positively to signals. It can be calculated from the ordinates (probability densities) corresponding to the normal deviates of the hit and false alarm probabilities:

$$\beta = \frac{\text{ordinate of signal-plus-noise distribution}}{\text{ordinate of noise distribution}} .$$

When $\beta = 1$, it cuts off equal segments of each distribution. As β increases, the criterion point moves closer to the mean of the signal distribution and farther from the mean of the noise distribution; therefore a larger β indicates the use of a stricter criterion producing fewer hits and fewer false alarms.

When changes in hits and false alarms are in the same direction, the decision criterion is assumed to have changed. When there are differential changes in the probabilities associated with hits and false alarms, detectability or sensitivity is assumed to have changed. Factors such as signal probability, instructions to adopt a risky or a sure criterion, manipulation of the payoff matrix (the costs and advantages associated with hits and false alarms) influence the setting of the criterion. Signal strength, practice, and a high memory load coupled with a high event rate are some of the factors known to alter sensitivity.

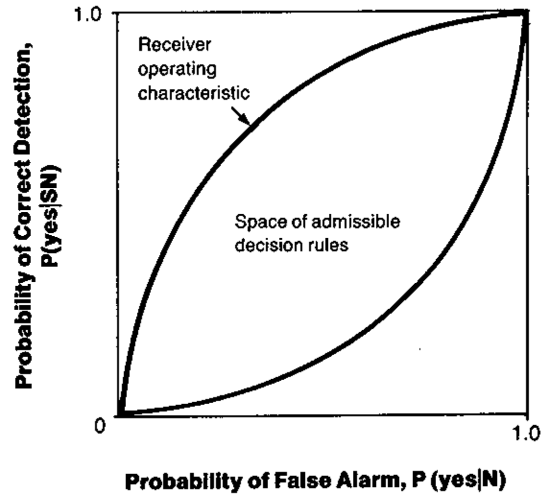

Figure 1. The convex set is formed by all possible pairs of hit (correct detection) and false alarm probabilities associated with a particular binary decision at a particular level of detectability (or observer sensitivity). The upper curve is the receiver operating characteristic (ROC) curve, and it contains the only rules that cannot be changed to yield better performance. (From Ref. 1)

Criticisms of the Use of Signal Detection Theory

Criticisms of the use of signal-detection theory in vigilance performance analysis are directed at the validity of the two parameters, which are based on assumptions of (1) normal distributions and (2) equal variances of both distributions; unfortunately, these are often not true for vigilance tasks. Also, the size of β is usually significantly greater than in the psychophysical experiments for which signal-detection theory was derived. A third criticism is that β, associated with a likelihood ratio in most psychophysical tasks, is not related to likelihood ratios in some vigilance tasks.

Two major approaches to adapting signal detection theory to vigilance situations avoid these probems:

1. Other parameters which have been developed to replace β and d' do not rely on the equal variance or normal distribution assumptions. For a discussion of these, see Ref. 1.

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2. The empirical receiver operating characteristic curve is often used, and is not dependent on the equal variance assumption.

The Receiver Operating Characteristic Curve

A receiver operating characteristic (ROC) curve is a graphic depiction of hit and false alarm probability pairs. An empirical ROC is derived for signals of a given detectability by varying the response criterion, usually by asking observers to rate the confidence with which they are responding. All possible hit/false alarm pairs for a given detectability form a convex set (shown in Fig. 1), representing the totality of decision rules for choosing between two alternatives (signal or noise). The only rules that cannot be improved are those lying on the upper bound of the convex set in Fig. 1, which is the ROC curve.

In an ROC analysis of vigilance decrement (Fig. 2), the ROC can be used to determine whether a given change in vigilance performance results from a change in detectability (sensitivity) or in the decision criterion. Theoretical ROCs are shown on both (a) linear and (b) normalized (double probability) axes. Movement along the same ROC (e.g., from A to A′) represents a change to a more strict criterion, leading to a reduction in the probability of both hits, *p* (yes|S), and false alarms, *p* (yes|N). Movement from one ROC to another (e.g., from A to A′) indicates a change in sensitivity.

In practice, these changes in detectability and criterion may be hard to distinguish graphically if there are few false alarms and the ROC is limited to a very narrow decision space (e.g., to the left of the dotted line in Fig. 2a), which occurs for many vigilance tasks. Also, the monotonically decreasing slope of an ROC assumed in the signal detection theory model may not be produced in vigilance situations (see Ref. 1). No solution for these criticisms has been found, but they can be minimized by (1) using care in estimating parameters, (2) inspecting individual underlying data, (3) using reaction time, as well as rates for hits and false alarms, and (4) using confidence rating scale responses in vigilance tasks.

Conclusion

Although there are still some questionable areas in the use of signal detection theory in the evaluation of vigilance performance, careful application of the theory results in a more complete analysis of the behaviors underlying vigilance behavior than has otherwise been possible.

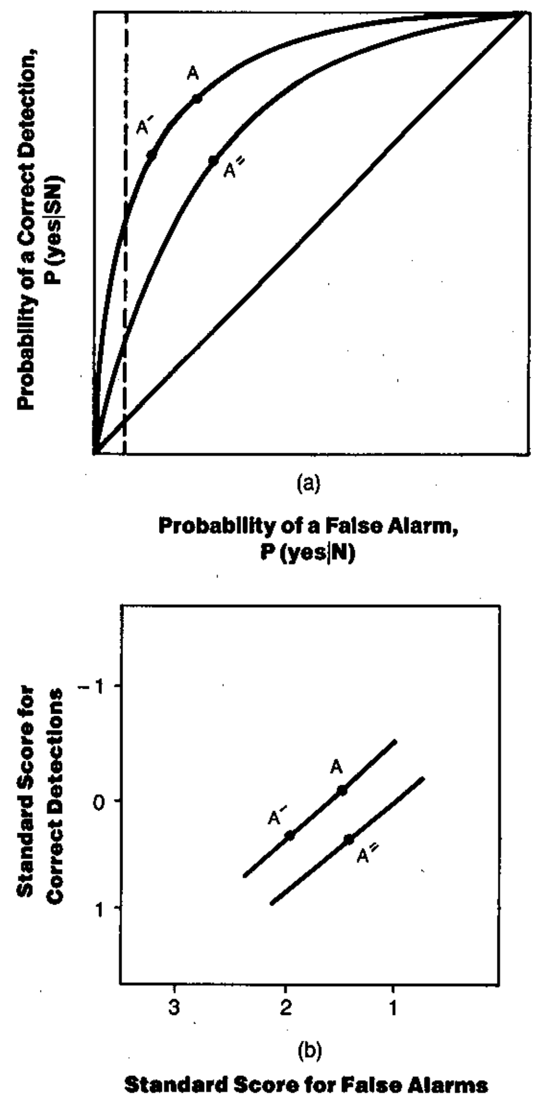

Figure 2. Theoretical receiver operating characteristic (ROC) curves on (a) linear and (b) normalized (double probability) axes. Movement between the named points indicates a change in criterion (A to A′) or a change in detectability or sensitivity (A to A″). (From Ref. 1)

Key References

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2. Swets, J. A. (1977). Signal detection theory applied to vigilance. In R. R. Mackie (Ed.), *Vigilance theory operational performance and physiological correlates (pp. 705-718)*. New York: Plenum.

Cross References

7.205 Performance operating characteristic;

7.402 Methods of measuring vigilance, monitoring, and search;

7.420 Signal detection theory

7.406 Characteristics of the Signal that Affect Vigilance, Monitoring, and Search

Key Terms

Decision criteria; monitoring; target detection; vigilance decrement; visual search

General Description

Although the signal that is being monitored in vigilance, monitoring, and search tasks cannot be independent from task and environmental factors, some dimensions of the signal can be varied within an experimental paradigm. Such signal variation can affect both the overall level of vigilance performance and the amount of decrement in performance over time. The table contains a list of signal characteristics that affect vigilance performance, indicates whether the characteristics influence sensitivity (d') or the response criterion (β) and the direction of the effects, and includes constraints and sources of more information.

Constraints

- Interactions among variables listed in the table, and interactions between these and task, environmental, and individual variables, may change the results.
- Detection rate and detection latency (reaction time) are most often used as measures of vigilance performance, but those measures reported here do not always reflect optimal vigilance efficiency, as they do not include the rate of incorrect detections (false alarms).

Signal Characteristic	Affects Sensitivity or Criterion	Direction of Effect	Constraints	Source
Strength	Sensitivity and criterion	Signal strength is a combination of two separable, but not independent, factors (duration and intensity)		
duration		Longer durations increase the probability of detection (higher vigilance level) and decrease the vigilance decrement	Shown on visual tasks; when no search factor in task and signal exceeds 2 sec, decrement is less likely to occur	Ref. 1
intensity	Higher intensity yields greater probability of detection (higher vigilance level); low intensity yields more rapid decrement, but the evidence is equivocal		Shown on visual, auditory, and cutaneous tasks	Ref. 10
Frequency	Criterion	Probability of detection is inverted U-shaped function of increasing signal frequency; the best level of detection is at a moderate rate; the evidence is equivocal for the effect of frequency on decrement	Signal probability is likely the cause of the effects	Ref. 11
Probability	Criterion	Higher probability yields a greater level of detection and less decrement	Both real and expected probabilities have effects, so pretask training can influence decrement; real signal probability is learned over the task, and is not independent of event rate	Ref. 3 CRef. 7.411

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Signal Characteristic	Affects Sensitivity or Criterion	Direction of Effect	Constraints	Source
Artificial signals	Criterion	If artificial signals are identical to real signals, they have the same effect as increasing signal probability; if artificial signals are different from real signals, they add to task complexity		Ref. 12 CRef. 7.411
Intersignal interval	Criterion	Intersignal interval has two interactive factors, regularity and duration.		
regularity		More regular intervals yield greater probability of detection; increased variability yields an increased decrement. Reaction time is a decreasing function of interval in low variability conditions, invariant in medium, and an increasing fuction in high variability conditions	Experimental results are too contradictory to be summarized; regularity is not independent of duration	CRef. 7.404
duration		Duration of intersignal interval has not been studied independently of interval regularity or of signal frequency; its effect appears to be moderated by causing expectancies about signal probabilities	Estimates of optimal duration may be task specific	Ref. 8
Modality	Sensitivity	Auditory signals yield better performance than visual signals, and visual is better than cutaneous; redundant audio-visual is best	Modality of the signal is part of the modality of the task	CRefs. 7.409, 7.411
			Individuals differentially respond to modality	Ref. 2 CRef. 7.413
Complexity	Not studied in these terms	Tasks that are too simple or too complex cause an overall low vigilance level and a high decrement; moderate complexity yields optimal perceptual load and best vigilance performance	Optimal load depends on task type and other variables	CRef. 7.403
		A detection task yields better vigilance performance than a task requiring estimation of magnitude or other post-detection decisions		Ref. 7
Variability in space		When signals vary widely in spatial location, they induce a search process that is a task characteristic rather than a signal characteristic		CRef. 7.411
Location in space	Sensitivity	When visual fixation is required, peripheral signals tend to be overlooked; these omissions cause an overall low vigilance level		CRef. 7.407

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

7.404 Reaction time patterns in vigilance performance;

7.407 Effect of signal target location on visual search;

7.409 Simultaneous versus independent visual and auditory monitoring;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

7.420 Signal detection theory;

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Notes

7.407 Effect of Signal Target Location on Visual Search

Key Terms

Monitoring; target detection; target location; vigilance decrement; visual search

General Description

For observers scanning a radar display, search time to locate long-range (peripheral) targets is considerably longer than search time to locate short-range targets that appear near the center of the display. Although the center-scanning bias (also called edge effect) is present even when observers are fresh, alert, and warned of the target (Fig. 1), the bias is accentuated as time on task increases. Measurement of observers' eye movements indicate that individuals differ widely in scanning patterns. There is a general tendency to scan the inner portion of the display more closely than is appropriate; in addition, there is a considerable amount of time spent looking away from the display.

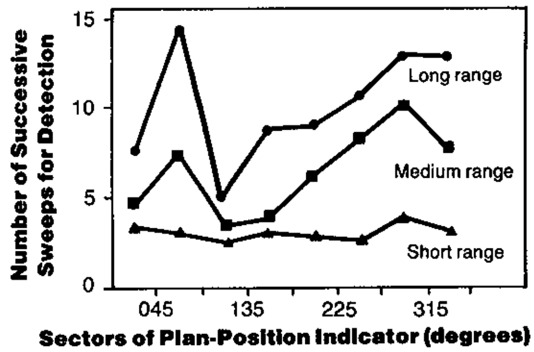

Figure 1. Number of successive "paints" on a radar screen before target detection as a function of target location and range. Range is positively correlated with distance from center of display. Performance is optimal, with observers receiving warnings that a signal was about to appear. (From Ref. 5)

Methods

Test Conditions

- Plan-position-indicator (PPI) CRT radar display in full-scale mock-up of cockpit; direction-finding auditory watch had white-noise background (75 dB sound pressure level) presented via headset with trains of three 835-Hz pure-tone pulses as signals
- Cockpit noise at 66 ± 2 dB and lighting at "twilight" level
- Targets were radar echoes (2-mm diameter) repeatedly painted on tube by rotating radial line of light (moving at ~40 rpm) until target detected; controlled but variable background noise and clutter
- Ten radar targets and ten auditory signals per hour with varied time intervals between targets
- 3-hr watchkeeping session, with or without short breaks in radar watch; pre-watch and post-watch sessions in which observer was warned that signal was about to occur
- Measurement of eye-movement by electrodes near eyes (measured changes in potential difference between front and rear of eyeball) in separate experiment

Experimental Procedure

- Independent variables: short-to-long range of signal target (corresponds to central-to-peripheral appearance on PPI), time on task, continuous or interrupted watch, week of session, ratings or officers as observers
- Dependent variable: number of sweeps of radial pointer before detection of signal (search time)
- Observer's task: press response button to indicate detection of radar or auditory signal; then orally confirm target presence and, if radar target, describe location
- 10 experienced radar operators (5 ratings and 5 officers); unknown number of experienced radar operators for measurements of eye movements

Experiment Results

- The number of repeated "paints of" the signal required for detection increases as the range of the radar target increases [i.e., the more peripheral the target on the plan-position indicator (PPI) display]. Optimal results during the pre-watch condition (with warnings prior to signals) are shown in Fig. 1 (averaged over five weekly sessions).
- Post-watch measures of optimal performance do not differ from the pre-watch measures.
- A marked fall-off in performance from the optimal level occurs as soon as the experimental session begins and only a slight fall-off (vigilance decrement) occurs in each successive hour. Pre-watch and watchkeeping performances correlate with $r = \sim 0.71$.
- Measurement of eye movements indicate a general tendency to view the inner portion of the display more closely than is appropriate, and a considerable portion of the time is spent looking away from the display.
- There are large differences among the visual search patterns of observers.

Variability

There are large individual differences, but variability is not quantified. There are no discernible differences between ratings and officers.

Repeatability/Comparison with Other Studies

10-15% more target radar pips were missed in outer locations than in inner locations of the circular display (Ref. 1). Bias toward the center area of a stationary display of aerial maps has been demonstrated (Ref. 3), and the number of fixations falling outside the display is related to display size. Reference 2 reports a different result for medium search time as a function of radial position of a target: search times decrease somewhat from the display center to the middle target position (one-half of distance to edge of display) and then rapidly increase for the more peripheral positions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- False alarms occurred, but were not analyzed for location.
- Display size may be a crucial factor (Ref. 3).
- Date rate, target density, and the size of the blip-scan ratio may influence variability (Ref. 5).
- Moving and stationary displays may be scanned differently.
- Whether biased scanning has a detrimental effect on vigilance performance may depend on task type (Ref. 4).

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Cross References

7.302 Sampling behavior during process-control monitoring;

7.319 Queuing model of display monitoring;

7.502 Visual search rates with eye movement;

Handbook of perception and human performance, Ch. 43

7.408 Effect of Signal Discriminability on Vigilance Performance

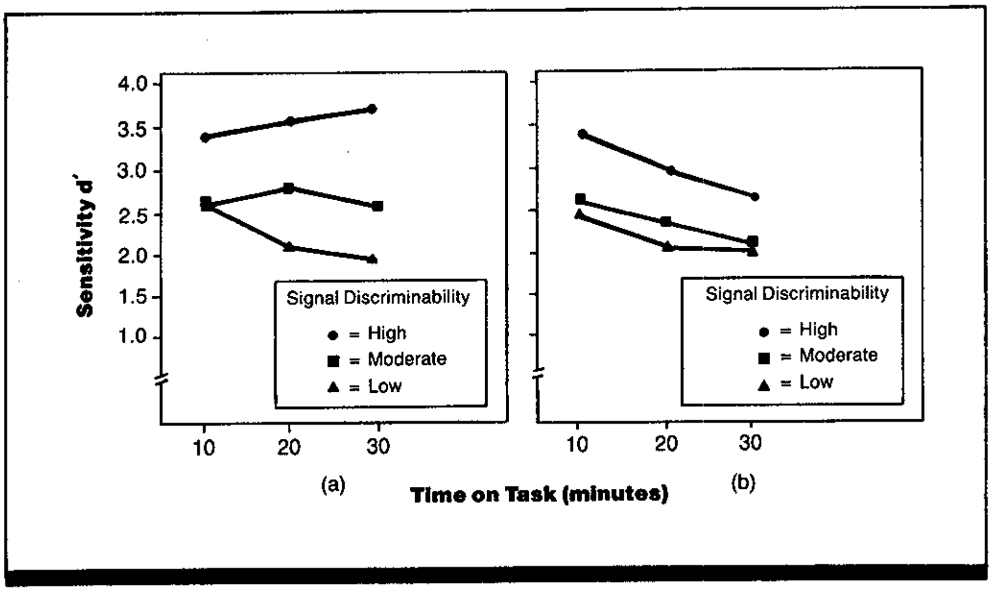

Figure 1. Mean values of sensitivity, as indexed by *d'*, as a function of time on task for (a) simultaneous- and (b) successive-discrimination tasks at three levels of signal discriminability (low, moderate, and high). (From Ref. 3)

Key Terms

Decision criteria; sensitivity decrement; signal discriminability; vigilance decrement

General Description

Performance on a vigilance task will usually decrease over time. Perceptual sensitivity decrements (d') interact with task difficulty. For stimuli that are hard to discriminate, the decrement occurs for both simultaneous tasks (observer compares two stimuli presented at the same time) and successive tasks (observer compares current stimulus with one previously presented). With stimuli that are easy to discriminate, the decrement occurs only with successive presentations.

Methods

Test Conditions

- Pair of vertical lines presented at eye level for 150 msec at 40 pair/min; dark background
- Standard pairs were 36-mm long and separated by 14 mm
- Simultaneous task: one of the lines of the pair was shorter than the standard length; successive task: both of the lines were shorter than the standard length
- Three levels of discriminability (low, medium, high) equalling d' of 2.0, 2.5, or 3.0: difference in line length was 1.2, 2.2, or 3.0 mm, respectively, for simultaneous task, and 2.2, 3.4, and 4.3, respectively, for successive task
- Task lasted for three continuous 10-min periods with 40 signals and 360 nonsignals (same as standards) per period; signal presentations were random except never sequential; signal probability was 0.1
- Signal discriminability blocked in sessions; order of discriminability was counterbalanced; each session comprised of 10-min practice period, 5-min break, and then three continuous 10-min periods

Experimental Procedure

- Independent variables; task type, signal discriminability
- Dependent variable: sensitivity, measured in terms of d'
- Observer's task: observe stimulus and press space bar on keyboard if one or both lines were not standard length; observers were given knowledge of results
- 11 male and 13 female young adults (ages 18-29); 12 observers per task type

Experimental Results

- A vigilance decrement (a decrease in performance over time) occurs in all conditions ($p < 0.001$).
- Performance is better for simultaneous tasks than for successive tasks ($p < 0.025$).
- Performance increases as signal discriminability increases ($p < 0.001$).
- For the successive discrimination task, perceptual sensitivity, as measured in terms of signal detection theory d', decreases for all three levels of signal discriminability. For the simultaneous discrimination task, perceptual sensitivity decreases only for low signal discriminability.

Variability

Significance of differences was determined by analyses of variance

Repeatability/Comparison with Other Studies

Similar results have been reported in Ref. 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Head restraint can eliminate the vigilance decrement in both successive and simultaneous spatial-visual vigilance tasks (e.g., comparing the relative lengths of two lines).

Key References

1. Dittmar, M. L., Warm, J. S., & Dember, W. N. (1985). Effects of knowledge of results on performance in successive and simultaneous vigilance tasks. In R. E. Eberts & C. G. Eberts (Eds.), *Trends in ergonomics/human factors II* (pp. 195-202). Amsterdam: North-Holland.

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7.409 Simultaneous Versus Independent Visual and Auditory Monitoring

Key Terms

Intersensory interactions; monitoring; target detection

General Description

Simultaneous presentation of targets in auditory and visual modalities (i.e., redundant signals) improves vigilance performance over single modality presentation when performance is measured by hit (correct detection) rate. Performance with auditory signals alone is better than performance with visual signals alone (Fig. 1). Monitoring for both auditory and visual signals separately (nonredundant signals) in the same watch appears to improve vigilance performance for the auditory signal and to impair performance for the visual signal.

Methods

Test Conditions

- Visual: 2.54-cm^2, ground-glass aperture in black box (viewing distance not given); non-signal stimuli were 1-sec light flashes of unspecified brightness; signals were brighter flashes
- Auditory: headphone presentation; non-signal stimuli were 1-sec, 750-Hz tones of unspecified amplitude; signals were louder tones
- Signal increments set by 90% detection rate under short-term alerted condition
- Hand-held response button
- 2-sec interstimulus intervals; 24 signals per hour, randomized with constraint of six per 15 min; intersignal interval ranged from 9 sec to 5 min
- Each subject stood fifteen 1-hr watches, three under each display condition; morning and afternoon watch on odd-numbered days, morning watch only on even-numbered days

Experimental Procedure

- Independent variables: increment in brightness of light or loudness of tone; watch condition, as defined by signal type:
  1. Visual condition: visual signals only
  2. Auditory condition: auditory signals only
  3. Redundant condition: simultaneous presentation of visual and auditory signals
  4. Nonredundant condition: one-half visual signals, one-half auditory signals, but not both simultaneously
  5. Partially redundant: one-third visual signals, one-third auditory signals, one-third simultaneous visual and auditory signals
- Dependent variable: percentage of hits (correct detections)
- Subject's task: press response button to indicate detection of increment in light and/or tone
- 27 students at the Fleet Anti-Submarine Warfare School in San Diego (homogeneous in age, education, aptitudes, and visual and auditory acuity), with some practice

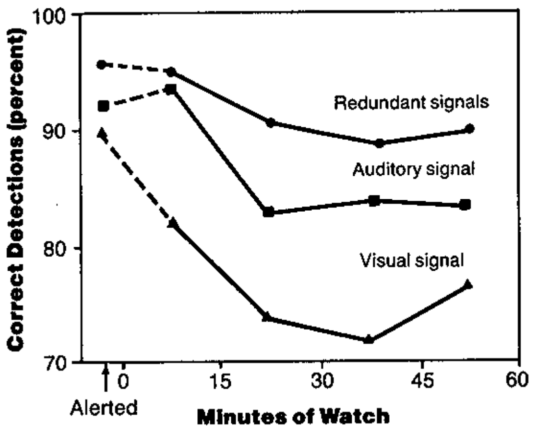

Figure 1. Percentage of correct detections as a function of minutes of watch for redundant (simultaneous) auditory and visual signals, auditory signals only, and visual signals only. Initial data points represent 2-min pretest scores. (From Ref. 1)

Experimental Results

- Decrements in vigilance performance occur under each of the five experimental conditions.
- Decrement in vigilance is least for the redundant task, moderate for the auditory, and greatest for the visual (Fig. 1).
- The total percentage of hits (correct detections) is greatest for the redundant task and least on the visual (Fig. 1).
- The probability of detection on the redundant task (0.91) is superior to the probability of detection on either the auditory (0.86) or the visual (0.76) task.
- Detection performance on the redundant task (0.91) is slightly less than the 0.97 that would have been predicted if the probabilities of detecting an auditory or a visual signal were independent.
- For nonredundant and partially redundant conditions, vigilance performance equals the average performance on watches when the signal sources were separately monitored. Also, for those same conditions, vigilance performance for auditory signals is better than in the auditory-only condition and worse for visual signals than in the visual-only condition.

Variability

Individual differences account for an overwhelming share of the total variance, and those individual differences that are specific to a task modality account for more of the variance than individual differences generally contribute to other tasks.

Repeatability/Comparison with Other Studies

Vigilance performance for auditory signals has repeatedly been shown to be better than for visual signals (Ref. 3) or for cutaneous signals (Ref. 4). Performance for redundant auditory/visual signals is better than performance for either auditory or visual signals alone (Ref. 3). Redundant auditory/cutaneous signals do not greatly improve performance (Ref. 5).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- No method of equating task difficulty (across modalities and for successive versus simultaneous signals) is described, and alerted condition (Fig. 1) shows differences.
- Results may not generalize to signal characteristics other than intensity (e.g., hue, frequency, etc.).
- Incorrect detections were not reported in terms of relative frequency in the various experimental conditions.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

7.419 Intertask correlations in vigilance performance;

Handbook of perception and human performance, Ch. 43

7.410 Maintenance of Vigilance Level By Adaptive Changes in Signal Detectability

Key Terms

Signal detection; target detection

General Description

Vigilance can be maintained at a preset level by changing signal detectability, with changes based on observer's earlier detection rate.

Methods

Test Conditions

- 16.5 × 22.9-cm (6.5 × 9-in.) CRT display, viewed at ~1.2 m; CRT ~30.5 cm below eye level
- Stimuli were two dots centered on CRT and separated horizontally by ~10.8 cm; dots presented for 150 msec with 850 msec **interstimulus interval**; 32 signals per 48-min session
- Signals were two dots with greater horizontal separation; initial dot separation for signals was ~13.4 cm and ranged from ~13 to ~15 cm
- Horizontal separation of dots in every odd-numbered signal determined by number of hits for last eight signals (< 6 caused increased separation by ~0.3 cm; > 6 caused decreased separation by ~0.3 cm)

Experimental Procedure

- Signal schedule randomized with constraint that eight signals occurred in each 12-min block and no two signals closer than 0.3 min apart; mean intersignal interval of 1.5 min
- Independent variable: distance between target dots
- Dependent variable: number of correct detections of signals
- Observer's task: press button within 2.5 sec to indicate detection of signal
- 13 undergraduates, with no practice

Experimental Results

- To keep signal detection performance within a constant predetermined range, signal detectability (separation distance of a pair of dots) must be increased as time on task increases. Dot separation for signals is increased from 24% greater separation than nonsignal dots to 37% greater by the end of the session.
- The performance curve obtained using this adaptive technique is similar to the performance functions obtained using signal-by-signal analysis for standard detection tasks; those functions also showed a decrement in vigilance level over time.

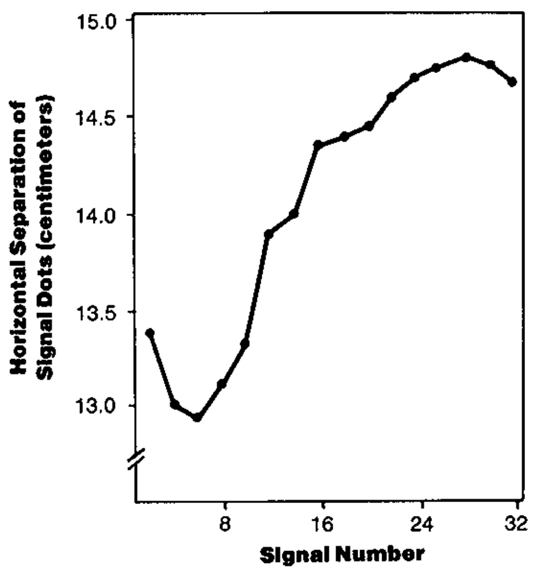

Figure 1. Amount of horizontal separation of two signal dots necessary to maintain vigilance performance at a predetermined level during a 48-min session containing 32 signals. Non-signal pairs of dots separated by ~10.8 cm. (From Ref. 2.)

Variability

Considerable variability between observers was reported, but no values were given.

Repeatability/Comparison with Other Studies

Similar results with different tasks have been reported (Ref. 3). Adaptive measurement of performance has been used in manual-control tasks and in training research (Ref. 1).

Constraints

- Although signal detection rate was extremely stable at ~65%, it tended to be near the lower limit of the preset range.
- Commissive errors (false alarms) were not taken into account in altering the adaptive (independent) variable, and a high false-alarm rate did not correlate with a high detection rate.
- The method of computing the score that determines alteration of signal is crucial to results. Several other methods were tried prior to the method reported here.
- There is a time lag between the last scored response and the presentation of the next adaptive signal.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

Handbook of perception and human performance, Ch. 43

7.411 Characteristics of the Task that Affect Vigilance, Monitoring, and Search

Key Terms

Incentive; monitoring; vigilance decrement; visual search

General Description

Vigilance tasks differ from each other along many dimensions. Some of the variables are not directly related (e.g., the size of a display is irrelevant to the auditory modality), while others are almost impossible to separate from each other (e.g., perceptual load and memory load) or from characteristics of the signal (e.g., the sensory modality employed defines both the task of the observer and the signal to be detected) or from the work environment (e.g., number of monitors). Certain characteristics of the task serve to differentiate vigilance, monitoring, and search tasks from each other, yet they may also be used as independent variables in the experimental measurement of vigilance performance (e.g., varied number of sources for the signal). Other inherent task characteristics are common to all task types (e.g., duration or pacing). Although some peripheral characteristics are mentioned here (e.g., incentives), they are covered in more detail under training. The table lists task characteristics that affect vigilance performance, shows the variations that have been studied, describes the effects, and cites sources of more information.

Constraints

- Although an element of task design may improve some aspect of vigilance performance, it may also have a negative effect on another aspect (e.g., decreasing the vigilance decrement, but creating an unsatisfactorily low level of overall performance).
- Task design that would optimize vigilance performance might be impractical or too costly in other respects to be implemented in the vigilance task.

Task Characteristic	Variations	Effect on Vigilance	Comments	Source
Modality	Single modality			
	Auditory	Higher level and less decrement than visual and cutaneous		CRef. 7.409
	Visual	Lower level and more decrement than auditory	Visual modality with multi-source signal defines a search task	
	Cutaneous	Lower level and more decrement than auditory	Visual and cutaneous not compared	
	Multimodal			
	Simultaneous signals (redundant information)	Higher level and less decrement for audio and visual than for either alone; little improvement for audio and cutaneous		
	Signal cueing	Improves level and decrement	Also used in training	Ref. 2 CRef. 7.415
	Alternate signals (both relevant)	See Time sharing (under Complexity)		
	Alternate signals (only one relevant)	See Extraneous Stimulation (under Complexity)		

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Task Characteristic	Variations	Effect on Vigilance	Comments	Source
Complexity	Time sharing (two tasks, both relevant)			Ref. 2
	Different modalities	Lower level and less decrement		
	Same modality	Lower level and less decrement; effect is greater than for different modalities; performance is worst for visual modality		
	Extraneous stimulation (two tasks, only one relevant)			Ref. 1
	Different modalities	Some contradictory results, but can improve level and decrement	Effect depends on which modality is relevant and on discriminability of the signals in each task	
	Same modality	Some contradictory results	Effect depends on which modality and task type	
	Source of signal (one source or multisource)	Lower level and less decrement with multisource; peripheral sources less attended than central sources	Effect depends on many variables (e.g., duration, discriminability of signal, size of display)	CRef. 7.406
	Size of display (compact or spread out)	Lower level and less decrement with multisource; peripheral sources less attended than central sources	Not separable from number of sources	
	Perceptual load (small or large)	A small load leads to boredom and thus a low level and a great decrement; a large load leads to fatigue and thus to a low level and great decrement	Not separable from memory load	CRef. 7.406
	Memory Load (small or large)	A small load leads to boredom and thus to a low level and a great decrement; a large load leads to fatigue, thus to a low level and a great decrement	Successive presentations of signals cause greater memory load than simultaneous presentations	CRef. 7.406
	Report/inference	Inference usually shows less decrement, but performance may be at lower level than for report	Not separable from memory load; degree of inference defines monitoring	
Response	Type of response			
	"Yes" only or "Yes" and "No"	No performance difference when using either one response button ("Yes only") or two ("Yes" and "No")		Ref. 3
	Confidence ratings	Evidence suggests that use decreases decrement		Refs. 4, 5
Number of monitors	Single (in isolation or with others in area)	Having other people in area seems to improve level and decrement over isolation		Ref. 2
	Multiple			
	Alternating	No improvement over single with others in area		Ref. 2
	Simultaneous	Contradictory results, although most suggest improvement with two people	Unrealistic number of people necessary for 100% detection rate	Ref. 2

Task Characteristic	Variations	Effect on Vigilance	Comments	Source
Duration of watch	Knowledge of long watch			
	Long watch	Rapid and increased decrement		Ref. 2
	End of watch	Brief burst of improvement in last few minutes of watch (some contradictory data)		Ref. 2
	Length of watch			
	Short	Greatest decrement within first 30 min		Ref. 2
	Long	Greatest decrement found around 18- or 24-hr task		Ref. 2
	Breaks in watch			
	Rest	As little as 5-min break can abolish decrement if placement in task is appropriate		Ref. 2
	Other activity	Can abolish decrement as rest does, but also can lower overall vigilance level (depending on kind of activity)	Variability seems to be the important consideration	Ref. 2
	Length of breaks	30-sec break has no effect; 10-min break is better than 5-min break	Experiments too different in other respects for more specific comparison	Ref. 2
	Placement of breaks	To abolish decrement, brief pauses must come within first 30 min of task	There is to be a tradeoff between how much good the pause does and how much task time is lost	Ref. 2
	Practice on task	Can improve both level and decrement		CRef. 7.414
Pacing	Self-paced, slow- or fast-paced	Evidence is equivocal, but self-paced reduces workers' complaints of boredom or fatigue		Ref. 2 CRef. 7.406
Incentives	Type of incentive			Ref. 2
	Financial	All kinds improve performance when utilized; better performance for higher-value signals		
	Cognitive	Some carry-over after removal		
	Social	Presence of others improves performance, as can experimenter attitude		
	Changeover	When incentives are changed, overall performance is most improved		

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.409 Simultaneous versus independent visual and auditory monitoring;

7.414 Effect of practice on vigilance;

7.415 Effect of instruction on vigilance;

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7.412 Vigilance for Sequential Events

Table 1. Factors affecting vigilance for sequential events.

Variables	Values Studied	Effect	Implications	Source
Number of letters (categories), total number of presentations per trial, and rate of presentation (Fig.1)	Letter categories: two (Q, R), three (Q, R, S), or four (Q, R, S, T); total number of letters presented (8-20); one letter every 0.5, 1.0, 2.0, 3.0, or 4.0 sec, with letter duration equal to one-half of rate	With 2 categories: at faster rates, mean error increases with trial length; at slower rates, there is little change with trial length With 3 categories: at faster rates, increases in mean error as a function of trial length are more pronounced; at 2.0 sec, increase is of smaller magnitude With 4 categories: at all rates, error increases with trial length	Small number of categories best for accuracy The slower the rate of presentation, the better the performance	Ref. 5 Ref. 1
On/Off ratio	One letter every 1.0, 2.0, 3.0, or 4.0 sec: (a) 0.1 sec on-time, remainder off; (b) on half time, off half time; (c) 0.1 sec off-time, remainder on	At faster rate, there is little effect of on/off ratio At intermediate rates, performance is best with shorter on-time At slower rate, the shortest on-time yields worst performance	Optimal on/off ratios should be determined for each situation	Ref. 6
Irregular presentation rate	No description	Degraded performance		Ref. 3
Irrelevant information	Letters, Q, R, S, U, V, W, with only Q, R, S relevant	Led to performance that is equal to or better than a regular rate of presentation	Causes irregular rate of relevant information, but slows average rate of presentation of relevant information	
Paced rehearsal	Green light of 0.3 sec duration immediately preceded letter stimulus	Performance improved with cue light	Pacing is desirable	
Character of stimulus	Symbols (plus, square, heart, triangle); letters (Q, R, S, T); numbers (2, 3, 4, 5)	Performance is worst for symbols that have no inherent order	Stimulus classes with inherent order result in better performance	Ref. 3
Stimulus array	Letters or symbols scrambled on single display or four displays with one for each symbol or letter or four displays but letters or symbols could occur on any	Ordered condition is superior to single or scrambled	When possible, categories should be sorted prior to display and aligned spatially	
Addition versus subtraction	Letters on red background to be subtracted from tally; letters on green background to be added to tally	Performance deteriorates as the percentage of subtractions increases, peaking between 50 and 75%; however, 100% subtractions yield the same mean error as 100% additions	Subtractions are perceived as more difficult than additions when both are required	Ref. 3
Differential value of stimuli	Greater monetary reward for accuracy for S and T than for Q and R (or vice versa)	Differential reward yields selectively so that letters with high value are tallied more correctly, but at a cost of poorer performance on letters with lower value		Ref. 2

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Variables	Values Studied	Effect	Implications	Source
Simultaneous display	One, two, or three letters simultaneously presented on adjacent displays at 2.0, 4.0 or 6.0 sec rate with on-time equal to ½ of rate	When information rate is held constant at one letter every 2 sec, performance is nearly identical whether rate is fast and number of letters is small or rate of presentation is slow and number of letters per exposure is large	Number of categories displayed simultaneously can be increased to at least three provided that information rate (presentation rate divided by number of letters per exposure) can be kept constant	Ref. 1
Auditory Stimuli		Show several similar patterns to visual; the same general principles seem to apply		Ref. 4

Key Terms

Cognitive tasks; memory

General Description

When required to keep a running mental tally for several categories of information, observers have a fairly low capacity for keeping track of changing information. The main variables that must be considered are the number of categories, the rate at which information is added, and the length of the trial (or total number of symbols presented). Increasing each of these three basic task parameters increases error rate as shown in Fig. 1; also, the parameters interact with all the other variables that have been studied. The table lists important variables and briefly describes the values studied, the effects (including interactions), the implications for task design, and sources of more information.

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Cross References

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

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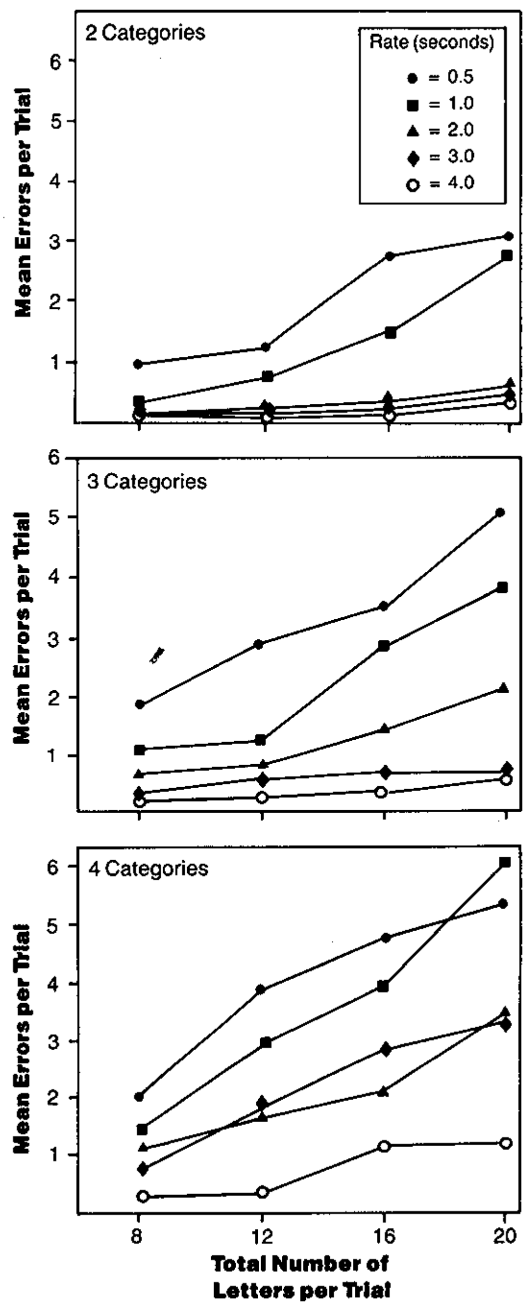

Figure 1. Effect of total number of letters per trial, number of different letters (categories), and rate of presentation on error rate when observers had to keep a running tally of the number of presentations of each letter. (From Ref. 3)

7.413 Characteristics of the Observer that Affect Vigilance, Monitoring, and Search

Observer Variable	Direction/ Consistency of Effect	Variables Not Controlled	Source
Age	Young adults perform slightly better than older adults, but there is great diversity of results	Cut-off point for young/old grouping may be 35 or 60; memory load of task	Effect: Ref. 14 No effect: Ref. 19
Sex	Contradictory findings show no effect, women superior or men superior	Often incidental variable; interaction effects with main independent variables	Refs. 5, 8, 13
Intelligence	No effect unless brain damage or sometimes when retardation is present, but some diversity of findings	Different measures used; cut-off point for low/high may differ	Effect: Ref. 6 No effect: Ref. 18
Personality or temperament	(Note: the measures listed under this heading are not independent of each other)		
Intro/extroversion	Introverts show less decrement; introverts may have better level of performance, but there is some diversity of findings	Different measures used; differing cut-off points for the dimension	Summary: Refs. 3, 4 Effect: Ref. 1; CRef. 7.804
Impulsivity	High impulsivity correlates with high false alarm rate	Cut-off point between high/low differs; different measures used; usually portion of intro/extro-version measure	Ref. 16
Boredom	Subjects that give self-reports of high boredom show longer reaction times (RTs) and greater decrements	Different measures used; cut-off point between high/low differs	Ref. 17
Distractability	Subjects that give self-reports of high distractability show longer RTs and more variance of RTs over time on task	No replication	Ref. 15
Field dependence/ independence	Field-dependent observers show better performance on some measures, but there is conflicting evidence on complex tasks	Cut-off point for dependence/independence differs	Effect: Ref. 2 No effect: Ref. 7
Physiological factors			
Skin conductance; mean heart rate; respiration rate; muscle tension	No correlation with vigilance performance, although individual variation exists. There is some inconsistency of findings	For summary, see Ref. 3	Ref. 3
Heart rate variability	Low variability is related to high detection rate		Ref. 12
Adrenaline and noradrenaline levels	Low adrenaline is related to a high vigilance decrement		Ref. 11

Key Terms

Individual differences; monitoring; search

General Description

In most vigilance tasks and vigilance experiments, there is a wide range of variation in performance between individual observers. Efforts to devise methods for selecting observers best at vigilance have attempted to correlate vigilance performance with membership in a class or group, with scores on various tests or self-reports, or with physiological measures. One major study of individual differences (Ref. 10)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

employed a battery of 17 tests and found that vigilance performance correlated well only with a measure of clerical abilities, but this result did not replicate (Ref. 9). The table lists the observer variables, describes the consistency and directions of the findings, suggests factors (in addition to the general factors listed in the Constraints section) that may contribute to the inconsistencies, and cites sources of further information.

Constraints

- Often a variable listed in the table was not one of the major independent variables in the study given as the reference.
- Interactions of the variables with each other and with signal, task, and environmental characteristics can yield different results.
- Studies looking at any given variable have used different types of vigilance tasks, different response types, different response measures (hit rate, reaction time, error rate, etc.), and different experimental designs; these differences make comparisons of results very difficult.
- Motivation, expectation, and other such subjective variables have been studied only in terms of instruction, pay-off matrix manipulation, and other incentives, not in terms of individual differences.

Key References

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Cross References

7.402 Methods of measuring vigilance, monitoring, and search;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.415 Effect of instruction on vigilance;

7.416 Effect of different training methods on vigilance;

7.804 Effects of stress on performance for introverts and extroverts

7.414 Effect of Practice on Vigilance

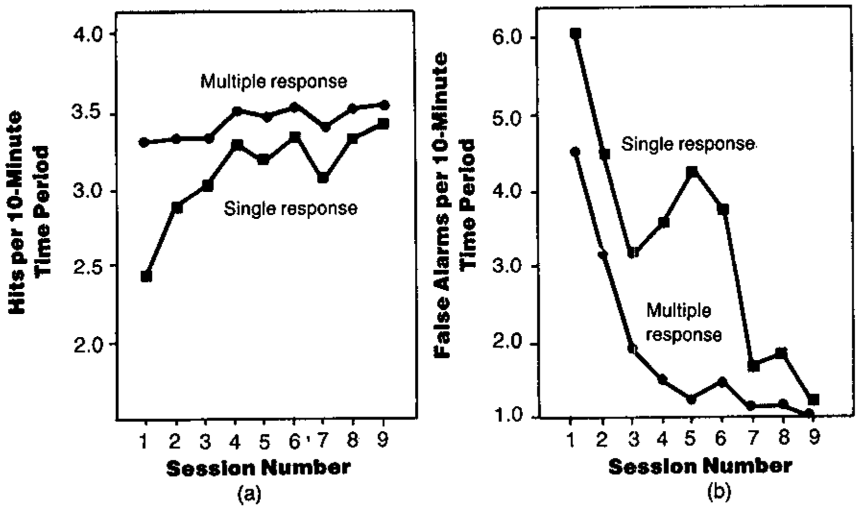

Figure 1. Change in (a) hit (correct detection) rate and (b) false alarm rate for two response conditions as a function of practice over sessions. (From Ref. 2)

Key Terms

Monitoring; practice; target detection; training

General Description

In a vigilance task where subjects must detect intensity changes in a noise pulse, increased practice on the task leads to an increase in the correct detection (hit) rate and a decrease in the incorrect detection (false alarm) rate. The differential change in hit and false alarm rates suggests that practice helped subjects to better discriminate signals (targets) from nonsignals. In contrast, a vigilance decrement occurs within sessions; both the hit and false alarm rates decrease. All trends are similar in both single- and multiple-response conditions, but the multiple-response condition is associated with better overall performance.

Methods

Test Conditions

- Targets were pulses of Gaussian noise; pulse duration of 0.5 sec; interpulse interval of 2.5 sec; Grason-Stadler HD 30 earphones used in an insulated sound-shielded room
- **Sensation level** (threshold) for each observer determined by method of limits during training session
- Nonsignal pulses at 60 dB above threshold; signal pulses at 61.8 dB above threshold
- Random intersignal interval with uniform distribution (mean of 2 min with constraints that no intersignal interval is <10 sec nor >240 sec)
- Response button (single-response conditon) or buttons (multiple-response condition) on a panel on table in front of subject
- One training session (duration not given) and nine vigilance sessions of 80 min each

Experimental Procedure

- Method of limits
- Mixed design
- Independent variables: amplitude of noise pulse, single-response or multiple-response condition
- Dependent variables: correct (hits) and incorrect (false alarms) detection rates, decision criterion (β, a ratio of the signal-plus-noise distribution to the height of the noise distribution at a given point of overlap), sensitivity (d', the distance between the mean of the noise distribution and the mean of the signal-plus-noise distribution)
- Subject's task: press single response button to indicate detection of louder signal pulse or press one of three buttons (very sure, moderately sure, possibly) to indicate confidence level of detecting louder signal pulse
- 24 college students, paid \$1.50/hr with \$20.00 bonus for "best performance"

Experimental Results

- Over the nine experimental sessions, hit rate increases and false alarm rate decreases for both single and multiple-response conditions (Fig. 1).
- Within individual sessions, both hit rate and false alarm rate decrease (Fig. 2).
- The within-session decrease in hits and false alarms is greater for early sessions and almost negligible for later sessions.
- Within-session changes can be explained primarily as an increase in β (towards a stricter criterion) probably reflecting a downward revision of subject's estimates of signal probability.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• The differential trends for hits and false alarms across sessions can be explained by an increase in d′ (sensitivity).
• The difference between single and multiple-response conditions is most marked in the within-session trends, although hit rate is always higher and false alarm rate is always lower for the multiple-response condition (CRef. 7.415).

Variability

There were a few extreme scores in each condition. Wilcoxon T-tests and analysis of variance were used to test significance.

Repeatability/Comparison with Other Studies

Similar session-to-session improvement has been reported in some cases (Refs. 1,4), but not in others (Ref. 3).

Constraints

• Contradictory findings on the effect of practice indicate that type or modality of task, pretask training, discriminability of signal targets, and other variables may greatly alter the results.
• A small within-session decrease in d′ (sensitivity) is not explained.

Key References

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Cross References

7.405 Application of signal detection theory (SDT) to vigilance;

7.415 Effect of instruction on vigilance;

7.416 Effects of different training methods on vigilance;

7.420 Signal detection theory;

Handbook of perception and human performance, Ch. 43

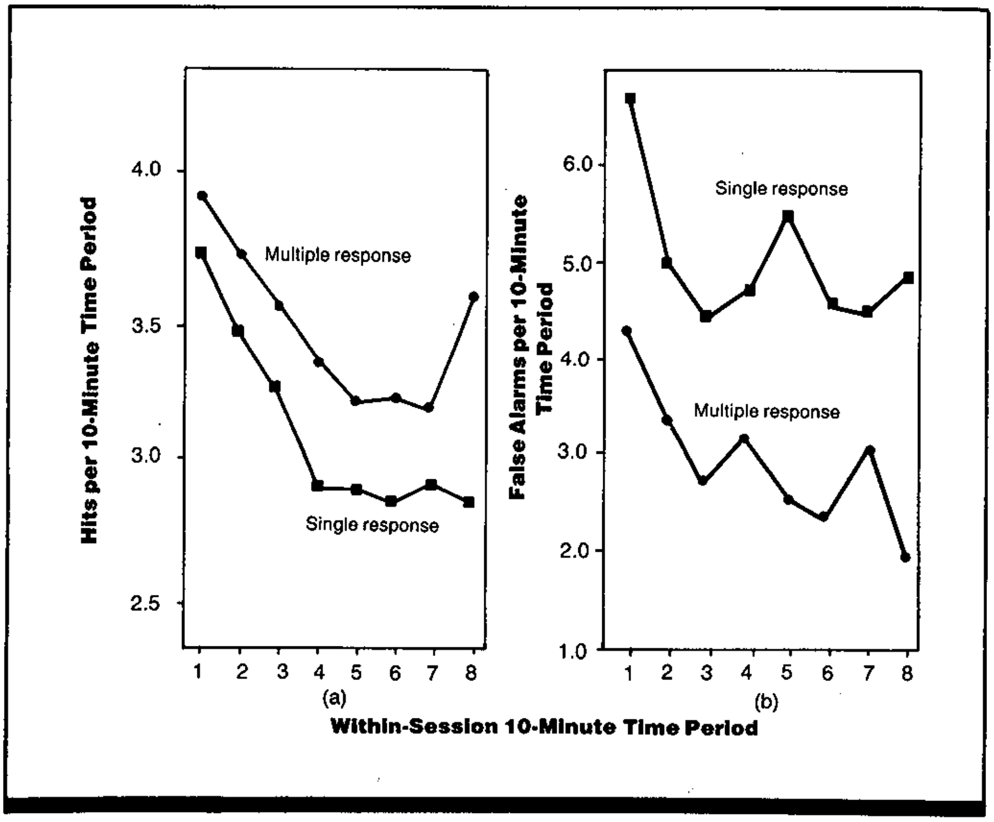

Figure 2. Change in (a) hit (correct detection) rate and (b) false alarm rate over successive 10-min time periods within sessions. Sessions were divided into eight 10-min blocks and the data averaged across sessions and across subjects. (From Ref. 2)

7.415 Effect of Instruction on Vigilance

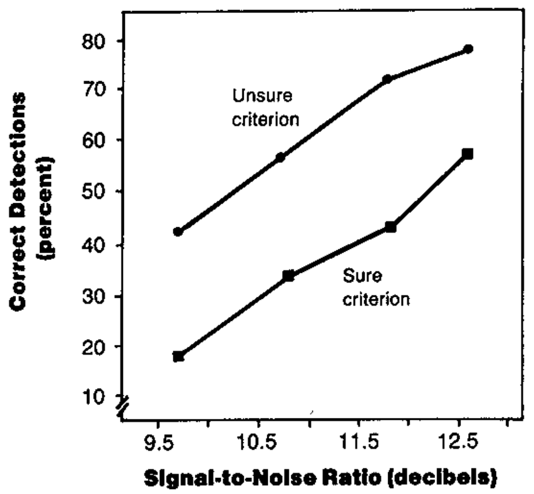

Figure 1. Percentage of correct detections as a function of signal strength (measured in terms of the signal-to-noise ratio) for two types of instructions: subjects were either to be quite "sure" that a signal was present, or to respond if they thought a signal might be present ("unsure"). (From Ref. 1)

General Description

On a simulated sonar task, subjects achieved a much lower detection rate at all signal strengths when instructed to respond only if quite certain they heard a signal than when told to respond to any sound that might be a signal.

Methods

Test Conditions

- Sonar task simulated by electronic device with a variable signal-to-noise amplitude (S/N) ratio capability
- Continuous 900-Hz tone presented via earphones with amplitude modulated by a low bandwidth (0-10 Hz) random-noise source
- Signal pulses produced by removing noise modulation and raising tone amplitude for 200 msec; four pulse amplitudes from weak to strong with S/N ratios of 9.7, 10.8, 11.8, and 12.6 dB ("noise" amplitude calculated as root mean square of modulated tone); pulse rise time set to obviate sharp transients
- 36 signals during each 45-min session; random intersignal intervals, with constraint that three signals of each strength occurred in each 15 min of session; random order of different signal strengths within each 15-min period
- Responses >3 sec after signal counted as false alarms
- Subjects instructed to be certain before they indicated presence of signal ("sure") or to indicate presence of anything that might be a signal ("unsure"); half of the subjects got one type of instruction at beginning of Session 1 and other type of instruction at beginning of Session 5; other half of subjects received reversed order of instructions

Experimental Procedure

- Independent variables: S/N amplitude ratio for four signal strengths, instruction type (sure or unsure)
- Dependent variables: hit (correct detection) rate, false alarm (incorrect detection) rate, decision criterion (β = the ratio of the height of the signal-plus-noise distribution to the height of the noise distribution at a given point of their overlap), sensitivity (d' = the distance between the mean of the noise distribution and the mean of the signal-plus-noise distribution)
- Subject's task: report detection of a signal by closing a contact switch
- 12 enlisted men of the Royal Navy who were previously unfamiliar with this form of monitoring, but had several hours practice

Experimental Results

- Significantly more signals are detected in the "unsure" procedure (61.8%) than in the "sure" procedure (37.6%).
- Median false alarm rate is 3.5 times higher for the unsure procedure than for the sure procedure.
- Signal detection analysis of the hit and false-alarm probabilities indicates that β (the decision criterion) is significantly greater for the sure (2.0) than for the unsure (5.6) instructions, reflecting a higher degree of caution in responding (i.e., a stricter criterion); d' does not significantly differ for the different instructions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Those subjects who had the sure instructions first have a lower overall mean detection rate than those subjects who had the unsure instructions first.
• There is a positive, apparently linear relationship between signal strength and probability of detection (Fig. 1).

Variability

Analysis of variance was used to test significance.

Repeatability/Comparison with Other Studies

For a simulated radar task, instruction to adopt a "risky" reporting set caused earlier detections and more false alarms than instructions to adopt a cautious set (Ref. 2).

Constraints

• Although the increase in probability of false alarms (0.022) is considerably smaller than the increase in probability of correct detections (0.242) under the unsure instructions, there may be cases when any increase in false alarms is unacceptable.
• Only a successive-presentation task and one modality were tested.

Key References

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Cross References

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.420 Signal detection theory;

Handbook of perception and human performance, Ch. 43

7.416 Effects of Different Training Methods on Vigilance

Key Terms

Feedback; incentive; instructions; practice; training; vigilance decrement

General Description

Training for vigilance tasks may include practice with different variables, different instructions, and incentives of several kinds, including various types of feedback. Training is designed to reduce temporal or spatial uncertainty in locating the signal, to increase sensitivity to the signal, and/or to manipulate the decision criterion to produce optimal vigilance performance. Some of the training methods listed here may also be considered characteristic of certain vigilance tasks; for example, incentives may be used in industrial situations to directly improve vigilance performance on the job rather than during training. There is also overlap among the items listed here; for example, an instruction can also be an incentive. The table lists training methods that have been experimentally analyzed, describes the use and results of the methods, identifies constraints, and gives sources of more information.

Applications

Design of training programs for vigilance tasks.

Constraints

- At present, practice on a specific task seems to be the best training for that task.

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Cross References

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.414 Effect of practice on vigilance;

7.415 Effect of instruction on vigilance

Training Method	Description of Use	Carryover	Consequences	Constraints	Source
Practice	Pretask practice in almost all vigilance tasks; continues with time on task	Definite carryover; optimum amount varies with signal discriminability and with signal and task complexity	Improves sensitivity and sets decision criteria placement	Setting wrong signal probability by crammed practice leads to increased decrement	Ref. 3 CRefs. 7.406, 7.414
with artificial signals	Fake signals may be: Identical to real signal (increases signal probability)	Initial improvement	Improves sensitivity by greater practice in discrimination, but sets incorrect decision criteria	Setting wrong signal probability by addition of same signals increases decrement	CRef. 7.406
	Less discriminable than real signal	Some carryover, but contradictory results	Improves sensitivity		Ref. 3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Training Method	Description of Use	Carryover	Consequences	Constraints	Source
Practice (cont.)					
with signal cueing	Signal in one modality is cued by immediately prior presentation of a stimulus in another modality (e.g., a tone before a visual target); timing and coupling of cue with signal may vary greatly	Best carryover when one cue to one signal and close together in time (improved detection rate by 14.2% and decreased false alarm rate by 4%)	Improves sensitivity (especially for signals with low discriminability) and makes decision criteria more stringent		Refs. 1, 2
Instruction	Subjects told to respond only when certain versus responding even when doubtful	Subjects do as they are told	Only affects placement of decision criterion		CRef. 7.415
	Subjects informed of signal probabilities (information given to subjects may be true or false)	Subjects set decision criteria on basis of rate given	Only affects decision criterion	Giving subjects an overrated signal probability increases decrement	CRef. 7.406
	Task is described to subjects as "required chore," "important task," and/or "has consequences for them" (a purely verbal incentive)	Performance is better for "important task" and "subject consequences" conditions than for "required chore"	Affects decision criterion and motivation		Ref. 6
Incentives					
knowledge of results	Subjects have been given true and complete, true and partial, or false knowledge of results	Results are contradictory, but even false feedback reportedly yields an improvement in performance	Improves sensitivity and placement of decision criterion; data on feedback now suggest that knowledge of results is motivational in resource-limited tasks where error rates are low and the amount of effort that subjects devote to the task determines performance efficiency; on the other hand, in data-limited tasks, where performance is determined by the quality of the data that the subject receives, knowledge of results has instructive properties that are tied to the kind of knowledge of results supplied (i.e., hits, misses, or false alarms)	May be confounded with effects of supervision, especially in industrial settings	CRefs. 7.406, 7.411, 7.414, 7.415
financial incentives	Various schedules of payment and charge for errors and correct detections can be used	Effects vary with schedule used and size of payments	Affects decision criterion and motivation		Refs. 3, 5

7.417 Effect of Boredom on Detection Efficiency

Key Terms

Boredom; target detection

General Description

Subjects who report an extremely high level of boredom at the end of an hour of performing a simulated air traffic control task have significantly greater response times (detection latency) than those who report an extremely low level of boredom. An increase in detection latency over time on task for the high group and a decrease for the low group makes the difference between the groups more marked by the second half of the 1-hr task.

Methods

Test Conditions

- Stimuli were projected onto the rear of a 40-cm (diameter) Polacoat rear protection screen located in a console resembling an air traffic control radar unit; with each successive filmstrip frame (one per 15 sec), targets advanced at simulated airspeeds of 300 or 600 knots
- Nonsignal targets: blips representing aircraft with adjacent alphanumeric symbol, consisting of two letters (identifying aircraft), three numbers (representing altitude), and the letter "C" (indicating aircraft maintaining assigned altitude)
- Signal target: letter "N", indicating that aircraft had departed from assigned altitude; 10 targets per 30-min period, randomized; mean intersignal interval of 3 min; only one signal on a given frame; number of targets per frame: 6-10 with mean of 8; targets distributed across all quadrants of screen
- Before task, observers instrumented for physiologic recording and asked to rate their present levels of attentiveness, fatigue, strain, boredom, and irritation on a nine-point scale

Experimental Procedure

- Independent variable: boredom level (high or low)
- Dependent variables: mean response latency; standard deviation of response latencies; number of critical stimuli missed (no response within 14 sec), skin conductance; heart rate; gross movement; blood pressure; oral temperature; subjective boredom rating scale score
- Subject's task: press button on right of console as rapidly as possible to indicate detection of signal target
- 45 male undergraduate subjects, 18-25 yr, right-handed, no prior experience with task; results reported for 8 subjects with highest post-task scores (nine-point scale) of boredom and monotony (means of 2.0 and 1.2) and 8 subjects with lowest scores (means of 7.4 and 6.8)

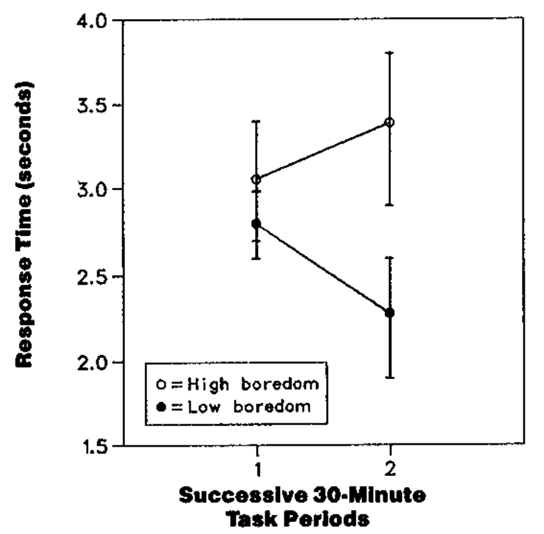

Figure 1. Response time as a function of task period for observers high and low in boredom scores. (From *Handbook of perception and human performance*, adapted from Ref. 2)

Experimental Results

- High-boredom subjects exhibit longer detection times (slower responses) than did low-boredom subjects, especially for the second 30-min period of the 1-hr task ($p < 0.05$) (Fig. 1).
- The significant interaction effects for mean detection time and its variability (with task periods) can be attributed to an increase in the duration of long response times for the high-boredom group and a decrease in duration of long response times for the low-boredom group.
- Because all subjects detected all critical stimuli, this performance measure does not discriminate between high- and low-boredom subjects.
- A significant interaction effect ($p < 0.05$) between task period and high/low groups shows that heart rate variability decreases from first to second period of the task for low-boredom subjects and increases for high-boredom subjects.

Variability

Error bars (in Fig. 1) are ± 1 standard error of the mean. Pretask boredom and monotony scores were the same for both groups. Significance was determined by analysis of variance.

Repeatability/Comparison with Other Studies

Subjective assessment of boredom and monotony correlates with detection efficiency in a simple pursuit rotor task and in a repetitive addition task (Ref. 1). A similar pattern of vigilance performance is related to self-reports of distractability (Ref. 3).

Constraints

- Boredom and monotony are difficult to define operationally.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

Handbook of perception and human performance, Ch. 44, Sect. 3.5

7.418 Sex Differences in Vigilance Performance

Key Terms

Individual differences; monitoring; sex differences

General Description

The performance of males on vigilance tasks is similar to that of females. Female subjects correctly detect 10% fewer signal targets and commit slightly more false alarms (incorrect detections), but sex differences account for only 4% of the variance of correct detection performance and <1% of the variance of the false alarm rate.

Methods

Test Conditions

- Subject seated in three-sided cubicle
- Visual display with IEE one-plane readout (no dimensions or other description given)
- Nonsignal targets: dot of light 0.32 cm in diameter moved downward 1.58 cm for 0.3 sec, returned to original position for 0.3 sec, repeated the sequence, and returned to original position for remainder of event interval; 30 events per min
- Signal target (24 per hr): second downward deflection increased from 1.58 cm to 2.22 cm
- Low-level white noise (level not specified) played on loudspeaker throughout 1-hr session
- Arc sine transformation performed before analysis to normalize the data

Experimental Procedure

- Visual vigilance task (detect defined, frequently appearing targets)
- Independent variables: sex, time period (hour session divided into three 20-min periods)
- Dependent variables: correct detections (defined as a response occurring within 1.6 sec after signal target) averaged for 20-min periods, incorrect detections (false alarms) averaged for 20-min periods
- Subject's task: press response button at end of bicycle hand grip when signal target appears
- 220 male and 220 female undergraduate subjects, some practice

Experimental Results

- Sex and time period directly affect correct detection rate ($p < 0.001$). (Fig. 1). Female subjects correctly detect 10% fewer signals; both sexes detect more signals during the first period than during the second or third.
- Time period ($p < 0.001$) and the interaction between gender and time period ($p < 0.05$) directly affect false alarm rate (Fig. 1). Female subjects commit more false alarms in the initial time period.

Variability

Significance was determined by analysis of variance.

Repeatability/Comparison with Other Studies

No comparable studies have been conducted with large sample size and sex as major variable. Advantage in vigilance performance has been found on average for males (Ref. 1), for females (Ref. 3), and for neither (Ref. 4).

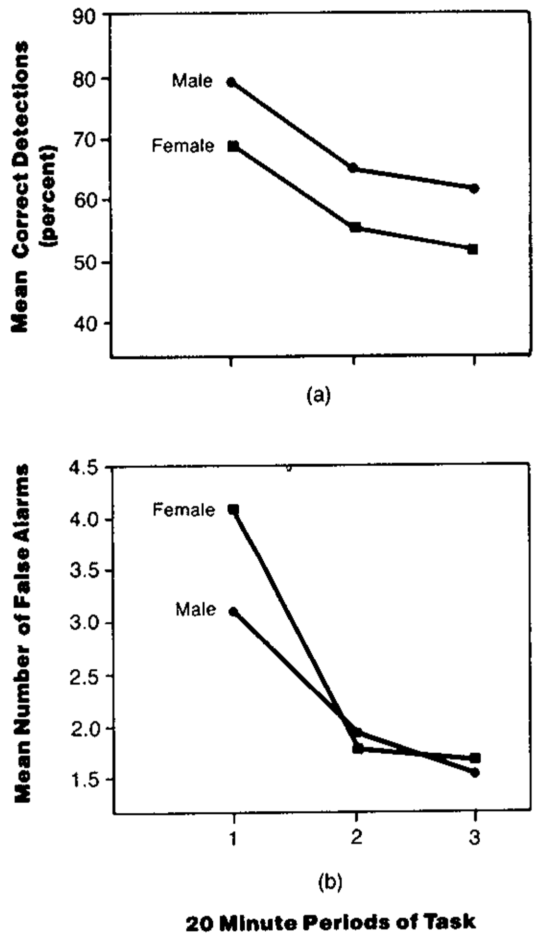

Figure 1. Mean correct detections (a) and false alarms (incorrect detections) (b) as a function of time period and sex. (From Ref. 5)

Constraints

- Because males and females find different tasks more or less difficult and more or less challenging, differences in performance between the sexes may relate to task type (Ref. 2).
- Sex differences represent group averages, and as groups greatly overlap, must not be applied to single individuals.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search

7.419 Intertask Correlations in Vigilance Performance

Key Terms

Intertask correlation; signal discrimination

General Description

Tasks that involve comparisons of successive stimuli (e.g., comparisons of brightness or pitch) require "perceptual speed," and tasks that involve finding some type of signal within a background (e.g., a circle in a background of squares) require "flexibility of closure." These two task abilities form one dimension for classification of vigilance tasks into two categories. Vigilance tasks may also use the same or different sense modalities (e.g., auditory or visual). Increasing task similarity by classifying tasks according to the speed/closure dimension and the modality dimension increases correlations among the performance data for the tasks (Fig. 1).

Methods

Test Conditions

- Task difficulty for all six tasks matched for equal detectability for "alerted" short-duration detection; event rate was 15/min; signals irregularly presented at mean rate of 1/min
- Visual Speed Task 1 (VS1): flash presentation; intermittently flashing circular light source presented to right eye in approximately **Maxwellian view** at visual angle of 2 deg (luminance level not given); signal flash dimmed by 9.2 cd/m^2
- Visual Speed Task 2 (VS2): slide presentation at 1-m viewing distance; two vertical lines each 10 cm long (horizontal separation not given); decrease of 1 cm in horizontal separation of lines for signal
- Visual Closure Task 1 (VC1): light flashes as in VS1 task, but signal was small pink flash at the center of light flash
- Visual Closure Task 2 (VC2): projected vertical lines as in VS2 task; signal was a central 0.5-cm gap in both lines
- Auditory Speed Task (AS): intermittently pulsing 1- kHz tone; signal was 1 dB increase in intensity of tone
- Auditory Closure Task (AC): regularly pulsed noise bursts, but signal was the same 1-kHz tone as in AS task
- Observers randomly assigned to either intramodal or intermodal group and tested on pairs of tasks (one task per session with sessions 7 days apart)

Experimental Procedure

- Vigilance task
- Independent variables: speed or closure task, auditory or visual modality, flash or slide presentation
- Dependent variable: mean rate of correct detections of signals (hits)
- Observer's task: indicate detection of signal (mode of response not specified)
- 60 male observers (ages 18-28 yr), with previous experience in monitoring and inspection work, and some practice

Experimental Results

- Increasing task compatibility generally increases the product-moment correlations between pairs of vigilance tasks for both sensitivity (d') data and correct-detection (hits) data.
- All correlations for pairs of tasks requiring the same observer ability (perceptual speed or flexibility of closure) are significant (10 observers), even when the tasks are in different modalities (visual or auditory).
- All correlations for pairs of tasks that do not require the same observer ability (perceptual speed or flexibility of closure) are not significant (10 observers).

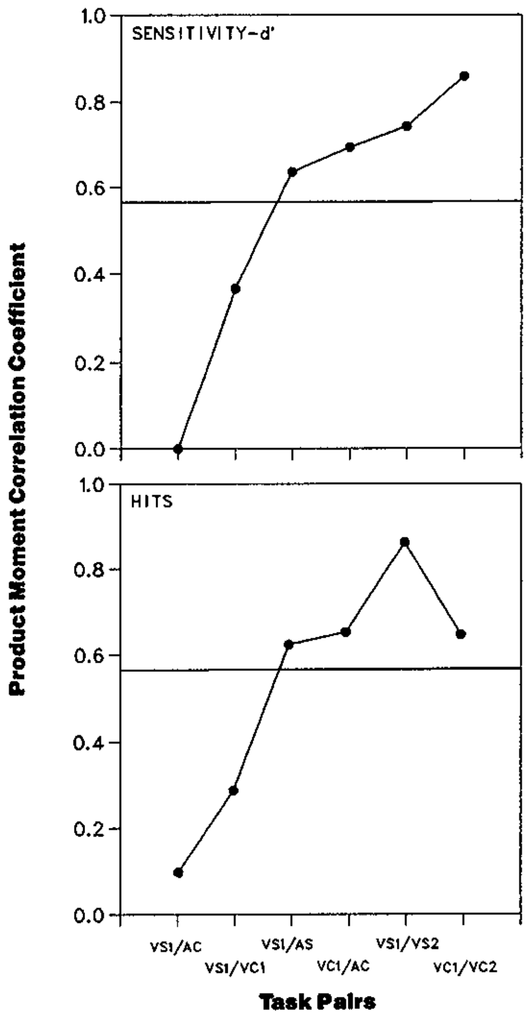

Figure 1. Product-moment correlation coefficients (r-values) for sensitivity (d') and correct detection (hits) data for pairs of vigilance tasks. V = visual; A = auditory; S = perceptual speed; C = flexibility of closure; 1 = light flashes; and 2 = vertical lines (see text for full description of conditions). Horizontal midlines indicate significance at p <0.05. (From Ref. 3)

Variability

The results address the issue of individual differences: the pattern of individual differences becomes more consistent for more compatible tasks.

Repeatability/Comparison with Other Studies

The importance of type of signal discrimination to performance on attention tasks has been confirmed (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Factors affecting vigilance performance are numerous; even if signal discrimination type is held constant, lower correlations may be obtained if the displays differ in some other important respect not identified in the task classification system (e.g., visual search, signal duration, pacing, event rate).

• The correlation coefficients shown are for mean performance over the 45-min session; intertask correlations for all groups are high in the first 15 min of a session, so the dependence of the intertask correlation on task type emerges clearly only in the latter half of the sessions.

• Tasks requiring the same ability, such as perceptual speed, might be made more compatible if they required the same type of judgments, for example, the visual speed tasks, in which one required luminance judgments and the other required spatial judgments.

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Cross References

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.408 Effect of signal discriminability on vigilance performance;

7.411 Characteristics of the task that affect vigilance, monitoring and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

Handbook of perception and human performance, Ch. 43, Sect. 5.2

7.420 Signal Detection Theory

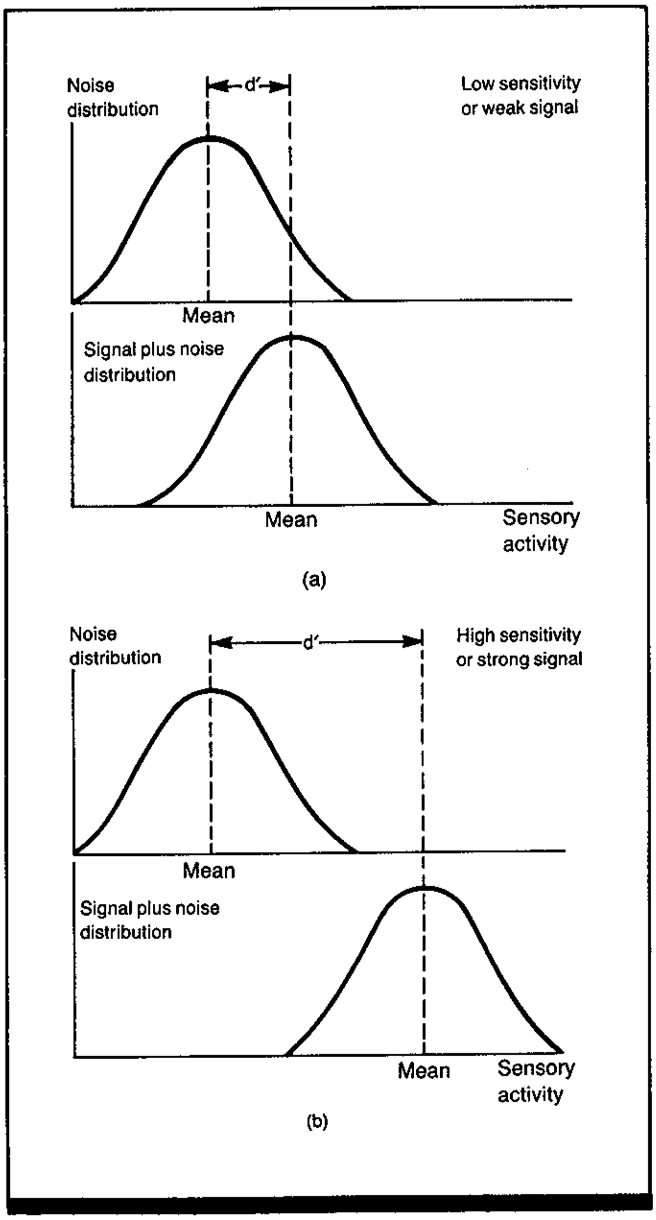

Figure 1. The effect of signal strength (observer sensitivity) on the distance between the noise and signal-plus-noise distributions. *d′* is an index of that distance; the signal in (b) is stronger than that in (a) and/or observer sensitivity is greater. (From Ref. 1)

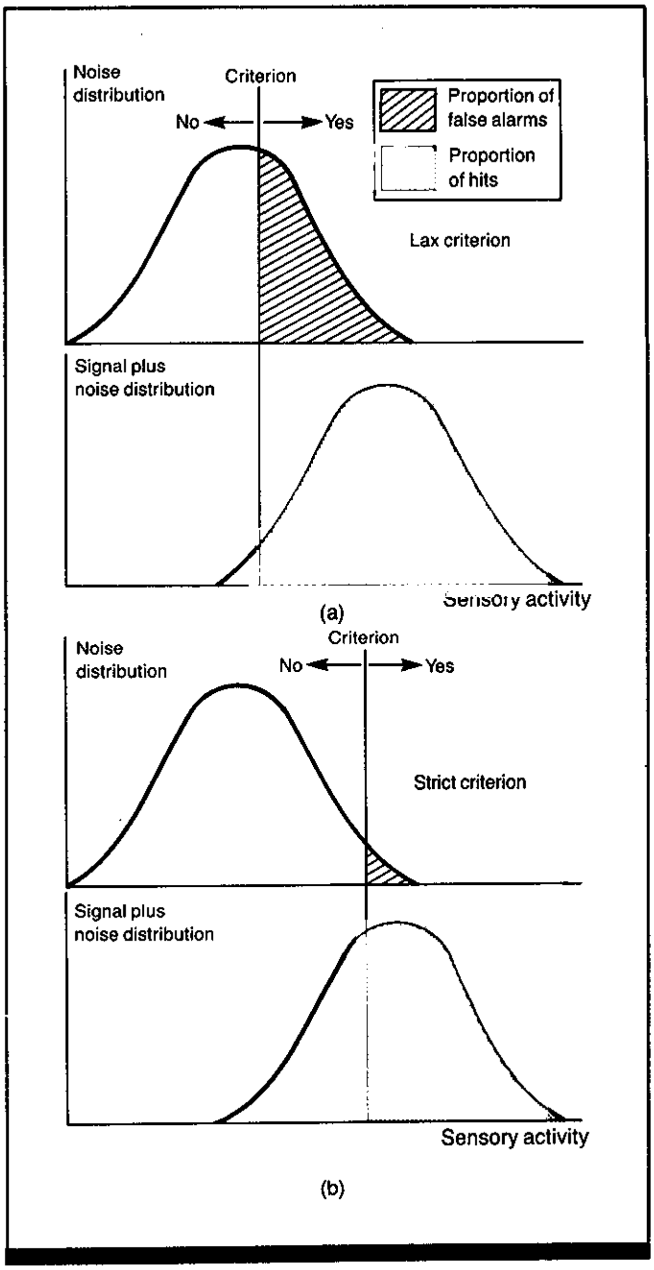

Figure 2. The effect of expectations and/or motivation on the placement of the decision criterion: (a) illustrates a "lax" criterion and (b) illustrates a "strict" criterion. (From Ref. 1)

Key Terms

Decision theory; receiver operating characteristics; signal detection theory

General Description

Classical psychophysical conceptualizations of observer performance in settings requiring detection of a target stimulus assume that performance is controlled by the existence of a sensory threshold. Stimuli exceeding that threshold will be detected; stimuli falling below the threshold will go unnoticed. However, because most experiments designed to determine threshold values deal with very weak stimuli, the observer is usually faced with the difficult task of trying to decide whether a stimulus occurred. Consequently, it is crucial to distinguish between the observer's sensitivity to the stimulus and the decision criterion governing the observer's response. Signal detection theory provides the means to account for the role of decision processes in detection situations.

Theoretical Assumptions Underlying the Theory of Signal Detection

The detection of signals always takes place against a background of noise. The noise may be considered as existing in the physical stimulus itself (e.g., static) or as the underlying spontaneous neural activity in the observer. Both of these will tend to interfere with the detection of signals if the signal intensity is weak relative to the noisy background. Noise is assumed to be a continuous random variable and therefore takes the form of a **normal distribution**. Any signal value added to this noise distribution will shift the mean of the signal + noise (*SN*) distribution away from the noise (*N*) distribution, although the variability (and thus the shape) of the two distributions will remain the same (Fig. 1).

The distance between the means of the two distributions is called d', and is a measure of signal strength. Alternatively, d' can be considered a measure of observer sensitivity, because the concepts of signal strength and observer sensitivity are equivalent. d' is expressed in standard score units by the following relationship:

$$d' = \frac{\mu_{SN} - \mu_N}{\sigma_N},$$

where μ_{SN} indicates the mean of the signal plus noise (SN) distribution, μ_N is the mean of the noise (N) distribution, and σ_N is the **standard deviation** of the noise distribution.

Signal strength alone does not determine observer performance. The observer sets up a criterion for judging the presence or absence of a signal based upon the magnitude of sensation resulting from observation. Any sensation whose magnitude is greater than the criterion will result in the observer's response that a signal was present; a sensation whose magnitude is less than the criterion will result in the observer's response that the signal was absent. A very strict criterion will be placed farther to the right in the *SN* distribution (Fig. 2a) and will require sensations of greater magnitude to yield a "present" response; lax criteria will be placed farther to the left (Fig. 2b), so that a "present" response may be elicited by fairly weak sensations. Placement of the criterion is reflected in the value of a likelihood ratio, β, which is the ratio of the ordinate value of the *SN* distribution at the criterion to the ordinate value of the *N* distribution at the criterion.

$$\beta = \frac{\text{ordinate value of } SN \text{ distribution at criterion}}{\text{ordinate value of } N \text{ distribution at criterion}}.$$

That is to say, the observer's likelihood of responding in a particular way depends not only on sensitivity, but on placement of the criterion. It is critical to note that the criterion may be moved independently of signal strength. This independence is at the heart of signal detection theory; it allows the investigator to separate observer sensitivity from the response criterion adopted by the observer. Four outcomes are possible as a result of criterion placement (Table 1). If the observer responds "present" when the signal is present, this is a correct decision and is called a "hit." Responding "absent" when the signal is present is an error and is termed a

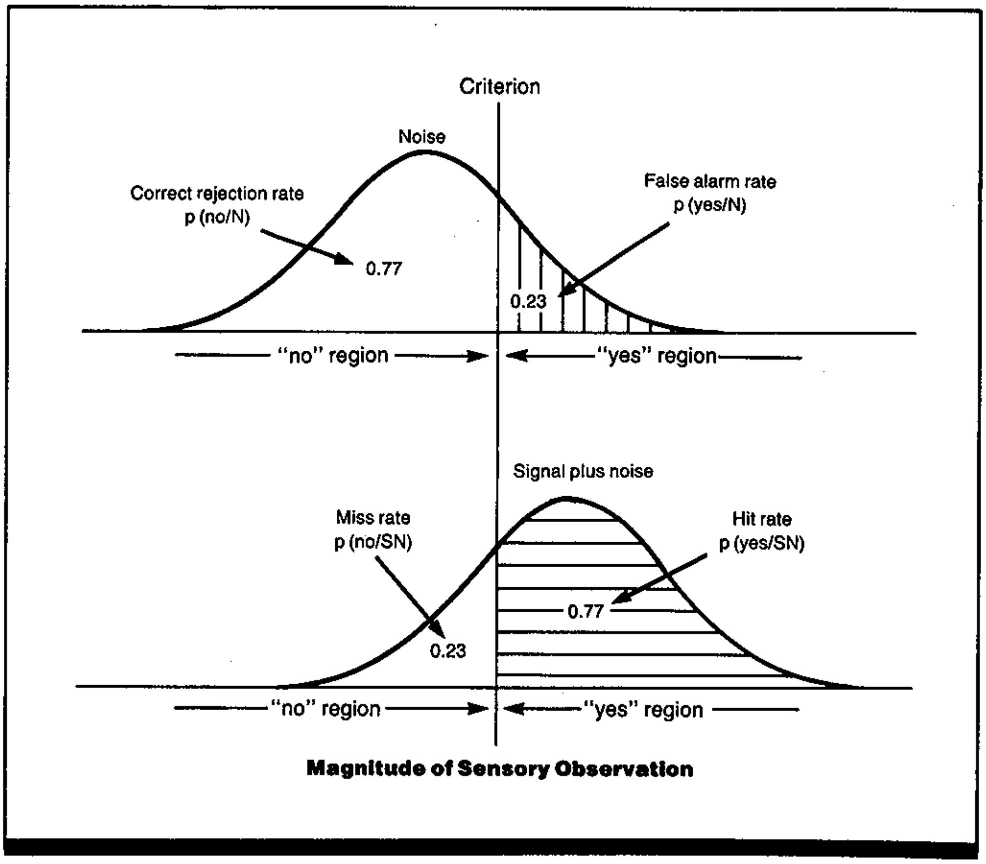

Figure 3. Hypothetical probabilities of the four possible response outcomes (see Table 1) based upon criterion placement. (From Ref. 2)

"miss." If the signal is absent and the observer responds "absent," this is a correct decision and is called a "correct negative," or correct rejection. If the observer responds "present" when the signal is absent, an error again has occurred, which is termed a "false alarm." The likelihood of each of these four outcomes is represented as a region under the *N* and *SN* distributions. The size of each of these regions will change depending upon criterion placement, even when d' is constant (Fig. 3).

Placement of the criterion is influenced by several factors, including the observer's motivation and the a priori signal probability. Observer motivation is affected by the payoffs for various responses. For example, if the cost of a false alarm is likely to be great, criterion placement will be very strict. However, if the cost of a miss is very great, criterion placement will be very lax. A priori stimulus probability will influence observer expectations. High expectancy of signal occurrence will result in a high likelihood of saying a signal was present, which will make the observer's criterion more lax. Low expectancy of signal occurrence will have just the opposite effect.

The Receiver Operating Characteristic

Signal detection data may be plotted as a function relating the hit rate to the false alarm rate. This function is known as a receiver operating characteristic (ROC). The function generally takes the shape of bowed curve above the major diagonal.

ROC-curve data points are obtained by having a single observer adopt several different criteria for signal detection. (This may be done, for example, by varying signal probabilities or costs associated with particular response outcomes.) Figure 4a shows how different points on a single ROC curve relate to criterion placement. The lower left point corresponds to strict criterion placement, in which the hit rate is moderate and the false alarm rate is very low. As the criterion is loosened, the hit rate increases, but at the cost of more false alarms (middle point). Finally, at the most lax criterion (upper point), both hit rate and false alarm rate are very high.

The "bowedness" of the ROC curve is a function of d'. Figure 4a is drawn for a case in which $d' = 1$. The major diagonal corresponds to $d' = 0$, and represents chance performance. In Fig. 4b, the *SN* and *N* distributions exactly overlap; this means that an observer cannot distinguish signal from noise and must resort to random guessing. Consequently, the ROC curve is identical to the major diagonal. Figure 4c shows an ROC curve for $d' = 2$. The *SN* and *N* distributions are further apart than in Fig. 4a, indicating greater signal strength (observer sensitivity). Figure 5 depicts a family of ROC curves for different values of d'.

It should be noted that the position of a data point along the ROC curve represents a single criterion placement, and that a single ROC curve represents a single d' value. Thus the criterion may "slide" anywhere on the ROC curve, and d' will remain constant; the observer's decision criterion may change independently of sensitivity.

Calculation of d' and β

The simplest case for the calculation of d' and β occurs when the *SN* and *N* distributions have equal variance. In that case, subtracting the false alarm rate from 1.0 and converting this proportion to a standard score gives Z_N, the location of the criterion on the abscissa of the *N* distribution. Similarly, subtracting the hit rate from 1.0 and converting this

Table 1. Outcomes of signal detection experiment.

Signal	Observer Response: "Signal Present"	"Signal Absent"
Present	Hit	Miss
Absent	False Alarm	Correct Rejection

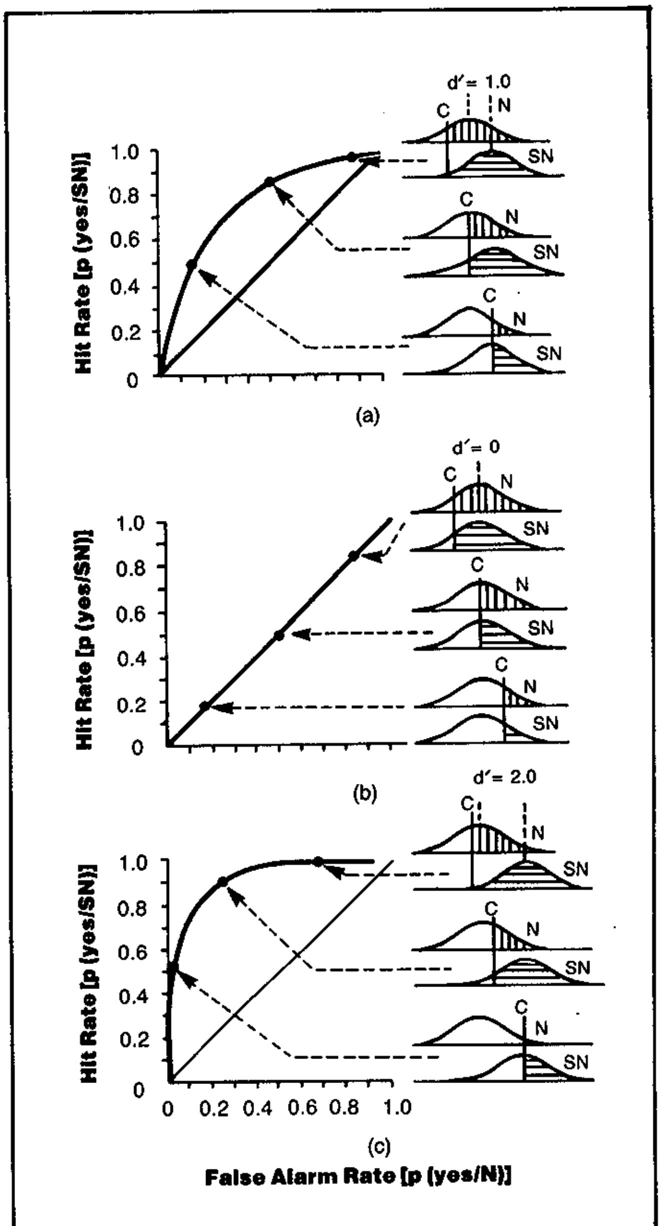

Figure 4. Receiver operating characteristic curves and the corresponding signal-pulse-noise (*SN*) and noise (*N*) distributions for three different criteria when (a) $d' = 1.0$, (b) $d' = 0.0$, and (c) $d' = 2.0$. *C* indicates the decision criterion. (From Ref. 2)

proportion to a standard score gives Z_{SN}, the location of the criterion on the abscissa of the *SN* distribution. Using these two standard scores,

$$d' = Z_N - Z_{SN}$$

which in essence gives the distance between the means of the two distributions. β may be calculated by dividing the ordinate value of the *SN* distribution at criterion by the ordinate of the *N* distribution at criterion.

Whether or not the variances of the *SN* and *N* distributions are equal can be determined by plotting a standard score ROC curve (Fig. 6). This is simply an ROC curve in which the proportions of hits and false alarms are plotted as their corresponding standard scores. Under the assumption that the *SN* and *N* distributions are normal in form, this ROC curve will be a linear function. If the equal-variance assumption holds, the slope of this function will be 1.0, which means the units on the abscissas of the *SN* distribution and the *N* distribution are equal.

In the more general case, sensitivity may be calculated as:

$$\text{Sensitivity} = Z_N - \left(\frac{\sigma_{SN}}{\sigma_N}\right) Z_{SN}$$

where σ_{SN} and σ_N are the standard deviations of the *SN* and *N* distributions, respectively; the coefficient for Z_{SN} makes allowance for differences in the size of Z_N and Z_{SN} units due to unequal variance. When the equal variance assumption is met, the equation reduces to the form given earlier.

Sensitivity Indices from a Single Experimental Session

To use the standard score ROC curve to test the equal-variance assumption and calculate d' requires that hit and false alarm rates based upon several different criteria are available. Usually, this will entail several experimental sessions consisting of hundreds of trials each, where the observer adopts a different criterion in each session. When this is impractical, a measure of sensitivity can be calculated in several other ways.

When the observer has participated in only a single session and employed a single criterion, an ROC curve cannot be plotted. However, false alarm and hit rates are still available. One measure of sensitivity employed under such circumstances is called A' (Ref. 2), and is calculated as follows from the probability (p) of hits and false alarms:

$$A' = 0.5 + \frac{[p(\text{hits}) - p(\text{false alarms})]\,[1 + p(\text{hits}) - p(\text{false alarms})]}{[4p(\text{hits})]\,[1 - p(\text{false alarms})]}.$$

It is possible, however, to obtain an ROC curve from a single session by employing a confidence rating procedure. Instead of simply responding "yes" or "no" to indicate signal presence or absence, the observer applies a number to each yes/no judgment. For example, the observer says "five" if he or she is sure a signal was present, "four" if fairly sure a signal was present, "three" if unsure, "two" if fairly sure a signal was not present, and "one" if sure a signal was not present. It is assumed that the observer adopts a different criterion for response in each category, as depicted in Fig. 7. The proportion of responses associated with each criterion is calculated and plotted as hit and false alarm rates. Calculation of d' then proceeds as described earlier.

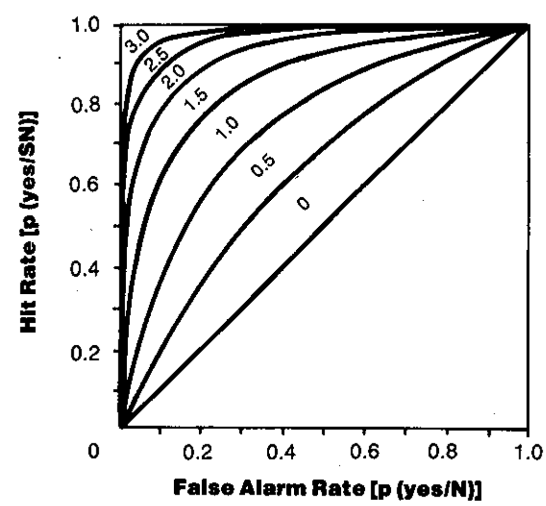

Figure 5. A family of receiver operating characteristic curves corresponding to *d'* values ranging from 0.0-3.0. (From Ref. 2)

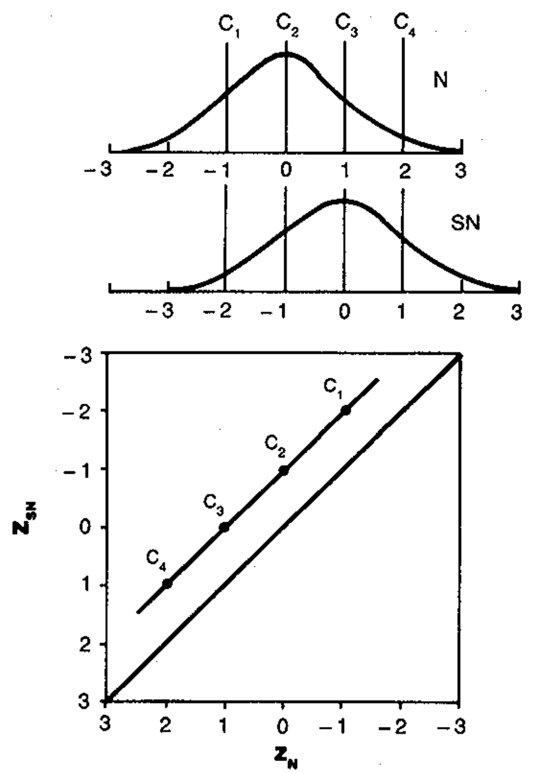

Figure 6. Signal-plus-noise (*SN*) and noise (*N*) distributions expressed in standard scores (*Z*) and the corresponding standard score receiver operating characteristic curve. C_1 – C_4 represent four decision criteria. (From Ref. 2)

Applications

Signal detection theory was developed specifically to describe the role of an observer's decision-making processes in detection situations. However, the theoretical framework of signal detection theory has been applied in a number of different settings:

Detection. Situations in which operators must detect weak stimuli, such as a radar or sonar display monitoring. Performance may be described by an ROC curve where d' indicates signal strength (observer sensitivity).

Attention. Situations in which operators must attend to two different locations or sources of information, when a signal may come from either source or location. In this setting, the allocation of attention among sources can be described by an attention operating characteristic (AOC curve). Here, d' indicates the success of sharing attention among different sources (CRef. 9.104).

Multiple task performance. Situations in which operators must engage in more than one task at a time. The allocation of resources among different tasks, reflected in operator performance, can be described by a performance operating characteristic (POC curve). In this case, d' indicates the success of sharing resources among different tasks (CRefs. 7.702, 7.723).

Recognition memory. Situations in which operators must recognize stimuli as having been seen before or not. Performance may be described by a memory operating characteristic (MOC curve), in which d' indicates strength of memory representation (Ref. 9).

Constraints

- The assumptions of both normal distributions and equal variance for the calculation of d' are crucial because d' can then be related linearly to the physical units in which the parameters of signal and noise are measured. (Ref. 4)

Empirical Validation

The independence of d' and β has been experimentally demonstrated. Variables that cause a shift in an observer's criterion do not contaminate d' (Ref. 7). Compared to classic psychophysical threshold values, values of d' remain relatively unchanged by different experimental procedures (Refs. 6, 8).

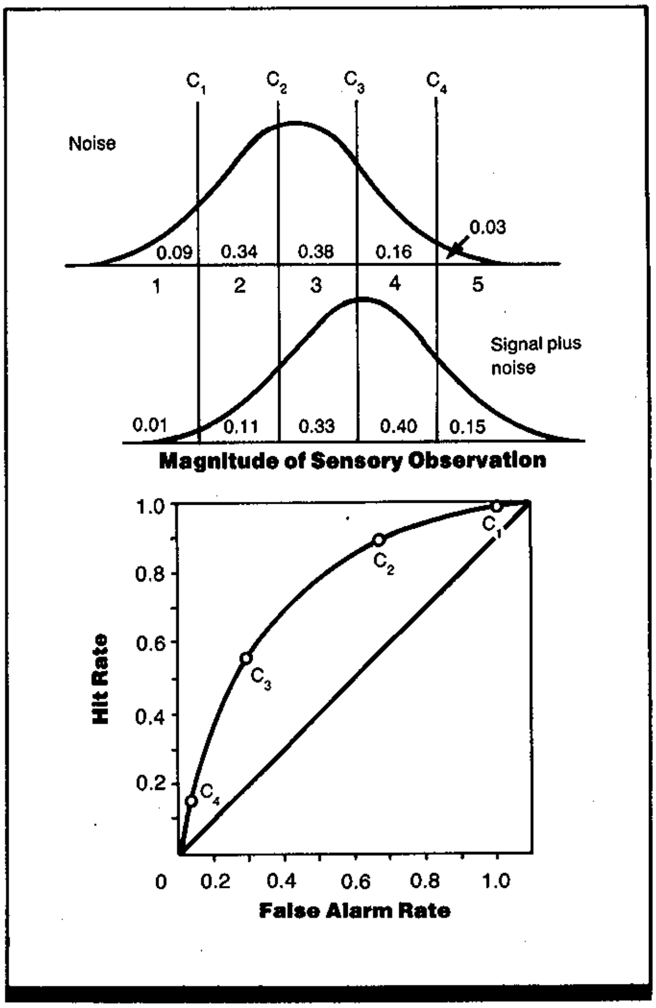

Figure 7. Signal-plus-noise (*SN*) and noise (*N*) distributions and receiver-operating characteristic curve for a hypothetical observer in a confidence rating experiment. $C_1 - C_4$ indicate the decision criteria. (From Ref. 2)

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Cross References

7.702 Sensitivity requirements and choice of a workload assessment technique;

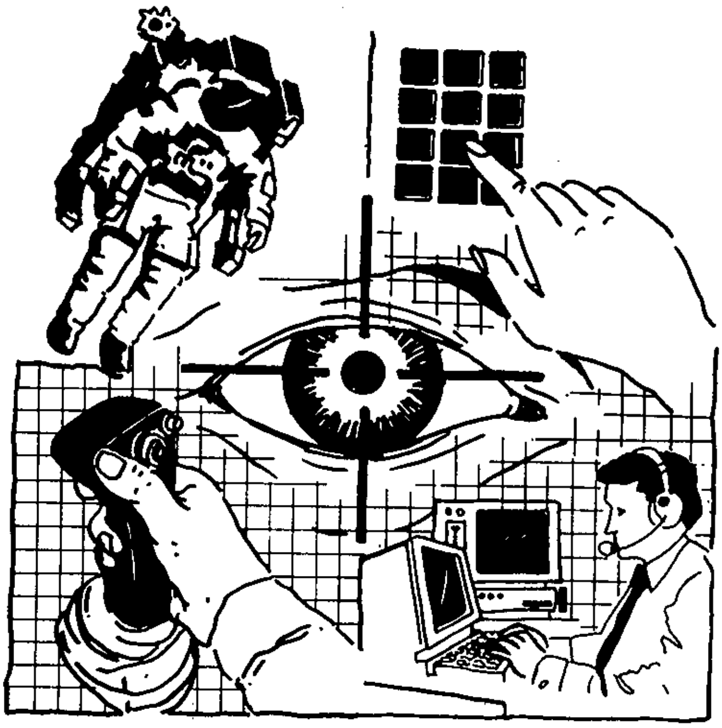
7.723 Use of embedded secondary tasks in workload assessment;

9.104 Attentional limitations in reaction time tasks

Notes

Notes

Section 7.5 Visual Search



7.501 Factors Affecting Visual Search with Monochrome Displays

Table 1. Display variables and effects on visual search.

Display Variables	Effects on Visual Search	Source
Target and background object size	Search times decrease when size differences between targets and background objects are introduced	Ref. 1
	Search times are inversely proportional to differences between the logs of target and non-target diameters	Ref. 1
	Relative size of targets against background is a moderately salient dimension in directing eye movements	Ref. 11
Non-target density	Search times increase with increases in non-target density (and number) when search area is constant	Refs. 4, 7, 8
Irrelevant stimuli	Search times increase when amounts of irrelevant information in a display increase	Ref. 5
	Search times increase when degrees of similarity between relevant and irrelevant items increase	Ref. 9
Display size	Large search field must be searched even if the target is distinct and the background is homogeneous	Ref. 6
	There is a tendency to search the center of a display more often than the edges	Ref. 3
	Lack of systematic search by observers persists despite training	Ref. 10
Multiple targets	After considerable practice, observers are able to scan as rapidly for multiple targets as for single targets	Ref. 9
	Observers cannot search as rapidly *and* accurately for multiple targets as for single targets; there is a tradeoff between speed and accuracy	Ref. 12
Number of background characters	Search time is approximately proportional to the number of items presented in a display	Ref. 2
	Increasing number of background characters (and search area, with density constant) produces increases in search time	Ref. 2
	When combinations of area and density are chosen to give specific numbers of background characters, the major effect on search time comes from number of background characters rather than display area or density	Ref. 2
Observer psychological variables	Visual search performance depends on briefing, cueing, training, experience, stress, workload, motivation, and vigilance	

Key Terms

Attention; display complexity; display density; distractors; monochrome displays; multiple targets; size; stress; target acquisition; vigilance; visual displays; visual search time; workload

General Description

When a target is clearly distinguishable from its immediate background and the display subtends no more than a few degrees of visual angle, visual search is not required to locate the target. When a target is not clearly distinguishable from its immediate background, target acquisition depends on search factors. Targets can be distinguished from background elements along several dimensions, including display density, target size, and number and type of background elements. The table lists factors known to affect visual search and summarizes the nature of their effects.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

The information in the table enables the user to identify relationships among a number of display factors and search times useful for development of display formats that optimize acquisition performance.

Constraints

- Results cited in the table were usually obtained without variations in target/background contrast. Contrast can influence the relationships reported.
- Display luminance and surrounding illuminance were not varied in experiments cited in the table, but can influence the relationships reported.
- Displays used were monochrome. Data may not be directly applicable to color presentations.
- The studies cited were not conducted in high-stress environments. High stress levels could influence performance.
- No standard metrics exist for quantifying scene complexity.

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Cross References

1.960 Factors affecting coordination of head rotation and eye movements;

7.503 Effect of head and eye movement on target acquisition;

7.514 Effect of irrelevant stimuli on search performance;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.519 Search time: effect of color coding;

7.524 Visual search for multiple targets;

7.608 Multiple regression model of target acquisition

7.502 Visual Search Rates with Eye Movements

(a)	(b)	(c)	(d)
EHYP	ZVMLBQ	ODUGQR	IVMXEW
SWIQ	HSQJMF	QCDUGO	EWVMIX
UFCJ	ZTJVQR	CQOGRD	EXWMVI
WBYH	RDQTFM	QUGCDR	IXEMWV
OGTX	TQVRSX	URDGQO	VXWEMI
GWVX	MSVRQX	GRUQDO	MXVEWI
TWLN	ZHQBTL	DUZGRO	XVWMEI
XJBU	ZJTQXL	UCGROD	MWXVIE
UDXI	LHQVXM	DQRCGU	VIMEXW
HSFP	FVQHMS	QDOCGU	EXVWIM
XSCQ	MTSDQL	CGUROQ	VWMIEX
SDJU	TZDFQB	OCDURQ	VMWIEX
PODC	QLHBMZ	UOCGQD	XVWMEI
ZVBP	QMXBJD	RGQCOU	WXVEMI
PEVZ	RVZHSQ	GRUDQO	XMEWIV
SLRA	STFMQZ	GODUCQ	MXIVEW
JCEN	RVXSQM	QCURDO	VEWMIX
ZLRD	MQBJFT	DUCOQG	EMVXWI
XBOD	MVZXLQ	CGRDQU	IVWMEX
PHMU	RTBXQH	UDRCOQ	IEVMWX
ZHFK	BLQSZX	GQCORU	WVZMXE
PNJW	QSVFDJ	GOQUCD	XEMIWV
CQXT	FLDVZT	GDQUOC	WXIMEV
GHNR	BQHMDX	URDCGO	EMWIVX
IXYD	BMFDQH	GODRQC	IVEMXW
QSVB	QHLJZT		
GUCH	TQSHRL		
OWBN	BMQHZJ		
BVQN	RTBJZQ		
FOAS	FQDLXH		
ITZN	XJHSVQ		
VYLD	MZRJDQ		
LRYZ	XVQRMB		
IJXE	QMXLSD		
RBOE	DSZHQR		
DVUS	FJQSMV		
BIAJ	RSBMDQ		
ESGF	LBMQFX		
QGZI	FDMVQJ		
ZWNE	HQZTXB		
QBVC	VBQSRF		
VARP	QHSVDZ		
LRPA	HVQBFL		
SGHL	HSRQZV		
MVRJ	DQVXFB		
GADB	RXJQSM		
PCME	MQZFVD		
ZODW	ZJLRTQ		
HDBR	SHMVTQ		
BVDZ	QXFBRJ		

Figure 1. Examples of the visual displays used in the visual search experiments. (a) Target letter is K; (b) target is a line *not* containing Q; (c) and (d) target letter is Z. (From Ref. 4)

Key Terms

Eye movements; memory search; multiple targets; target acquisition; target detection; target discrimination; target location; uncertainty; visual search

General Description

The time to scan an alphanumeric matrix for a specified target property is a linearly increasing function of the position of the target property in the display (i.e., the line, or row, number for the target property). The slope of the function (e.g., the slope of the line in Fig. 2) is an estimate of the visual search rate, and is unaffected by whether the critical line contains one or two targets. The rate of search depends upon whether observers are searching for the presence or the absence of a target and upon the similarity between the target and the letter context in which it is embedded.

Applications

Situations in which operators must scan information displays for the presence or absence of particular targets.

Methods

Test Conditions

• Fourteen lists of 50 single-spaced lines of letters; one set of displayed letters was comprised of J, P, Q, S, T, V, X, and Z (other display sets were used in related experiments); for each list, all lines contained either two or six letters
• Seven target properties were presence of Q, presence of Z, presence of Q or Z or both, absence of Q, absence of Z, presence of Q or absence of Z or both, or absence of Q or presence of Z of both
• Each list had one line with one target property; line number for target property ranged from 9-41
• Alternate rows were flanked by dots; observers turned response switch clockwise if critical item had dots and counterclockwise if no dots, to prevent premature responding

Experimental Procedure

• Repeated-measures design
• Independent variables: position of target property in list (critical line number), target property, row width (two or six letters)
• Dependent variable: scanning rate, defined as the slope of the function relating search time to position of critical line
• Observer's task: search display by scanning from top down for target property and stop clock when found
• 3 college students with some practice

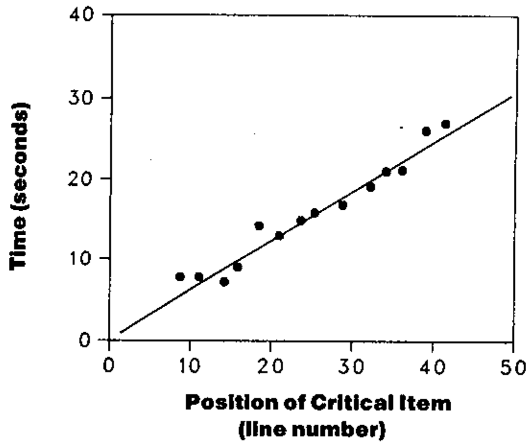

Figure 2. Sample data showing search time as a linearly increasing function of position of critical row (line) in display. (From Ref. 4)

Experimental Results

• Search time to locate the target property is a linearly increasing function of position of the critical line in the target display.
• The visual search rate, which is represented by the slope of the search time function (calculated by the method of least squares), depends on the type of search; for example, searching for the absence of a target property takes longer than searching for its presence (i.e., the slope is greater), implying more thorough processing to identify each item scanned.
• The slope is unaffected by whether the critical line contains one or two target properties.
• The slope is unaffected by time to begin scanning or to respond; these times are reflected in the *y*-intercept (CRef. 4.103).
• Related experiments have shown that it takes longer to search for a target in the context of targets with similar features (e.g., rounded letters in the context of other rounded letters, CRef. 6.321) than in the context of targets with dissimilar features (e.g., rounded letters in the context of letters with only straight lines).

Variability

All data points that significantly differed ($p < 0.05$ by *t*-test) from the linear function were dropped prior to calculations of slopes, intercepts, and standard errors. No information was given about the number of points dropped.

Repeatability/Comparison with Other Studies

The methodology employed here to describe search processes can be compared to work on memory search rates (CRef. 4.103).

Subsequent work has shown that, provided error rates are kept low, the search rate is 3-10 items per sec (Refs. 1, 2, 4, 6). However, a study measuring visual search rate uncontaminated with eye movements yielded search rates of ~10 msec per character (Ref. 7). In that study, subjects visually searched arrays of 2-25 letters for a single numeral in one of the arrays; to prevent eye movements, the arrays were briefly presented sequentially in the same position on a CRT screen. However, the search rates reported in Ref. 7 may not hold for other stimuli; the target could be found by discriminating between two overlearned categories.

Constraints

• The search rates obtained here are not pure measures of visual comparison times because they contain eye movement times and thus are limited by saccade rates and eye-movement strategies (CRef. 7.508).

Key References

1. Gordon, I. E. (1968). Interactions between items in visual search. *Journal of Experimental Psychology, 76*, 348-355.

2. Kaplan, I. T., & Carvellas, T. (1965). Searching for multiple targets. *Perceptual and Motor Skills, 21*, 239-243.

*3. Neisser, U. (1963). Decision-time without reaction time: Experiments in visual scanning. *American Journal of Psychology, 76*, 376-385.

4. Neisser, U. (1964). Visual search. *Scientific American, 210*, 94-102.

5. Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.

6. Neisser, U., & Beller, H. K. (1965). Searching through word lists. *British Journal of Psychology, 56*, 349-358.

7. Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. (1971). Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science, 174*, 307-311.

Cross References

1.627 Target detection: effect of spatial uncertainty;

4.103 Memory search rates;

6.321 Theories of pattern recognition;

7.501 Factors affecting visual search with monochrome displays;

7.508 Visual search rates without eye movements;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.512 Search time: effect of number of targets and target complexity;

7.514 Effect of irrelevant stimuli on search performance;

7.515 Processing of nontarget items in visual search

7.503 Effect of Head and Eye Movement on Target Acquisition

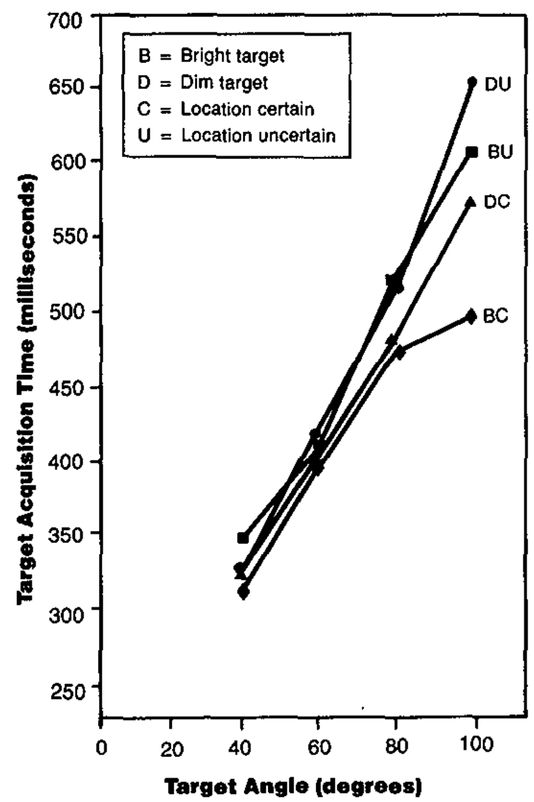

Figure 1. Mean target acquisition times as a function of target angle and the luminance and certainty conditions of Experiment 2. (From Ref. 4)

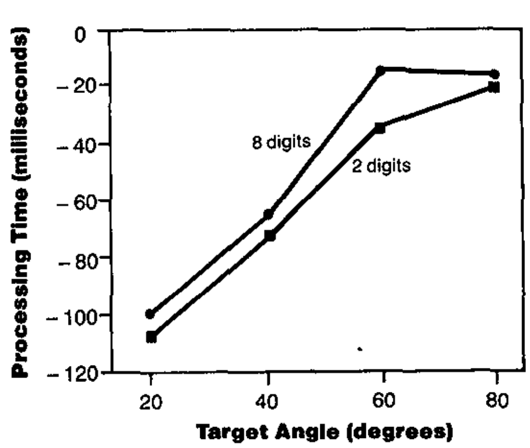

Figure 2. Processing time (acquisition time minus standard choice reaction time) as a function of target angle and target complexity. (From Ref. 4)

Key Terms

Alcohol-induced stress; head-eye coordination; head movement; saccadic latency; target acquisition; target angle; target detection; visual search; visual search time

General Description

Eye and head dynamics (reaction time of eye and head, number of eye movements, and maximum head velocity) were measured during visual search as a function of target angle, luminance, information content, location, and alcohol-induced stress (Ref. 4). The results demonstrate that it is possible to estimate time lost for locating peripheral targets as a function of eye and head reaction. As target angle increases, both target acquisition time and processing time increase (Figs. 1, 2). Target processing time also increases with target complexity (Fig. 2).

Applications

Performance assessment or design of electronically generated displays where the time lost in locating peripheral target as a function of eye and head movements must be kept to a minimum (e.g., in the cockpit).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Observer seated with eyes fixated
- Six single-digit, single-plane, rear-projection display screens mounted at eye level and to the right of observer at 20 deg intervals on an 80-cm horizontal radial arc
- White targets on black background were 2.3 cm-high and 1.5 cm-wide digits subtending visual angles of 1.6 and 1.1 deg respectively
- Movement of eye with respect to the head measured by an infrared corneal reflection instrument
- Eye-measurement data processed on an analog-digital converter and then transformed digitally to linear form
- Head movements measured by rotary meter attached to the top of a helmet worn by observer and suspended by a parallelogram double arm
- Ambient room light provided by one 100-W indirect light

Experimental Procedure

- Independent variables: target complexity (four or eight random and equally probable decimal digits), stress condition (sober or blood alcohol level of 0.075% in Exp. 1), observer certain of target location (Exp. 1), uncertain of target location (40, 60, 80 or 100 deg off- axis, Exp. 2), target luminance (dim or bright; luminance values not reported)
- Dependent variables: eye reaction time, head reaction time, head movement occurrence, number of eye movements prior to target acquisition, maximum head velocity, target acquisition time (TAT), angle of eye at TAT, angle of head at TAT, total experimental trial time, fixation at TAT, and processing time
- Observer's task: identify digit on display screen and push matching response button
- 5 observers (Exp. 1); 3 observers (Exp. 2)

Experimental Results

- Mean reaction time of the eye increases with targets of either higher luminance ($p < 0.01$) or greater location uncertainty ($p < 0.05$).
- Mean reaction time of the head increases with target uncertainty ($p < 0.05$).
- Number of eye movements increases both with increasing target angle ($p < 0.001$) and lower target luminance ($p < 0.05$).
- Head movement increases with increasing target angle ($p < 0.001$).
- Target acquisition time increases as both target angle ($p < 0.001$) (Fig. 1) and target uncertainty ($p < 0.05$) increase.
- Processing time (time from end of acquisition to response) increases with target complexity ($p < 0.001$) and increases linearly with increasing target angle ($p < 0.001$) (Fig. 2).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Eye and head movement data are consistent with previous findings (Refs. 1, 2, 5). Later data (Ref. 3) also support these findings.

Constraints

- Applications of linear functions to realistic visual search tasks should be empirically verified.

Key References

1. Bizzi, E. (1974). The coordination of head movements. *Scientific American, 23*, 100-106.

2. Miller, L. (1969). Eye movement latency as a function of age, stimulus uncertainty, and position in the visual field. *Perceptual and Motor Skills, 28*, 631-636.

3. Robinson, G. (1979). Dynamics of the eye and head during movement between displays: A qualitative and quantitative guide for designers. *Human Factors, 21*, 343-352.

*4. Robinson, G., Koth, B., & Ringenbach, J. (1976). Dynamics of the eye and head during an element of visual search. *Ergonomics, 19*, 691-709.

5. Vossius, G. (1972). The control of eye movement. *Proceedings: International Conference on Cybernetics and Society* (pp. 27-31). New York: IEEE Systems, Man, and Cybernetics Society.

Cross References

1.932 Factors influencing the latency of saccades;

1.960 Factors affecting coordination of head rotation and eye movements;

7.501 Factors affecting visual search with monochrome displays;

7.502 Visual search rates with eye movements;

7.506 Search time: effects of target conspicuity and fixation eye movements;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.608 Multiple regression model of target acquisition;

7.614 Factors affecting target acquisition on television

7.504 Role of Saccadic Eye Movements in Search

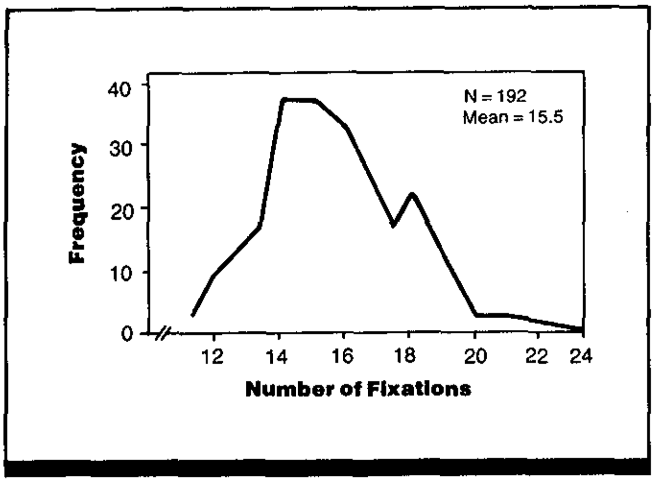

Figure 1. Frequency distribution showing number of fixations in a 5-sec free search. (From Ref. 1)

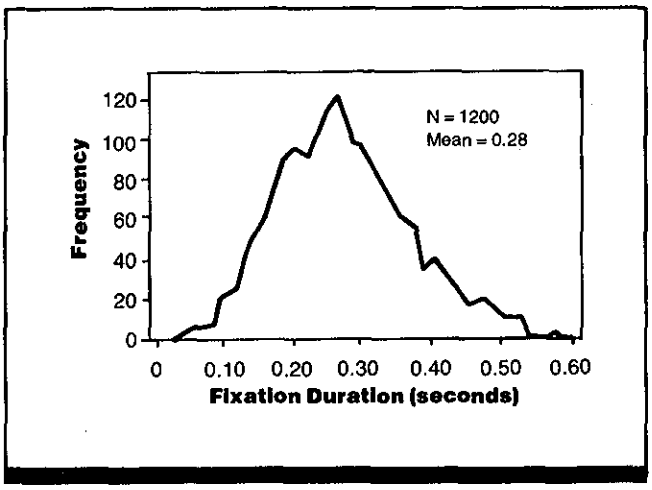

Figure 2. Frequency distribution of fixation length from a sample of 100 fixations at the start of the study and 100 fixations at the end of the study for each of 6 observers. (From Ref. 1)

Key Terms

Pursuit eye movements; saccadic eye movements; tracking; tracking eye movements; visual fixation; visual search; visual tracking

General Description

Many normal viewing conditions elicit combinations of smooth eye movement and saccades (for visual tracking across a plane of vision) and disjunctive movement (to track an object in depth). When an observer is searching for a target in an otherwise blank visual field, the eye movements follow fairly consistent patterns, initially showing many large saccadic movements and a few short saccadic jumps. Practiced observers tend (1) to develop a circular path around the perimeter of the visual field and (2) to use peripheral vision to supplement the area of direct fixation.

Applications

The path of visual scan may be important in tasks which call for an observer to spot the sudden appearance of a target during free search.

Methods

Test Conditions

- 30-deg visual angle circular field; tungsten illumination at 8.575 cd/m^2 (2.5 fL); observer's gaze steadied via bite board
- White circular target of 2.54-cm diameter, luminance either at brightness threshold or slightly above threshold, appeared at random positions in visual field
- 120 trials of 5 sec each, with rest period after every 15 trials; measurement made only on trials with blank field (i.e., when no target appeared, 18 out of 30 trials; total time per observer ~2 hr
- Electro-oculography (EOG) used to measure corneo-retinal potential associated with eye movements, with continuous output monitoring horizontal and vertical eye movements across time; oscillographic records

Experimental Procedure

- Dependent variables: fixation rate, fixation duration, movement amplitude, spatial distribution of fixations
- Observer's task: scan visual field until target located or until 5 sec elapsed
- 6 observers with normal vision

Experimental Results

- Observers average three fixations per sec, or ~15 fixations in the 5-sec scanning time (Fig. 1).
- The average duration of fixation is 0.28 sec, with the distribution of fixations showing slight positive skew (Fig. 2).
- The average saccadic eye movement spans 7-10 deg for individual observers, with modes from 3-9 deg (i.e., a positive skew) (Fig. 3).
- Observers tend to pattern fixations in a circular fashion around the perimeter of the visual field, with few fixations at the exact center of the field (Fig. 4).

Variability

Number of fixations ranged from 11-22 and amplitude of movement ranged from 7-10 deg of visual angle per 5-sec trial.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Intra-observer reliability across sessions is not established.
- Present analysis relates only to fixation points, not movement pathways.
- Duration of fixation time will depend on characteristics of target or target field.

Key References

*1. Ford, A., White, C. T., & Lichtenstein, M. (1959). Analysis of eye movements during free search. *Journal of the Optical Society of America, 49,* 287-292.

Cross References

1.915 Effects of target characteristics on eye movements and fixation;

1.932 Factors influencing the latency of saccades;

1.934 Elicitation of saccades: effects of target size and proximity to fovea;

1.935 Patterns and errors in saccadic eye movements: effects of visual task;

1.936 Timing and accuracy of saccades to briefly lit targets;

7.502 Visual search rates with eye movements;

7.505 Eye movements during visual search and pattern perception

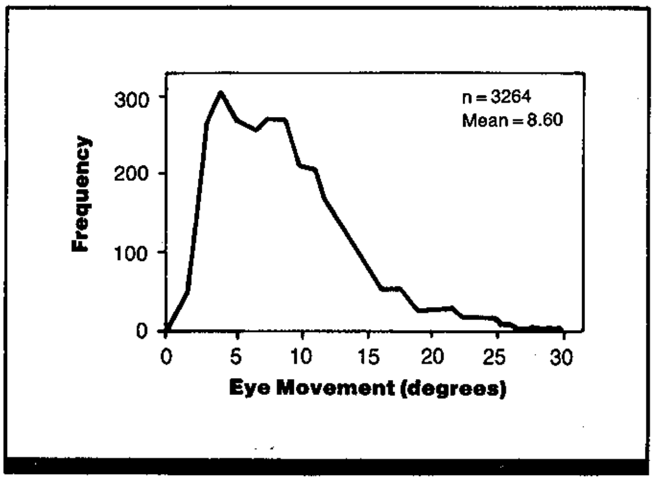

Figure 3. Frequency distribution of amplitude of saccadic movements in degrees of visual angle, based on ~500 observations from each of 6 observers. (From Ref. 1)

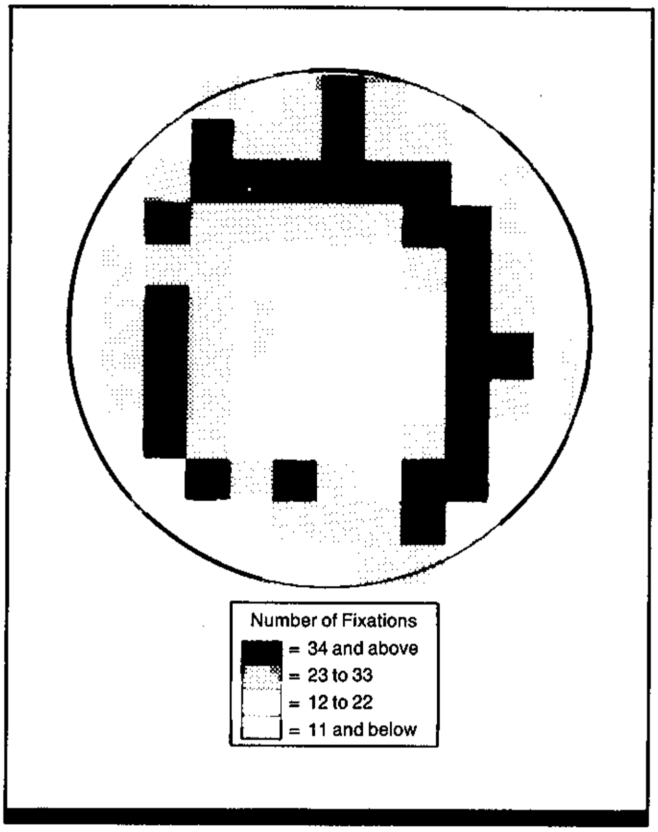

Figure 4. Relative number of fixations within 2.5-deg areas in scanning. Darker blocks reflect greater number of fixations at that locus. (From Ref. 1)

7.505 Eye Movements During Visual Search and Pattern Perception

Key Terms

Micro-saccades; saccadic eye movements; scanpath; target acquisition; training; visual displays; visual fixation

General Description

When we view a picture containing several elements, we fixate longer on some elements than on others. The table describes factors influencing visual search behavior, including scanning patterns, fixations, and types of eye movements.

Applications

Understanding visual search behavior leading to target detection and/or pattern recognition is critical in the design of visual displays and in selection and training of display operators. Existing technology allows us to monitor and record eye movements, analyze scanpaths, superimpose them on displays, and artificially simulate scanpaths using probability matrices.

Constraints

• These data must be tailored carefully to specific display situations, as they were obtained experimentally under a wide variety of conditions.

Key References

1. Baker, C. (1962). *Man and radar displays.* New York: Pergamon Press.

2. Fisher, D., Monty, R., & Senders, J. (1981). *Eye movements: Cognition and visual perception.* Hillsdale, NJ: Erlbaum.

3. Norton, D., & Stark, L. (1971). Scanpaths in eye movements during pattern recognition. *Science, 171,* 308-311.

4. White, C., & Ford, A. (1960). Eye movement during simulated radar search. *Journal of the Optical Society of America, 50,* 909-913.

Cross References

1.915 Effects of target characteristics of eye movements and fixation;

1.932 Factors influencing the latency of saccades;

1.934 Elicitation of saccades: effects of target size and proximity to fovea;

1.935 Patterns and errors in saccadic eye movements: effects of visual task;

1.936 Timing and accuracy of saccades to briefly lit targets;

7.502 Visual search rates with eye movements;

7.603 Sighting range for targets detected against horizon;

7.613 Effect of alerted and unalerted search on target acquisition

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Factor	Effects on Eye Movements and Visual Search	Source
Scanning pattern	Pattern changes after target recognition	Ref. 2
	Influenced by observer's cognitive model (mental map)	Ref. 2
	Same observer uses different scanpaths for different displays	Refs. 2, 3
	Initial scanpath for repeated search of same picture is same as previously learned scanpath	Ref. 2
	During learning, 25% of total viewing time, eye movements are on established scanpath	Ref. 2
	Different when searching radar screen compared to free search	Ref. 4
	Successive fixations follow a circular path when tracking an oscilloscope sweep line	Ref. 1
	Linear movements used for scanning radar scope	Ref. 1
Fixation frequency	When viewing human face, during learning phase 10.1 fixations with average duration 4.2 sec; during recognition phase, 7.3 fixations with average duration 2.5 sec	Ref. 2
	For 15 deg of visual angle and 30 deg radar display, average fixation time 0.37 sec	Ref. 4
	Duration on radar displays is 430 msec for orienting; 475 msec when navigating; 830 msec for target identification; 1,270 - 1,815 msec during bombing	Ref. 1
Eye movement duration	30-35 msec for radar display during orientation, navigation, and target identification	Ref. 1
	20 msec for radar display during bombing	Ref. 4
Eye movement frequency	Decreases when target recognition occurs	Ref. 2
Fixation regions	Influenced by observer's cognitive state	Ref. 2
	Fixations are not equally distributed across points of interest	Ref. 2
	Based on informational relevant subfeatures	Ref. 2
Stability of gaze	Normal is within 0.5 deg diameter of fixational fovea	Ref. 2
	Synchronization of the two eyes and fixation stability decline as excursion and movement frequency increase	Ref. 1
Saccadic eye movement	Reposition fovea during active search	Ref. 2
	Micro-saccades during fixation range from 2-30 min	Ref. 2
	Idiosyncratic and repetitive sequentially	Ref. 2
	Occur during fixations when searching radar display using radar scanline	Refs. 1, 4
	7,000 saccades made in a 2-hr radar watch	Ref. 1
Micro-drift movements	Conjugate drifts related to smooth pursuit occur with velocities <0.25 deg/sec	Ref. 2
	Micro-tremors occur with amplitudes of 10 sec arc and velocities <1.0 deg/sec	Ref. 2
Size of display	Fixations distributed around midradius for 15-deg and 30-deg radar displays	Ref. 4
	Number of fixations per unit area and percent targets detected are correlated highly	Ref. 4
	Optimum size circular aerial map for search subtends 9 deg at the eye; small maps produce excessive fixations outside display; larger map displays decrease performance because of non-uniform fixation patterns	Ref. 1
Display complexity	Regions of high information density attract more fixations	Ref. 2

7.506 Search Time: Effects of Target Conspicuity and Fixation Eye Movements

Key Terms

Area of search; attention; conspicuity; eye movements; selective attention; target acquisition; target location; visual fixation; visual search; visual search time

General Description

The size of a conspicuity area is defined as the field of vision or eccentricity (from the point of eye's fixation) at which targets are noticed 50% of the time. The size of the area increases nearly linearly with the absolute difference between target disk size and size of background disk (non-target disk in visual field). Often, even when an observer is asked to fixate a point away from the target object, small involuntary eye movements occur in the direction of the target. If an observer is asked to search for a target, the probability of finding it quickly increases with target conspicuity.

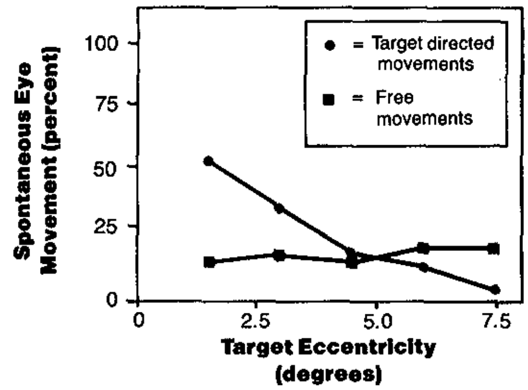

Figure 1. Percentage of spontaneous eye movements to 0.69-deg target as a function of eccentricity. (From Ref. 3)

Methods

Test Conditions

- Observer seated 57 cm from TV monitor on which stimuli appeared; screen 22.3 x 16.8 deg of visual angle; head held stable by forehead rest, bite board, and dental cast
- Target disk appeared in 1 of 50 randomly determined positions in each test field in a background of 220 other disks; diameter of background disks was 0.55 deg; diameter of test disk was 0.34, 0.45, 0.63, or 0.69 deg
- Luminance of disks was 11.5 cd/m^2, of background 0.45 cd/m^2, and of rest field (between stimulus fields) 0.34 cd/m^2
- 1-sec presentation of stimulus field on TV monitor for determining conspicuity, with a 1-sec presentation of rest field between stimulus presentations (fixation cross present in rest field); for search task, 4-sec presentation of stimulus field
- For search task, one large and one small target appeared on screen together; one was designated the target, the other the non-target
- 5 dummy stimulus patterns preceded each stimulus series
- Eye movements monitored by cornea-reflection technique; although display was viewed binocularly, only left-eye movements recorded
- Each stimulus series presented four times

Experimental Procedure

- Independent variables: size of target disk, location of target disk
- Dependent variables: proportion of targets seen as a function of target eccentricity; size of conspicuity area, defined as the eccentricity at which 50% of targets seen; size, direction, and delay of eye movements
- Observer's task: for conspicuity determination, fixate central cross, push button if target perceived; for search task, move eye if desired, push button if target perceived
- 2 experienced subjects

Experimental Results

- Size of conspicuity area increases linearly with absolute difference in diameter between target and background disks (6.8-2.4 deg for one observer, 6.5-2.0 deg for other observer).
- Proportion of targets seen decreases with increasing eccentricity, but is greater at all eccentricities for test targets whose absolute size differs greatly from background disks.
- There are small eye movements in the direction of the target. The more eccentric the target, and the more similar in size to the background disks, the greater is the delay and the less likely the eye movement (delay range ~250-550 msec).
- 30-40% of target discoveries are preceded by these spontaneous eye movements of ~0.7 deg.
- In search task, involuntary eye movements, similar in size to those in conspicuity task, are toward conspicuous items.
- Search time was approximately inversely proportional to difference in diameter between background and target disks.

Variability

All experiments were performed on a third, inexperienced observer, with very similar results.

Repeatability/Comparison with Other Studies

In another study (Ref. 2) with a larger range of diameter differences between target and background disks, the size of the conspicuity area was fitted to a logarithmic function of the "contrast" of diameter ($\log |(D - D_O)/D_O|$), where D_O is the diameter of the background disk.

Constraints

The expected increase in delay time of eye movements with increasingly eccentric targets is diminished if the target appears by itself; for example, a 30-deg difference in eccentricity might result in only 50-msec increase under these circumstances.

Key References

1. Engel, F. L. (1971). Visual conspicuity, directed attention and retinal locus. *Vision Research, 11*, 563-576.

2. Engel, F. L. (1974). Visual conspicuity and selected background interference in eccentric vision. *Vision Research, 14*, 459-471.

*3. Engel, F. L. (1977). Visual conspicuity, visual search and fixation tendencies of the eye. *Vision Research, 17*, 95-108.

Cross References

1.915 Effect of target characteristics on eye movements and fixation;

1.932 Factors influencing the latency of saccades;

1.934 Elicitation of saccades: effects of target size and proximity to fovea;

1.937 Voluntary control of saccadic eye movements;

1.948 Involuntary anticipatory eye movements;

7.525 Target acquisition in real-world scenes;

7.526 Detection of objects and events in real-world scenes;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectabiltiy;

11.403 Target coding: effect on search time

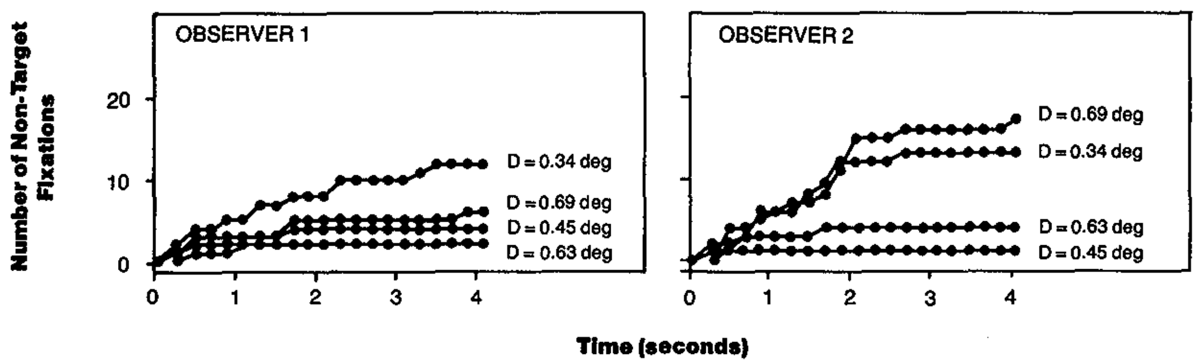

Figure 2. Cumulative polygons of the number of spontaneous non-target fixations during search for the target as a function of their moment of occurrence for 2 observers. *D* is diameter of test disks in degrees. (From Ref. 3)

7.507 Search Time and Detection Rate: Effect of Accommodative Aids

Key Terms

Accommodation; empty field myopia; reticle; target detection; visual aids; visual search time

General Description

An aid to accommodation (eye focus), such as a small central grid, a large grid, or a dot pattern located as background at the same distance as the target (optical infinity), increases detection of targets in an otherwise empty visual field.

Applications

Environments such as high-altitude flight where absence of pattern detail may lead to **accommodation** errors that can reduce visual performance.

Methods

Test Conditions

- Bright uniform field 32 x 24 deg of visual angle, luminance 352 cd/m^2, presented using collimating lens to produce effective viewing distance of optical infinity; target of two small dots subtending 9 min each; target presented in 1 of 64 positions defined by an 8 x 8 matrix 19.5 deg square
- Four background conditions: small central grid, large grid, dot pattern, no accommodative aid
- Luminance level of targets adjusted to ensure middle range of detection probabilities; luminance ranges were high (59.2, 42.5, or 25.3 cd/m^2), intermediate (34.6, 24, or 13 cd/m^2), or low (20.2, 13.4, or 4.5 cd/m^2)
- All targets within boundaries of largest background grid; no target >3.5 deg from nearest dot in outer ring of dot background when presented in corner portions of matrix; monocular viewing
- Target present until response made or until 10 sec elapsed

Experimental Procedure

- Method of constant stimuli
- Independent variables: type of background, target intensity level
- Dependent variables: number of targets correctly detected, response time
- Observer's task: press button as soon as target detected; feedback provided for errors
- 3 observers

Experimental Results

- Accommodative aids increase target detection by 80-100% (p <0.001).
- All three accommodative aids improve target detection and yield similar performance levels.
- Variability in search times is high; analysis of variance does not show a significant effect of background condition on response time. However, a post-hoc statistical test indicates that search time is significantly faster with a dot pattern in the background than with an empty field.

Variability

Two-way analysis of variance was performed to evaluate the effect of the independent variables and interactions. Posthoc test was Duncan Multiple Range Test. Standard error of the mean was ~5%.

Repeatability/Comparison with Other Studies

Results support finding in Ref. 2 that the lack of cues for correct accommodation impedes target detection at optical infinity in an empty field.

Table 1. Mean performance as a function of background type. (From Ref. 1)

Measure	Empty Field	Small Grid	Large Grid	Dots	Standard Error
Percent correct	30.1	57.6	54.2	60.8	4.80
Search time (sec)	4.62	3.58	4.24	3.83	0.55

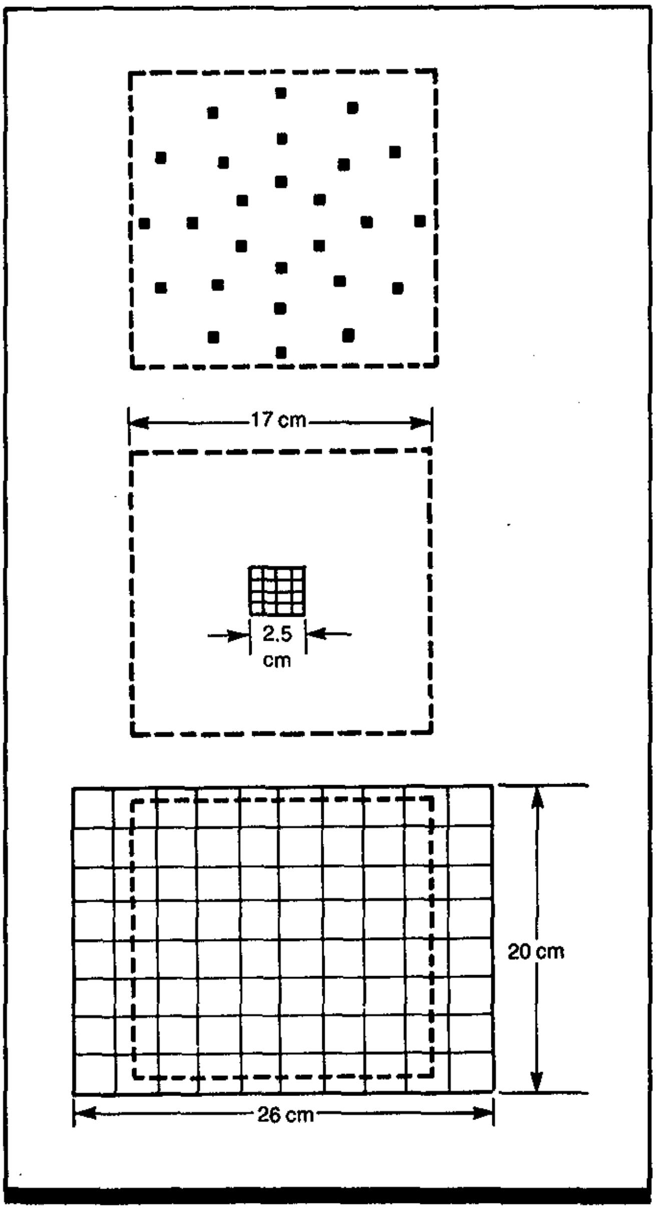

Figure 1. Configurations of three aids to accommodation; broken line defines target area. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Accommodative state of the eye was inferred from a general performance measure.
- Illusory breakup or darkening of the field in the empty field condition (ganzfeld-like disturbance) was reported by observers (CRef. 1.239).
- Accommodation is affected by the age of the observer. (CRef. 1.222).

Key References

*1. Mathews, M. L., Angus, R. G., & Pearce, D. G. (1978). Effectiveness of accommodative aids in reducing empty field myopia in visual search. *Human Factors, 20,* 733-740.

2. Whiteside, T. C. D. (1953). Vision in an empty field: Choice of a collimated pattern. *Flying Personnel Research Committee Report, 854.*

Cross References

1.222 Visual accommodation;

1.223 Resting position of accommodation;

1.227 Eye focus in dim illumination (night myopia)

1.239 Visual effects of empty-field (ganzfeld) viewing

7.508 Visual Search Rates Without Eye Movements

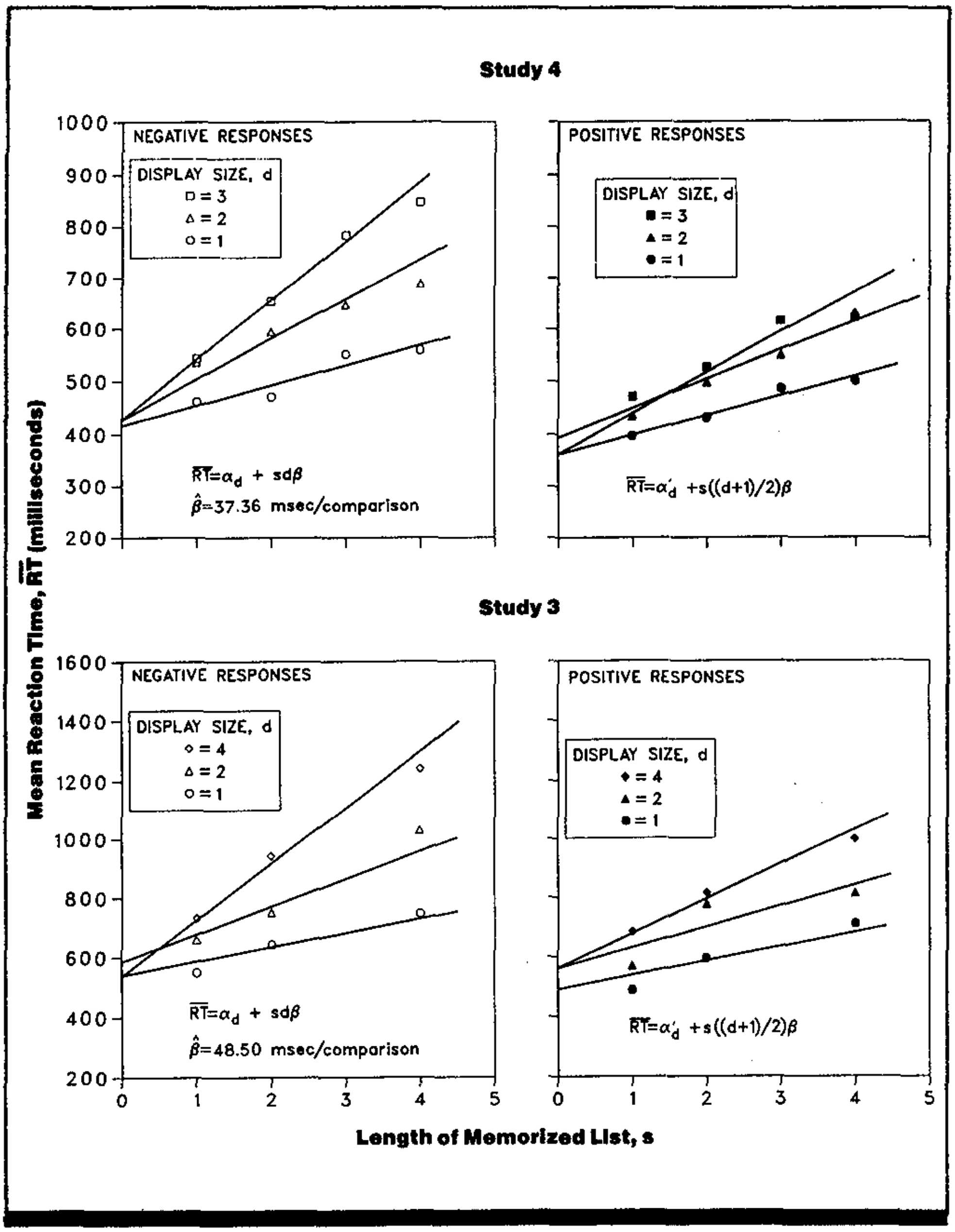

Figure 1. Response time as a function of memory set size (s) and display size (d) for Study 4 (Ref. 4) and Study 3 (Ref. 3). A positive response indicates the target letter is present in the display. (From Ref. 4)

Key Terms

Eye movements; target acquisition; visual displays; visual memory; visual search

General Description

Visual search rates measured without contamination from eye movements produce rates <50 msec per comparison (item). These times are much faster than those obtained in studies in which search time includes eye movements, and approximate the times obtained for studies of memory search rates. Table 1 summarizes four studies investigating visual search under these conditions.

Applications

Situations in which operators must scan alphanumeric displays for the presence or absence of particular characters, especially when the duration of the display is brief (400 msec or less).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- The search rates described here range from ~50 msec per comparison to 25 msec per comparison.
- The search rates described approximate memory search rates (CRef. 4.103).
- The nature of the visual search process appears to vary in the different studies described here. While the search rates are fairly consistent between studies, whether the process takes place in a serial-exhaustive fashion or in a serial self-terminating fashion is open to question (CRef. 4.103).

Variability

Linear functions accounted for 91% and 95% of the variance about the overall mean in Studies 3 and 4, respectively. Linear fit of the data for Study 1 reported as "exceptionally good," but percent of variance accounted for not reported. No variability information on Study 2 was available.

Repeatability/Comparison with Other Studies

The four studies described here produce fairly consistent estimates of visual search rates when those rates do not include eye movements. These rates are from two to four times faster than those obtained in studies that included eye movement times as part of the search rate (CRef. 7.502).

Constraints

- The switching that takes place between elements in a visual display should not be equated with the switching of fixation from one element to the next (CRef. 7.218).
- It is critical that the observer is attending to the field where the information will be displayed and is ready for its presentation.

Key References

*1. Atkinson, R. C., Holmgren, J. E., & Juola, J. F. (1969). Processing time as influenced by the number of elements in a visual display. *Perception & Psychophysics*, *6*, 321-326.

*2. Chase, W. G., & Posner, M. I. (1965, May). *The effect of auditory and visual confusability on visual memory and search tasks.* Paper presented at the meeting of the Midwestern Psychological Association, Chicago.

*3. Nickerson, R. S. (1966). Response times with a memory-dependent decision task. *Journal of Experimental Psychology*, *72*, 761-769.

*4. Sternberg, S. (1967). *Scanning a persisting visual image versus a memorized list.* Paper presented at the meeting of the Eastern Psychological Association, Boston, April, 1967.

Cross References

4.103 Memory search rates;

7.218 Visual attention switching without eye movements;

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.502 Visual search rates with eye movements;

7.520 Controlled and automatic visual search;

9.210 Time and accuracy of fast control movements;

Handbook of perception and human performance, Ch. 28, Sect. 2.1

Table 1. Summary of studies of visual search without eye movements.

Targets	Task	Results	Study
1-5 consonants in a linear array (2.2-deg largest display) presented for 400 msec; 1 consonant held in memory	Search display and decide on the presence or absence of a single visually presented target letter; 8 observers	Visual search rate is 25 msec per comparison	Study 1 (Ref. 1)
One to four letters in a 3-deg circular foveal display; one to four items in memory	Search display and decide on the presence or absence of a single visually presented target letter	The foveal search rate is slightly faster than the memory search rate (40 versus 59 msec per comparison, respectively) Search process is exhaustive for both visual and memory search (both slopes are the same)	Study 2 (Ref. 2)
One, two, or four consonants presented until observer responded; one, two, or four consonants held in memory	Memory and visual search and comparison; 21 observers	Search rate is estimated at 48.5 msec for both visual and memory search (see Fig. 1) Memory search occurs exhaustively whereas visual search is self-terminating	Study 3 (Ref. 3)
One to three digits in a 1.5-deg linear array presented for 70 msec; one to three digits held in memory	Memory and visual search and comparison; 12 observers	Search rates for scanning a memorized list or a visual display are approximately equal (37 msec) (see Fig. 1) Memory search occurs exhaustively whereas visual search is self-terminating	Study 4 (Ref. 4)

7.509 Search Time for Single Disks: Effect of Target Contrast

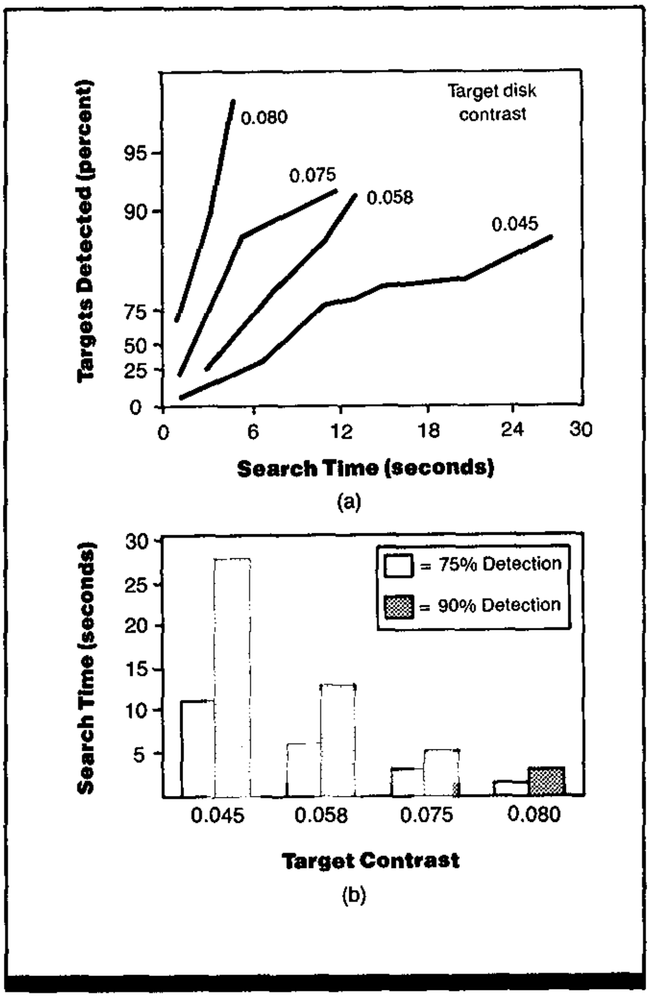

Figure 1. (a) Percent detection as a function of search time and target contrast; (b) search time for 75 and 90% detection as a function of target contrast. (From Ref. 1)

Key Terms

Contrast; contrast sensitivity; target acquisition; uncertainty; visual search time

General Description

Searching for a stationary target in a broad, unstructured field can take considerable time, 30 sec or more, when target size is small, target contrast is low, and location is unspecified.

Methods

Test Conditions

- Single, stationary, circular disk, 13 min arc of visual angle, displayed on 32-deg circular field of search
- Viewing distance 183 cm (6 ft)
- Luminance of field 42 cd/m^2 (12.4 fL)
- Target disk contrast 0.045, 0.058, 0.075, and 0.080; target location unspecified
- Observers dark-adapted for 10 min before each session
- Binocular viewing; maximum presentation time 30 sec

Experimental Procedure

- Independent variable: target contrast
- Dependent variable: search time to find target
- Observer's task: to search field for target of specified size and identify display quadrant in which it appeared; false alarms discouraged
- Four data points per observer combined to give mean performance data
- 4 observers with ≥ 10 hr of practice on a similar task

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Search time to find a disk target increases as target contrast decreases (Fig. 1a).
- Minimum search time needed to detect a target on 90% of trials is more than twice as long as that needed for 75% detection (Fig. 1b).

Variability

No information on variability was given.

Constraints

- Many factors, such as practice, adaptation conditions, field luminance, target size, and response biases can influence search performance and must be considered in applying these results to other viewing conditions.

Key References

*1. Krendel, E. S., & Wodinsky, J. (1960). Visual search in unstructured fields. In A. Morris & E. P. Horne (Eds.), *Visual search techniques—Proceedings of an NRC Symposium* (Publication 712). Washington DC: National Academy of Sciences.

2. Farrell, R. J., & Booth, J. M. (1984). *Design handbook for imagery interpretation equipment.* San Diego, CA: Boeing Aerospace Co.

Cross References

7.315 Effect of display size on visual fixation;

7.501 Factors affecting visual search with monochrome displays;

7.516 Target acquisition in distractor target arrays;

7.521 Effect of target lag and sequential expectancy on search time;

7.522 Visual search for moving and static targets;

7.524 Visual search for multiple targets;

7.526 Detection of objects and events in real-world scenes

7.510 Search Time: Effect of Target Luminance, Size, and Contrast

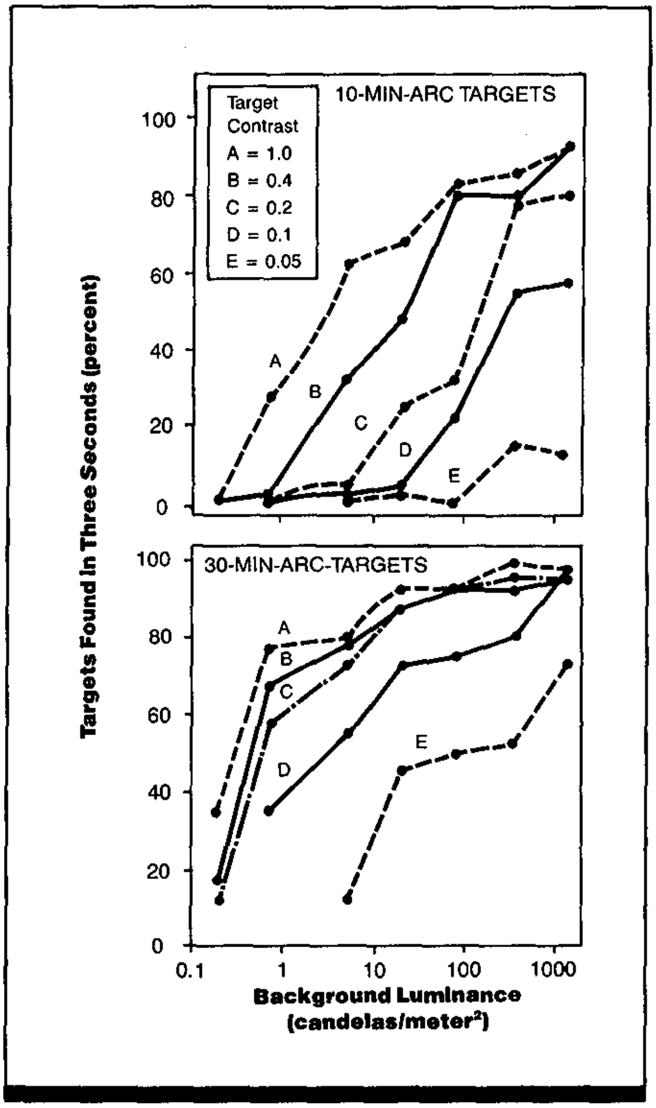

Figure 1. Percentage of targets found in 3 sec for 10-min-arc and 30-min-arc targets as a function of background luminance. Target contrast is the parameter for the curves. (From Ref. 2, adapted from Ref. 1)

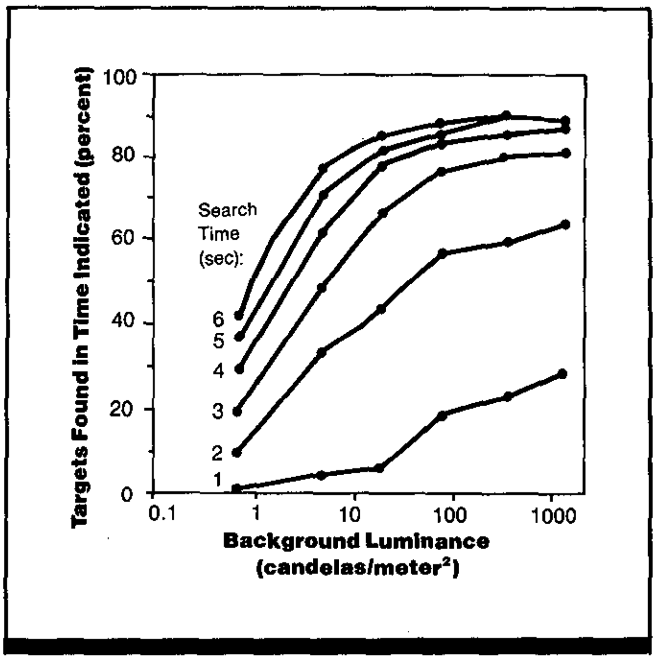

Figure 2. Percentage of targets found as a function of background luminance with search time as the parameter; 10-min-arc with target contrast of 1.0. (From Ref. 2, adapted from Ref. 1)

Key Terms

Contrast; eye movements; luminance; shape; size; target acquisition; uncertainty; visual search time

General Description

One kind of visual search task involves looking for a square-shaped target in a large array of circular-shaped distractor items. In this situation, search performance is better for large targets with high contrast in a field with high background luminance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Searching for targets in a large array with many distractors.

Methods

Test Conditions

- One square, dark target and 15 dark circles (or only 16 dark circles) of equivalent area and contrast presented on square field, 20 x 20 deg arc of visual angle
- Target width was 10 min arc (Exp. 1) or 30 min arc of visual angle (Exp. 2)
- Background luminance was 0.19, 0.69, 5.1, 20, 79, 360, or 1370 cd/m^2; observers presented with adapting field at beginning of each trial with luminance equal to background luminance for that trial
- Target contrast was 0.05, 0.1, 0.2, 0.4, or 1.0
- Observer sat 57.4 cm from stimulus display; binocular viewing

Experimental Procedure

- Independent variables: target width, background luminance, target contrast
- Dependent variable: search time to find target
- Observer's task: press button to present stimulus display, search display for square target, and press button when target detected
- Monetary rewards and penalties used to ensure low **false alarm** rate
- 10 observers (4 male, 6 female) for all background luminances (Exp. 1); 2 observers for factorial design of target size x background luminance x target contrast (Exp. 2)

Experimental Results

- Searching through a large visual array for a square target among circular distractors is better for larger squares (30 arc-min versus 10 arc-min) of high contrast with high background luminance (Fig. 1).
- More difficult conditions benefit more from higher background luminances than do easier conditions; maximum performance for high-contrast targets occurs at a lower luminance level than maximum performance for low-contrast targets (Fig. 1).
- More 30-min-arc targets than 10-min-arc targets are found in 3 sec (Fig. 1).
- In search for high-contrast targets, the highest luminances help observers find targets more quickly, but do not increase the level of maximum performance (Fig. 2).

Variability

There are between-subject differences.

Constraints

- Many factors, such as the variables studied here and payoffs for different response conditions, can influence search performance and must be considered in applying these results to other conditions.

Key References

*1. Boynton, R. M., & Boss, D. E. (1971). The effect of background luminance and contrast upon visual search performance. *Illuminating Engineering, 66,* 173-186.

2. Farrell, R. J., & Booth, J. M. (1984). *Design Handbook for imagery interpretation equipment.* Seattle, WA: Boeing Aerospace Co.

Cross References

1.941 Gain of tracking eye movements: effects of target luminance and visual field location;

1.952 Vergence eye movements: eliciting target characteristics;

1.960 Factors affecting coordination of head rotation and eye movements;

7.502 Visual search rates with eye movements;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.512 Search time: effect of number of targets and target complexity;

7.516 Target acquisition in distractor target arrays;

7.524 Visual search for multiple targets

7.511 Search Time and Eye Fixations: Effects of Symbol Color, Size, and Shape

Key Terms

Color coding; color displays; conspicuity; display clutter; shape coding; size coding; target acquisition; target coding; target recognition; uncertainty; visual fixation; visual search time

General Description

For a highly cluttered search field containing objects differing widely in size, color, and shape (Fig. 1), observers can locate specific objects considerably faster when they know in advance the object's color rather than its size or shape (Table 1). Observers also selectively fixate more frequently on displayed objects that are specified on the basis of color rather than size or shape.

Applications

Displays in which color, shape, or size coding of symbols may be desirable to compensate for display clutter.

Methods

Test Conditions

- Stimuli rear-projected onto 1.22-m^2 screen; viewing distance 1.72 m; resulting search area 39 deg of visual angle square
- 200 search fields projected from 35-mm slides; each field contained 100 forms of varying sizes, colors, and shapes; sizes: 2.8, 1.9, 1.3, or 0.8 deg; colors: blue, green, yellow, orange, or pink; shapes: circle, semicircle, triangle, square, or cross; different two-digit numbers, approximately 0.3 deg in height, contained on each form
- Instruction slides with text description of target specification preceded each search field slide; target specification also appeared in small box at center of search field slide; the words "very large," "large," "medium," or "small" described target sizes
- Search times measured automatically from appearance of search field slide until observer depressed hand-held button indicating specified target had been located; eye fixations measured using corneal-reflection technique.

Experimental Procedure

- Independent variable: target specification (number only, size only, color only, shape only, color and size, color and shape, size and shape, color and size and shape)
- Dependent variables: search time to locate target in sec, percentage of eye fixations falling on forms in the search field
- Observer's task: read target specification slide, operate hand-held control to display search field, search for specified target, operate hand-held control when target located
- 200 trials per observer, different search field on each trial
- 30 male observers, normal acuity and color vision

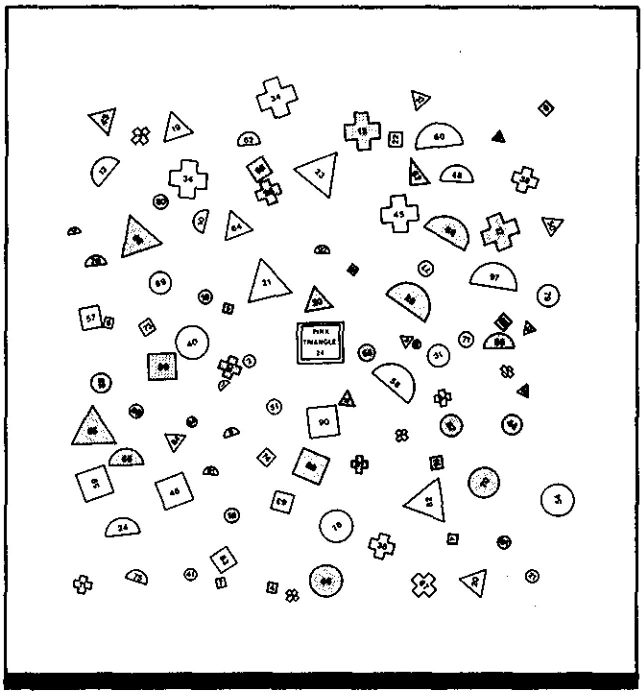

Figure 1. Representative search field showing target coding. (From Ref. 5)

Experimental Results

- When color is part of the target specification, mean search time is approximately 6.8 sec. When size only or size and shape specify the target, mean search time increases to about 16.1 sec. Mean search time increases to 20.7 sec when only shape specifies the target and to 22.8 sec when only a two-digit number specifies the target (Table 1).
- 61% (approximately 115,000) of eye fixations fall on specific forms in the search field. Analysis of fixations is based on these data.
- When color is a component of the target specification, approximately 60% of fixations are on the specified color.
- When the very large (2.8 deg) size is part of the target specification, approximately 54% of fixations are on very large targets. However, for all other sizes only approximately 30% of fixations are on the specified sizes.
- Eye fixations are comparable for all shapes when shape is a component of the target specification. About 26% of fixations fall on specified shapes.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results of the study are in good agreement with other reports in the literature (Refs. 1, 2, 3, and 4).

Constraints

- Luminance and color contrasts were not specified.
- Applications of results to smaller display areas should be verified.
- Interpretation of eye fixation results is based on only 61% of all fixations.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Heglin, H. J. (1973). *NAVSHIPS display illumination design guide: Section II: Human factors* (NELC-TD-223). San Diego, CA: Naval Electronics Laboratory Center. (DTIC No. AD770478)

2. Reynolds, R. E., White, R. M., Jr., & Hilgendorf, R. L. (1972). Detection and recognition of colored signal lights. *Human Factors, 14*, 227-236.

3. Smith, S. L. (1963). Color coding and visual separability in information displays. *Journal of Applied Psychology, 47*, 358-364.

4. Wagner, D. W. (1977, March). *Color coding—An annotated bibliography* (NWC-TP-5922). China Lake, CA: Naval Weapons Center. (DTIC No. ADA041061)

*5. Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics, 1*, 315-318.

Cross References

7.313 Eye fixations and eye movements during display monitoring;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.512 Search time: effect of number of targets and target complexity;

7.513 Search time: effect of number of colors and information density;

7.517 Search time: effect of number of background characters and display density;

7.519 Search time: effect of color coding;

7.526 Detection of objects and events in real-world scenes;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.126 Color misregistration: effect on symbol identification;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.317 Data entry displays;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

Table 1. Mean time to find targets of different target coding specifications. (From Ref. 5)

Target Coding Specifications	Mean Time (Sec)
Color Only	7.6
Color and Size	6.1
Color and Shape	7.1
Color and Size and Shape	6.4
Size Only	16.4
Size and Shape	15.8
Shape Only	20.7
Number Only	22.8

7.512 Search Time: Effect of Number of Targets and Target Complexity

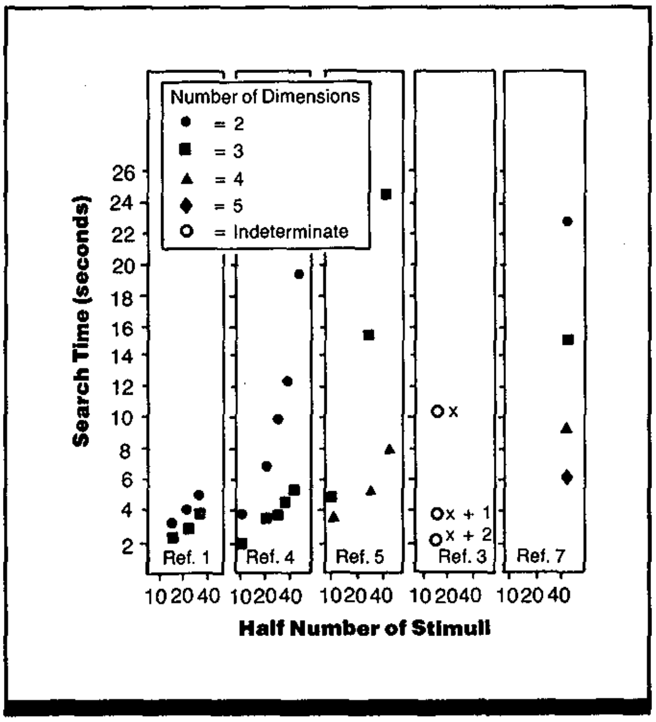

Figure 1. Search time as a function of the half number of stimuli for five different studies. An x in the fourth panel indicates the minimum indeterminate number of dimensions defining a target stimulus; more complex stimuli are identified in terms of dimensions >x. (From Ref. 6)

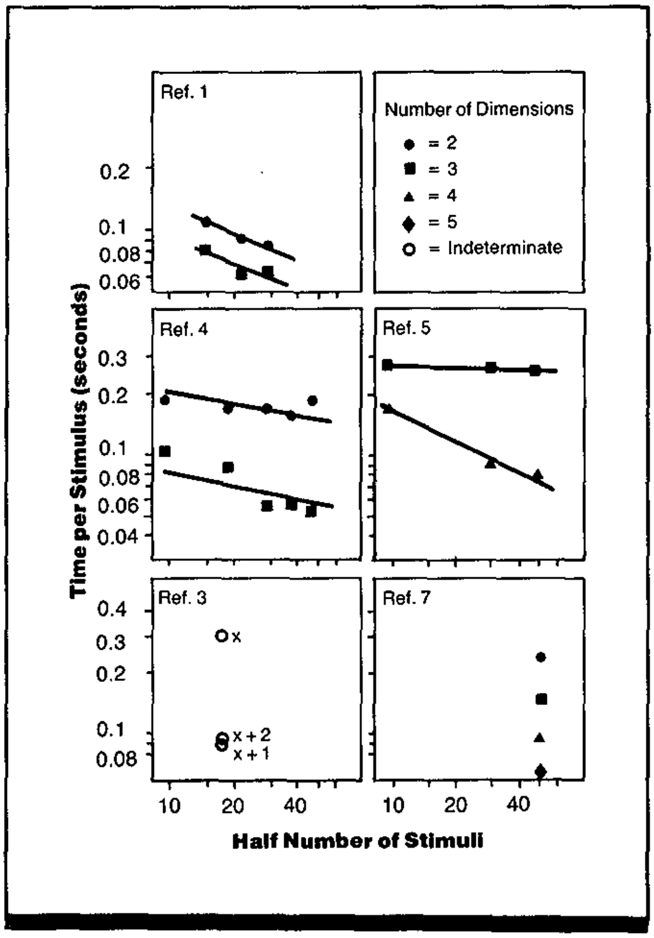

Figure 2. The data in Fig. 1 are plotted with time per stimulus calculated by dividing search time by the total number of displayed stimuli. (From Ref. 6)

Key Terms

Color coding; display brightness; information analysis; information portrayal; practice; shape; size; target acquisition; target complexity; target detection; uncertainty; visual search time

General Description

In the search for a target in a visual array, search time decreases and target-processing rate increases as the number of dimensions in a multidimensional target increases and as the number of displayed targets increases.

Applications

Searching for targets in a complex display; determining processing rates for video displays.

Methods (across studies)

Test Conditions

- Possible locations of the one target per display known by observer
- Display available to observer until target reported
- Targets easily detectable and identifiable
- Levels or magnitudes of each target dimension easily discriminable; dimensions could be either physical (e.g., color) or cognitive (e.g., letters of the alphabet)
- Target dimensions for each study were: two-digit numbers, color (Refs. 1, 4); color, shape, brightness (Ref. 3); two-digit numbers, color, letter (Ref. 5); and two-digit numbers, color, form, and size (Ref. 7)
- Number of target dimensions ranged from 1-3 (indeterminate for one study)
- Number of targets displayed ranged from 10-1024

Experimental Procedure

- Independent variables: number of dimensions, number of targets in an array
- Dependent variable: search time from display onset to responses indicating target found
- Observer's task: search array and locate target
- Observers in each study were young adults

Experimental Results

- For all five studies, search time decreases as the number of target dimensions increases (Fig. 1). This effect occurs even when visual noise (clutter) is presented with the targets.
- As shown in Fig. 1 (the first, second, and third panels), increasing the number of targets in a display increases search time, but this effect is smaller when there are more dimensions.
- Search time per target decreases when the number of target dimensions is increased and when the number of displayed targets is increased (Fig. 2).

Variability

Error rates did not exceed 5.5%.

Constraints

- Many factors (such as detectability of target and discriminability of stimulus magnitudes) affect search and should be considered in applying findings.
- Visual search is strongly affected by practice.

Key References

1. Green, B. F., & Anderson, L. K. (1956). Search time in a redundant visual display. *Journal of Experimental Psychology, 83*, 391-399.

2. Lehtio, P. K. (1970). The organization of component decisions in visual search. In A. F. Sanders (Ed.), *Attention and performance III* (pp. 93-105). Amsterdam: North-Holland.

3. Newman, K. M., & Davis, A. R. (1962). Non-redundant color, brightness, and flashing rate encoding of geometric symbols in a visual display. *Journal of Engineering Psychology, 1*, 47-67.

4. Smith, S. L. (1962). Color coding and visual search. *Journal of Experimental Psychology, 64*, 434-440.

5. Smith, S. L. (1963). Color coding and visual separability in information displays. *Journal of Applied Psychology, 47*, 358-364.

*6. Teichner, W. H., & Mocharnuk, J. B. (1979). Visual search for complex targets. *Human Factors, 21*, 259-275.

7. Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics, 1*, 315-318.

Cross References

4.301 Information theory;

7.502 Visual search rates with eye movements;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.513 Search time: effect of number of colors and information density;

7.514 Effect of irrelevant stimuli on search performance;

7.515 Processing of nontarget items in visual search;

7.516 Target acquisition in distractor target arrays;

7.518 Search time: effect of target surround density;

7.519 Search time: effect of color coding;

7.524 Visual search for multiple targets;

7.525 Target acquisition in real-world scenes;

7.608 Multiple regression model of target acquisition

7.513 Search Time: Effect of Number of Colors and Information Density

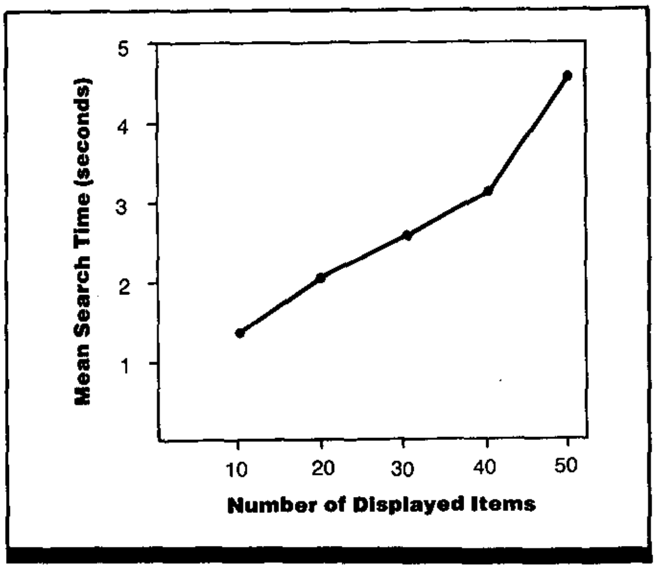

Figure 1. Search time as a function of number of displayed items. (From Ref. 1)

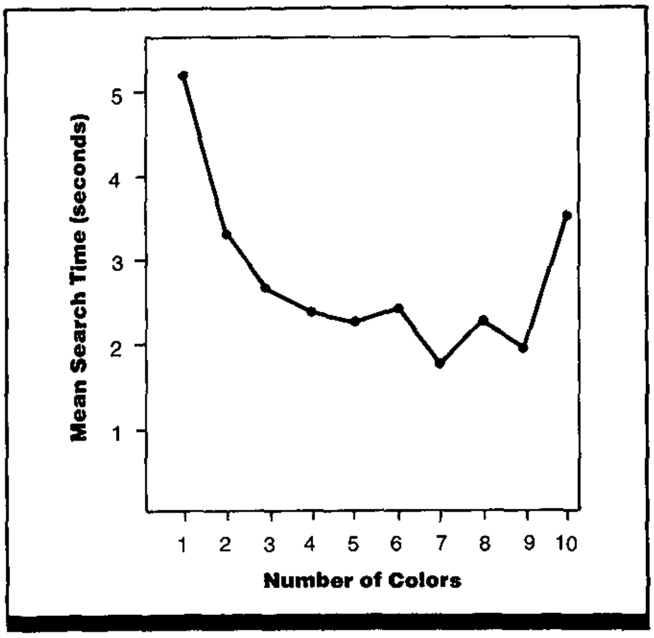

Figure 2. Search time as a function of number of code colors. (From Ref. 1)

Key Terms

Color coding; color displays; display density; information portrayal; numeric displays; rear-projection displays; target acquisition; visual search; visual search time

General Description

Both number of displayed items and size of the color coding set affect visual search performance. In general, more items in a display generate longer search times (Fig. 1) and more colors yield shorter search times, except for high-density information displays (Fig. 2). When the number of items per color category is held constant, search time increases as more than about four colors are added to the code (Fig. 3). The data indicate that when display density is increased, the number of color coding levels used should be kept small, probably not over seven (Fig. 4).

Applications

Selection of the size of a color coding set for a given display density.

Methods

Test Conditions

- Rear screen projection; item color (on 7.6 x 50.8 cm rectangle to right of main display) and array of three-digit random numbers simultaneously displayed; tachistoscopic shutter controlled by subject-held control; search time to 0.01 sec recorded automatically; overhead fluorescent ambient illumination; display luminance not specified
- Display density was defined as the number of items on a display; 10, 20, 30, 40, or 50 items; color code size was defined as the number of colors used to redundantly code displayed elements; yellow, purple, orange, light blue, red, buff, green, purplish-pink, blue, and yellowish-pink, each chosen for maximum contrast and mutual discriminability (Ref. 3)
- Angular subtense of digits 22 mm high and 16 mm wide, at 1.5-m viewing distance, was 50 min arc of visual angle
- Observer seated, unrestrained by headrest or bite board; five practice trials and 50 data-gathering trials

Experimental Procedure

- Repeated measures, factorial design
- Independent variables: display density; color code size
- Dependent variables: search times (defined as the time for observer to find a designated item or target)
- Observer's task: search for three-digit numbers by their color and the first two digits
- 15 male and 5 female college students, ages 18-27, screened for normal color vision

Experimental Results

- The value of color coding varies with information density. Search times increase with larger color coding sets at higher display densities.
- Search time increases as more code colors are added to the display when the number of items per color category is held constant: there can be too many colors.
- Display information density and color code size significantly ($p < 0.001$) influence performance. The interaction between display density and color code size is significant ($p < 0.01$).

Variability

No information on variability was given.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Repeatability/Comparison with Other Studies

The finding that search-time increases as display density increases is in line with previous research (Refs. 2, 4). However, the increase in search time with more colors is at odds with the hypothesis (Ref. 2) that search time is proportional to the number of items in the color categories of the target item. This implies that search times should be equal when there is a constant number of items per color category. Performance benefits from larger color coding sets (e.g., 7-10 depending on density) were found in Refs. 2 and 4, where a maximum size of five per set was recommended. This is likely due to the use of easily discriminable colors.

Constraints

- There are no standard measures of display density, extent of display formatting, or operator task loading. Thus, mission-critical expectations of operator performance enhancement from display color coding should be empirically verified.
- This study (and most research in this area) used randomly distributed targets. When data are systematically formatted, the effects of color code size and display density on visual search performance may be less pronounced.
- Detailed specifications of the colors used were not given by the authors.
- Situational factors (e.g., low ambient illumination, low symbol luminance, high operator workload, large angle of regard, etc.) may reduce the number of colors that can be reliably discriminated.

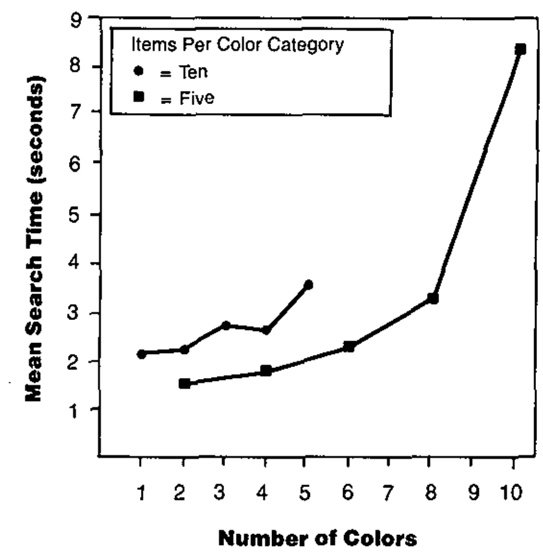

Figure 3. Search time as a function of number of code colors with a constant number of items per color category. (From Ref. 1)

Key References

*1. Cahill, M., & Carter, R. C., Jr. (1976). Color code size of searching displays for different density. *Human Factors, 18*, 273-280.

2. Green, B. F., & Anderson, L. K. (1956). Color coding in a visual search task. *Journal of Experimental Psychology, 51*, 19-24.

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Cross References

7.517 Search time: effect of number of background characters and display density;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.126 Color misregistration: effect on symbol identification;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

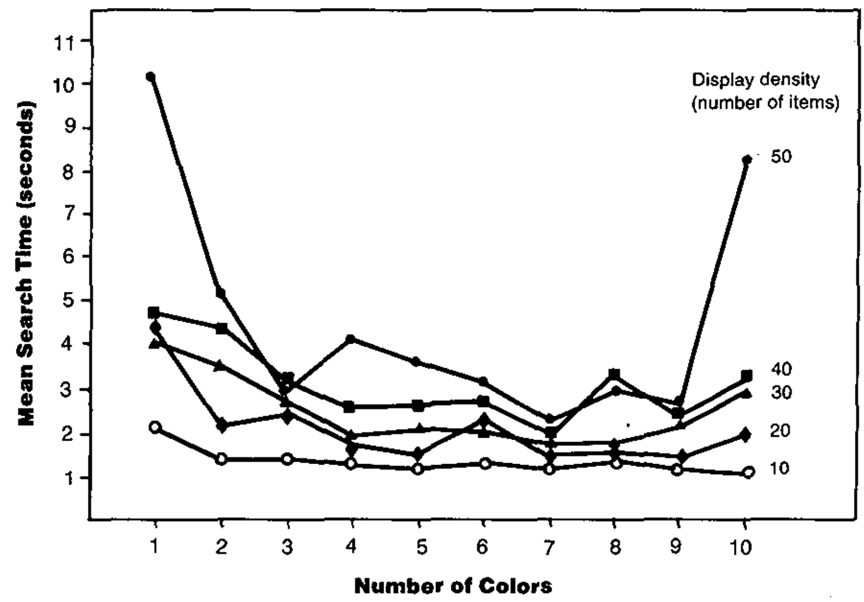

Figure 4. Search time as a function of number of colors in code for five display densities. (From Ref. 1)

7.514 Effect of Irrelevant Stimuli on Search Performance

Key Terms

Camouflage; display clutter; distractors; target acquisition; target complexity; uncertainty; visual attention; visual displays; visual search; visual search time

General Description

Search times increase with the amount of irrelevant information in a display. In Exp. I, a single letter was searched for against backgrounds of one to four different, irrelevant, non-target letters. In Exps. II and III, dot-pattern targets were searched for against backgrounds of one to four different, irrelevant, non-target dot-patterns. While overall mean search time per item is greater with unfamiliar than with familiar stimuli, the increase in search time (i.e., slow down in performance) produced by irrelevant items is similar. Doubling the number of irrelevant items from one to two and from two to four leads to approximately the same increases in overall mean search time per item. Thus, search time/item varies inversely with the amount of irrelevant information. The results suggest that search time increases are due to increased display heterogeneity and not to increases in sampling or inspection times. Observers appear to encode irrelevant (non-target) information in a search task, but apparently do not process it to the point of identification.

Applications

Predicting trends in target search times when amount of irrelevant display information can be measured.

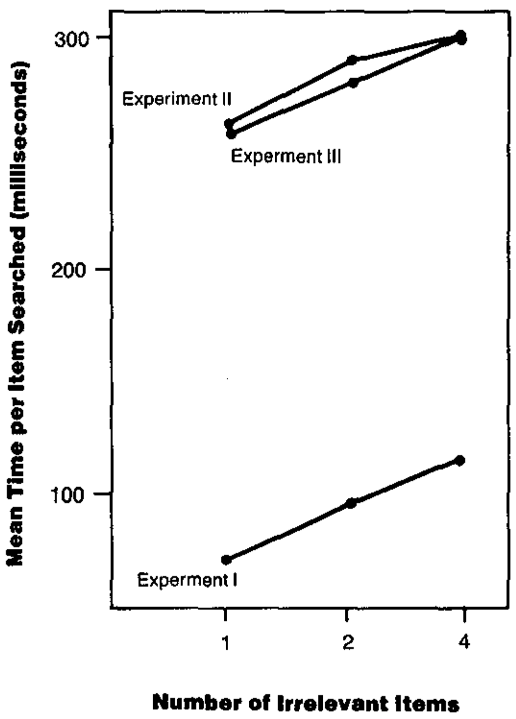

Figure 1. Target search times as a function of number of different irrelevant, non-target items. (From Ref. 1)

Methods

Test Conditions

Experiment I

- Visual materials: 14 printed lists each containing 1,000 lower case letters in 40 single-spaced rows of 25 letters per row; 50 lower case a's (target items to be cancelled when located) randomly located in lists; frequency and spatial distribution of a's similar across lists
- Remaining spaces in lists filled with one, two, or four irrelevant, non-target letters (b's, c's, d's, or e's); four lists with one non-target letter; six lists with two non-target letters; four lists with four non-target letters
- Each list printed on 7.6 x 20.3 cm (3 x 8-in.) paper strip

Experiment II

- Visual materials: 14 printed lists each containing 150 squares, each 7 x 7 mm, separated by 2 mm; each square divided into 3 x 3 matrix of cells; four cells in each matrix contained one black dot each
- Eight squares used as target stimuli; remaining 142 squares contained non-target patterns; non-target dot patterns never overlapped (occupied any matrix position of) target patterns
- Four lists with one non-target pattern; six lists with two non-target patterns; four lists with four non-target patterns
- Each list consisted of 10 rows of 15 patterns each

Experiment III

- Visual materials and other conditions same as Exp. II except that one dot of non-target patterns occupied a matrix position of target patterns
- All experiments: observers signaled to start; performed search task for 30 sec; signaled to stop, mark place reached on list, and rest for 25 sec between trials

Experimental Procedure

- Independent variables: number of non-target stimuli, Exp. I: one, two, or four non-target letters, Exps. II and III: one, two, or four non-target dot patterns
- Dependent variables: number of errors of omission and commission (Exp. I only), time in sec per item searched
- Observer's task: search lists and place oblique stroke through each target using a pencil
- All experiments: observers instructed to work as quickly as possible and to minimize errors
- Exps. II and III: observers shown 0.61 x 0.61-m drawing of target dot pattern and required to reproduce it ten times in practice matrix; enlarged target drawing on display during experimental trials
- 40 observers in Exp. I; 16 observers in Exps. II and III

Experimental Results

- Errors of omission (Exp. I) occur <0.4% and are not analyzed; errors of commission are extremely rare.
- In all experiments, mean search time per item increases with increases in the number of non-target items ($p < .001$).
- No significant differences in mean search times per item are found between Exps. II and III.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other studies have shown that shape of relevant items (Ref. 2) and degree of similarity between relevant and irrelevant items (Ref. 3) influence search time. Similar search effects have been demonstrated using lists generated on CRT displays (Ref. 5). Major findings (Ref. 4) showed stimulus processing increases as the number of dimensions in a multidimensional target increases, and rate of processing increases as a function of total stimulus information.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Predictions from these experiments are restricted to situations in which degree of configurational similarity between relevant and irrelevant items can be measured or controlled.

Key References

*1. Gordon, I. (1968). Interactions between items in visual search. *Journal of Experimental Psychology, 76*, 348-355.

2. Neisser, U. (1963). Decision-time without reaction time: Experiments in visual scanning. *American Journal of Psychology, 76*, 376-385.

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4. Teichner, W. H., & Mocharnuk, J. B. (1979). Visual search for complex targets. *Human Factors, 21*, 259-275.

5. Yonas, A., & Pittenger, J. (1973). Searching for many targets: An analysis of speed and accuracy. *Perception & Psychophysics, 13*, 513-516.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.512 Search time: effect of number of targets and target complexity;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.519 Search time: effect of color coding;

7.524 Visual search for multiple targets

7.515 Processing of Nontarget Items in Visual Search

Key Terms

Camouflage; color coding; directed eye movements; display complexity; display density; distractors; focused search; preattentive processing; serial-parallel processing; uncertainty; visual fixation

General Description

Visual search depends in part on the characteristics of the nontarget ("distractor" items) in which targets are embedded. The speed and accuracy of search for a target will be greater to the degree that there is less processing of nontarget items. Nontargets can be ignored or at least only partially processed most readily when they differ in color or size from targets and the search requires multiple fixations.

Nontargets may also receive only partial processing when they differ only in form from targets and the search requires multiple fixations. In this case, partial processing is more likely than complete processing to the degree that (a) nontargets are dissimilar from targets, (b) the set of possible nontargets is small, (c) the amount of practice at finding the targets increases, and (d) the set of possible targets is large.

Applications

Maps, schematic drawings, instrument panels, and other complex, multi-attribute visual displays that require visual search.

Constraints

- Little is known about tradeoffs among color, size, and form as a function of variations in discriminability within each dimension.

Key References

*1. Cavanaugh, J. P., & Chase, W. G. (1971). The equivalence of target and nontarget processing in visual search. *Perception & Psychophysics, 9*, 493-495.

*2. Ellis, S. H., & Chase, W. G. (1971). Parallel processing in item recognition. *Perception & Psychophysics, 9*, 379-384.

*3. Gordon, I. E. (1968). Interactions between items in visual search. *Journal of Experimental Psychology, 70*, 348-355.

*4. Gould, J. D., & Dill, A. B. (1969). Eye-movement parameters and pattern discrimination. *Perception & Psychophysics, 6*, 311-320.

*5. Neisser, U. (1963). Decision-time without reaction time: Experiments in visual scanning. *American Journal of Psychology, 76*, 376-385.

*6. Neisser, U. (1964). Visual search. *Scientific American, 210*, 94-102.

*7. Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.

*8. Rabbitt, P. M. A. (1964). Ignoring irrelevant information. *British Journal of Psychology, 55*, 403-414.

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Cross References

7.501 Factors affecting visual search with monochrome displays;

7.502 Visual search rates with eye movements;

7.506 Search time: effects of target conspicuity and fixation eye movements;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.514 Effect of irrelevant stimuli on search performance;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.519 Search time: effect of color coding;

7.520 Controlled and automatic visual search;

7.524 Visual search for multiple targets;

11.403 Target coding: effect on search time

Table 1. Summary of studies on the processing of nontarget ("distractor") items during visual search.

Test Conditions	Task	Results	Source
Multiple fixation, multi-attribute displays: Color, size, form varying			
Square displays (size = 39 deg of visual angle) filled with 100 randomly placed figures of various colors, sizes, and forms, each with a two-digit number in the center; varied mapping; 200 displays; 4-6 hr of practice in two sessions; 30 college males with some practice	Visual search for single target identified by a specific two-digit number and with color, size, form or any combination of the three specified prior to start of search or with no prior specification of color, size, or form	Specifying color or (to a limited extent) size of target figure reduces the probability of fixating nontarget figures Specifying form does not affect nontarget processing Search time is directly related to probability of fixating nontargets	Ref. 9
Multiple fixation, multi-attribute displays: Size and form varying			
Nearly square (~16 deg of visual angle) Nine element (3 x 3) displays; each element a matrix of asterisks; 5 matrix sizes x 5 density levels at each size; 200 trials; 7-9 sessions; 10 college students	Count number of targets in display	Probability of fixating a nontarget decreases with greater differences in target-nontarget "level," a mixture of size and form differences Nontargets at same level as targets are as likely to be fixated as the targets Fixation durations are shorter for nontargets than for targets at all levels Target fixations are shorter with dissimilar nontargets	Ref. 4
Multiple fixation, multi-attribute displays: Color, size, form varying			
Deck of 48 5 x 7-cm cards with 1-9 5-mm stenciled capital letters; constant mapping; 10 sorting trials; young adults	Speeded card sorting	Sorting time increases with number of nontargets (all different) Positive but not perfect transfer after 5 sorting trials to a new set of nontargets	Ref. 8
14 lists of 1,000 letters or 150 dot patterns printed on 7 x 18-cm sheets; constant mapping; secondary school students	Letter or dot pattern cancellation	Search time increases with the number of different nontarget items Perfect positive transfer to new nontargets after 10 days of practice	Ref. 3
50-line lists with 2-6 letters per line; 2-4 problems per session, 15-20 trials/problem; 16-30 sessions, 30-45 min each; constant mapping; college students	Visual search	Search is faster to find row with target than row without target Search is slower when nontargets are similar to targets Search is slower the more nontargets per row Nontargets are seen as a "blur"	Ref. 5, 6, 7
Single fixation, multi-attribute displays: Color and form varying			
Uppercase letters (18 min of visual angle); varied mapping, 1-4 item memory load; 144 trials, one 30-min session; 10 college students	Indicate whether test letter was a member of memorized set of letters	Faster rejection of distinctly colored nontargets for memory loads > 1 There is equal processing of nontargets and targets when they are only different in form	Ref. 2
Upper case letters (18 min of visual angle) within 1 deg of visual angle; varied mapping, 1-6 item memory, 216 trials, two 1-hr sessions; 16 college students	Two alternative forced choice of targets or indicate whether test letter was member of memorized set of letters	There is equal processing of nontargets and targets for memory loads > 2 or 3	Ref. 1

7.516 Target Acquisition in Distractor Target Arrays

Key Terms

Automatic search; concurrent processing; distractors; parallel processing; practice; target acquisition; training; visual search time

General Description

Under certain conditions, visual search rates are fast and essentially independent of the number of possible targets (up to at least 10 targets). The principal condition for this result is the *constant mapping rule* (Ref. 7) that targets and nontargets constitute disjoint sets (i.e., items used as targets are never used as nontargets and items used as nontargets are never used as targets). In addition, it matters whether targets and nontargets are in the same category (i.e., digits or letters). With targets and nontargets in different categories, search rate is often independent of number of targets at the outset of practice. With targets and nontargets in the same category, search rates at the outset of practice are slowed by increasing the number of targets, but with extended practice the search rates for varying numbers of targets converge.

Table 1. Summary of data on visual search for multiple targets.

Test Conditions	Task	Results	Source
Matrix of digits or letters (6 columns × 35 rows); 25 trials per block, 3 blocks per session; single session (n = 8) or five sessions (n = 4); males and females ages 16-26	Locate target in matrix	Faster search rates when targets and nontargets are in different classes (except for one subject); after five sessions of practice, scan time is ∿0.14 sec per item to find any item or specified target when targets and nontargets are in different classes.	Ref. 1
Foveal display of 2, 4, or 6 letters or digits, at a radius of 1.7 deg from fixation point; 150 msec exposure, respond if target present or (in separate groups) if target absent; single session, 18 practice, 108 data trials; 48 college students	Report presence or absence of target	Speed of detecting target presence or absence is independent of *display* size when targets and nontargets are in different categories Search rate is ∿26 msec per item when targets and nontargets are in the same category Response time is faster for target present than for target absent	Ref. 4
Rectangular or square displays of letters within 2 deg of fixation; sequential search procedure, with 18-24 displays shown in rapid sequence; 2 highly practiced subjects	Report digit location in array of letters	Estimated scanning rates to find any one of 10 digits are almost as fast as rate to find a single digit; scan time estimates are 8-14 msec per letter Scanning accuracy varies from 0.01-0.719 for specific targets Displays of 9-25 items are optimal	Ref. 8
One, two, or four test letters in 2 × 2 matrix 60 mm per side; memory load of one, two or four letters; six blocks of 48 trials per block per session; 9 sessions; constant or varied mapping; 36 college students	Indicate presence or absence of target(s) in memory set; button-press response	Display size and target set size both affect speed and accuracy of recognition There are much larger effects of display size and target set size for varied mapping than for constant mapping Practice reduces effects of display size and target set size more for constant mapping (40-45%) than for varied mapping (20% or less)	Ref. 2

Test Conditions	Task	Results	Source
Lists of 50 surnames usually with between 9 and 15 targets (mean = 12); target set of one, three, five or seven names; constant mapping; 18 sessions, 90 min each, over 7 days; 3 college students	Scan to find all target surnames	With extended practice performance becomes nearly errorless and equally fast (12 sec per list) for set sizes of three to seven items; set size one is slightly faster (10 sec per item) Subjects cannot recall nontargets after extensive exposure Scan time is doubled and error rates increase to 8% when nontargets are made targets Time increases 1.3-2.8 sec per list with shift to lower case letters	Ref. 3
50-item lists (letters and digits), one of six characters per row; target set sizes of one, five, and ten; constant mapping; 26-48 days practice on each set size; 8 male college students	Search to locate a single target	Scanning rates improve with practice and equalize at $\sim$0.2 sec per item for target set sizes >1. There is a small advantage for target set size = 1 (with $\sim$0.17 sec per item) under conditions with low ($<4\%$) error rates	Ref. 5
50-item lists (letters and digits), one item of six characters per row; target set sizes of one, five, or ten; constant mapping; 27 days practice on each set size; 6 college students	Search to locate a single target	Scanning rates improve with practice, equalizing at $\sim$0.1 sec per item for all set sizes under conditions of high ($>20\%$) errors No disruption with introduction of new nontargets on Day 26	Ref. 6
145 item lists (29 rows of five characters each displayed on CRT); target set size of one or four; constant mapping; 40 days of practice; 3 college students	Search to locate a single target	Practice reduces scan time per line by 60-80% to 46-110 msec per line. Scan for target set size one is faster than scan with target set size four, even after extensive practice and with high ($>25\%$) error rate Scan time varies for specific targets; more letter O difficult than D, J, U Difference in results from other studies may be due to separate speed and error analyses for each subject and each target	Ref. 9

Constraints

• Little is known about whether irrelevant variations in dimensions like color and size interfere with development of rapid search rates independent of target set size.

• Similarity between targets and nontargets is likely to affect how much practice is needed to produce converging search rates when targets and nontargets are in the same category.

Key References

*1. Brand, J. (1971). Classification without identification in visual search. *Quarterly Journal of Experimental Psychology, 23,* 178-186.

*2. Briggs, G. E., & Johnsen, A. M. (1972). On the nature of central processing in choice reactions. *Memory and Cognition, 1,* 91-100.

*3. Graboi, D. (1971). Searching for targets: The effects of specific practice. *Perception & Psychophysics, 10,* 300-304.

*4. Jonides, J., & Gleitman, H. (1972). A conceptual category effect in visual search: O as letter or as digit. *Perception & Psychophysics, 12,* 457-460.

*5. Kristofferson, M. W. (1972). Types and frequency of errors in visual search. *Perception & Psychophysics, 11,* 325-328.

*6. Neisser, U., Novick, R., & Lazar, R. (1963). Searching for ten targets simultaneously. *Perceptual and Motor Skills, 17,* 955-961.

7. Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: Detection, search, and attention. *Psychological Review, 84,* 1-66.

*8. Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. (1971). Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science, 174,* 307-311.

*9. Yonas, A., & Pittenger, J. (1973). Searching for many targets: An analysis of speed and accuracy. *Perception & Psychophysics, 13,* 513-516.

Cross References

7.512 Search time: effect of number of targets and target complexity;

7.513 Search time: effect of number of colors and information density;

7.514 Effect of irrelevant stimuli on search performance;

7.519 Search time: effect of color coding;

7.524 Visual search for multiple targets;

7.526 Detection of objects and events in real-world scenes;

Handbook of perception and human performance, Ch. 28, Sects. 2.2, 2.3

7.517 Search Time: Effect of Number of Background Characters and Display Density

Key Terms

Camouflage; color coding; display clutter; display density; display size; target acquisition; target recognition; uncertainty; visual acuity; visual search

General Description

Search time is approximately proportional to the number of items present in a display. When combinations of area and density (number of background characters per deg^2) are chosen to give specific numbers of background characters ("clutter"), the major effect on search time comes from number of background characters rather than from area or density. Density has a separate effect: for a given number of background characters, search performance is enhanced with increasing density (CRef. 7.518 and Constraints section.

Applications

Number of non-target elements in a visual display is a primary determinant of search performance. The separate effect of density indicates that it is more efficient to search densely packed items than spaced items; close packing more than compensates for camouflage effects. Display design should then capitalize on the fact that, for a given number of non-target elements, increased density, or packing, will enhance search performance.

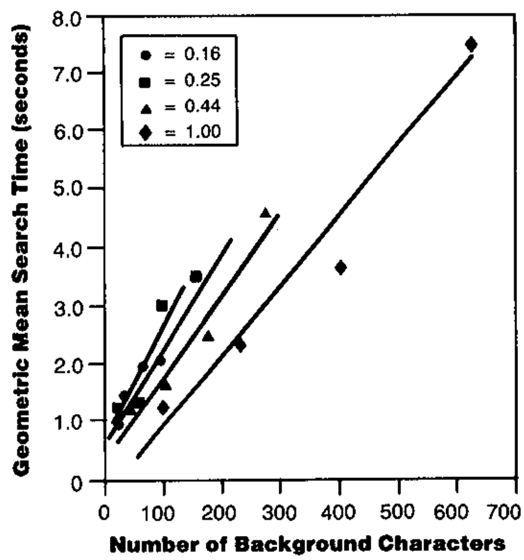

Figure 1. Geometric mean search time for different numbers of display background characters and different display densities (characters per deg^2). (From Ref. 1)

Methods

Test Conditions

- Letter displays photographed onto 35 mm slides were projected onto screen 2.13 m from observer
- Each display consisted of 25 x 25 possible positions, each filled by a background character (A, I, or H), a blank, or a target (F); each letter subtended 1 deg of visual angle; single target located randomly within each search field
- Other stimulus and viewing conditions not specified

Experimental Procedure

- Independent variables: display density, or letter separation (0.16, 0.25, 0.44, and 1.0 characters per deg^2) and display area 10 x 10, 15 x 15, 20 x 20, or 25 x 25 degrees), resulting in 16 condition combinations
- Dependent variable: time to locate target
- Observer's task: timer started when stimulus appeared on screen; when target located, observer pressed response key to stop timer and remove stimulus
- 8 observers, Air Force second lieutenants, 22-24 yr old, 7 had 20/20 or better vision (corrected or uncorrected); 8th had 20/50 and 20/40 in left and right eyes, respectively

Experimental Results

- Equal numbers of background characters do not give equal geometric mean search times (GMST); the effects of area and density cannot be combined into one measure.
- The largest effect on search times is from number of background characters; a smaller but significant effect ($p<0.05$) of area and packing density shows up as relatively shorter search times than would be expected on the basis of number of background characters with increasing density.
- Multiple regression analysis shows that number of background characters alone accounts for 86% of variance ($p<0.0001$) in geometric mean search time. Area (display size) and packing density account for an additional 8.25% of variance ($p<0.005$).

$$\text{GMST} = 0.9066 - 1.2269\,(\text{density} + 0.0015) \times (\text{area}) + 0.0106\,(\text{number of background characters})$$

$$R^2 = 0.97$$

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other studies have found a number-of-background-items effect (Refs. 2, 3). These studies, however, did not separate out the effects of area and density. Ryll (Ref. 4) developed an analytical detection/recognition model for predicting multiple object confusion probability, which is given by:

$$P = \left[1 + \left(\frac{M}{29T^{0.93}}\right)^{1.29}\right]^{-1}$$

where M is the number of confusing objects in the field and T is the frame time. This formulation yields a decrease in performance according to the number of confusing background items (Ref. 1). Ryll's formulation was subsequently made a part of various target acquisition models, including GRC and MARSAM (CRef. 7.607).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The effects of clutter density may be either a linear increase or a linear decrease, depending on the nature of the target, the clutter, and other conditions. Letter reading (this entry) is an overlearned skill that yields a linear decrease; in contrast, simple visual density (CRef. 7.518) yields a linear increase of visual search time with clutter. Thus real-world situations must be tested to see which result applies.
- There is no evidence as to whether density effects result from close packing of display items or from introduction of regularity into the display.
- In the real world, larger areas usually include more nontargets.
- In the real world, targets and many nontargets are often difficult to distinguish.

Key References

*1. Drury, C., & Clement, M. (1978). The effect of area, density, and number of background characters on visual search. *Human Factors, 20*, 597-602.

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3. Green, B. F., & Anderson, L. K. (1956). Color coding in a visual search task. *Journal of Experimental Psychology, 51*, 19-24.

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Cross References

7.315 Effect of display size on visual fixation;

7.501 Factors affecting visual search with monochrome displays;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.512 Search time: effect of number of targets and target complexity;

7.513 Search time: effect of number of colors and information density;

7.514 Effect of irrelevant stimuli on search performance;

7.518 Search time: effect of target surround density;

7.519 Search time: effect of color coding;

7.526 Detection of objects and events in real-world scenes;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.608 Multiple regression model of target acquisition

7.518 Search Time: Effect of Target Surround Density

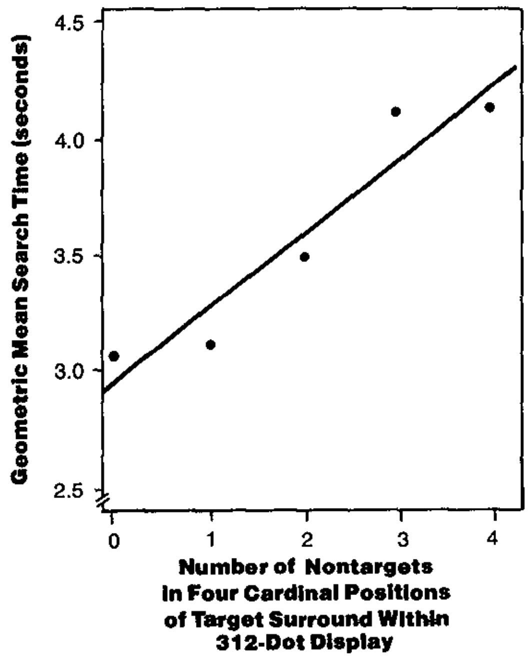

Figure 1. Target geometric mean search time (GMST) as a function of number of non-targets in target surround in cardinal display positions. (From Ref. 4)

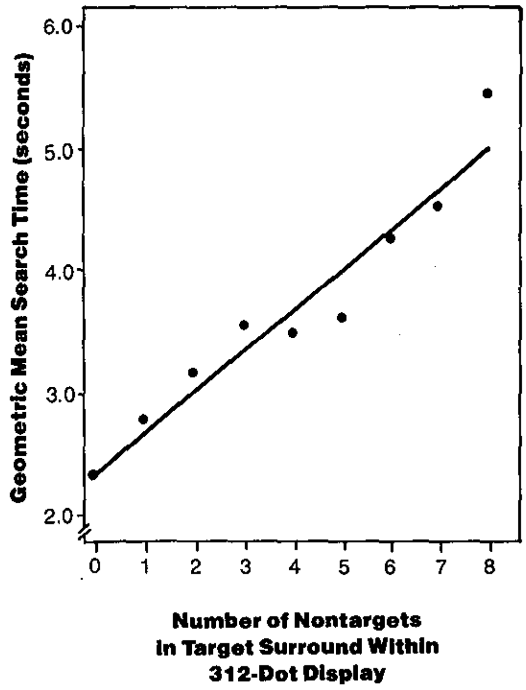

Figure 2. Target (GMST) as a function of number of non-targets in target surround. (From Ref. 4)

Key Terms

Camouflage; color coding; display clutter; display density; target acquisition; target identification; training; uncertainty; viewing context; visual search; visual search time

General Description

Visual search time increases linearly with non-target density ("clutter") in the area of display immediately surrounding a target (CRef. 7.517 and Constraints section). This effect may be responsible for the increase in search time often found with increases in overall non-target density of a display.

Applications

The effect of target surround density is one of camouflage rather than facilitation. In general, geometric mean search time is proportional to target surround density. The number of non-targets in any subset of the target surround can be used as a linear predictor of search time.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Displays were computer-generated random-dot arrays presented on an oscilloscope with P31 green phosphor; square display capable of presenting 625 (25 x 25) dots and subtending 5 deg 3 min arc of visual angle at viewing distance of 61 cm; headrest-controlled viewing distance
- Each display comprised of 312 ± 5 randomly displayed dots, altered to conform to experimental conditions; displays created beforehand and recorded on magnetic tape
- Non-targets were single dots of 2.4 min arc diameter, separated by at least 12.6 min arc; targets were double dots separated horizontally by 1.2 min arc; one target appeared in each display; non-targets 3.8 cd/m^2; targets 22.4 cd/m^2
- Observers seated in sound attenuating cubicle

Experimental Procedure

- Independent variables: Experiment 1: five values of number (n') of non-targets (0, 1, 2, 3, 4) in four cardinal display positions of the target surround (north, south, east, west); target surround defined as array of possible non-target positions surrounding target; Experiment 2: four values (0, 1, 3, 4) of n' combined with four values (0, 1, 2, 4) of number (c') of non-targets in four corner target surround positions (NE, SE, SW, NW)
- Dependent variables: target identification time for correctly identified targets, defined as time from when display shown until target identified; geometric mean search times computed; target identification accuracy
- Observer's tasks: listen for altering tone, depress key causing display to be shown, release key when target identified, and use two potentiometer controls to position moveable dot over target for identification accuracy measurement.
- 8 observers per experiment

Experimental Results

- Target identification error rates are low (1.28 and 1.02% in Exps. 1 and 2, respectively) and were not analyzed.
- In Exp. 1, analysis of variance shows the effect of n' (number of non-targets in four cardinal display positions) is significant ($p < 0.001$). A least-squares fitted straight line accounts for 91% of the variance in the relationship between number of non-targets and geometric mean search times (GMST).
- In Exp. 2, analysis of variance shows the effect of c'(number of non-targets in four corner surround positions) and n' to be significant (each $p < 0.0001$), with no significant interaction. A least-squares fitted straight line accounts for 93% of the variance in the relationship between number of non-targets (n' and c') and GMST.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other studies (Refs. 2, 3, 5) show search time to increase linearly with overall non-target density. Linear relationships found in these studies may be due to increasingly congested target surrounds produced by increasing overall non-target density. Bailey (Ref. 1) formulated a visual detection model in which the density of confusing objects (i.e., scene complexity) is important only within observer's effective scanning aperture. Aperture size depends upon observer's prior knowledge of the target's size and contrast. Bailey's model is:

$$P_t = 1 - \exp(700\, a_T t / M A_S)$$

where a_T is target area; A_S is search area; t is search time, and M is the density of confusing forms within observer's scanning aperture.

Constraints

- When the non-target objects (clutter) are processed by an overlearned skill (e.g., letter reading in CRef. 7.517), visual search time decreases rather than increases with increasing clutter. Thus real-world situations must be empirically tested to see which result applies.
- Results may not be applicable to search in structured fields.
- Target color coding may decrease identification times significantly.
- In the real world, other objects are often confused with targets. Also, targets often appear to be non-targets, and context is important.

Key References

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5. Smith, S. L. (1962). Color coding and visual search. *Journal of Experimental Psychology, 64,* 434-440.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.519 Search time: effect of color coding;

7.524 Visual search for multiple targets;

7.608 Multiple regression model of target acquisition

7.519 Search Time: Effect of Color Coding

Key Terms

Camouflage; color coding; color contrast; conspicuity; display clutter; size; target acquisition; target detection; visual search time

General Description

In the search for three-digit color targets among three-digit color background distractors, search time decreases as the difference in color between a target and background distractor objects increases (Refs. 1, 3). When there is no difference between the target and background distractor color, search time depends on display density. As color differences between the target and background distractors become more distinct, search time depends on the number of distractor objects having the same color as the target.

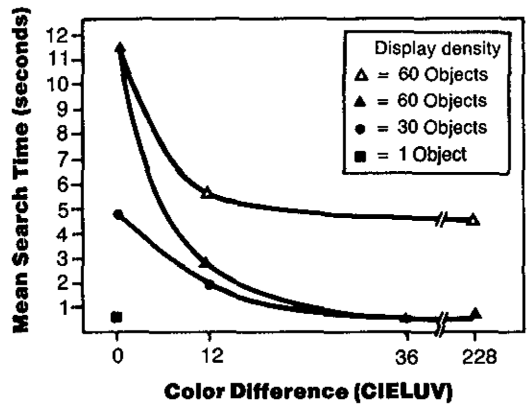

Figure 1. Mean target search time as a function of color difference between target and background objects, target class size, and display density. Each mean represents 648 searches. Open symbols, 30 objects (half of the 60 objects displayed) sharing target's color; closed symbols, one object sharing target's color. (From Ref. 1)

Applications

Procedures to quantitatively describe color differences are available (Refs. 4, 6). Target search performance may be improved by applying the procedures to optimize color differences between targets and background distractor objects.

Methods

Test Conditions

- 1 x 1-m viewing console, neutral-gray surround field with 0.76 cd/m^2 luminance; circular display screen (29.4-cm diameter) centered in surround (14-deg visual angle and 0.011 cd/m^2 luminance
- Targets and background distractors three-digit numbers; area 0.75 deg^2; self-luminous
- Four colors used for targets and background distractors; dark purplish red, luminance 4.71 cd/m^2; light purplish red, luminance, 5.47 cd/m^2; yellowish green, luminance 6.84 cd/m^2; green, luminance 1.18 cd/m^2; combinations of target and background colors yielded CIELUV differences of 0.0, 11.8, 36.4, 228.0 (Ref. 6)
- Viewing distance and other viewing conditions not specified

Experimental Procedure

- Each of ten different combinations of experimental conditions represented by 36 displays searched by one of ten groups of 18 observers each
- Independent variables: target class size, defined as number of objects sharing the target's color (1 or 30); display density, defined as number of objects displayed (1, 30, or 60); CIELUV color difference between target class objects and other displayed objects
- Dependent variables: search time measured to nearest 0.01 sec and defined as time display illuminated by observer's action
- Observer's task: depress button to illuminate display and start timer, search for target, release illumination timer button, stop timer, and report target's unique third digit
- Before each search trial, observer told first two digits of target; reporting unique third digit provided accuracy check; target's color was known and unvarying for all of each observer's trials
- 180 observers in 18 groups of 10 each; ages 17-35; normal acuity and color vision

Experimental Results

- No search errors occurred.
- Search time decreases as target-background distractor color difference increases.
- In the absence of target-background distractor color difference, search time is dependent on display density.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results have been replicated under similar conditions (Ref. 2). Different target-background color combinations have different conspicuity, although background color does not significantly affect response time (Ref. 5). As luminance contrast decreases, visibilities of some color combinations decrease considerably before rising rapidly to a maximum at zero luminance contrast. These effects predominate at luminance contrasts below 0.4 (Ref. 3).

Constraints

- No statistical tests of significance among means were reported.
- Only a few color differences were represented in the study reported (Ref. 1).
- Absolute target color also is an important determinant of search time.
- Targets and distractors were highly similar (all were three-digit numbers). The full magnitude of decreases in search time observed for large target/distractor color differences might not be realized where targets and distractors are dissimilar along other dimensions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Carter, E. C., & Carter, R. C. (1981). Color and conspicuousness. *Journal of the Optical Society of America, 71*, 723-729.

2. Carter, R. C. (1982). Search time with a color display: Analysis of distribution functions. *Human Factors, 24*, 203-212.

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6. Robertson, A. (1977). The CIE color difference formula. *Color Research Applications, 2*, 7-11.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.511 Search time and eye fixations: effect of symbol color, size and shape;

7.513 Search time: effect of number of colors and information density;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.524 Visual search for multiple targets;

7.525 Target acquisition in real-world scenes;

7.608 Multiple regression model of target acquisition;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.126 Color misregistration: effect on symbol identification;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

7.520 Controlled and Automatic Visual Search

Key Terms

Attention; automatic search; controlled search; memory; target acquisition; visual search

General Description

Consistent mapping (CM), or pairing, of stimuli and responses results in an automatic process, which is a well learned behavioral sequence cued by some input and does not require attention. Varying stimulus-response mapping (VM) results in a controlled process, one that requires memory and attentional capacity. Search for multiple targets is impeded to a much greater degree in a controlled search than in an automatic search. Once learned, automatic responses are virtually impossible to ignore.

Applications

Displays in which an operator must search for a target against a changing background, especially when the target (or class of targets) changes from moment to moment.

Methods

Test Conditions

Study 1 (Ref. 5)

- Memory set of one, two, or four target characters (digits or consonants) presented for as long as observer wished
- Five frames (presented sequentially) per trial, each with four elements forming a square around a central fixation dot; elements in third frame were one, two, or four digits or consonants (frame size) with random dot masks as any remaining elements; other frames contained only four random-dot masks; stimulus-onset intervals between frames of 160 msec and **interstimulus intervals** of 15 msec
- Four elements in third frame were some combination of targets, distractors, and masks; four mapping conditions: (1) a search for digits among consonants; targets were never distractors (consistent); (2) a search for consonants among consonants; targets could be distractors on other trials (varied); (3) a search for consonants among digits; targets were never distractors (consistent); and (4) a search for digits among digits; targets were distractors on other trials (varied)

Study 2 (Ref. 5)

- Memory set was one or four target characters (digits or consonants) presented for as long as observer wished
- 20 frames (presented sequentially) per trial, each with four elements forming a square around a central fixation dot; elements were one, two, or four digits or consonants (frame size); remaining elements were random dot-masks; frame size constant for each trial
- Stimulus-onset intervals were 40, 70, or 120 msec; interstimulus interval was 15 msec
- Targets never appeared in first three or last two frames
- Same four mapping conditions as in Study 1

Experimental Procedure

Study 1

- Independent variables: memory-set size, frame size, mapping condition
- Dependent variable: search rate, defined as the slope of the function relating reaction time to memory-set size
- Observer's task: press key if any member of the memory set detected in a frame, or press a different key after last frame if no target detected; feedback provided
- Observers instructed to maintain high accuracy but to respond as quickly as possible; observers had to be 90% accurate before starting test trials
- 4 observers, all with corrected 20/20 vision and extensive practice; 2 assigned to Mapping Conditions 1 and 2, and 2 to Mapping Conditions 3 and 4

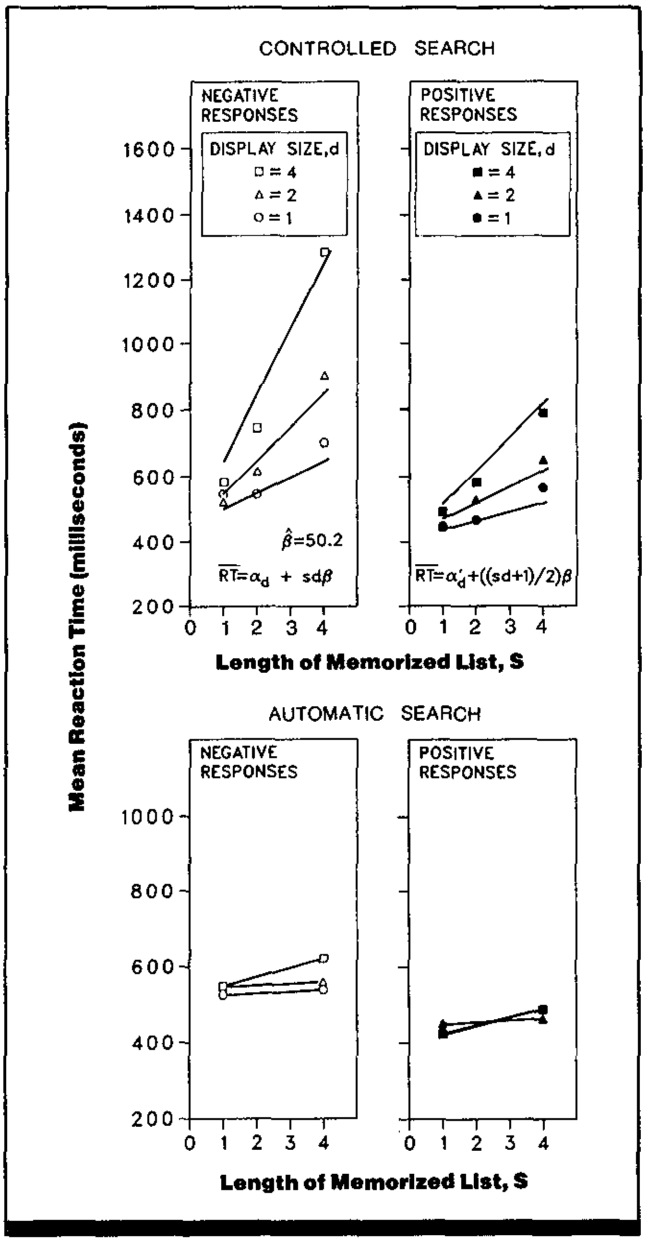

Figure 1. Linear functions relating mean reaction time to memory-set size for each of the three frame sizes in Study 1. Each data point represents an average of 400 observations. Positive and negative responses indicate that memory set member was or was not detected in frame, respectively. (From Ref. 5)

Study 2

- Independent variables: memory-set size, frame size, stimulus-onset interval, mapping condition
- Dependent variable: detection rate, defined by percentages of hits and false alarms on search task
- Observer's task: press key if any member of the memory set detected in a frame, or press a different key after last frame if no target detected; feedback provided
- Observers instructed to maintain highest possible level of accuracy

Experimental Results

- In Study 1, the linearly increasing reaction time (RT) function with increases in memory-set size accounts for 95.8% of variance in the varied-mapping condition. This implies that frequently changing targets result in a controlled search, involving a serial comparison process that requires memory and attention capacity. The rate of the comparison process, indicated by the slope of the RT function, is ~50 msec.
- In Study 1, the RT function is relatively unaffected by

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

memory-set size in the consistent mapping condition. This implies that well-learned target sets result in an automatic search, involving a parallel comparison process, that does not require memory and attentional capacity.

- Error rates in Study 1 for consistent mapping never exceed 5% for varied mapping, error rates never exceed 10%.
- In Study 2, increasing the numbers of comparisons (i.e., increasing frame size and memory-set size) results in a monotonic decrease in hit rate in the varied mapping condition, implying a time-consuming serial comparison process (Fig. 2b). In the consistent mapping condition there is almost complete independence between hit rate and number of comparisons, indicating a parallel search process (Fig. 2a). These results support the dichotomy between controlled and automatic processes of Study 1.
- In a related study, observers with 20,000 trials of consistent mapping experience massive interference when stimulus-response mapping is reversed. This implies that it is virtually impossible to ignore automatically learned responses (Ref. 5).

Variability

Standard deviation for the comparison rate in Study 1 is 53.57 msec. In Study 2, standard error of the mean for each point is at most 0.032.

Repeatability/Comparison with Other Studies

These results replicate findings of other studies for controlled search (Refs. 1, 4, 6) and for automatic search (Ref. 4). The methodology provides a way to empirically distinguish between controlled and automatic search processes.

Constraints

- Memory-set lists employed here were small (maximum of four items), and were drawn from only two classes (constants and digits).
- Computed values for the slope of the reaction time (RT) function given here hold only for conditions described and should not be applied, except qualitatively, when conditions differ.
- Automatic versus controlled processing was manipulated in Ref. 3 by confounding within- and between-category search. (a) This may confound two different sets of processes and, (b) category effects in visual search are controversial (Refs. 2, 3). With only one target, the presence or absence of a category effect can be manipulated by manipulating the physical confusability of target and distractors.

Key References

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2. Duncan, J. (1983). Category effects in visual search. *Perception & Psychophysics, 34*, 221-232.

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Cross References

4.103 Memory search rates;

4.104 Skilled memory effect;

4.106 Memory for visual patterns: effect of perceptual organization;

7.512 Search time: effect of number of targets and target complexity;

Handbook of perception and human performance, Ch. 7, Sect. 2.3

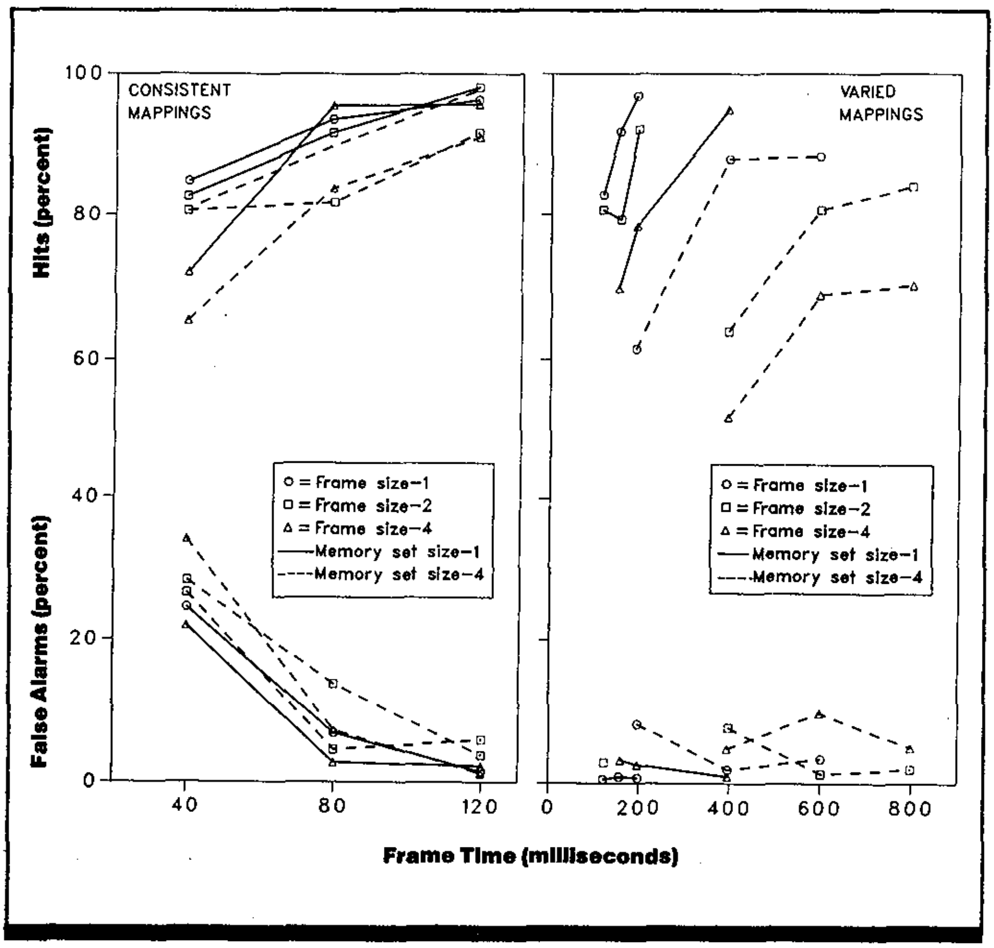

Figure 2. Hit rates and false-alarm rates for each of the frame times in the consistent and varied mapping conditions in Study 2 as a function of frame size and memory-set size. Each data point represents 60 observations. (From Ref. 5)

7.521 Effect of Target Lag and Sequential Expectancy on Search Time

Key Terms

Display evaluation; expectancy; target acquisition; time delay; visual search time

General Description

Target lag is the time from the appearance of the display background until the target is displayed. Using target lag to systematically control the observer's search time, post-target search time (PTST, total search time minus target lag) increases with target lag when target lag is varied randomly from trial to trial. Sequential expectancy effects occur; PTST for trials on which target lag is the same as the immediately preceding trial is only slightly higher than for the zero lag condition. However, for trials on which target lag changes from the immediately preceding trial, PTST is slightly higher than for the greatest lag condition tested (15 sec).

Applications

The prediction of target search times on displays such as radar when intervals between appearances of targets may be variable over repeated observations.

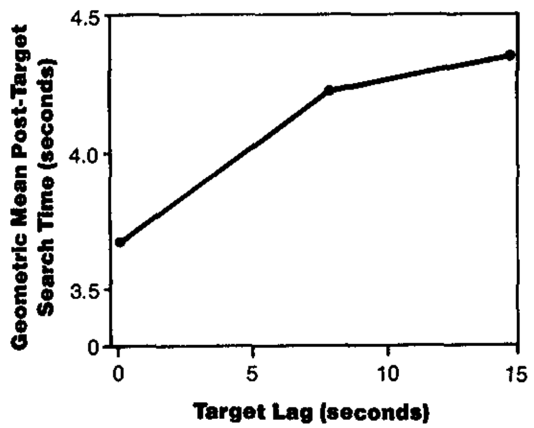

Figure 1. Geometric mean post-target search time as a function of target lag and lag repetition. (Data from Ref. 2)

Methods

Test Conditions

- Displays presented on oscilloscope with P31 green phosphors; non-targets (background) were 199 dots randomly distributed in 20 x 20 matrix of possible positions; distribution of non-targets changed randomly from trial to trial; non-target luminance 10.6 cd/m^2
- Target also a dot (dot size not specified but dots easily identifiable individually); target position varied randomly from trial to trial in one of 201 target display positions; target luminance 15.8 cd/m^2
- Viewing distance controlled at 620 mm by headrest; lens (125 mm focal length) was 10 mm from display surface; produced magnified display image subtending 7 deg 30 min at observer's eye
- Observers and display in sound-attenuating cubicle; ambient illumination not specified

Experimental Procedure

- Independent variable: one of three lags (0, 7.5, or 15 sec) from appearance of display background until appearance of target
- Dependent variables: post-target search time, number of target identification errors
- Observer's task: monitor for an alerting tone signifying start of each trial, depress a response key causing display to be presented, release key when target located; position cursor over target for identification accuracy measurement
- 3 observers, 1 male, 2 female, mean age 22 yr with 20/20 vision (corrected in two cases), with some practice

Experimental Results

- Trials with errors of identification (2.75% error rate) are about equally split among the lag conditions tested. Data for incorrect trials were excluded from all subsequent analyses.
- PTST data were transformed to natural logarithms to yield acceptably normal data distributions.
- Repeated presentations of one lag value generate shorter PTSTs than other trials ($p < 0.05$).
- PTST increases significantly with target lag ($p < 0.05$).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other studies have demonstrated the presence of target repetition effect (shorter search times for repeated targets, Ref. 2), which may be related to sequential expectancies.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Generalization of laboratory data to operational applications should improve empirical verification.

Key References

1. Monk, T. H. (1974). Sequential effects in visual search. *Acta Psychologica, 38*, 315-321.

*2. Monk, T. H. (1977). Sequential expectancy in visual search. *Human Factors, 19*, 601-606.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.503 Effect of head and eye movement on target acquisition;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.520 Controlled and automatic visual search

7.522 Visual Search for Moving and Static Targets

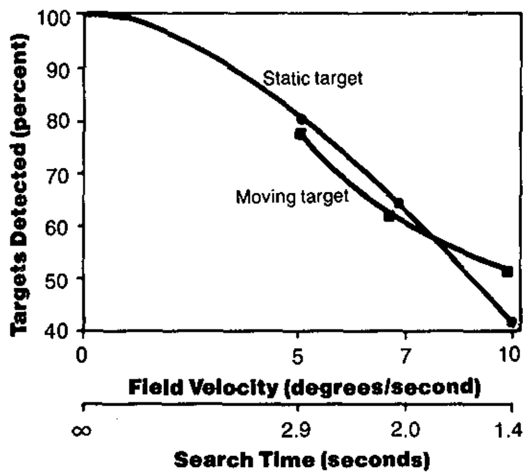

Figure 1. Search performance for a Landolt-C target in an array of solid rings with static and moving fields, collapsed across object density. Search time for static targets is equated with exposure time for moving targets as shown in the bottom scale. (From Ref. 2)

Key Terms

Dynamic visual acuity; spatial resolution; target acquisition; target detection; target motion; visual acuity; visual search time

General Description

Visual search for a **Landolt-C** target in an array of black rings does not differ significantly for a static target versus one moving at low velocity. Observers show no change in search performance when total field (including target and distractors) is moving slowly as compared to when it is static.

Methods

Test Conditions

- Field of 15, 31, or 47 black rings with outside diameter of rings 1.3 cm (0.5 in.) and inside diameter 0.8 cm; display included one Landolt-C target with gap subtending 3.6 min arc of visual angle; contrast of ring and target against screen about − 0.95; 61-cm (2-ft) square display within 2.4-m, flat-back surround; 2.44-m viewing distance
- Visual search of static field or a field moving at velocity of 5, 7, or 10 deg/sec
- Luminance of field ~600 cd/m^2 (176 fL)

Experimental Procedure

- Method of constant stimuli
- Independent variables: velocity of movement in moving-field condition, elapsed search time for static-field condition
- Dependent variable: percent correct detection of Landolt C targets (results collapsed across number of rings per field)
- Observer's task: to search field of rings for Landolt C and to respond with button press and vocal response indicating direction of gap as soon as target is sighted
- 16 male observers (ages 23-41), with some practice

Experimental Results

- There is minimal difference in target detection performance between static and moving displays.
- Search performance for a Landolt-C target in a field of solid rings decreases as the velocity of display movement increases from 5-10 deg/sec and as search time decreases.

Variability

Split-half reliabilities for 15 of 17 performance scores of observers were of acceptable magnitudes (>0.78). Hence, observers were quite stable in their performance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Tests were always ordered from easiest to most difficult, and this ordering was repeated within sessions for object density.
- Many factors, such as velocity, search strategy, luminance, target size, and number, can influence acuity and must be considered in applying these results to other viewing conditions.

Key References

1. Erickson, R. A. (1964). *Visual search for targets: Laboratory experiments* (NAVWEPS-8406). China Lake, CA: Naval Ordinance Test Station. (DTIC No. AD448468)

*2. Erickson, R. A. (1964). Visual search performance in a moving structured field. *Journal of Optical Society of America, 54*, 399-405.

Cross References

1.915 Effects of target characteristics on eye movements and fixation;

1.939 Factors affecting smooth pursuit eye movements;

1.940 Gain and phase of smooth pursuit eye movements: effect of target motion;

1.941 Gain of tracking eye movements: effects of target luminance and visual field location;

1.942 Latency and velocity of smooth pursuit eye movements: effect of target velocity;

1.945 Accuracy of tracking eye movements: effect of target velocity;

1.960 Factors affecting coordination of head rotation and eye movements;

7.502 Visual search rates with eye movements;

7.516 Target acquisition in distractor target arrays;

7.524 Visual search for multiple targets;

9.203 Fitts's Law: movement and reaction time as a function of target distance and size

7.523 Target Counting: Effects of Grouping

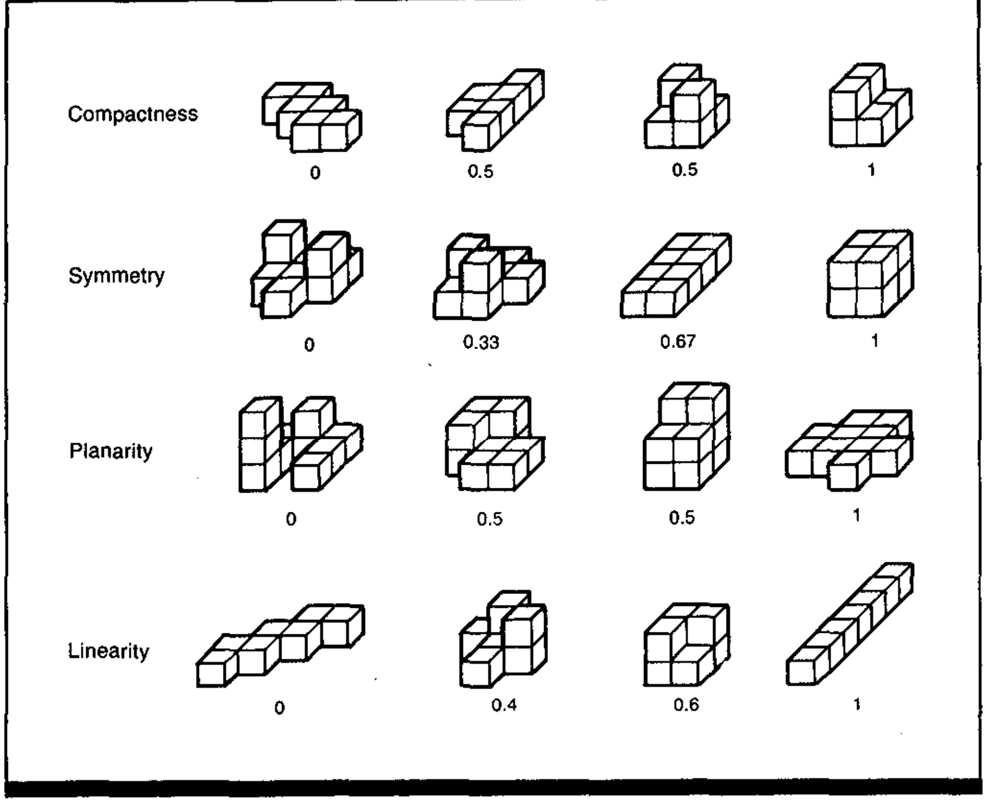

Figure 1. Block structures used in Study 1, varying in compactness, symmetry, planarity, and linearity from lowest value (0) on the left to highest value (1) on the right. (From Ref. 1)

Key Terms

Counting; grouping; subitization; target acquisition

General Description

The time it takes to determine how many objects are in the visual field increases as a bilinear function of the number of objects (Figs. 2, 3). One linear function reflects subitization, a rapid, accurate quantification of one to three or four objects. The other linear function reflects a slower, less accurate quantification, perhaps by grouping and adding of four or more objects. Quantification is influenced by the display's structural properties; the second process is best expressed as a function of number of perceptual groups (spatially proximate objects sharing a preattentive feature).

Applications

Displays that require quantification of number of objects present will yield more rapid and accurate performance when objects are presented in familiar groupings.

Methods

Test Conditions

Study 1 (Ref. 1)

- Perspective line drawings of three-dimensional block structures scaled to fall within 5 deg of visual angle (Fig. 1) presented tachistoscopically
- Each display contained 1-10 blocks; 20 displays per block size; displays varied in compactness, symmetry, planarity, and linearity (Fig. 1)
- Observer initiated trial by button press and terminated trial by response via voice-operated relay

Study 2 (Ref. 3)

- Random-dot patterns, with 0.4-deg minimum interdot spacing and 1.8-deg maximum visual angle for pattern, presented tachistoscopically
- Each display contained 1-10 dots; 16 displays per pattern size
- Observer initiated trials by button press and terminated trial with a voice-activated microphone ~30.5 cm away

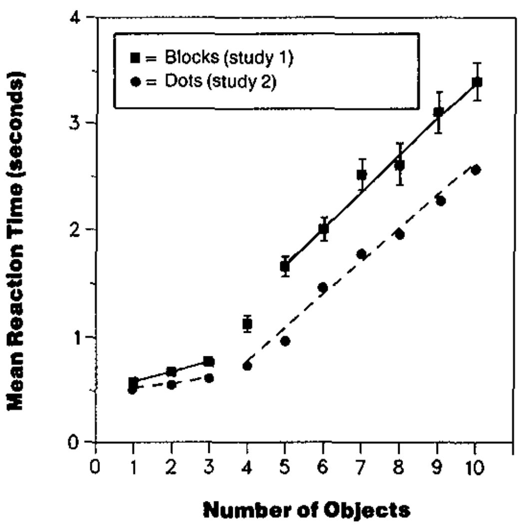

Figure 2. Reaction time for quantification as a function of number of items in the visual field for block structures (Study 1) and dot patterns (Study 2). (After Ref. 1)

Experimental Procedure

Study 1

- Within-subject design
- Independent variables: display size, compactness, symmetry, planarity, linearity
- Dependent variable: reaction time to initiate oral quantity report
- Observer's task: report number of blocks in each display
- 14 observers, ages 15-51, with some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Study 2

- Within-subject design
- Independent variable: display size
- Dependent variable: reaction time (RT) to initiate oral report of quantity, number of quantification errors
- Observer's task: report number of dots in each display
- 12 observers, 3 with some practice

Experimental Results

- Reaction time to quantify is a bilinear function of number of objects in the visual field, with a discontinuity between displays of three objects or less and four objects or more (Fig. 2).
- Composite lines of best fit for Study 1 (solid lines in Fig. 2) calculated separately for subitization (range of 1-3 items) and counting (range of 4-10 items) yield estimated processing times of 94 msec per item for subitization and 363 msec per item for counting. Calculations for Study 2 (dashed lines in Fig. 2) yield estimated processing times of 46 msec per item for subitization and 307 msec per item for counting.
- Structural variables (compactness, symmetry, planarity, and linearity) have a small effect on quantification time. Compactness is the most influential structural variable; in a study using procedures similar to those of Study 2 but using up to 12-block displays, compactness was found to determine the number of perceptual groups (Fig. 3). As a comparison of Figs. 3a and 3b indicates, the data are better fit when number of perceptual groups, rather than number of blocks, is used.

Variability

In Study 1, 11 of 14 subjects were judged to subitize over a range of 1-3 objects, and the remaining 3 subjects were judged to subitize over a range of one to four objects. Composite lines of best fit in the figure are based on a weighted mixture of fits for these two groupings of subjects, with the point for four objects excluded because it fell within the subitizing range for some subjects but not for others.

In Study 2, separate lines of best fit were calculated for n = 1-3 and for n = 4-10.

Error bars in Fig. 2 show ±1 standard error of the mean. Within-subject variability is similar in magnitude. In Study 1, standard deviations for slopes and intercepts of composite fits are 37.1 and 61.3, respectively, for subitization, and 96.6 and 452.0, respectively, for counting. In Study 2, standard deviations for slopes are 5.4 and 65.9 for subitization and counting, respectively.

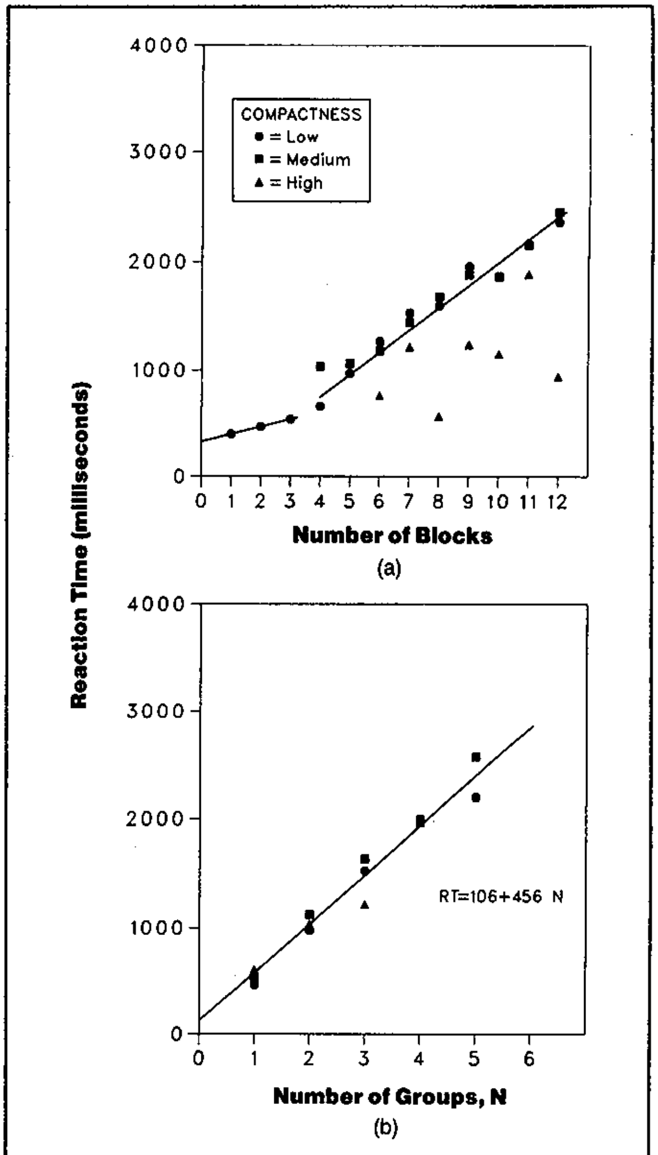

Figure 3. (a) Reaction time for quantification for a single subject as a function of number and level of compactness; (b) the same data as a function of number of reported perceptual groupings. (After Ref. 2)

Repeatability/Comparison with Other Studies

The discontinuity in quantification error and reaction time functions at four to six items is a highly reliable effect.

Constraints

- Absolute values of reaction times will depend on measurement parameters (e.g., distance from subject to microphone).
- When there are a large number of objects in the visual field, people use estimation procedures as well as counting in judging quantity.
- Values obtained for slope and intercept are likely to vary with practice and familiarity of patterns in the display.
- The sharp break between subitization and counting ranges may be attenuated with practice.

Key References

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*3. Chi, M. T. H., & Klahr, D. (1975). Span and rate of apprehension in children and adults. *Journal of Experimental Child Psychology, 19,* 434-439.

Cross References

6.301 Principles of Gestalt grouping and figure-ground organization;

6.310 Perceived shape of partially hidden objects;

7.302 Sampling behavior during process-control monitoring;

7.310 Optimal estimation model;

Handbook of perception and human performance, Ch. 28, Sect. 2.4

7.524 Visual Search for Multiple Targets

Table 1. Mean search time (in msec) for single and multiple targets. (Data from Ref. 3)

	Single Target Condition					Multiple Target Condition				
Sessions	**D**	**J**	**O**	**U**	**Overall**	**D**	**J**	**O**	**U**	**Overall**
1-10	199	142	177	154	167	274	260	277	287	249
11-20	123	72	122	94	103	152	135	159	147	150
21-30	87	60	96	69	77	111	103	105	108	108
31-40	67	44	74	47	57	83	81	84	77	82

Mean time per five-character line for four sets of ten sessions in single and multiple target conditions. Data are for trials on which targets were correctly identified

Table 2. Mean miss rates for each target in single target and multiple target conditions (Sessions 21-40). (Data from Ref. 3)

Targets	Single Target Condition	Multiple Target Condition	Difference (Multiple-Single)
D	0.27	0.23	−0.04
J	0.24	0.13	−0.11
O	0.29	0.36	+0.07
U	0.27	0.21	−0.06
Overall	0.27	0.23	−0.04

Key Terms

Display complexity; practice; target acquisition; target identification; training; uncertainty; visual displays; visual search; visual search time

General Description

After considerable practice, observers can search for multiple targets almost as fast as for single targets, although search times remain somewhat higher for multiple-target conditions (Table 1). Identification accuracy can decrease and search time can increase when additional targets are added to the search set; however, changes in performance depend on specific targets (Table 2). When averaged across target types, miss rates (non-identifications) are comparable for single-target and multiple-target conditions. In general, the addition of targets to a search set will either increase error rates or increase search times.

Applications

The design of target acquisition search strategies where tradeoffs between speed and accuracy must be considered. The design of target acquisition training programs where acceptable performance levels may require extensive practice.

Methods

Test Conditions

- Lists of target and non-target letters displayed on IBM 1510 CRT; different lists randomly generated for each trial; lists 29 rows long by five letters wide; non-target background letters, X, F, G, H, K, P, T, V; target letters D, J, O, U; target letters chosen to be equally discriminable; target position in lists varied randomly
- Viewing distance ~38 cm; resulting display area ~5 x 31 deg
- No information about room conditions reported; displays presumably quite visible
- At start of each trial, target displayed on left side of CRT; observer looked at fixation point appearing at same location as center point of first line of list; depressed button to display list and start timing; observers instructed to scan lists from top to bottom as rapidly as possible; observer pressed button again when target found or list completed without identifying target to stop timer; then blanking field covered letters in list and observer located target position with light pen or placed light pen on special target area if target not located; if observer failed to identify target on any list, a comparable list was added
- Monetary payoff schedule encouraged speed over accuracy

Experimental Procedure

- Lists presented in counterbalanced orders over 40 days; single and multiple-target lists presented in each daily session
- Independent variables: single target and multiple targets
- Dependent variables: search time per five-letter row; miss rates, defined as number of trials per session on which observer failed to identify target divided by number of trials per session on which target appeared
- Observer's task: look at fixation point on display and read displayed target letter; after depressing button to start trial, scan list as quickly as possible for target and depress button when target found or list completed without finding target; position light pen over approximate target location or in special area when target not found
- 3 observers

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Target search times decrease with practice; final search times are approximately one-third as long after 40 practice sessions.
- Addition of targets to the search set may either increase error rates or reduce search speed.
- The four targets in the multiple target search condition are not equally identifiable. Two observers show higher miss-rates for the "difficult" (O) target versus the "easy" (J) target.
- Probability of detecting "difficult" target decreases when the number of targets is increased.
- When error rates for each target in the multiple target condition are pooled, the low, "easy" target error rate cancels out the high error rate of "difficult" targets, producing similar error rates for both conditions.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Erickson (Ref. 1) has reported similar results of accuracy versus speed in searching for multiple targets. Other studies have shown that observers can scan for many targets as rapidly and accurately as for one (Ref. 2), but error rates for all targets in multiple-target conditions were pooled, leaving open the possibility that the error rate for the target in the single target condition increased when other targets were added to the search set.

Key References

1. Erickson, R. A. (1964). Visual search performance in a moving structured field. *Journal of the Optical Society of America, 54,* 339-405.

2. Neisser, U. (1963). Decision-time without reaction time: Experiments in visual scanning. *American Journal of Psychology, 76,* 376-385.

*3. Yonas, A., & Pittenger, J. (1973). Searching for many targets: An analysis of speed and accuracy. *Perception & Psychophysics, 13,* 513-516.

Cross References

7.512 Search time: effect of number of targets and target complexity;

7.513 Search time: effect of number of colors and information density;

7.514 Effect of irrelevant stimuli on search performance;

7.516 Target acquisition in distractor target arrays;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.525 Target acquisition in real-world scenes

7.525 Target Acquisition in Real-World Scenes

Key Terms

Display complexity; reaction time; schemas; target acquisition; target detection; viewing context; visual search time

General Description

The overall coherence of an object's setting in the real world affects the speed of its detection by an observer (the greater the coherence, the faster the detection). Apparently schemas can precede and facilitate the processing of detailed features in a visual scene. Facilitation is greatest when the target has a very low probability of occurrence in a scene (e.g., an automobile tire in a kitchen).

Applications

Understanding the influence of context when designing electronically generated displays.

Methods

Test Conditions

- Stimuli were 112 black and white slides (35 mm) made from real-world scenes (street, etc.)
- Scenes in slides either coherent (normal) or jumbled (scenes segmented in six sections) which were rearranged (not rotated) to destroy natural spatial relationships with one section left in its coherent position; each scene contained at least four intact, well defined objects, with one of the objects always in the section that was identical in both coherent and jumbled versions of a scene
- Scenes subtended 19 deg of visual angle and were projected by a slide projector with fast rise-time shutter; viewing distance and room conditions such as luminance not reported
- Subject studied photograph of target object for ~5 sec before slide was presented

Experimental Procedure

- Independent variables: scene version (coherent or jumbled), response category (x-axis in Fig. 1): object present in scene ("yes" response); object not present but is possible object within scene context (i.e., dishwasher in kitchen) (possible/"no" response); object not present and not supported by scene context (i.e., automobile tire in kitchen) (impossible/"no" response)
- Dependent variables: reaction time (RT) in sec, percent correct responses
- Observer's task: decide whether object is in scene and then press either "yes" or "no" response key
- 36 observers, university students

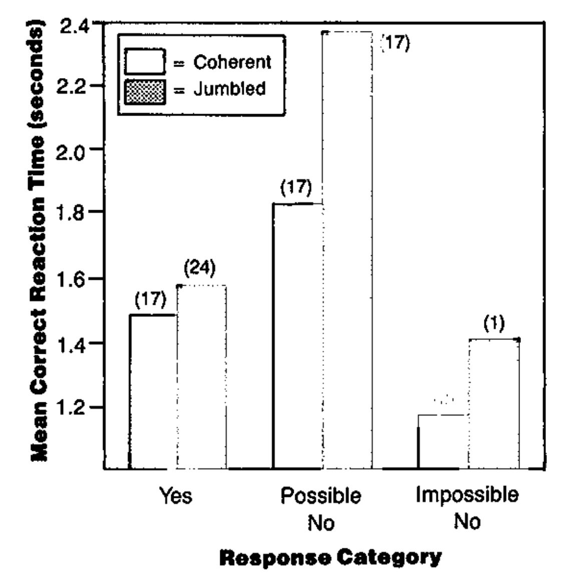


Figure 1. Average of medians of correct reaction times as a function of scene version (coherent or jumbled) and response category. Numbers in parentheses are percent errors. (From Ref. 1)

Experimental Results

- Overall reaction time (RT) for coherent scenes is shorter than for jumbled scenes ($p < 0.01$).
- Overall RT for impossible/"no" responses is faster (average 0.75 sec) than for possible/"no" responses ($p < 0.01$).
- Subjects make very few errors when an object has a low probability of occurrence in a scene (the impossible/"no" condition), and make many errors when an object is in a scene but the scene is jumbled.

Variability

No information on variabilty was given but analyses of variance were used to test significance.

Repeatability/Comparison with Other Studies

Recent studies on target recognition (Refs. 2, 3, 4) support the results of this experiment.

Constraints

- Scene complexity may have influenced the results; an object in a coherent scene may have been divided into separate parts (i.e., become several objects) in the jumbled version of the scene.
- Significance of difference in reaction time for coherent and jumbled scenes was not tested separately for each of the three conditions; there was a significant interaction term for coherency and response category ($p < 0.05$). The coherent and jumbled RTs for yes responses may not significantly differ; error analysis indicates the effect of coherence could be underestimated if there is a speed-accuracy tradeoff.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Biederman, I., Glass, A. L., & Stacey, E. W., Jr. (1973). Searching for objects in real-world scenes. *Journal of Experimental Psychology*, *97*, 22-27.

2. Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive Psychology*, *3*, 674-698.

3. Michie, D. (1971). On not seeing things. *Experimental programming report No. 22*. Edinburgh, Scotland: University of Edinburgh, Department of Machine Intelligence and Perception.

4. Rumelhart, D. E. (1970). A multicomponent theory of the perception of briefly exposed visual displays. *Journal of Mathematical Psychology*, *7*, 191-218.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.512 Search time: effect of number of targets and target complexity;

7.514 Effect of irrelevant stimuli on search performance;

7.518 Search time: effect of target surround density;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability

7.526 Detection of Objects and Events in Real-World Scenes

Table 1. Summary of data on role of visual organization in information extraction from scenes.

Materials	Task	Variables	Results	Source
Photographic slides of real-world scenes, sectioned in sixths and shown as coherent or scrambled pictures	Identification of an object in a cued location at brief (300-700 msec) durations in foveal vision	Coherent versus scrambled scenes, precue versus post-cue, known versus unknown response alternatives	Correct identifications are higher for coherent than for scrambled scenes under all conditions. Scores range from 45% (postcue, scrambled scenes, unknown response alternatives) to 75% (precue, coherent scenes, known alternatives)	Ref. 1
Photographic slides of real-world scenes, sectioned in sixths and shown as coherent or scrambled scenes	Visual search to find target object	Coherent versus scrambled scenes, presence versus absence of object, compatibility of target with scene (i.e., whether or not the target would likely appear in the scene, such as car on a street or in a kitchen)	Search is faster for coherent than for scrambled scenes; the largest advantage comes from establishing the absence of a compatible target	Ref. 2
Videotaped sequences of a ballgame and a hand-game, with tapes seen via a mirror arrangement that visually superimposed one tape over the other	Detecting events in dynamically changing displays	Number of episodes monitored, binocular versus dichoptic viewing, number of events per episode	Subjects can effectively ignore one episode and monitor the other (<3% error), but they can not accurately monitor both (20-40% error)	Ref. 3

Key Terms

Attention; event perception; image interpretation; object identification; pattern perception; selective attention; target detection; visual search time

General Description

Detection and identification of objects and events in a naturalistic scene, whether a static picture or a dynamically changing sequence, is faster and more accurate when the scene can be given a single, meaningful organization. Disorganized scenes or those that require multiple concurrent organizations substantially disrupt performance. Table 1 summarizes the results of several studies investigating information extraction from real-world scenes.

Constraints

- Little is known about how much the relative difficulty of monitoring multiple or disorganized scenes can be reduced by practice or incentive.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Biederman, I. (1972). Perceiving real-world scenes. *Science, 177*, 77-79.

2. Biederman, I., Glass, A. L., & Stacy, E. W., Jr. (1973). Searching for objects in real-world scenes. *Journal of Experimental Psychology, 97*, 22-27.

3. Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology, 7*, 480-494.

Cross References

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.513 Search time: effect of number of colors and information density;

7.514 Effect of irrelevant stimuli on search performance;

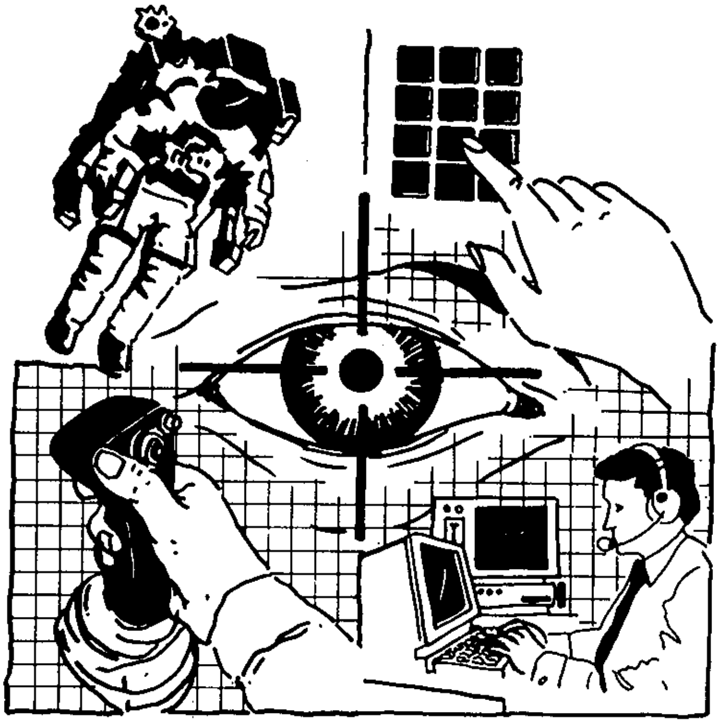
7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.525 Target acquisition in real-world scenes

Notes

Section 7.6 Target Acquisition



7.601 Atmospheric Conditions and Visual Effects

Key Terms

Accommodation; apparent contrast; atmospheric MTF; contrast attenuation; contrast ratio; identification; target detection; target recognition

General Description

Target acquisition (detection, recognition, and identification) is directly proportional to target angular size and apparent target-background luminance ratio (contrast). **Contrast attenuation** of a target increases with distance (range) from the observer to the target due to atmospheric filtering (scattering and absorption), which varies with wavelength and altitude.

The most complete statement of the attenuation of visual images by the atmosphere is expressed by the atmospheric modulation transfer function (AMTF). The approach uses formulas applied to specific sinusoidal frequencies. If the **spatial frequency** signature of a target is known, expected modification of the spatial frequency signature by viewing at far distances through the atmosphere can be estimated using AMTF. This provides a basis for computing target detail loss due to atmospheric attenuation. While not affecting overall contrast (and target detection), detail loss reduces target recognition and identification probabilities.

Applications

Target acquisition probability under long-distance viewing through the atmosphere can be estimated from expected target angular size and expected apparent target-background contrast at each spatial frequency.

Method of Application

Contrast attenuation by the atmosphere reduces inherent contrast (C_i) to apparent contrast (C_a) where inherent contrast is defined as:

$$C_i = \frac{\text{Target Luminance} - \text{Background Luminance}}{\text{Background Luminance}}$$

Apparent contrast along a non-horizontal slant path is determined by:

$$C_a = C_i\Big[1 - K\Big(1 - \exp\{(3.912R/V)(h_0/h) \times [1 - \exp(-h/h_0)]\}\Big)^{-1}\Big]$$

where K is the sky-ground ratio of sky luminance to background luminance, $/V$ is the visibility (meteorological range) at sea level, h is the altitude of the observer on the target (the other is assumed to be at sea level), R is the slant range from observer to target, h_o is a meteorological constant = 21.7 for the standard atmosphere, if V, h, and R are all in units of feet.

Using the standard h_o value, the expression for apparent contrast becomes:

$$C_a = \frac{C_i}{1 - K\Big[1 - \exp\Big(\{84{,}900R[1 - \exp(-0.0000461h]\}/Vh\Big)\Big]}$$

This expression can be simplified considerably if the visibility *along* the slant path is known. In that case:

$$C_a = C_i\{1 - K[1 - e^{3.912R/V}]\} - 1\,.$$

Furthermore, if viewing is along a horizontal slant path, so that the sky is the background (so $K = 1$), then apparent contrast is simply

$$C_a = C_i e^{-3.912R/V}\,.$$

Note that the coefficient 3.912 causes C_a to be 2% of C_i when $V = R$. (This is the definition of visibility range.) References 2, 3, and 5 give derivations and applications of the contrast reduction equations. Reference 3 provides representative environmental data, including sky-ground luminances (contrasts) and visibilities.

Constraints

- To be accurate, computational corrections for atmospheric factors must be based on data that are representative of the place and time of search.
- To be effective in operational settings, data collection and computation must be automated.
- Some aspects of model computations are based on laboratory rather than field data, and thus involve approximations of unknown accuracy.
- Effects of possible errors in original data are not fully known regarding computed values.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Duff, E. A. *Atmospheric contrast transmission: Application to the visual detection and electro-optical lock-on problem* (GEP/PH/72-4). Dayton, OH: USAF Institute of Technology. (DTIC No. AD743560)

2. Duntley, S. Q. (1948). The reduction of apparent contrast by the atmosphere. *Journal of the Optical Society of America, 37*, 236-237.

3. *Electro-optics handbook* (EOH-11). Harrison, NJ: RCA Corporation.

4. Middleton, W. E. K. (1958). *Vision through the atmosphere*. Toronto, Canada: University of Toronto Press.

Cross References

1.218 Fourier description of the eye's imaging property;

1.228 Accommodation: effect of dark focus, luminance level, and target distance;

1.502 Flicker sensitivity: effect of background luminance;

1.616 Visual acuity: effect of viewing distance and luminance level;

1.625 Target detection: effect of target spatial dimensions;

1.627 Target detection: effect of spatial uncertainty;

1.628 Factors affecting contrast sensitivity for spatial patterns;

1.655 Vector models of visual identification;

7.507 Search time and detection rate: effect of accommodative aids;

7.514 Effect of irrelevant stimuli on search performance;

7.518 Search time: effect of target surround density;

7.526 Detection of objects and events in real-world scenes;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability

7.602 Nomographic Charts for Daylight and Overcast Sky Conditions

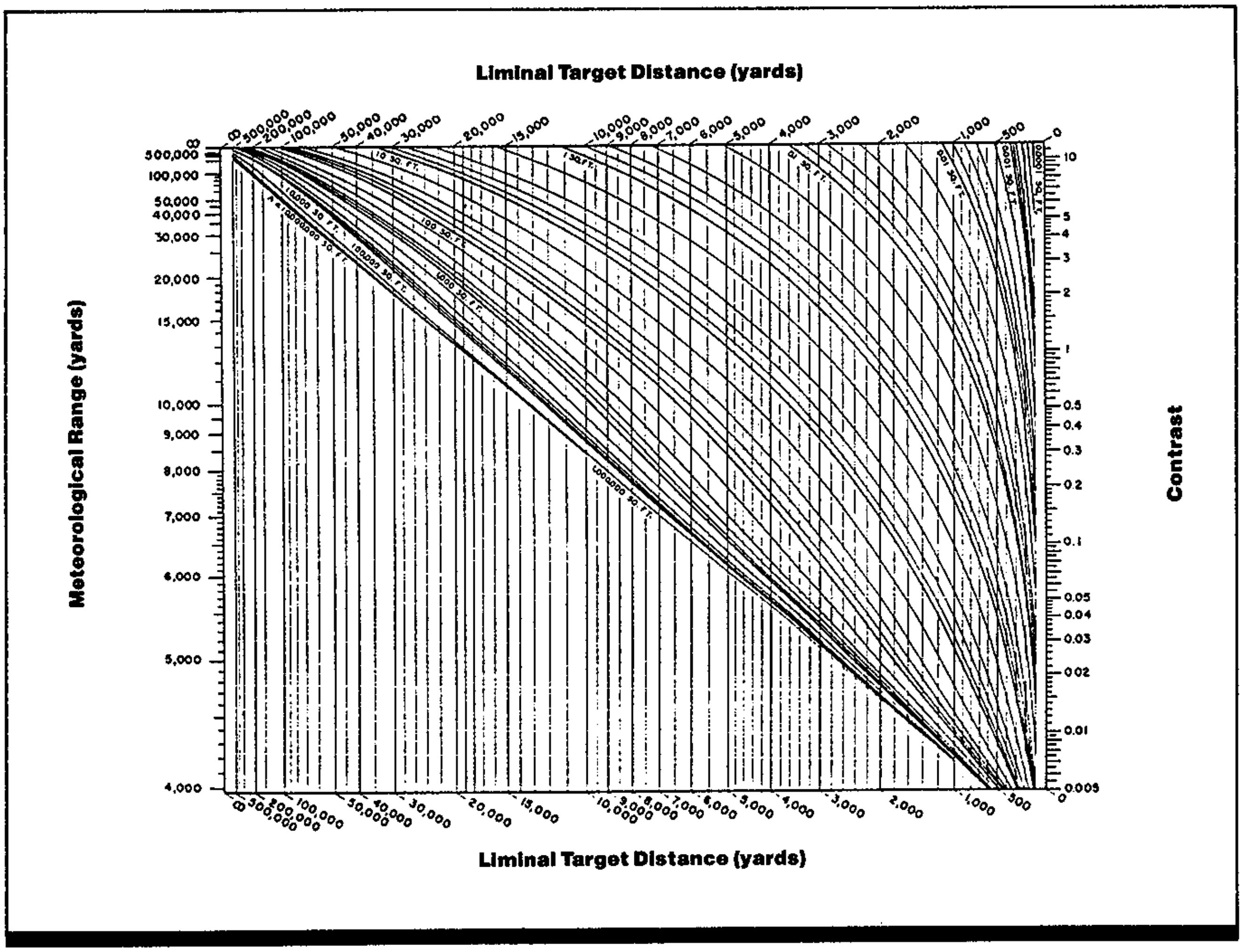


Figure 1. The farthest distance at which an object of a given area and contrast can be seen in bright daylight through an atmosphere of a given meteorological range. (From Ref. 3)

Key Terms

Atmospheric conditions; contrast sensitivity; distance vision; target detection; visibility

General Description

The farthest distance at which an object can be seen depends on the light level of the sky, the clarity of the atmosphere, and the size and contrast of the object. Figures 1 and 2 are nomographs that allow the calculation of distances at which there is 50% probability of target detection in bright daylight (Fig. 1) and under an overcast sky (Fig. 2).

These nomographs were constructed mathematically rather than experimentally. First, the reduction in apparent contrast for various targets at increasing distances through air of various clarities was measured; then Blackwell's (Ref. 1) determinations of contrast thresholds for objects of various sizes were used to specify threshold distances for targets of different apparent size and contrast. (The contrast thresholds had an average deviation of approximately 12%.)

Applications

Allows the limiting range of visibility to be found under bright daylight or overcast conditions.

Method of Application

To use the nomographs, first draw a line from the meteorological range (left axis) to the target contrast (right axis). The intersection of this line with the curve corresponding to the target area falls on the vertical line for the maximum distance at which the target can be seen with free binocular viewing under the specified conditions. In Fig. 1, for example, if the meteorological range is 20,000 yards and the tar-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

get contrast is 0.1, a target with an area of 10 ft^2 can be seen at a distance of 2400 yards in bright daylight. Fig. 2 shows that the same target can be seen at slightly less than 2200 yards under an overcast sky. (The meteorological range is defined as the distance per 2% contrast transmittance of the atmosphere.)

Constraints

- Values are based on the performance of practiced observers under ideal laboratory conditions. Actual ranges may be reduced because of fatigue, discomfort, distraction, and the need to search for the target.
- The atmosphere is not homogeneous, which may alter the ranges.
- The nomographs do not take the color or shape of the target into account; these may alter the ranges.
- Data are based on 50% detection thresholds. To arrive at a more confident visibility range, divide the target contrast by two before entering the nomographs.

Key References

1. Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36*, 624-643.

2. Duntley, S. Q. (1948). The reduction of apparent contrast by the atmosphere. *Journal of the Optical Society of America, 38*, 179-190.

3. Duntley, S. Q. (1948). The visibility of distant objects. *Journal of the Optical Society of America, 38*, 237-249.

Cross References

1.615 Visual acuity: effect of viewing distance;

1.616 Visual acuity: effect of viewing distance and luminance level;

1.627 Target detection: effect of spatial uncertainty;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.640 Contrast sensitivity: effect of viewing distance and noise masking;

1.653 Threshold models of visual target detection;

1.654 Continuous-function models of visual target detection;

7.510 Search time: effect of target luminance, size, and contrast;

7.601 Atmospheric conditions and visual effects;

7.603 Sighting range for targets detected against horizon;

7.611 Prediction of aircraft detectability

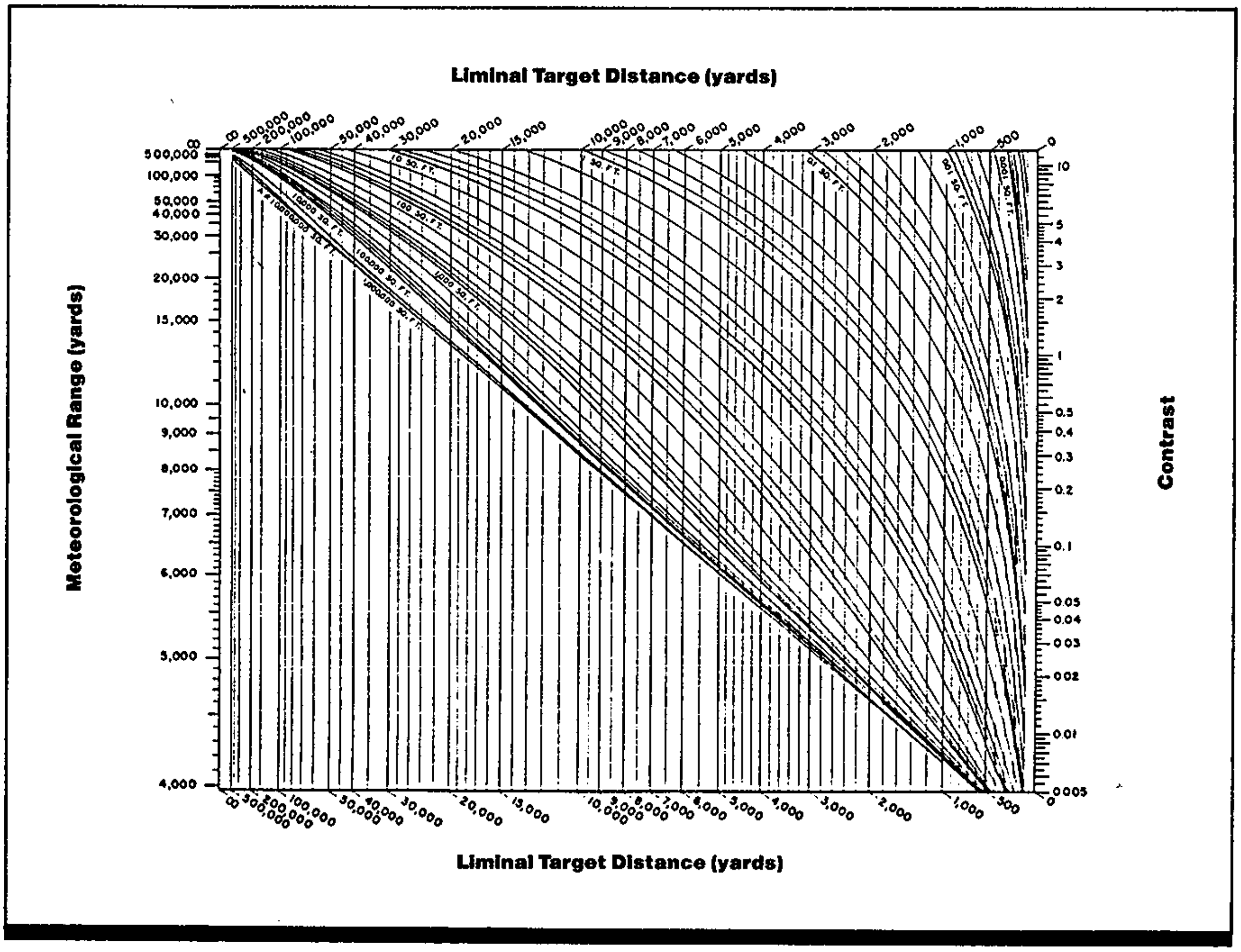


Figure 2. The farthest distance at which an object of a given area and contrast can be seen on an overcast day through an atmosphere of a given meteorological range. (From Ref. 3)

7.603 Sighting Range for Targets Detected Against Horizon

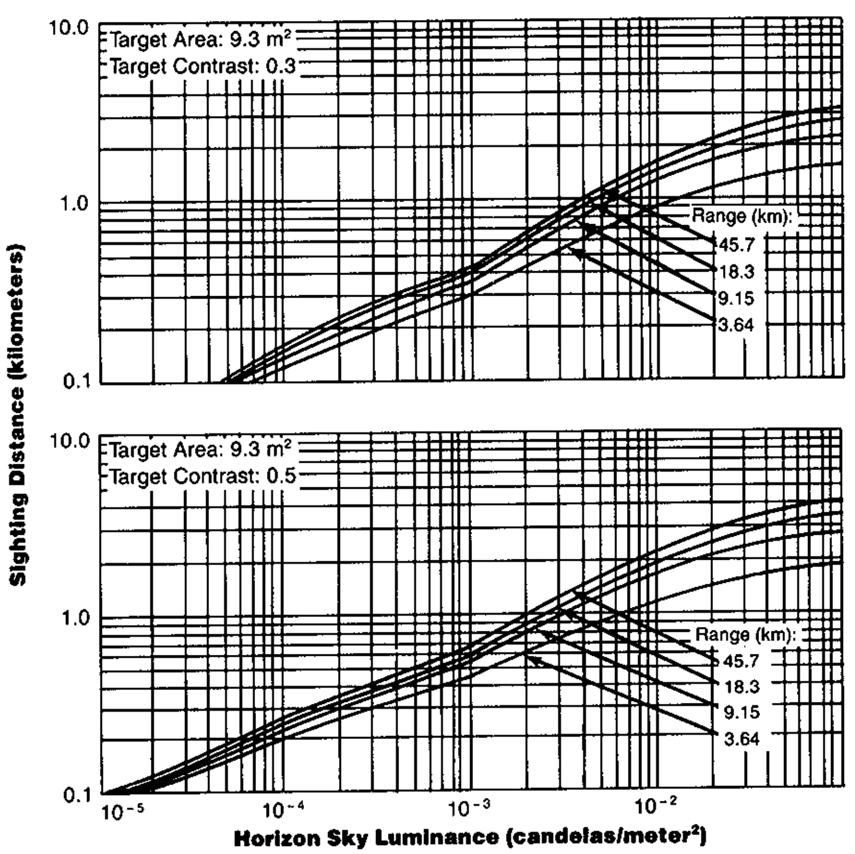


Figure 1. Distances at which a target can be detected against the sky as a function of luminance of the sky and meteorological range; target area = 9.3 m^2, contrast = 0.3 or 0.5. (From Ref. 3)

Key Terms

Atmospheric conditions; contrast sensitivity; distance vision; target detection; visibility

General Description

The farthest distance at which an object can be seen depends on the light level of the sky, the clarity of the atmosphere, and the size and contrast of the object. Figures 1-3 are nomographs that give the distances at which there is a 95% probability of detection of targets of three sizes and two levels of contrast for each size, under various light levels and atmospheric conditions.

These nomographs are revisions of the nomographs in CRef. 7.602; the determinations of contrast thresholds for targets of various sizes were divided by 2 to increase probability of detection from 50% to 95%. There are 24 such graphs in Ref. 3 but six examples are included here; target area ranges from 3.7-90 m^2 (40-1000 ft^2) and target contrast ranges from 0.3-0.9 for the original graphs.

Applications

When the limiting range of visibility needs to be predicted at twilight and at night.

Method of Application

In Fig. 1, which is for a target with a contrast of 0.3 and an area of 9.3 m^2, the target will be seen at a distance of 0.9 km if the luminance of the horizon sky is 10^{-2} and the meteorological range is 3.64 km. (The meteorological range is defined as the distance for 2% contrast transmittance of the atmosphere.)

Table 1 lists the subjective conditions that correspond to some horizon-sky luminance values, but large variations in the values can occur because of extreme meteorological conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

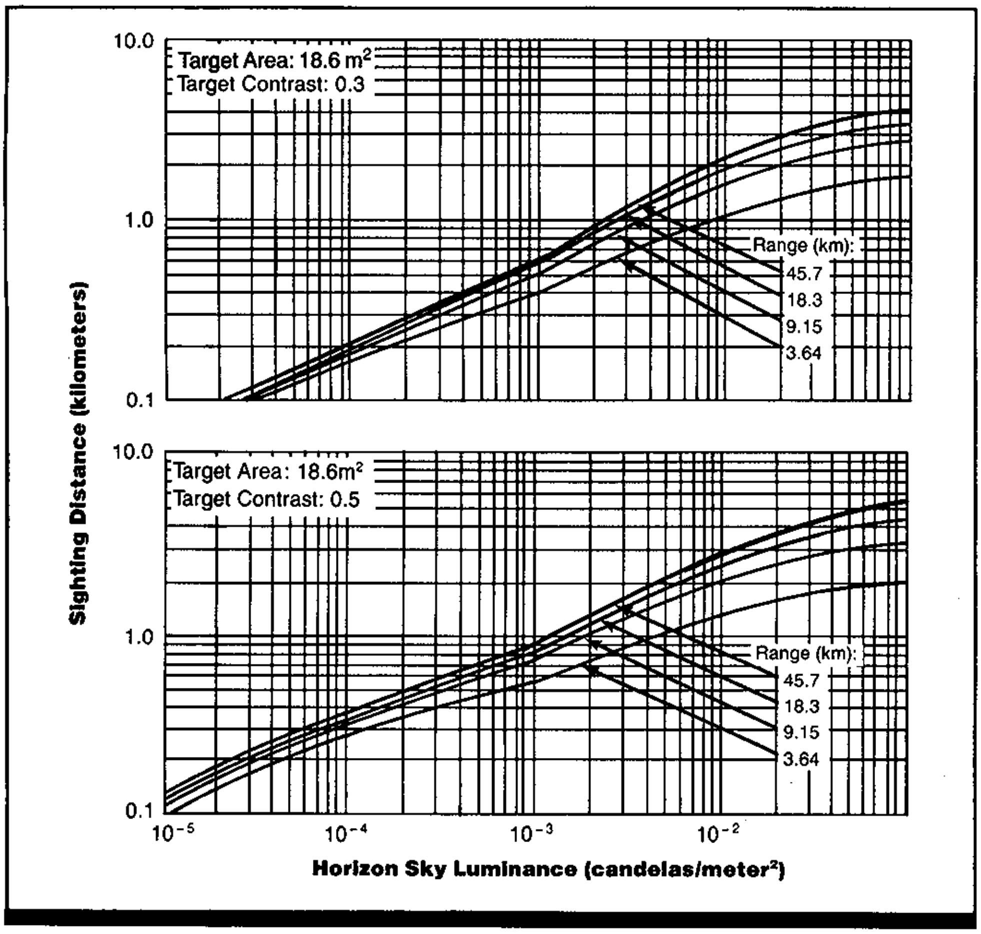


Figure 2. Distances at which a target can be detected against the sky as a function of luminance of the sky and meteorological range; target area = 18.6 m^2, contrast = 0.3 or 0.5. (From Ref. 3)

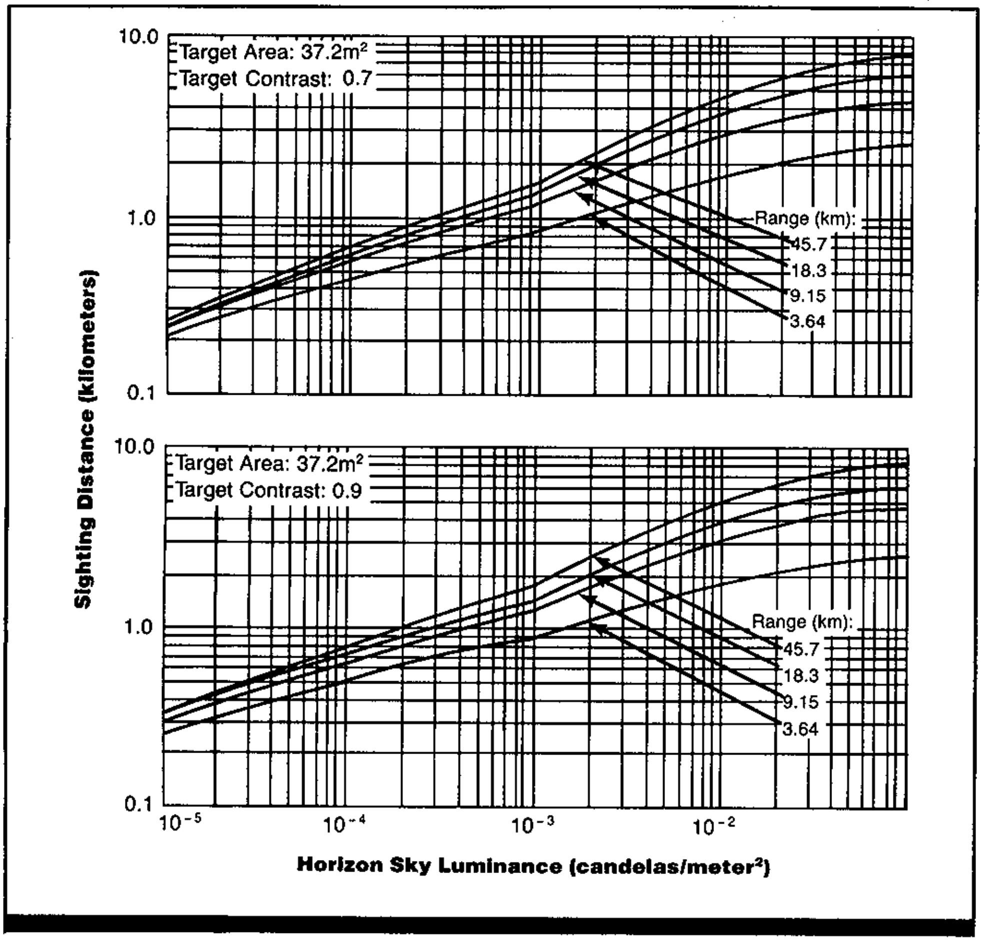


Figure 3. Distance at which a target can be detected against the sky as a function of luminance of the sky and meteorological range; target size = 37.2m^2, contrast = 0.7 or 0.9. (From Ref. 3)

Constraints

• Data are based on the performance of practiced observers under ideal laboratory conditions. Actual ranges may be reduced because of fatigue, discomfort, distraction, and the need to search for the target.

• The atmosphere is not homogeneous, which may alter the ranges.

• The nomographs do not take into account the color or shape of the target, which may alter the ranges.

Key References

1. Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36*, 624-643.

2. Duntley, S. Q. (1948). The visibility of distant objects. *Journal of the Optical Society of America, 38*, 237-249.

3. Townsend, C., & Mace, J. (1967). *Sighting range of targets against the night horizon sky* (Report No. R67ELS-24). Syracuse, NY: Electronics Laboratory.

Cross References

1.615 Visual acuity: effect of viewing distance;

1.616 Visual acuity: effect of viewing distance and luminance;

1.627 Target detection: effect of spatial uncertainty;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.640 Contrast sensitivity: effect of viewing distance and noise masking;

1.653 Threshold models of visual target detection;

1.654 Continuous-function models of visual target detection;

7.510 Search time: effect of target luminance, size, and contrast;

7.601 Atmospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.611 Prediction of aircraft detectability

Table 1. Subjective descriptions of the horizon sky at night with associated luminance values. (Adapted from Ref. 3)

Subjective Description	Luminance (candelas/ meter^2)	Luminance (footlamberts)
Sunset, overcast	10	2.9
Fairly bright moonlight	10^{-2}	2.9×10^{-3}
Clear moonless night	10^{-3}	2.9×10^{-4}
Overcast moonless night	10^{-4}	2.9×10^{-5}

Notes

7.604 Effect of Number of Displayed Gray Levels on Target Acquisition

Key Terms

CRT displays, gray levels; information portrayal; information transmission; radar; reconnaissance; target detection; target recognition; TV displays; visual perspective; visual search; visual simulation

General Description

The number of gray shades used to produce an image refers to the number of luminance steps used to depict a scene normally viewed in continuous luminance distributions. Search for and recognition of visual targets (presented via an electronic medium) typically increases as the number of gray levels in a **photopic** display increases. However, this result is task dependent; an increased number of gray levels is more important for more demanding tasks (e.g., recognition rather than search). A thoroughly briefed operator with strong expectations about what will be seen (e.g., looking for landmarks) is less affected by differences in number of gray levels than an operator who must discriminate between types of targets (e.g., tanks versus jeeps). In general, eight gray levels (three bits) is adequate for a simple search task with high operator expectations, but recognition tasks require at least 16 gray levels (four bits). Table 1 summarizes several studies investigating how the number of gray levels in an image affects visual performance.

Applications

Analog-to-digital conversion of visual scenes, visual simulation, photo-interpretation.

Constraints

- Many factors such as luminance level, noise level, target size, and different backgrounds can influence target detection and recognition; these factors should be considered in applying these results.

Key References

1. Bartleson, C. J., and Witzel, R. F. (1967, July-August). Source coding of image information. *Photographic Science and Engineering*, *11*, 263-269.

*2. Carel, W. L., Herman, J. A., & Olzak, L. A. (1978, May). *Design criteria for imaging sensor displays* (ONR-CR213-107-1F) Washington, DC: Office of Naval Research. (DTIC No. ADA055411)

3. Gaven, J. V. Jr., Tavitian, J., & Harabedian, A. (1970, January-February). The informative value of sampled images as a function of the number of gray levels used in encoding the images. *Photographic Science and Engineering*, *14*, 16-20.

4. Goldberg, A. A. (1973, August). PCM encoded NTSC color television subjective tests. *Journal of the Society of Motion Picture and Television Engineers*, *82*, 649-654.

Cross References

1.627 Target detection: effect of spatial uncertainty;

1.629 Contrast sensitivity: effect of field size;

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.525 Target acquisition in real-world scenes;

7.526 Detection of objects and events in real-world scenes;

7.603 Sighting range for targets detected against horizon;

7.611 Prediction of aircraft detectability;

11.119 Estimation of the number of perceptible gray levels

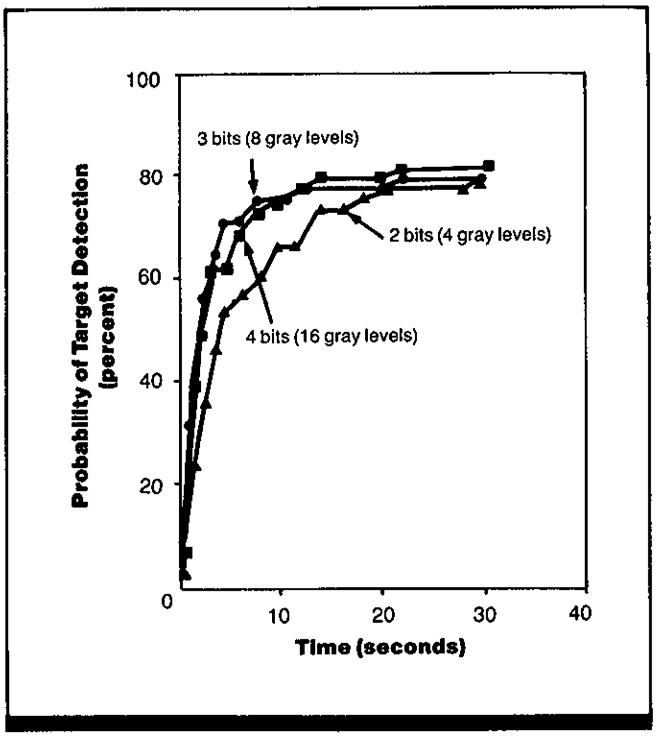


Figure 1. Probability of target detection within a given time period for displays of differing gray levels. (From Ref. 2)

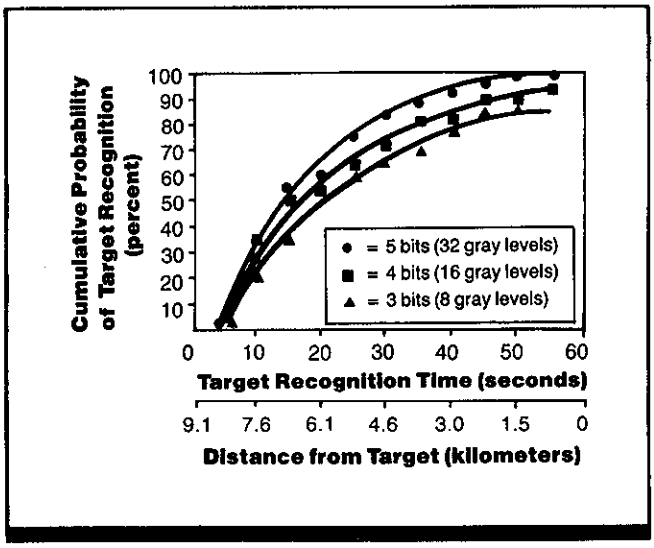


Figure 2. Cumulative probability of detecting a target within a given display duration (target recognition time) for displays with differing gray levels. (From Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Effects of number of gray levels on performance.

Task	Method	Results	Source
Find landmarks (e.g., road junctions) on high-quality, side-looking radar	Operators thoroughly studied aerial photographs before each trial	There is no increase in performance when number of gray levels is increased from 8-16 (3-4 bits). Performance with 4 gray levels (2 bits) is slightly lower (Fig. 1)	Ref. 2
Find targets in display with oblique aerial perspective, simulating aircraft in shallow glide closing in on target	Operators studied vertical area photographs	Probability of target detection increases as number of gray levels increases (8-32 gray levels or 3-5 bits), with display duration (target recognition time) held constant (Fig. 2)	Ref. 2
Identify a small vehicular target on quantized video	Target was circled so that no search was necessary; operator could increase target size using a zoom control until correct recognition occurred	Performance improves as number of gray levels increases when size is held constant (Fig. 3)	Ref. 2
Identify vehicle in an array of vehicles from overhead photograph	Either 20, 30, or 45 scans per vehicle; plain background for vehicle array	Identification accuracy improves with increasing scan lines/vehicle; identification accuracy increases rapidly as gray levels increase from 2-8 (1-3 bits) (Fig. 4)	Ref. 3
Estimate the amount of original scene (photograph) information that could be obtained from a copy with limited gray levels	Continuous tone standard photograph and from 2-32 gray levels (1, 2, 3, 4, or 5 bits) in copies; 25 observers	Estimated amount of information increased up to 32 gray levels (5 bits), with biggest gains from 2-8 gray levels (1-3 bits)	Ref. 1
Judge impairment of standard television images using the European Broadcasting Union Impairment Scale	From 16-256 gray levels (4-8 bits); observers were experienced engineers	A picture with 16 gray levels was objectionable; image with 32 gray levels was somewhat to definitely impaired; image with 64 gray levels had little impairment; and images with 132-256 gray levels were not impaired; there were some individual differences in judged image impairment	Ref. 4

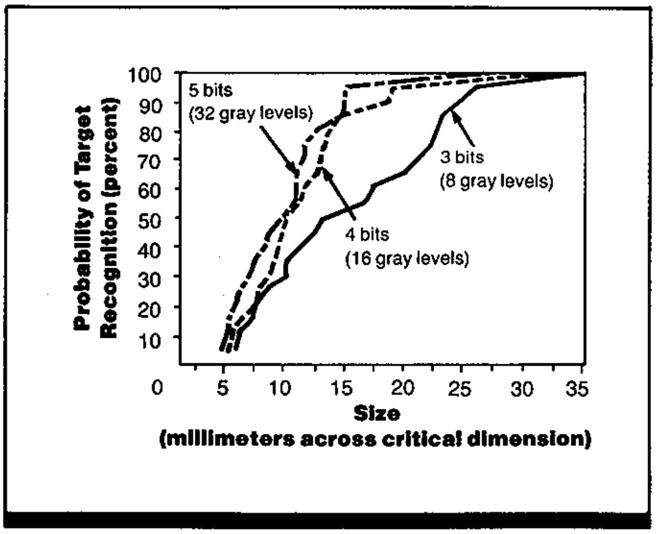


Figure 3. Probability of target recognition for targets of a given size for displays of differing gray levels. (From Ref. 2)

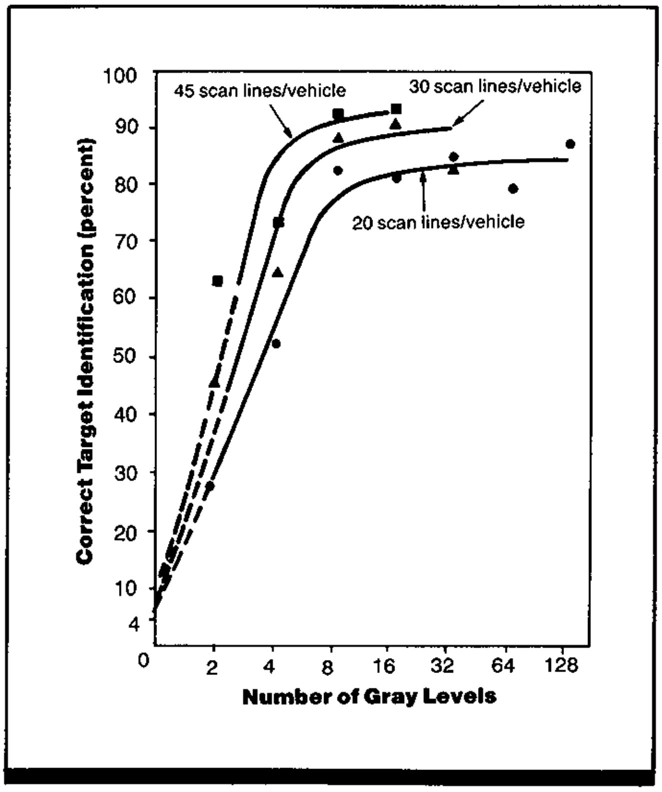


Figure 4. Correct target (vehicle) identification as a function of the number of gray levels in the display and the number of scan lines per vehicle. (From Ref. 2)

7.605 Heap's Visual Carpet

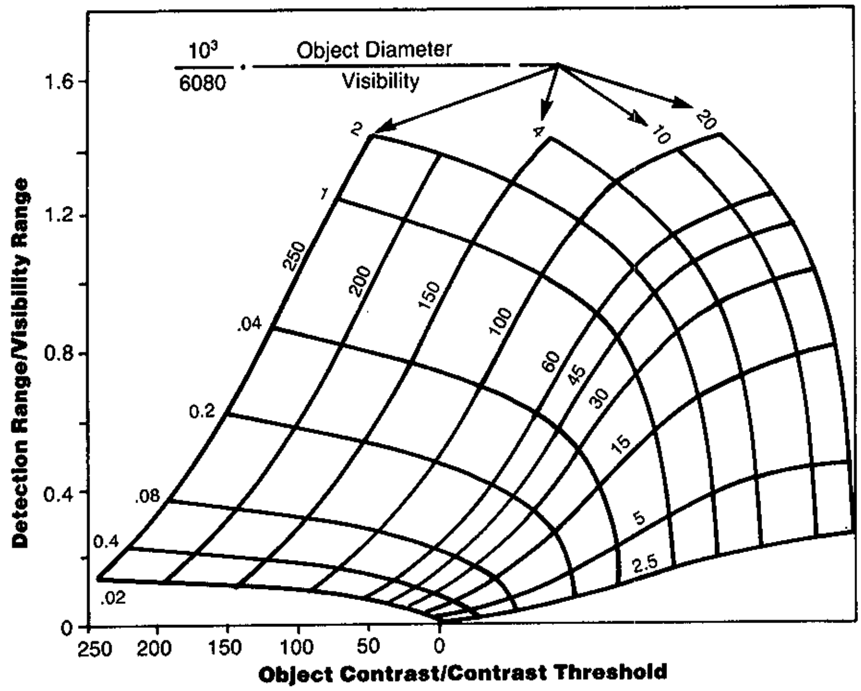


Figure 1. Detection range/meteorological range as a function of object contrast/minimum threshold for objects of various diameters (feet). (From Ref. 4)

Key Terms

Air-to-ground detection; atmospheric conditions; contrast sensitivity; distance vision; target detection; visibility; visual search

General Description

The maximum range at which an object is visible depends on its size and contrast, the light level, and the clarity of the atmosphere. The three-dimensional graph in Fig. 1 (Heap's visual carpet) predicts the maximum detection range of objects when the luminances of the horizon sky and the ground are both 3500 cd/m^2, as with an overcast sky and fresh snow.

The figure is based on the size-contrast threshold measurements of Blackwell and McCready for 1/3-sec viewing (Ref. 2), modified for more realistic estimates of detections in the field. The object's contrast, defined by

$$\frac{\text{brightness}_{\text{object}} - \text{brightness}_{\text{background}}}{\text{brightness}_{\text{background}}} \times 100,$$

divided by the contrast threshold for an object under those conditions—that is, its effective contrast—is plotted on the x-axis. The family of curves ranging from 0.02-20 gives the object diameter in feet divided by the range of visibility through the atmosphere in nautical miles, multiplied by $10^3/6080$ to convert to visual angle in minutes of arc. The maximum distance in miles at which that object can be seen, divided by the range of visibility, is given on the y-axis.

For example, assume the contrast threshold of an object would be 5 and its actual contrast is 150, giving it an effective contrast of 30. If its diameter is 120 ft and the range of visibility through the atmosphere is 10 mi, then its size value is $(10^3/6080)\,(120/10) = 2$. From Fig. 1 we see that its detection range/visibility is 0.84 (by drawing a line from the intersection of the curves for 30 and 2 to the y-axis). Because the visibility range is 10 mi, the maximum range at which the object will be detected is 8.4 mi.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

• Nomograph was constructed mathematically based on Blackwell and McCready's (Ref. 2) contrast threshold curves. These thresholds were then degraded for more realistic viewing behavior, and the reduction in apparent contrast at increasing distances through air of various clarities was calculated. Finally, these sets of values were combined to specify detection distances for targets of different size and contrast.

Experimental Results

• Detection range increases as both the contrast and shape of the target increase and as the clarity of the air increases.

Variability

No specific information on variability was given for the original experimental work used as a basis for developing the formula. In Blackwell's original contrast threshold study (Ref. 1), thresholds had an average deviation of approximately 12%.

Constraints

• Horizon brightness and attenuation through a given volume of air are assumed to be constant at all ranges and altitudes; theory therefore applies to near horizontal viewing at sea level.
• The resulting values may be somewhat optimistic, particularly for peripheral viewing.
• Nomograph does not take shape or color of target into account.
• Illumination level, exposure time, prior knowledge of probable target location, and method of displaying object can all influence the results.

Key References

1. Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36*, 624-643.

2. Blackwell, H. R., & McCready, D. W., Jr. (1958). *Foveal contrast thresholds for various durations of single pulses* (Engineering Research Institute Rep. 2455-13-F). Ann Arbor, MI: University of Michigan, Engineering Research Institute.

3. Duntley, S. Q. (1948). The visibility of distant objects. *Journal of the Optical Society of America, 38*, 237-249.

*4. Heap, E. (1966). Mathematical theory of visual and televisual detection lobes. *Journal of the Institute of Mathematics and Its Applications, 2*, 157-185.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.601 Atmospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.606 Foveal and peripheral threshold contrasts predicted by five different models;

7.607 Mathematical modeling of air-to-ground target acquisition

7.606 Foveal and Peripheral Threshold Contrasts Predicted by Five Different Models

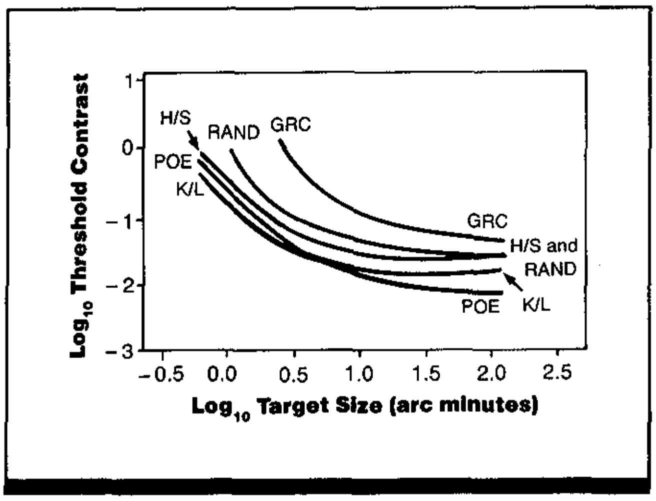


Figure 1. Foveal threshold contrast as a function of target size predicted by five mathematical models: the five models are K/L (Koopman/Lamar), H/S (Hammill/Sloan), RAND (Rand Corporation), GRC (General Research Corporation), and POE (developed by A.C. Poe III for the U.S. Army Missile Research and Development Command). (From Ref. 1)

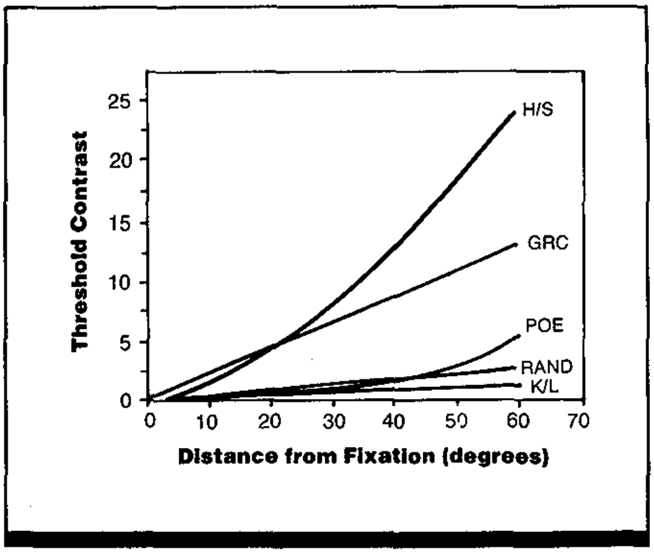


Figure 2. Peripheral threshold contrast for targets of 3.6 min arc of visual angle as a function of retinal eccentricity predicted by the same mathematical models as in Fig. 1. (From Ref. 1)

Key Terms

Air-to-air search; contrast sensitivity; target detection; visibility; visual search

General Description

Threshold detectability of a single target in an unstructured surround is influenced by several physical factors: contrast, target size, exposure duration, retinal position, and background luminance. Several mathematical models predicting threshold contrast have been developed from laboratory data. The Koopman/Lamar (K/L) model is based on data from Lamar (Ref. 5); the Hammill/Sloan (H/S) on data from Sloan (Ref. 6); the Rand on foveal data from Taylor (Ref. 7) and Blackwell and McCready (Ref. 4) and also the peripheral formulation of the General Research Corporation (GRC) model; the GRC on foveal data from Blackwell (Ref. 2) and peripheral data from Taylor (Ref. 7); and the A. C. Poe III (POE) model on foveal data from Blackwell and McCready (Ref. 4) and peripheral data from Taylor (Ref. 7) and Sloan (Ref. 6). The models primarily use the visual angle of the target (α), the angular distance from fixation (θ), and the frequency-of-seeing curves, each obtained in the laboratory under various conditions. Table 1 summarizes the five models.

The variability of the predictions made by these models is evident in Fig. 1, which shows the threshold contrast as a function of target size, and in Fig. 2, which shows threshold contrast for a given size target as a function of distance from fixation. These figures make clear the variability of predictions of visibility based on different testing conditions and procedures (Ref. 3).

Applications

Situations in which the visibility of low-contrast targets must be predicted.

Experimental Results

- Threshold contrast is degraded as target size, exposure duration, and background luminance decrease, and as distance from fixation increases.
- The predictions of different models vary by as much as an order of magnitude.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- All the models are based on laboratory data collected from highly practiced observers under ideal conditions. No allowance was made for fatigue, stress, or other distractors.
- None of the models considers target attributes such as shape, motion, and color that can also affect detectability.

Key References

*1. Akerman, A., III, & Kinzly, R. E. (1979). Predicting aircraft detectability. *Human Factors, 21*, 277-291.

2. Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36*, 624-643.

3. Blackwell, H. R. (1952). Studies of psychophysical methods for measuring visual thresholds. *Journal of the Optical Society of America, 42*, 606-616.

4. Blackwell, H. R., & McCready, D. W., Jr. (1958). *Foveal contrast thresholds for various durations of single pulses* (Engineering Research Institute Rep. 2455-13-F). Ann Arbor, MI: University of Michigan, Engineering Research Institute.

5. Lamar, E. S., Hecht, S., Shlaer, S., & Hendley, C. D. (1947). Size, shape, and contrast in detection of targets by daylight vision. I. Data and analytical description. *Journal of the Optical Society of America, 37*, 531-545.

6. Sloan, L. L. (1961). Area and luminance of test object as variables in examination of the visual field by projection perimetry. *Vision Research, 1*, 121-138.

7. Taylor, J. H. (1961). *Contrast thresholds as a function of retinal position and target size for the light adapted eye* (Visibility Laboratory Rep. 61-10). La Jolla, CA: Scripps Institute of Oceanography.

Cross References

1.653 Threshold models of visual target detection;

1.654 Continuous-function models of visual target detection;

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.601 Atmospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability

Table 1. Summary of detection models. (From Ref. 1)

Model	Liminal Brightness Contrast Threshold	Frequency-of-Seeing Curve M	Frequency-of-Seeing Curve σ
Koopman/Lamar	$\frac{0.0175\sqrt{\theta}}{f_1(B)} + \frac{0.19\theta}{f_2(B)\,\alpha^2}$	0.97	0.27
Hammill/Sloan	$0.265\theta^{0.24} + 0.44\theta^{1.6}/\alpha^2$	0.97	0.27
Rand	$\left[1.0 + \frac{0.803(\theta - 0.54)}{\alpha^{0.4}}\right] \cdot 10^{\left\{\frac{1.0}{\log_{10}\alpha + 0.5} - 2.0\right\}}$	1.00	0.39
GRC	$\left[\frac{1.0 + 0.803(\theta - 0.54)}{\alpha^{0.4}}\right] \cdot 10^{\left\{\frac{1.033}{\log_{10}\alpha + 0.142} - 1.845\right\}}$	1.00	0.39
Poe	$a_0/\alpha^{b_0} + (\theta - 0.6)\,a_1/\alpha^{b_1}$, $\theta \leq 15$ $a_0/\alpha^{b_0} + [14.4a_1/\alpha^{b_1}] \cdot \exp\{0.000643(\theta^2 - 225)\}$, $\theta > 15; \alpha \leq 9.1$ $a_0/\alpha^{b_0} + [14.4a_1/\alpha^{b_1}] \cdot \left(\frac{690}{\alpha}\right)\{0.0001486(\theta^2 - 225)\}$, $\theta > 15; \alpha > 9.1$	1.00	0.32

Table shows representation of liminal contrast threshold for each model as well as the mean (*M*) and standard deviation (σ) of the associated frequency-of-seeing curve.

α is the diameter (in minutes of arc) of a disc with the same projective area as the target; θ is the distance of the target from fixation (in degrees). $f_1(B)$ and $f_2(B)$ are luminance adjustment factors; $f_1(B)$ is at unity for adaptation levels above 343 cd/m²; $f_2(B)$ is a fit to the relative contrast sensitivity function of Ref. 2 and equals 0.78 at 343 cd/m² and 0.95 at 4330 cd/m².

7.607 Mathematical Modeling of Air-to-Ground Target Acquisition

Table 1. General descriptions and significant features of selected air-to-ground target acquisition mathematical models.

Models	General Descriptions and Significant Features
CRESS/SCREEN (Combined Reconnaissance, Surveillance and SIGINT and parts of SRI Counter-surveillance Reconnaissance Effectiveness Evaluation models). Developed for U.S. Army by Stanford Research Institute (Ref. 4)	Visual model requiring inputs on target information and background, search geometry and environment; generates probabilities of detection, recognition, identification, nondetection and misrecognition; handles multifacet targets and vegetated backgrounds; includes modeling of target shadow as detection cue; incorporates complex decision matrix rather than simple probability
ADM (Autonetics Detection Model). Developed for Naval Air Development Center by Autonetics Group of Rockwell International (Refs. 4, 7)	Model to quantitatively evaluate relative target detection, localization, and identification; addresses different mission/weapon system combinations; has no search submodel; detection and recognition differ only by required resolution levels; visual lobe not represented
GRC MODEL A. Developed for Advanced Research Project Agency by General Research Corporation (Refs. 3, 4)	Electro-optical system model including an observer/display component; characterized by a fixed-frame series representing a forward-pointed sensor; uses a segmented structure; has visual lobe expressions modified to reflect field factors; has a target recognition submodel
MARSAM II (Multiple Airborne Reconnaissance Sensor Assessment Model). Developed for Air Force Avionics Laboratory (Ref. 4)	Broad scope modular model incorporating multiple sensor inputs; submodels as in GRC MODEL A plus a distinctive search submodel
VISTRAC, prepared for Joint Task Force 2 (Refs. 1, 4)	Characterizes acquisition as continuous; characterizes visual search as continuous, not saccadic; blends acquisition performance into one measure rather than separate measures for detection, recognition, and identification
DETECT II and III. In-house development of Air Force Studies and Analysis Group and Air Force Armament Laboratory at Elgin AFB (Ref. 4)	Models to estimate cumulative target detection probabilities for straight-in (II) and orbital (III) tactical target attacks; do not have recognition or misrecognition submodels; has visual lobe effect radius estimation procedure; has comprehensive atmospheric submodel; is not well documented

Key Terms

Air-to-ground detection; electro-optical displays; target detection; visual search

General Description

Six principal models of air-to-ground target-acquisition are described in Table 1 and contrasted in terms of significant features in Table 2. Most of the models place strong emphasis on purely optical aspects of target acquisition and neglect cognitive factors. Most also rely heavily on laboratory data, although some limited validations have been done. Except for search, MARSAM II submodels have been assessed using field data (Ref. 4). DETECT II and VISTRAC also have been at least partially validated against field data (Ref. 7). ADM predictions have been compared with results of cinematic simulations (Ref. 5). CRESS/SCREEN has been partially validated on field data (Ref. 2).

Applications

The information presented here is intended to identify several options of models for estimating air-to-ground target acquisition and, in part, to identify for the user the many variables and complexities associated with target acquisition. Most target acquisition mathematical models are built in component fashion; any one model may not be entirely appropriate to the design problem at hand, but some component submodels may be of use.

Information in the tables can be used to identify models that may be of value for design applications. Related references should be consulted for developmental and mathematical details of the models and components selected for use.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The models reviewed generated output similar to laboratory data for isolated, uniform targets on uniform backgrounds. They omit such variables as briefing level, nature of ground clutter, and observer experience level.
- Application of the models to operational environments should include empirical validation.

Key References

1. Bradford, W. H. (1966). *A mathematical model for determining the probability of visual acquisition of ground targets by observers in low-level, high-speed aircraft* (SCTM-66-54). Albuquerque, NM: Sandia Laboratory.

2. Franklin, M. E., & Wittenburg, J. A. (1965, June). *Research on visual target detection/identification model* (HSR-RR-65/4-DT). McLean, VA: Human Sciences Research, Inc. (DTIC No. AD619275)

3. Gilmore, H. F., & Czipott, A. Z. (1969, November). *Display-observer performance study* (GRC-CR-0495-4). Santa Barbara, CA: General Research Corp. (DTIC No. AD866858)

*4. Greening, C. P. (1976). Mathematical modeling of air-to-ground target acquisition. *Human Factors, 18*, 111-148.

5. Greening, C. P., & Wyman, M. J. (1970). Experimental evaluation of a visual detection model. *Human Factors, 12*, 435-445.

6. Ornstein, G. N., Brainard, R. W., & Bishop, A. B. (1961). *A mathematical model for predicting target acquisition system performance* (NA 61H-29). Columbus, OH: North American Aviation.

7. Stohler, R. C. (1972). *Effects of visual acquisition on air-to-ground attack capability*. Albuquerque, NM: Falcon Research and Development.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.606 Foveal and peripheral threshold contrasts predicted by five different models;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability;

7.613 Effect of alerted and unalerted search on target acquisition

Table 2. Comparisons of significant features of selected air-to-ground target acquisition mathematical models.

Model Features	Comments
Target characteristics	All cited models deal with target apparent size; target shape not explicitly treated in any of the models; none deal with detection as a function of a target's motion relative to its background; all except MARSAM II and CRESS/SCREEN deal only with acquisition of isolated targets; all use apparent contrast as input to detection submodel; only CRESS/SCREEN handles multifaceted targets, has a chromatic contrast element, and computes target detection as a function of target shadow
Scene characteristics	All models except GRC MODEL A incorporate effects of masking elements in target acquisition; only MARSAM II and GRC MODEL A have explicit clutter submodels; MARSAM II has an explicit term representing display portion not having to be searched; VISTRAC and DETECT models limited to daylight conditions
Observer characteristics	In all models observer properties represented in terms of relationships among luminance, contrast, and angular size between contrasting elements; optical properties represented include foveal and off-axis threshold performance; glimpse time handled as an input constant in all except MARSAM II, which uses available glimpse time submodule
Decision making	All models cited assume either random or systematic glimpse distributions; individual glimpse directions not accounted for; detection performance assumed to be a function of search time and contrast/target size/luminance values relative to thresholds; recognition/identification accuracies assumed to be a simple increasing function of viewing time and/or resolution capability

7.608 Multiple Regression Model of Target Acquisition

Key Terms

Contrast sensitivity; display resolution; field of view; identification; scene complexity; size; target detection; target recognition; visual search

General Description

Highly experienced observers viewed 32 variations of simulated forward-looking infrared (FLIR) imagery (Ref. 4). Each independent variable listed in the table significantly affects target detection as shown by the mean detection times. The figure shows cumulative detection probabilities over time for two display resolutions. Target detection time can be predicted by a multiple regression equation based on the experimental data.

Applications

Prediction of target detection times given various sensor, target, and scene characteristics.

Method of Application

The following regression coefficients can be used to estimate detection time for a particular image within the range of variables manipulated (Ref. 4). To do so, the selected value of the independent variable, shown in parentheses, is multiplied by its corresponding regression coefficient. Resulting products are summed with the Y-intercept value to yield estimated target detection time in sec.

Variable	Coefficient
(Y-Intercept = 19.9987)	—
Display Resolution (250 or 525 TV lines)	− 0.0227
Scene Complexity (low = 1, high = 2)	5.4844
Target Size (10.4 or 5.2 mrad)	− 0.7218
Number of Targets (one or four)	− 1.4802
Target-to-Background Contrast (0.10 or 0.40)	−10.3855
Field of View (6 or 33 deg)	0.1448

Methods

Test Conditions

- Targets were black tanks on 12.2 x 24.4 m terrain table having 600:1 scale; model representative of northern Germany with rolling, vegetated terrain, small villages, and prominent cultural features
- Imagery sensed using 1200-line 60 MHz TV system with infinity focus optical probe and displayed on 1200-line Conrac black and white monitor; overall resolution 4 min arc of visual angle per line pair
- Monitor photographed with 35-mm camera and color film; test imagery slides produced in reverse polarity to simulate FLIR imagery; slides rear-projected onto 30.5 x 30.5 cm commercially available ground glass screen; viewing distance 61 cm; other viewing conditions not specified
- Target-to-background contrast measured directly on terrain table; contrast computed from luminance of target and five points immediately around target
- High- and low-scene complexity subjectively determined; complex scenes had more background clutter around targets
- For 6 deg field of view (FOV), low range 1 km and high range 4 km; for 33 deg FOV, ranges reduced to yield same displayed image sizes as for 6 deg FOV; resulting target heights 35.66 min arc of visual angle (10.4 mrad) for low range and 17.83 min for high range when viewed at 61 cm
- Resolution calibrated using RETMA Resolution Chart in Tele-Measurement Light Box; 250-line resolution achieved by defocusing rear projector

Experimental Procedure

- Independent variables: stimulus resolution (250 or 525 TV lines), FOV (6 or 33 deg), target contrast (10% or 40%), number of targets per scene (one or four), scene complexity (high or low), target size (35.66 min arc of visual angle for low range or 17.83 min for high range)
- Dependent variable: target detection time, defined as time from stimulus presentation until observer identified number of targets displayed

Table 1. Mean detection times and standard deviations (in sec). (From Ref. 4)

Variable	Mean	Standard Deviation
Display resolution		
250 lines	13.4	6.1
525 lines	7.1	4.7
Scene complexity		
Low	7.5	4.6
High	13.0	6.1
Target size		
35.66 min (10.4 mrad)	8.4	3.7
17.83 min (5.2 mrad)	12.1	7.1
Number of targets		
1	12.5	6.1
4	8.1	4.6
Target contrast		
10%	11.9	5.3
40%	8.7	5.5
Field of view		
3 deg	8.4	4.3
33 deg	12.2	6.4

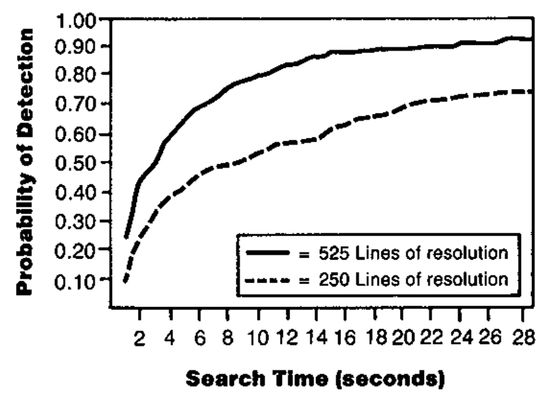


Figure 1. Cumulative detection probability as a function of search time and display resolution. (From Ref. 4)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Observer's task: search display and verbally respond "one" or "four" to identify number of targets detected; point to target for accuracy check

• Observers asked to be 80% confident of correct target location before reporting; maximum of 30 sec allowed to detect target(s)

• 12 observers highly practiced in target detection (10 current USAF and 2 ex-Navy fighter pilots with extensive experience in low-level attacks on tanks using head-down Maverick missile TV image cockpit display, and in aircraft simulator with FLIR sensor display used for terrain avoidance and target acquisition)

Experimental Results

• Increasing resolution from 250 to 525 TV lines reduces detection time by nearly 50% ($p < 0.001$), for both low and high scene complexity
• Overall, detection time decreases nearly 32% with narrow (6 deg) versus wide (33 deg) FOV ($p < 0.001$). However, FOV does not significantly affect detection time for 17.83-min. targets. Detection time is significantly ($p < 0.001$) shorter for the 6 deg FOV with larger targets.
• Overall, detection time is nearly 27% less for higher contrast targets ($p < 0.001$). Further analysis showed that the contrast effect is significant only for the 35.66-min target, low-range condition.
• Detection time is reduced by 42% when observers view low complexity scenes as compared to high complexity scenes ($p < 0.001$). The reduction is greatest for lower (250-line) resolution.
• A detection time reduction of 35% results when observers viewed four targets versus one ($p < 0.001$).
• In general, detection times are 30% shorter for 35.66-min targets. However, the difference is significant ($p < 0.055$) only for low scene complexity.
• A linear stepwise multiple regression analysis shows that all six independent variables contribute significant amounts to the total variance. The overall multiple correlation coefficient is 0.66.

Variability

One exercise of the multiple regression model yielded a predicted detection time of 19.9 sec. Actual mean detection time for the scene combination of variables is 17.7 sec.

Repeatability/Comparison with Other Studies

Other studies also show that television image quality affects target acquisition performance (Refs 1, 4). Alternative physical, rather than regression, models exist to predict target acquisition with FLIR and TV display systems (Refs. 2, 3).

Constraints

• Detection time measured to nearest second with stopwatch.
• Only tanks were used as targets. Generalizability of data to other target and terrain (background) types is uncertain.
• Display size can influence target detection performance. Displayed image size was not specified in the study reported. Other viewing conditions that could affect performance also were not specified.
• Only two levels of each independent variable were investigated. Detection performance for other values of the variables cannot be inferred.

Key References

1. Erickson, R. A. (1978). Line criteria in target acquisition with television. *Human Factors, 20,* 573-588.

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3. Greening, C. P. (1976). Mathematical modeling of air-to-ground target acquisition. *Human Factors, 18,* 111-148.

*4. Silbernagel, B. L. (1982). Using realistic sensor, target, and scene characteristics to develop a target acquisition model. *Human Factors, 24,* 321-328.

Cross References

1.615 Visual acuity: effect of viewing distance;

1.616 Visual acuity: effect of viewing distance and luminance level;

1.627 Target detection: effect of spatial uncertainty;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.640 Contrast sensitivity: effect of viewing distance and noise masking;

1.653 Threshold models of visual target detection;

1.654 Continuous-function models of visual target detection;

7.501 Factors affecting visual search with monochrome displays;

7.510 Search time: effect of target luminance, size, and contrast;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

7.517 Search time: effect of number of background characters and display density;

7.518 Search time: effect of target surround density;

7.526 Detection of objects and events in real-world scenes;

7.601 Atmospheric conditions and visual effects;

7.603 Sighting range for targets detected against horizon;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.611 Prediction of aircraft detectability

7.609 Koopman's Empirical Frequency-of-Seeing Curve

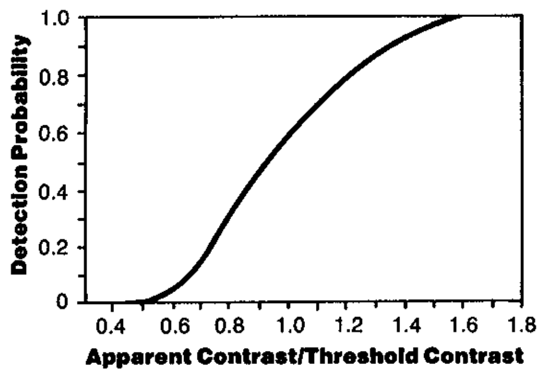

Figure 1. Probability of target detection as a function of target contrast for a 3-sec exposure. (From Ref. 1)

Key Terms

Contrast sensitivity; target detection; visibility; visual search

General Description

The probability of detecting a target as a function of its apparent contrast can be mathematically modelled on the basis of laboratory measurements of foveal and peripheral thresholds for targets of different sizes and shapes at daylight levels of luminance. For the curve shown in Fig. 1, contrast at a probability of detection of 0.57 is threshold contrast, and a 0.4 ratio of target contrast to threshold contrast yields zero probability of detection. The probability of detection varies systematically with changes in contrast.

Methods

Test Conditions

- Rectangles of light, 0.5-800 min^2, with length-to-width ratios of 2-200, presented foveally and 1.25 and 10 deg in the periphery
- Circular background, 30 deg in diameter, luminance 60 and 10,000 cd/m^2
- 3-sec exposure duration of target
- Monocular viewing through 2-mm artificial pupil

Experimental Procedure

- Method of constant stimuli
- Independent variables: brightness, area, shape, and location of target; foveal and peripheral viewing
- Dependent variable: minimum intensity required to detect the target five times out of eight trials
- Observer's task: detect and report target in one of eight locations around a fixation point
- 5 observers, ages <30 yr, with some practice; ~12 observers participated in various parts of the study

Experimental Results

- Probability of detection increases systematically as apparent contrast increases (Fig. 1).
- Contrast threshold decreases as target area increases.
- Contrast threshold increases as length-to-width ratio of the target increases.
- Contrast threshold increases with peripheral viewing.
- Contrast threshold increases at lower background luminance.
- Peripheral measurements show same trends as foveal data.

Variability

No specific information on variability is provided, but foveal contrast thresholds vary by ~12% between observers. Peripheral contrast thresholds may vary considerably more.

Constraints

- Figure 1 is modelled to encompass foveal and peripheral data as well as targets of different areas and shapes. Curves for specific target and viewing conditions will vary to some extent.
- Data are based on the performance of practiced observers under ideal laboratory conditions. Results may be affected by fatigue, discomfort, and distraction.
- Data are based on monocular thresholds. The probability of binocular detection is somewhat greater.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Akerman, A., III., & Kinzly, R. E. (1979). Predicting aircraft detectability. *Human Factors, 21,* 277-291.

2. Lamar, E. S., Hecht, S., Shlaer, S., & Hendley, C. D. (1947). Size, shape, and contrast in detection of targets by daylight vision. I. Data and analytical description. *Journal of the Optical Society of America, 37,* 531-545.

3. Lamar, E. S., Hecht, S., Hendley, C. D., & Shlaer, S. (1948). Size, shape, and contrast in detection of targets by daylight vision. II. Frequency of seeing and the quantum theory of cone vision. *Journal of the Optical Society of America, 38,* 741-755.

Cross References

1.653 Threshold models of visual target detection;

1.654 Continuous-function models of visual target detection;

7.501 Factors affecting visual search and monochrome displays;

7.525 Target acquisition in real-world scenes;

7.601 Atmospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.610 Threshold "detection lobe" curve;

7.611 Prediction of aircraft detectability;

7.613 Effect of alerted and unalerted search on target acquisition

7.610 Threshold "Detection Lobe" Curve

Key Terms

Air-to-air search; collision avoidance; contrast sensitivity; interception; peripheral detection; target detection; visibility; visual search

General Description

The threshold visibility of a target at a known location depends on its size and contrast and on the light level of the sky and the clarity of the atmosphere. When the observer does not know where to look and the target appears in the periphery of his visual field, it must be bigger to be seen; the required size of the target increases as the distance from the foveal field increases. Figure 1 shows the peripheral angle at which a target is detected by an alerted observer as a function of the ratio of the actual diameter of a target to the threshold target diameter when both actual and threshold conditions are daylight with a uniform background of horizon sky. For example, if the actual target diameter is equal to the threshold diameter, it can be detected only by direct foveal viewing. If the actual target diameter is five times the threshold diameter, it can be detected up to ~5 deg in the periphery.

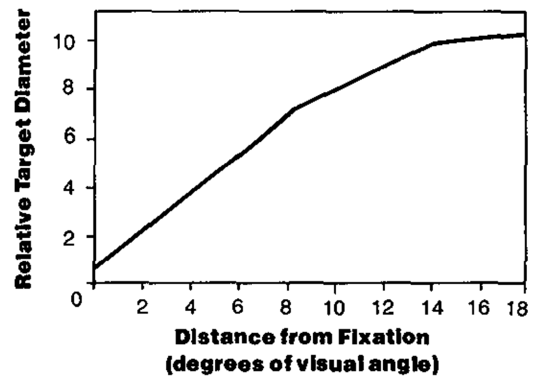

Figure 1. Peripheral angle at which a target is detected as a function of relative target diameter (the ratio of the actual target diameter required for detection to the threshold target diameter with foveal viewing). (Based on data from Ref. 4)

Applications

Visual detection of other aircraft on or near a collision course under daylight conditions.

Methods

Figure is drawn from mathematical calculations based on the results of several independent experimental investigations. Blackwell's determinations of contrast thresholds (Ref. 1) and Duntley's measurements of contrast reduction through the atmosphere (Ref. 2) were used to specify threshold diameters. These were modified using Krendel and Wodinsky's measurements of the time required to detect targets in unstructured visual fields (Ref. 3).

Experimental Results

• As a target appears farther in the periphery of the visual field, its diameter must progressively increase for it to be detected.

Variability

No specific information on variability is provided, but these calculations are based on contrast thresholds that had an average deviation of ~12% and on search times that can be expected to vary by at least 300% between observers.

Constraints

• These figures are based on the performance of practiced observers under ideal laboratory conditions. Results may be affected by fatigue, discomfort, and distraction.
• Threshold diameters are based on 50% detection thresholds that represent judgments of very low confidence.
• These results are based on experiments with circular targets; different shapes may alter the results.
• A homogeneous atmosphere and a uniform background of the sky illuminated to 3,500 cd/m^2 are assumed.
• The directional effect of the sun is ignored.
• A uniform distribution of fixations over the scanned area is assumed; this is known to be false.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36*, 624-643.

2. Duntley, S. Q. (1948). The visibility of distant objects. *Journal of the Optical Society of America, 38*, 237-249.

3. Krendel, E. S., & Wodinsky, J. (1960). Visual search in unstructured fields. In A. Morris and E. P. Horne (Eds.). *Visual search techniques* (Publication 712, pp. 151-169). Washington, DC: National Academy of Sciences, National Research Council.

*4. Short, E. A. (1961). *Visual detection of aircraft in mid-air collision situations* (Master's Thesis). Monterey, CA: United States Naval Postgraduate School. (DTIC No. AD480757)

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.519 Search time: effect of color coding;

7.601 Atmospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.606 Foveal and peripheral threshold contrasts predicted by five different models;

7.608 Multiple regression model of target acquisition;

7.611 Prediction of aircraft detectability;

7.613 Effect of alerted and unalerted search on target acquisition

7.611 Prediction of Aircraft Detectability

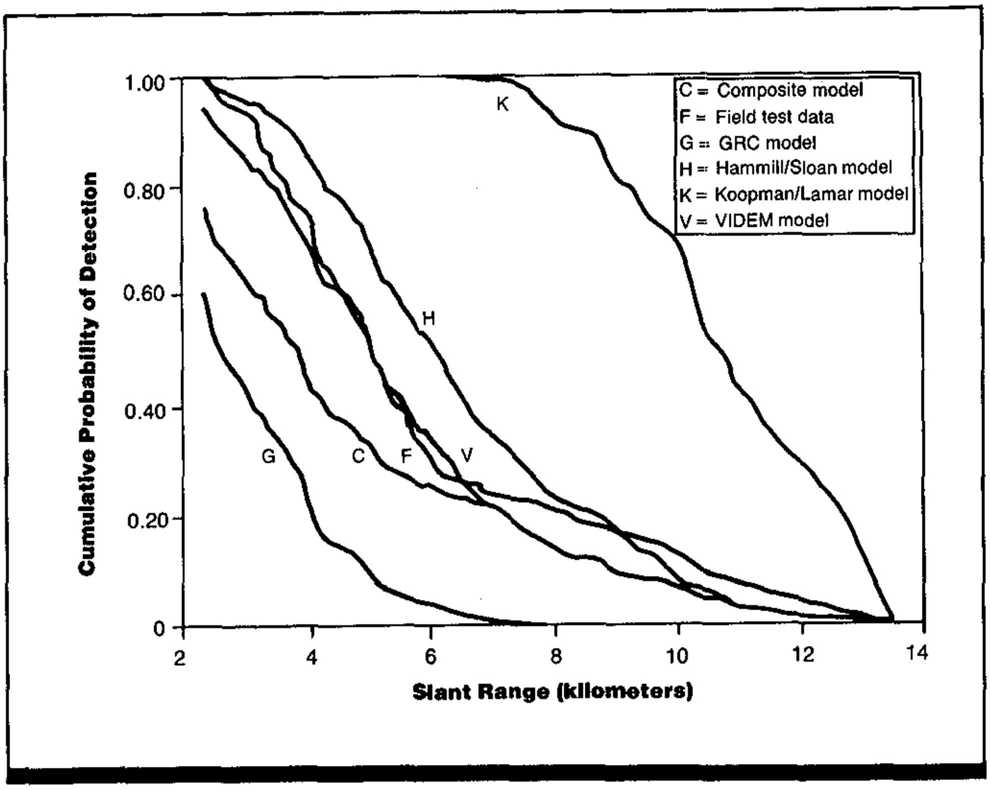

Figure 1. Cumulative detection probabilities as a function of slant range for 900 m aircraft-altitude flight profile as predicted by five mathematical models of visual search. (From Ref. 1).

Key Terms

Contrast sensitivity; target detection; visibility; visual search

General Description

The VIDEM visual-search mathematical model was constructed to predict single aircraft detectability against uniform sky backgrounds under **photopic** illumination levels (Ref. 1). The model was formulated by contrasting how five existing models predicted extant laboratory and field visual detection performance data, and by the refinement of one of the models. Performance of several models is contrasted with actual field test data in the figure. Performance of the VIDEM model closely matches actual aircraft detection field test date. The VIDEM model consists of four components: a liminal contrast (threshold), a frequency-of-seeing curve, a soft-shell search representation, and a discrete cumulation of single-glimpse detection probabilities.

Applications

The prediction of single aircraft detectability against uniform sky backgrounds under photopic illumination levels as a function of slant range distance. The design and evaluation of visual simulations.

Methods

- Five candidate models (Koopman/Lamar, Hammill/Sloan, Rand, GRC, and POE) prescreened using computer simulations to determine extents that each predicted laboratory search data (Refs. 3, 4); measure was mean target detection time for specified adaptation levels, search field size, target size, and target/background contrast; simulations assumed single target randomly located in uniform, extended background; based on results, two models (Hammill/Sloan and Composite GRC-Hammill/Sloan) selected for fit with field data acquired from flight tests at Eglin Air Force Base (AFB) between 1972 and 1974
- Model field test data generated during flight tests at Eglin AFB; 6 ground observers alerted at start of each aircraft pass, which started at ~18 km; nonsmoking aircraft flew random sequence (horizontal) profiles at 12 different altitude profiles between 150-3,000 m with offsets up to 1,500 m; 6 observers searched independently within 60 deg azimuth by 30 deg elevation field; observers not instructed in specific search procedures; photographic and photometric data collected throughout all aircraft passes
- Up to four parameters of models fitted to obtain minimal residual-sums-of-squares fits between predicted detection performance and field data in computer simulations; from the simulations a multiplying factor estimating liminal contrast in field data was derived, along with standard deviation associated with ogival frequency-of-seeing curve

Experimental Results

- VIDEM parameterization of the Hammill/Sloan model yields a 1.33 multiplying field factor and a standard deviation of 0.24.
- Average square error between predicted and actual cumulative probability of detection is 0.009.
- Parameterization of the Composite GRC-Hammill/Sloan also yields a 1.33 multiplying field factor.

Repeatability/Comparison with Other Studies

This study (Ref. 1) is in agreement with others showing that aircraft detectability mathematical models yield diverse predictions and do not agree (Ref. 5). A major problem is that each model is derived to fit specific and differing sets of conditions and data.

Empirical Validation

Seven flight profiles (60 observations each) for single-aircraft detectability in real-world, clear-sky conditions were used to compare predictions of five models. The VIDEM model provides the best fit between predicted and actual cumulative detection probabilities as a function of slant range.

Constraints

- The VIDEM model, like its forebears, is intended only to predict single aircraft target detectability against uniform sky backgrounds under photopic illumination levels.
- The VIDEM model underpredicts detection probabilities for target profiles below 900 m and overpredicts for higher altitudes, probably because the model was registered against field test data for 900 m altitude flight profile.
- The model assumes well-trained, highly motivated, and vigilant observers.
- Like others, the model does not consider psychological factors such as experience, fatigue, or stress.

Key References

*1. Akerman, A., III, & Kinzly, R. E. (1979). Predicting aircraft detectability. *Human Factors, 21*, 277-291.

2. Greening, C. P. (1976). Mathematical modeling of air-to-ground target acquisition. *Human Factors, 18*, 111-148.

3. Hammill, H. B., & Akerman, A., III (1975, October). *Visual detectability of chromatic contrast targets*. Paper presented at the annual meeting of the Optical Society of America, Boston, MA.

4. Krendel, E. S., & Wodinsky, J. (1960). Search in an unstructured visual field. *Journal of the Optical Society of America, 50*, 562-568.

5. Overington, I. (1976). *Vision and acquisition*. New York: Crone, Russak & Co.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.514 Effect of irrelevant stimuli on search performance;

7.525 Target acquisition in real-world scenes;

7.526 Detection of objects and events in real-world scenes;

7.601 Atomospheric conditions and visual effects;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.607 Mathematical modeling of air-to-ground target acquisition;

7.608 Multiple regression model of target acquisition

7.612 Correlation Between Performance on Visual Tests and Flying Performance

Table 1. Coefficients of correlation (*r*) between visual test results and performance in low-level flying tasks. (From Ref. 1)

Correlation	*r*	*p*
Between no-drop bombing accuracy and		
Flow pattern velocity discrimination	.67	.01
Perturbed changing-size tracking	.63	.02
Frontal-plane motion tracking	.52	.05
Between bombing accuracy (real bombs) and		
Flow pattern velocity discrimination	.71	.01
Perturbed changing-size tracking	.57	.04
Between no-drop bombing accuracy and bombing accuracy (real bombs)	.73	.01

Key Terms

Air-to-air search; aircraft landing; contrast sensitivity; formation flight; motion detection; optic flow pattern; pilot selection; Snellen acuity; tracking; visual acuity; visual tests

General Description

Standard visual tests, such as Snellen acuity, contrast sensitivity, and motion detection, do not correlate with either actual or simulated flying performance. But discrimination between two speeds of a radially expanding flow pattern and the ability to track a target moving either in depth or sideways both correlate with low-visibility landing performance in a flight simulator and with actual bombing accuracy. Success in air-to-air combat is correlated with the distance at which another aircraft can be detected and with sensitivity to a change in course of an approaching aircraft. The tracking test also correlates with the number of missiles fired in combat.

Methods

- Flight tasks in real aircraft included computer-scored "no-drop" bombing and bombing accuracy using real bombs (Table 1) and air-to-air combat training missions (Table 2); aircraft were A-4 and F-14 jet fighters; all flights carried out under ideal conditions
- Simulator flying tasks (Table 3) included bad visibility landing, formation flight, and bombing task following low-level approach under ground threat
- Psychophysical visual tests included: (1) flow pattern test—observer viewed test patterns of 10 concentric circles that expanded in size at a constant velocity; observer judged which of two such patterns was expanding more rapidly; (2) frontal-plane motion tracking—observer tracked motion of target moving in frontal plane; (3) changing-size tracking—target square alternately expanded and contracted in size in unpredictable manner, and observer adjusted size of target so as to maintain it at constant size; size oscillations were sometimes perturbed by addition of random frontal-plane motion
- Airborne visual tests (Table 2) were conducted with subject (designated as attacker) engaged in maneuvers with second aircraft (designated as target); tests included: (1) acquisition range (distance at which attacker first sighted target); (2) direction detection range (distance between attacker and target at time attacker first discriminated direction of escape turn executed by target); (3) angular deflection (angular displacement of target aircraft between beginning of escape turn and attacker's detection of turn direction)
- Standard tests administered for acuity, contrast sensitivity, and motion detection
- Actual flight tests: 12 experienced fighter pilots (Table 1), 11 experienced fighter pilots (Table 2); simulator tasks (Table 3): 12 instructor pilots, 12 student pilots, and 12 experienced fighter pilots

Experimental Results

- Standard visual tests such as acuity, contrast sensitivity, and motion detection do not correlate with flying performance.
- Success in air-to-air combat correlates with detection of other aircraft and their change in course.
- Low-visibility landing, bombing accuracy, and number of missiles fired correlate with discrimination between two speeds of radially expanding flow-patterns and with the ability to track a target moving in depth or sideways.
- Tracking tests distinguish between pilots and non-pilots.
- Tracking sideways motion distinguishes between the flying groups.
- Thresholds for motion perception correlated with flying grades.

Variability

Considerable differences in pilot performance were noted.

Constraints

- The artificialities of the experimental protocol in the flight simulator may penalize experienced pilots.
- The results may not be applicable to both smoking and non-smoking aircraft.
- The experimental protocol did not always allow pilots to fly as they were trained.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Kruk, R., & Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. *Aviation, Space and Environmental Medicine, 54,* 906-911.

*2. Kruk, R., Regan, D., Beverley, K. I., & Longridge, T. (1983). Flying performance on advanced simulator for pilot training and laboratory tests of vision. *Human Factors, 25,* 457-466.

Cross References

1.617 Visual acuity with target motion: effects of target velocity and target versus observer movement;

1.624 Factors affecting detection of spatial targets;

1.627 Target detection: effect of spatial uncertainty;

1.643 Contrast sensitivity: effect of target shape and illumination level;

1.645 Contrast sensitivity for a large population sample;

5.203 Factors affecting threshold for visual motion;

5.213 Judgment of impending collision between targets in the display field;

5.214 Judgment of impending collision with approaching targets;

Handbook of perception and human performance, Ch. 19, Sect. 5.0

Table 2. Coefficients of correlation (*r*) between laboratory and airborne visual test results and performance in simulated air-to-air combat using real aircraft. (From Ref. 1)

	Nonsmoking Aircraft (N = 6)		Smoking Aircraft (N = 8)	
	r	*p*	*r*	*p*
Correlation between acqusition range and				
Kills/engagement	.80	.03	.69	.01
Died/engagement	−.85	.02	NS	—
Win/loss ratio	.74	.05	NS	—
Direction detect range	.79	.03	.96	.001
Flow pattern velocity discrimination	−.60	.10	−.61	.02
Correlation between detection range and				
Died/shot at	−.77	.04	NS	—
Died/engagement	−.88	.01	NS	—
Win/loss ratio	.79	.03	NS	—
Kills/shot	NS	—	.66	.04
Angular deflection	−.91	.006	NS	—
Correlation between angular deflection and				
Shots/engagement	−.83	.02	NS	—
Shot at/engagement	.78	.03	.77	.01
Died/engagement	.69	.06	.79	.009
Win/loss ratio	−.85	.02	NS	.08
Frontal-plane motion tracking	NS	—	−.71	.02
Changing-size tracking	.80	.03	NS	—
Flow pattern velocity discrimination	NS	—	−.66	.04

	All aircraft	
	r	*p*
Correlation between shots/engagement and		
Changing-size tracking	−.67	.01
Perturbed changing-size tracking	−.67	.01

NS indicates that the correlation was not statistically significant.

Table 3. Coefficients of correlation (*r*) between simulator performance and performance on visual tests. (From Ref. 2)

Simulator Task	Fighter Pilots *r*	Fighter Pilots *p*	Instructors *r*	Instructors *p*	Student Pilots *r*	Student Pilots *p*
Landing: correction to runway	Frontal-plane tracking −.65	.01	Frontal-plane tracking −.61	.03	Frontal-plane tracking −.66	.009
Landing: crashes on runway	Changing-size tracking .63	.02	Flow pattern test −.82	.01		
Formation flight: time in position for fingertip task	Flow pattern test .61	.03			Flow pattern (n = 6) .52	.15
Formation flight: time in position for trail task			Flow pattern test .55 Changing-size tracking −.57	.05 .03	Perturbed changing-size tracking −.56	.03
Bombing: hits on target	Flow pattern test .74	.008	—			

7.613 Effect of Alerted and Unalerted Search on Target Acquisition

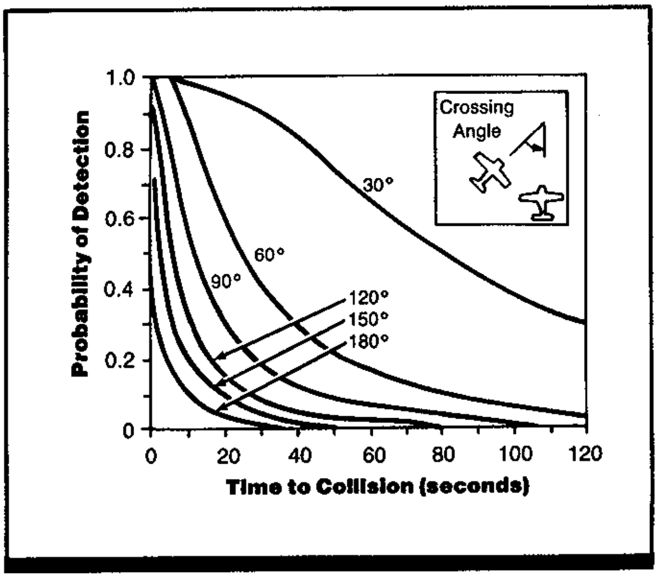

Figure 1. Probability of detection of a small plane on a collision course at several crossing angles for unalerted search by a single pilot. Speed of each plane is 100 knots; visibility is 15 nautical miles. (From Ref. 1)

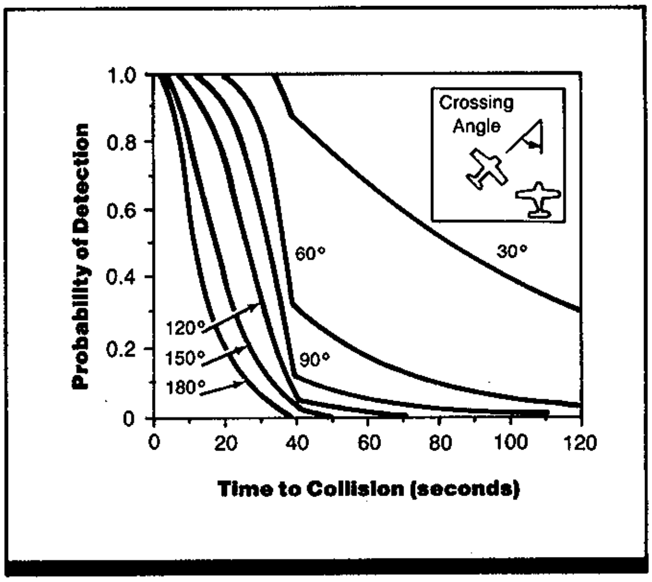

Figure 2. Probability of detection of a small plane on a collision course at several angles for alerted search by a single pilot. Speed of each plane is 100 knots; visibility is 15 nautical miles. (From Ref. 1)

Key Terms

Air-to-air search; alerting systems; collision avoidance; contrast sensitivity; interception; target detection; visibility; visual search; warnings

General Description

The probability that a pilot of a small plane will detect another small plane on a collision course was mathematically modelled on the basis of data collected during flight tests. The calculated probabilities are plotted as a function of the time to collision for various crossing angles in one specific encounter situation. Figure 1 gives the probabilities when the pilot is not alerted by an electronic warning system. Figure 2 gives the probabilities when pilot is alerted by a warning indicator 40 sec before the collision.

Applications

Situations in which a single pilot of a small plane might be on a collision course with another small plane.

Methods

Test Conditions

- Small planes flying at constant altitudes and headings at 100 knots
- With alerting system, pilot alerted when interceptor aircraft closer than 2 nautical miles or collision time <46-75 sec
- Visibility was 15 nautical miles
- Pilots flew simple 1-hr cross-country course
- Another plane conducted six or seven intercepts

Experimental Procedure

- Independent variables: angle of intercept, electronic warning or no warning of collision
- Dependent variable: sighting of interceptor aircraft
- Observer's task: detect interceptor aircraft
- Pilots with wide range of aviation experience; number of pilots not specified

Experimental Results

- Probability of detection decreases as crossing angle increases.
- Probability of detection is increased on average by a factor of nine when pilot is alerted by warning indicator.

Variability

No specific information on variability was provided, but individual differences in search time may exceed 300%.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Values hold only for these specific conditions and will vary with planes of different sizes and configurations, different speeds, visibility, size of search area, fraction of pilot's time devoted to search, and settings of electronic warning system.

• The distribution of fixations over the area to be scanned is assumed to be uniform. This is known not to be true.

Key References

*1. Andrews, J. W. (1977). *Air-to-air visual acquisition performance with pilot warning instruments (PWI)* (Report No. FAA-RD-77-30). Washington, DC: Federal Aviation Administration. (DTIC No. ADA039714)

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.525 Target acquisition in real-world scenes;

7.526 Detection of objects and events in real-world scenes;

7.602 Nomographic charts for daylight and overcast sky conditions;

7.603 Sighting range for targets detected against horizon;

7.610 Threshold "detection lobe" curve;

7.611 Prediction of aircraft detectability;

11.405 Visual warning signals: effect of visual field position and color;

11.406 Visual warning signals: effects of background color and luminance;

11.409 Visual warning signals: effect of size and location;

11.411 Visual warning signals: effect of flashing;

11.415 Coupling of visual and verbal warning signals: effect on response time

7.614 Factors Affecting Target Acquisition on Television

Key Terms

CRT displays; display resolution; field of view; scene complexity; signal-to-noise ratio; size; TV displays

General Description

Target acquisition performance with raster imaging systems is often estimated using image-quality characteristics. A number of measures of image quality for raster-scanned television (TV) systems can be related to observer performance. They include display systems resolution, number of television scan lines per target height, field of view, scene complexity, signal-to-noise ratio, target/background contrast, range, and target size. The table identifies the general effects of these image-quality variables on target detection, recognition, or identification, and notes interactions among the variables. The table is intended as a general guide for identifying likely effects of tradeoffs among the variables during system design.

Applications

Information in the table can be used to identify variables and variable manipulations that could influence human target-acquisition performance. For example, for a display system with a narrow field-of-view, the user should locate the field-of-view section of the table, identify the consequences of narrow field-of-view on target acquisition performance, and identify other variables (e.g., number of TV lines) that can be traded off with field-of-view. The references should be consulted for relevant methodological issues and detailed human performance data.

Constraints

- Displays used were monochrome. Data may not be directly applicable to color presentations.
- Target acquisition performance may be improved with newer technology display systems.
- The background against which targets are viewed can influence acquisition performance.
- Target characteristics (e.g., vehicles versus abstract forms) can influence acquisition performance.
- The studies cited did not include tasks with multiple targets. This factor would also influence acquisition performance.
- The studies cited were not conducted in high-stress environments. High stress levels could influence performance.
- No standard metrics exist for quantifying scene complexity.

Key References

1. Biberman, L. M. (1973). *Perception of displayed information.* NY: Plenum Press.

2. Brainard, R. W., & Marshall, R. H. (1965, January). *Resolution requirements for identification of targets in television imagery* (NA-63H-794). Columbus, OH: North American Aviation. (DTIC No. AD744902)

3. Craig, G. L. (1975, April). *Vehicle detection on television: A laboratory experiment* (NWC-TP-5636). China Lake, CA: Naval Weapons Center. (DTIC No. AD919898)

4. Erickson, R. A. (1978). Line criteria in target acquisition with television. *Human Factors, 20,* 573-588.

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6. Jones, D. B. (1973, March). *A collection of unclassified technical papers on target acquisition.* Vol. I. (0A-6201-Vol-I). Orlando, FL: Martin Marietta Aerospace. (DTIC No. AD758022)

7. Silbernagel, B. L. (1982). Using realistic sensor, target, and scene characteristics to develop a target acquisition model. *Human Factors, 24,* 321-328.

8. Wagner, D. W. (1975, October). *Target acquisition with color versus black and white television* (NWC-TP-5800). China Lake, CA: Naval Weapons Center. (DTIC No. ADB007717)

Cross References

7.514 Effect of irrelevant stimuli on search performance;

7.521 Effect of target lag and sequential expectancy on search time;

7.525 Target acquisition in real-world scenes;

7.608 Multiple regression model of target acquisition

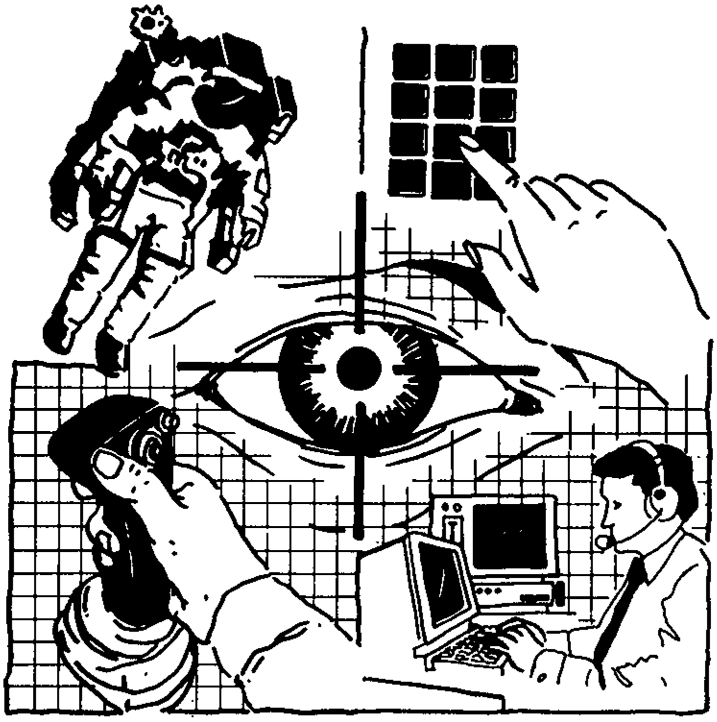
Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Image quality variables and effects on target acquisition.

Display Variable	Effects on Target Acquisition	Source
Display resolution (system line number)	In general, target recognition time is reduced and probability of recognition improves as a function of number of TV lines per picture height.	Refs. 1, 7
	Increasing display resolution from 250-525 TV lines reduces target detection time by nearly 50%.	Refs. 1, 7
	Effects of display resolution hold for both low- and high-complexity scenes.	Refs. 1, 7
Target scan lines	A larger number of scan lines are required for identification than for simple detection of targets.	Ref. 4
	10-12 scan lines over a target are sufficient for identification of most military targets (ships, vehicles, buildings, bridges, aircraft); increasing scan lines beyond 12 does not improve performance except for viewing times <3 sec.	Refs. 2, 5
	Seven scan lines over a target (military vehicles) are sufficient for target orientation; ability to orient vehicles does not increase as scan lines increase from 7 to 26.	Ref. 3
Field-of-view	Detection time decreases nearly 32% with narrow (6 deg) versus wide (33 deg) field-of-view (FOV)	Ref. 7
	FOV does not affect detection time at long ranges (i.e., 4 km).	Ref. 7
	Narrow FOVs reduce detection time at short ranges.	Ref. 7
	Detection accuracy doubles (41% versus 86%) with narrow versus wide FOVs.	Ref. 8
	Geographic orientation and target area acquisition are easier for wider FOVs (30 deg versus 10 deg)	Ref. 4
	For a given required identification range, FOV and number of TV lines can be traded off.	Ref. 4
Scene complexity	Detention time is reduced by 42% when observers view a scene of low complexity versus a highly complex scene.	Ref. 7
	Effects of scene complexity hold for both low and high display resolution and for both short and long ranges.	Ref. 7
	Scene complexity interacts with display resolution; low-resolution, high-complexity conditions result in long detection times; scene complexity has a larger negative effect at low than at high display resolution.	Ref. 4
Display signal-to-noise ratio (SNR_D)	Recognition and identification require at least $SNR_D = 2$, with performance increasing up to $SNR_D = 6$.	Ref. 6
Target/background contrast	Target detection time is reduced by 27% for targets with a 40% versus 10% contrast with the background.	Ref. 7
	Contrast interacts with range; contrast effects are strongest at short ranges.	Ref. 7
Range	Detection time of short-range test images is 30% lower than detection time of long-range images.	Ref. 7
Target size	There is not much difference between identification scores on 10- and 14-min arc of visual angle targets; scores for 6-min arc are poorer.	

Notes

Section 7.7 Workload Characteristics



7.701 Criteria for Selection of Workload Assessment Techniques

Table 1. Comparison of workload-assessment techniques. (From Ref. 2)

Technique	Sensitivity	Diagnosticity	Practical Constraints	Source
Primary-task measures	Discriminate overload from nonoverload situations	Non-diagnostic; a global index of workload	Data collection may require instrumentation that would limit use in field situations	CRef. 7.716
Secondary-task measures	Discriminate levels of workload in nonoverload situations; can assess reserve capacity not used by a primary task	Diagnostic; can discriminate differences in operator resource expenditure	Subject to primary task intrusion, except for embedded and adaptive task techniques; some operator training required to stabilize secondary task performance; potential for artificiality and lack of face validity	CRefs. 7.717 7.718, 7.719, 7.722, 7.723
Physiological	Discriminate levels of workload in nonoverload situations; can assess reserve capacity not used by a primary task	Pupillometry considered non-diagnostic; event-related potential recording considered diagnostic	Substantial instrumentation required which could result in interference with primary task; data collection generally restricted to laboratory settings	CRefs. 7.724, 7.725, 7.726
Subjective	Discriminate levels of workload in nonoverload situations; can assess reserve capacity not used in primary task	Non-diagnostic; a global index of workload	Some familiarization with procedures may be required	CRef. 7.715

Key Terms

Diagnosticity; pupillometry; sensitivity analysis; workload measurement

General Description

The general categories of workload assessment methodologies (performance, physiological, subjective) can be compared on five dimensions. These dimensions and the goals of the assessment study can be used as criteria when choosing the most appropriate methodology. The following definitions of the five dimensions are taken from Ref. 5

(1) Sensitivity is the ability of a technique to discriminate variations in the workload imposed by a task or design option (CRef. 7.702). (2) Diagnosticity is the ability of a technique to discriminate the workload imposed upon different operator resources (CRef. 7.703). (3) Intrusiveness is the tendency for a technique to cause degradations in ongoing primary task performance (CRef. 7.722). (4) Implementation requirements refer to the ease with which a particular technique can be employed. These might include special instrumentation or the training an operator must undergo before the technique can be implemented. (5) Operator acceptance is the degree of willingness of operators to follow instructions and requirements necessary for a particular technique. Acceptance will be related in part to artificiality and face validity of the technique.

Table 1 compares primary- and secondary-task methods (both are performance techniques), physiological techniques, and subjective techniques on the five dimensions; the dimensions of intrusiveness, implementation requirements, and operator acceptance are combined under the column heading of "Practical Constraints" in Table 1. Some general conclusions can be made, although each of these must be considered against the objectives of the workload investigation. (1) Primary-task techniques (measures) are generally considered less sensitive than the other three techniques. (2) Primary-task measures, subjective techniques, and some physiological methods (e.g., pupillometry; CRef. 7.728) are generally considered non-diagnostic, whereas secondary-task measures (CRef. 7.719) and the physiological method of brain-potential recording (CRef. 7.724) are considered more diagnostic. (3) Physiological methods and secondary-task techniques, other than the embedded secondary-task method, have the highest potential for primary-task intrusion. (4) Subjective techniques and primary-task measures carry the least implementation problems. (5) Subjective techniques and primary-task measures possess a high degree of operator acceptance, whereas the other methods all have the potential for artificiality and lack of face validity.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Empirical Validation

(1) Validation of sensitivity criteria comes from work that examines the variation in performance under different workload levels (Ref. 3). Tasks that do not result in differential performance under varying load levels are insensitive. Subjective, physiological, or secondary task measures are recommended when workload is low to moderate, because primary-task measures are insensitive at these load levels. Under moderate load levels, primary-task sensitivity increases, and thus these levels are sufficient for workload assessment. Finally, current methods are insensitive when load levels are extremely high. (2) Validation of diagnosticity employs much the same logic as the validation of sensitivity, except that performance under varying load levels is examined with the assumption that different tasks may use different information processing resources. Those measures that vary according to the resource(s) expended are said to be diagnostic (Refs. 1, 3, 4, 6). (3) There is little systematic data with regard to the practical constraints for the various techniques.

Constraints

- Many of the constraints on the techniques summarized here can be found under "Practical Constraints" in Table 1.
- It must be emphasized that the constraints which apply in a particular situation depend upon the goals of the workload assessment study.

Key References

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Cross References

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.703 Diagnosticity in the choice of a workload assessment technique;

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.716 Primary task measures for workload assessment;

7.717 Use of the loading-task paradigm in workload assessment;

7.718 Use of the subsidiary task paradigm in workload assessment;

7.719 Major classes of secondary task;

7.722 Use of adaptive-task techniques to counter primary task intrusion in workload assessment;

7.723 Use of embedded secondary tasks in workload assessment;

7.724 Transient cortical evoked responses as a physiological measure in workload assessment;

7.725 Use of the P300 spike with a secondary task;

7.726 Use of transient cortical evoked response in the primary task situation;

7.728 Pupil diameter as an indicator of workload

7.702 Sensitivity Requirements and Choice of a Workload Assessment Technique

Key Terms

Sensitivity analysis; subjective ratings; workload measurement

General Description

Sensitivity is the ability of a workload assessment technique to discriminate different levels of workload imposed upon an operator by a particular task or design option. Theoretically, workload and operator performance are related, as illustrated in Fig. 1. The relationship is based upon the assumption that the resources an operator applies to task performance are of limited capacity. In Region A, there is no decrement in performance, even though workload increases, because the operator has sufficient spare capacity to apply to the task. In Region B, the operator does not have sufficient resources to maintain performance levels as workload increases. Consequently, there is an inverse relationship between task performance and operator workload in this region. In Region C, workload reaches its highest levels and performance drops to a lower limit because operator resources are exhausted.

Workload assessment techniques vary in their degree of sensitivity at different workload levels. In Region A, primary-task measures are insensitive to workload because the operator can maintain performance levels by "working harder." Questions of workload in this region deal with the amount of reserve capacity left to an operator and with potential overloads should additional demands be placed upon an operator. Secondary-task methodology is designed to address this issue, in that secondary-task performance is an index of spare capacity after allocation of resources to the primary task (CRefs. 7.717, 7.718, 7.719). In addition, subjective techniques (CRefs. 7.714, 7.715) and physiological techniques (CRefs. 7.717, 7.718) successfully index workload in this region. In Region B, primary-task performance can be used to index workload because of the monotonic relationship existing between the two variables. Some studies employ multiple primary measures to guard against the possibility that specific measures may vary in sensitivity (Ref. 2; CRef. 7.716). Subjective, physiological, and secondary measures may also be used in Region B if it is necessary to discriminate small differences in workload and a primary measure is too insensitive. In Region C, primary-task performance will indicate exhaustion of operator resources, but cannot be used to index workload levels. Currently, there are no good techniques to assess load level in this region (Ref. 6).

Choice of a particular technique must be based upon the purpose of the workload assessment study as well as upon the sensitivity of a measure. For example, if the objective is simply to determine whether an overload exists, primary-task measures should be sufficient. However, if potential overloads are a concern, secondary, physiological, or subjective measures should also be used. Furthermore, choice of specific techniques will depend upon other aspects of workload assessment capabilities, such as diagnosticity or intrusiveness (CRef. 7.701).

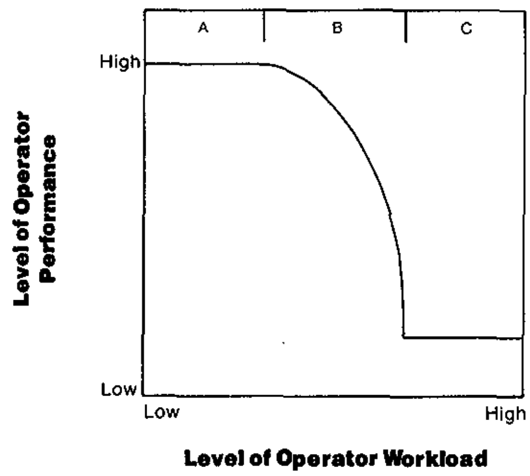

Figure 1. Hypothetical relationship between workload and operator performance. Regions A, B, and C are areas where different workload measures may be appropriate. (From Refs. 3, 5, & 7)

Applications

Selection of a workload assessment technique appropriate for use with a particular task or design option.

Empirical Validation

Validation of the sensitivity of a particular technique comes from work that examines the variation in performance and/or scores on the various techniques under different workload levels (Ref. 5). In addition, the relative sensitivity of measures can be examined by comparing the variability produced by different load levels (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Several investigators provide the effects of learning or operator skill level in their conceptualization of the relationship between workload and performance. Consequently, the three regions depicted in Fig. 1 may take on different appearances in highly skilled or relatively non-skilled operators. For example, a highly skilled operator will make more efficient use of resources, and so performance levels may be maintained well into Region B, making primary task measures insensitive at moderate workload levels. The investigator should be aware of a subject's skill level in order to choose techniques that will ensure optimum sensitivity (Refs. 4, 7).

Key References

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.714 Comparison of normalized subjective workload assessment technique (SWAT) ratings and normalized mean error scores in a memory task;

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.716 Primary task measures for workload assessment;

7.717 Use of the loading-task paradigm in workload assessment;

7.718 Use of the subsidiary task paradigm in workload assessment;

7.719 Major classes of secondary task;

7.725 Use of the P300 spike with a secondary task;

7.726 Use of transient cortical evoked response in the primary task situation

7.703 Diagnosticity in the Choice of a Workload Assessment Technique

Table 1. Diagnosticity of different types of workload indices.

Workload Index	Example of Methodology	Diagnosticity	Source
Subjective	Subjective Workload Assessment Technique (SWAT)	Non-diagnostic; rating scales employed represent a global measure of workload because of operator inability to discriminate individual resources	Ref. 8; CRef. 7.715
Performance	Primary-task measures	Non-diagnostic; measure overall workload, but unable to identify specific locus of overload	Ref. 5; CRef. 7.716
	Secondary-task measures	Considered diagnostic; choice of secondary task will determine the resource drawn upon (e.g., memory load will draw upon central processing resources)	Refs. 2, 3; CRef. 7.719
Physiological	Pupil diameter	Non-diagnostic; pupil diameter is related to general degree of arousal and therefore is correlated with workload; however, general arousal can be due to physical effort as well as to psychological effort	Ref. 1; CRef. 7.728
	Event-related brain potential	Considered diagnostic; early components (latency less than 250 msec) are related to sensory characteristics of the stimulus, whereas later components (latency greater than 300 msec) are related to stimulus evaluation. Within the later components, amplitude of the potential is related to workload	Ref. 4; CRef. 7.724

Key Terms

Diagnosticity; multiple resources; workload measurement

General Description

Diagnosticity is the characteristic of a workload measure that refers to the measure's ability to discriminate the load imposed upon different types of operator resources. The assumption underlying the concept of diagnosticity is that the operator possesses multiple resource pools tapped by various types of task performance (Ref. 6). For example, aircraft control requires perceptual processing, central processing, and motor resources. These resources are considered non-substitutable; for example, perceptual resources cannot be substituted for, or added to, motor resources to increase an operator's capacity. Diagnosticity can be represented as a dimension with indices of specific resource demands at one extreme and global workload assessment at the other extreme. Any given workload assessment technique lies somewhere on this dimension (Ref. 9).

The level of diagnosticity required in a situation depends upon the objectives of the workload assessment being conducted. If, as an initial step, it is important to screen tasks or design options for potential workload difficulties, then a measure with low diagnosticity should be employed. Such a measure will indicate workload problems on the task as a whole. After this initial step, however, it may be important to determine more specifically the source of the workload problem to implement task or design modification. At this point a measure with high diagnosticity would be used to specify the operator resources being drawn upon most heavily.

The table below summarizes diagnosticity for several types of workload indices and gives an example of methodology within each major type (the diagnosticity of a particular measurement type may depend upon the specific technique used in assessment). The table also contains sources for specific examples of the workload indices.

Constraints

- The concept of diagnosticity presupposes an operator with multiple resources. An alternative position, the central capacity model, assumes that the operator possesses a single resource pool (Ref. 7). If this position is correct, the concept of diagnosticity would be of questionable value, because diagnosticity means the ability to discriminate among different resources.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.716 Primary task measures for workload assessment;

7.719 Major classes of secondary task;

7.724 Transient cortical evoked responses as a physiological measure in workload assessment;

7.728 Pupil diameter as an indicator of workload

7.704 Measurements Used in Workload Assessment

Key Terms

Evoked potentials; pupillometry; rating scales; workload measurement

General Description

Workload is the portion of resources (i.e., maximum performance capacity) expended in the performance of a particular task. Because human resources are limited, it is important that the tasks performed or design options selected for a system do not overload human capacity and produce performance decrements. Many techniques have been employed to assess workload. These can be classified into three broad categories: subjective, performance, and physiological measures.

(1) Subjective measures use operator judgments to assess workload, and can require report of experiences with the task or design option under study. Standardization is often achieved by using rating scales.

(2) Performance measures focus on operator behavior in task performance. Primary-task (i.e., task on which workload is to be assessed) measures examine adequacy of performance on the main task, whereas secondary-task measures assess the workload for the primary task by examining the operator's ability to perform a second task concurrently with the primary task.

(3) Physiological measures correlate presumed workload with a physiological response of the operator. Once it is established that a particular technique is sensitive to workload, that technique may then be used to infer the level of workload inherent within a given task or design option. These measures include autonomic responses (e.g., pupil size), central nervous system responses (e.g., event-related brain potentials), and peripheral measures (e.g., muscle activity).

The list below indicates individual measures used within each general category, with application examples and cross references to other entries on specific measures. The list has been developed, in part, from material in Ref. 13.

Subjective Measures

- Rating scales (Refs. 3, 9; CRefs. 7.713, 7.714, 7.715)
- Interview and questionnaires (Ref. 12)

Performance Measures

- Primary-task measures (Ref. 10; CRef. 7.716)
- Secondary-task measures in subsidiary-task paradigm (Ref. 2; CRef. 7.718)
- Secondary-task measures in loading-task paradigm (Ref. 4; CRef. 7.717)
- Secondary-task measures with adaptive-task techniques (Ref. 8; CRef. 7.722)
- Secondary-task measures with embedded secondary tasks (Ref. 11; CRef. 7.723)

Physiological Measures

- Pupillometry (Ref. 7; CRef. 7.728)
- Cortical evoked response with a primary task (Ref. 5; CRef. 7.726)
- Cortical evoked response with a secondary task (Ref. 6; CRef. 7.725)
- Electromyography (Ref. 1; CRef. 7.729)

Constraints

- The portion of resources expended is not necessarily directly related to task demands; that is, an analysis of task complexity is not necessarily a good measure of resource requirements.

Key References

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Cross References

7.713 Subjective workload assessment technique (SWAT) ratings as a function of task difficulty;

7.714 Comparison of normalized subjective workload assessment technique (SWAT) ratings and normalized mean error scores in a memory task;

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.716 Primary task measures for workload assessment;

7.717 Use of the loading-task paradigm in workload assessment;

7.718 Use of the subsidiary task paradigm in workload assessment;

7.722 Use of adaptive-task techniques to counter primary task intrusion in workload assessment;

7.723 Use of embedded secondary tasks in workload assessment;

7.725 Use of the P300 spike with a secondary task;

7.726 Use of transient cortical evoked response in the primary task situation;

7.728 Pupil diameter as an indicator of workload;

7.729 Surface electromyograph as an index of physical workload

7.705 Cooper-Harper Aircraft Handling Characteristics Scale as a Subjective Measure of Workload

Table 1. Experimental investigations of the relationship between the Cooper-Harper scale and workload.

Test Conditions	Experimental Procedure
Study 1 (Ref. 2) • Tests conducted in a JC-131B test aircraft, modified to accommodate aircraft test apparatus, a standard profile required on each approach • Six modes of aircraft control: manual instrument loading system; manual with flight director; semi-automatic; workload sharing with copilot: pitch and power; workload sharing: roll and yaw; and full automatic • Order of aircraft control mode counterbalanced	• Independent variable: aircraft control • Dependent variables: glide slope error, localizer error, pitch steering bar error, bank steering bar error, pitch force, yaw force, roll force, Cooper and other subjective ratings. • Subject's task: fly all six modes with three approaches per mode • 8 experienced pilots
Study 2 (Ref. 3) • Tests conducted in fixed-based simulator; eye movement data obtained from an oculometer	• Independent variable: five simulated wind conditions, Cooper ratings used as independent variable • Dependent variables: glide slope error, localizer error, velocity error, eye movement changes. • 8 airline pilots and one test pilot
Study 3 (Ref. 4) • Tests were in-flight evaluations of X-22A V/STOL aircraft	• Independent variables: five types of control augmentation; three types of electronic display format, with two variations. • Dependent variables: Cooper-Harper rating, turbulence effect rating • Subject's task: fly a standard flight profile of an instrument approach • 1 pilot gave 38 ratings of 21 display-control configurations

Key Terms

Cooper-Harper rating; critical instability task; pilot ratings; secondary task; subjective ratings; workload measures

General Description

The Cooper-Harper Aircraft Handling Characteristics Scale, the most widely used evaluation technique for aircraft handling, makes use of a decision-tree format to obtain a pilot rating of various characteristics on a 10-point scale. The scale has been proposed as a measure of pilot workload because many of the rated characteristics refer to task demand and pilot workload. The assumption that pilot workload is related to handling characteristics has been tested in a number of studies; the task variables that affect workload also affect Cooper-Harper ratings. Therefore, the Cooper-Harper ratings are usually taken as indicative of task difficulty.

Methods

Details of the experimental methods are provided in Table 1.

Experimental Results

• Increasing automation of flight task, as well as the introduction of workload-sharing with a copilot, is reflected in decreasing (better) Cooper-Harper ratings.
• Cooper-Harper ratings may be used to measure task difficulty and to reveal variations in several parameters related to difficulty (e.g., error rate on a control task, pupil diameter, fixation duration, blink rate, and saccade length in eye movement recordings).
• Cooper-Harper ratings increase (get worse) with increasing control complexity and with increasing display sophistication; this might be expected because these add to the pilot's task.

Repeatability/Comparison with Other Studies

The studies reported here, and a number of others, consistently indicate that Cooper-Harper ratings vary in the expected direction with those factors that may affect pilot workload.

Constraints

• The Cooper-Harper scale (Table 2) measures only the demands of certain tasks in the flight context; it may not reflect the actual expenditure of capacity or mental effort used in performing the task.
• The scale does not precisely define the variables that may affect handling characteristics (e.g., display adequacy or vehicle stability).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Cooper, G. E., & Harper, R. P., Jr. (1969). *The use of pilot rating in the evaluation of aircraft handling qualities* (AGARD-567). Paris, France: Advisory Group for Aerospace Research and Development. (DTIC No. AD689722)

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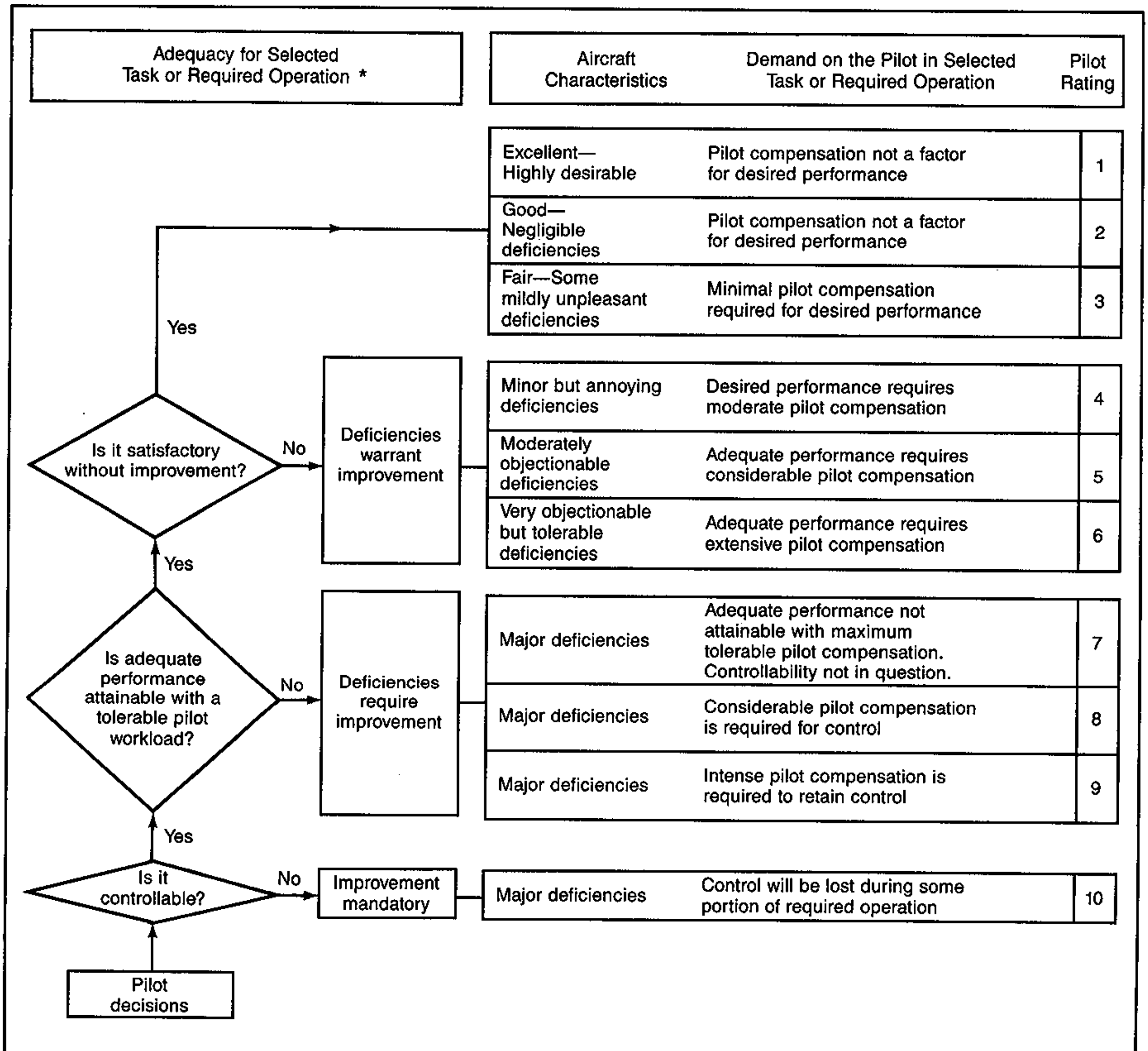
Cross References

7.706 Cooper-Harper aircraft handling ratings as a function of secondary task instability;

Handbook of perception and human performance, Ch. 42, Sect. 2.2

Table 2. The Cooper-Harper Aircraft Handling Characteristics Scale.



*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

The Cooper-Harper aircraft handling qualities rating scale follows a decision-tree format in which a pilot initially considers the adequacy of the aircraft for some specified task or operation. Based on the initial judgment of adequacy, more detailed decisions regarding aircraft characteristics and the demands placed on the pilot are made, resulting in an eventual rating of the ten-point scale which is illustrated.

7.706 Cooper-Harper Aircraft Handling Ratings as a Function of Secondary Task Instability

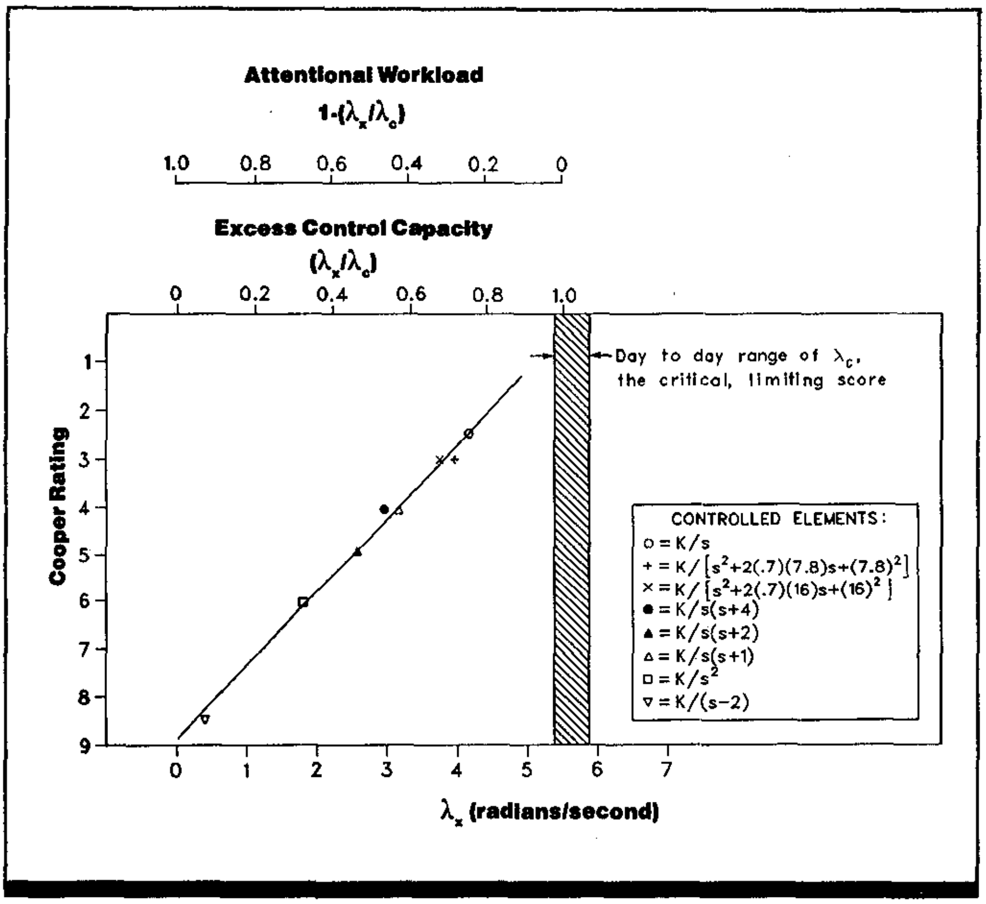


Figure 1. Cooper handling characteristic scale ratings as a function of λ_x, the level of control gain for a secondary task (a critical tracking task) at which subjects could no longer maintain a criterion level of performance on a primary tracking task. λ_c is the gain level at which secondary-task instability occurred without a concurrent primary task. When excess control capacity is measured in terms of λ_x/λ_c, it is not affected by individual differences in tracking skills. Attentional workload is calculated by subtracting the value of excess control capacity from 1. (Adapted from Ref. 2)

Key Terms

Cooper-Harper rating; critical tracking task; pilot workload; tracking; workload measures

General Description

The Cooper-Harper Aircraft Handling Characteristics Scale (CRef. 7.705, Table 2) is the most widely used evaluation technique for aircraft handling. It is also frequently taken as a measure of pilot workload, although this assumes that all workload in the flying task is related to handling characteristics. To test this assumption, a critically unstable tracking task (CRef. 9.527) has been used as a **secondary** task (CRefs. 7.717, 7.718, 7.721) workload measure by **cross-coupling** (CRef. 9.531) a critical tracking task with a primary tracking task. The secondary task is made more unstable by steadily increasing its control gain until it takes so much of the pilot's or operator's effort that **primary task** performance can no longer be maintained at criterion levels. The control gain at which this happens is considered a measure of the workload of the primary task.

Applications

Assessment of the workload imposed by the dynamics of a particular aircraft or other control system; useful in task assignment among crew members or making decisions about the implementation of automation.

Methods

Test Conditions

- Fixed-base simulator with CRT inside-out display and centered control stick
- Task used compensatory tracking in pitch
- For primary task, display showed a line like a horizon bar that moved with system dynamics
- Secondary task was displayed motion in roll (an unstable tracking task called a "critical tracking task") (CRef. 9.527)
- Inside-out display
- Command input was sum of 12 sinusoids at three bandwidths (1.88, 2.89, 4.77 radians/sec) and three amplitudes (0.5, 1.0, 1.5 cm root mean square), which resembled a random input
- Secondary-task difficulty was proportional to primary-task performance (i.e., good primary performance led to an increase in secondary-task difficulty, and vice versa)

Experimental Procedure

- Independent variables: dynamic configuration of controlled elements, as shown in Fig. 1; secondary-task difficulty, as measured by λ (gain)
- Dependent variable: Cooper-Harper type ratings of various task characteristics (there were also a number of other measures used that are not relevant here)
- Subject's task: tracking to minimize pitch error for 15 sec to arrive at steady tracking, followed by a 120-sec trial
- 2 experienced pilots served as subjects

Experimental Results

- A high control gain in the secondary task indicates a low workload in the primary task.
- Cooper-Harper ratings are clearly related to λ_x, the level of secondary-task control gain at which subjects can no longer maintain criterion performance on the primary task. Low Cooper-Harper scale values (reflecting favorable ratings of primary task characteristics) are associated with high gain on the secondary task (indicating low primary-task workload) and high scale values (unfavorable ratings of primary-task characteristics) are associated with low values of λ_x (high primary-task workload). This supports the usefulness of Cooper-Harper ratings as a measure of subjective pilot workload.

Variability

Individual differences in tracking skill can be normalized by dividing λ_x by λ_c (gain on secondary task by gain on primary task); thus, biases introduced by individual differences can be controlled (Fig. 1).

Constraints

- Such an application of the Cooper-Harper scale can obviously be used only for a tracking task.
- The Cooper-Harper scale does not define any variables that may affect handling characteristics (e.g., display or control configurations).

Key References

1. Cooper, G. E., & Harper, R. P., Jr. (1969). *The use of pilot rating in the evaluation of aircraft handling qualities* (NASA-TN-D-5153). Moffett Field, CA: Ames Research Center, National Aeronautics and Space Administration.

*2. McDonnell, J. D. (1968). *Pilot rating techniques for the estimation and evaluation of handling qualities* (AFFDL-TR-68-76). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory. (DTIC No. AD681845)

Cross References

7.705 Cooper-Harper aircraft; handling characteristics scale a as subjective measure of workload;

7.717 Use of the loading-task paradigm in workload assessment;

7.718 Use of the subsidiary task paradigm in workload assessment;

7.721 Guidelines for the use of secondary task measures in workload assessment;

9.527 Inherently unstable dynamics: the critical tracking task;

9.531 Multiaxis and multiloop control: manual control with multivariate systems;

Handbook of perception and human performance, Ch. 42, Sect. 2.2

7.707 Cooper-Harper Scale Modified for System Workload Assessment

Key Terms

Cooper-Harper rating; mental effort; pilot workload; subjective ratings; workload measures

General Description

The Cooper-Harper Scale is the most widely used scale for measuring aircraft handling characteristics and, on the basis of correlations with other measures, is also used as a measure of pilot workload (CRef. 7.705). It uses a decision-tree format in which the pilot makes a number of yes-no decisions, eventually arriving at a rating on a 10-point scale. Its usefulness has been extended to other types of systems by replacing the terminology of aircraft handling and controllability with more general terminology, as shown in Table 1. The terms that deal with mental workload or effort are operationally defined as they relate to task demand, errors, or controllability. The scale is also easy to use, and can probably be learned in one practice trial. Because the modified Cooper-Harper scale is sensitive to different types of loading (e.g., perceptual or problem-solving), it may serve as a global workload measure.

Applications

It should be possible to modify the Cooper-Harper decision-tree scale with appropriate terminology to measure operator mental workload in any system.

Methods

Test Conditions

- Tests conducted in a Singer-Link GAT-1B moving-base simulator modified with a computer for workload data collection
- Simulated "control tower" communications, with specific call signs (e.g., one-bravo-seven-zulu) transmitted on the average of every 12 (low workload), 5 (medium workload), or 2 (high workload) sec among other call signs; in medium and high conditions, 30 or 40% of non-target call signs might be permutations of the target call sign
- 16 workload measurement techniques were evaluated, including the modified Cooper-Harper scale
- Subjects divided into six separate groups based on flight experience

Experimental Procedure

- Mixed factorial design
- Independent variables: communications load level, type of workload measurement technique, flight experience
- Dependent variables: mean Cooper-Harper ratings, converted to a standard score based on a normal distribution for comparison with other techniques, scores for other workload measurement techniques
- Subject's task: fly simulator while monitoring communications from "control tower" for specific call sign
- 30 pilots evaluated all techniques, but one at each of six levels of flight experience evaluated modified Cooper-Harper scale; each had 8-min practice flight

Experimental Results

- Mean standardized Cooper-Harper ratings rose with increasing imposed workload, indicating that the measure is sensitive to real imposed-workload variations.
- Related experiments using other tasks (e.g., decision-making or problem-solving) showed similar results. The modified Cooper-Harper scale was more sensitive to workload variation than either of two secondary tasks (time estimation and interval production).

Constraints

- The fact that the scale is sensitive to several different kinds of workload variation indicates that it is a good overall measure of workload, but it may not discriminate among various workload sources.
- Variations in workload may need to be fairly large to produce significant results, since the scale always discriminated between low and high conditions, but not always between low and medium or between medium and high conditions.

Key References

1. Casali, J. G. (1982). *A sensitivity/intrusion comparison of mental workload estimation techniques using a simulated flight task emphasizing perceptual pilot behaviors.* Unpublished doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

*2. Casali, J. G., & Wierwille, W. W. (1983). Communications-imposed pilot workload: A comparison of sixteen estimation techniques. *Proceedings of Second Symposium on Aviation Psychology,* (pp. 223-235). Columbus, OH: Ohio State University, Aviation Psychology Laboratory.

3. Rahimi, M., & Wierwille, W. W. (1982). Evaluation of the sensitivity and intrusion of workload estimation techniques in piloting tasks emphasizing mediational activity. *IEEE 1982 Proceedings of the International Conference on Cybernetics and Society,* (pp. 593-597). Seattle, WA: Institute of Electrical and Electronics Engineers, Systems, Man and Cybernetics Society.

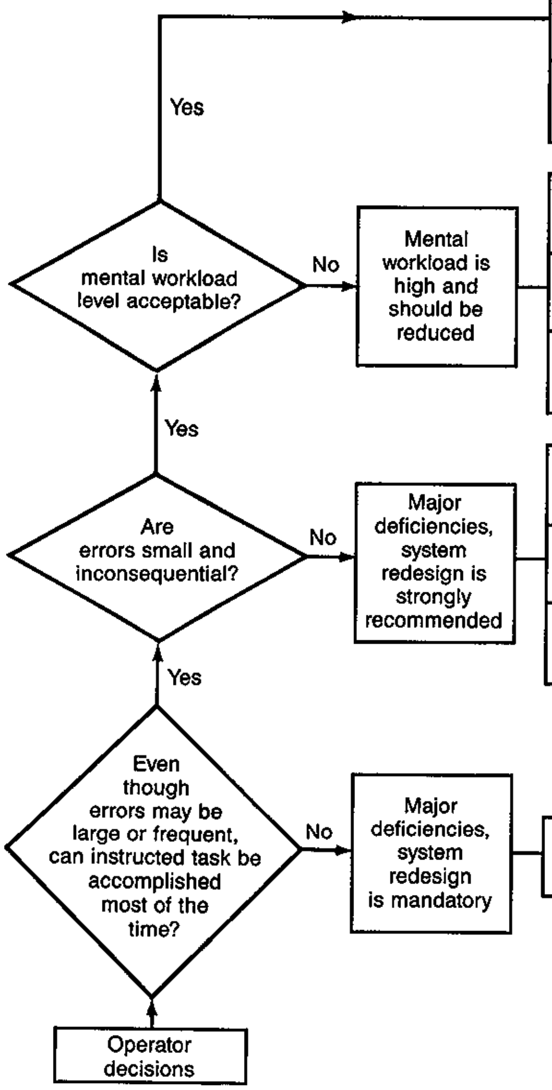
4. Wierwille, W. W., & Casali, J. G. (1983). A validated rating scale for global mental workload measurement applications. *Proceedings of the Human Factors Society 27th Annual Meeting,* (pp. 129-133). Norfolk, VA: Human Factors Society.

Cross References

7.705 Cooper-Harper aircraft handling characteristics scale as a subjective measure of workload;

Handbook of perception and human performance, Ch. 42, Sect. 2.2

Table 1. A modified version of the Cooper-Harper handling characteristics scale. (From Ref. 4)



Difficulty level	Operator demand level	Rating
Very easy, highly desirable	Operator mental effort is minimal and desired performance is easily attainable	1
Easy, desirable	Operator mental effort is low and desired performance is attainable	2
Fair, mild difficulty	Acceptable operator mental effort is required to attain adequate system performance	3
Minor but annoying difficulty	Moderately high operator mental effort is required to attain adequate system performance	4
Moderately objectionable difficulty	High operator mental effort is required to attain adequate system performance	5
Very objectionable but tolerable difficulty	Maximum operator mental effort is required to attain adequate system performance	6
Major difficulty	Maximum operator mental effort is required to bring errors to moderate level	7
Major difficulty	Maximum operator mental effort is required to avoid large or numerous errors	8
Major difficulty	Intense operator mental effort is required to accomplish task, but frequent or numerous errors persist	9
Impossible	Instructed task cannot be accomplished reliably	10

This version of the Cooper-Harper Aircraft Handling Characteristics Scale has been modified by replacing the references to aircraft handling, controllability, and pilot compensation in the original scale with terms that specifically deal with operator workload, mental effort, and performance. The decision-tree format of the original scale has been preserved so that the operator makes initial judgments regarding the adequacy of mental load and task performance and subsequently makes more refined estimates leading to a rating on the ten-point scale. In addition to dealing more directly with operator workload and effort, the wording on this scale should be applicable to a wide range of information processing and motor control tasks, thereby generalizing applications beyond the vehicular control environment treated in the original scale.

7.708 Stockholm 9-Point Scale for Subjective Workload Assessment

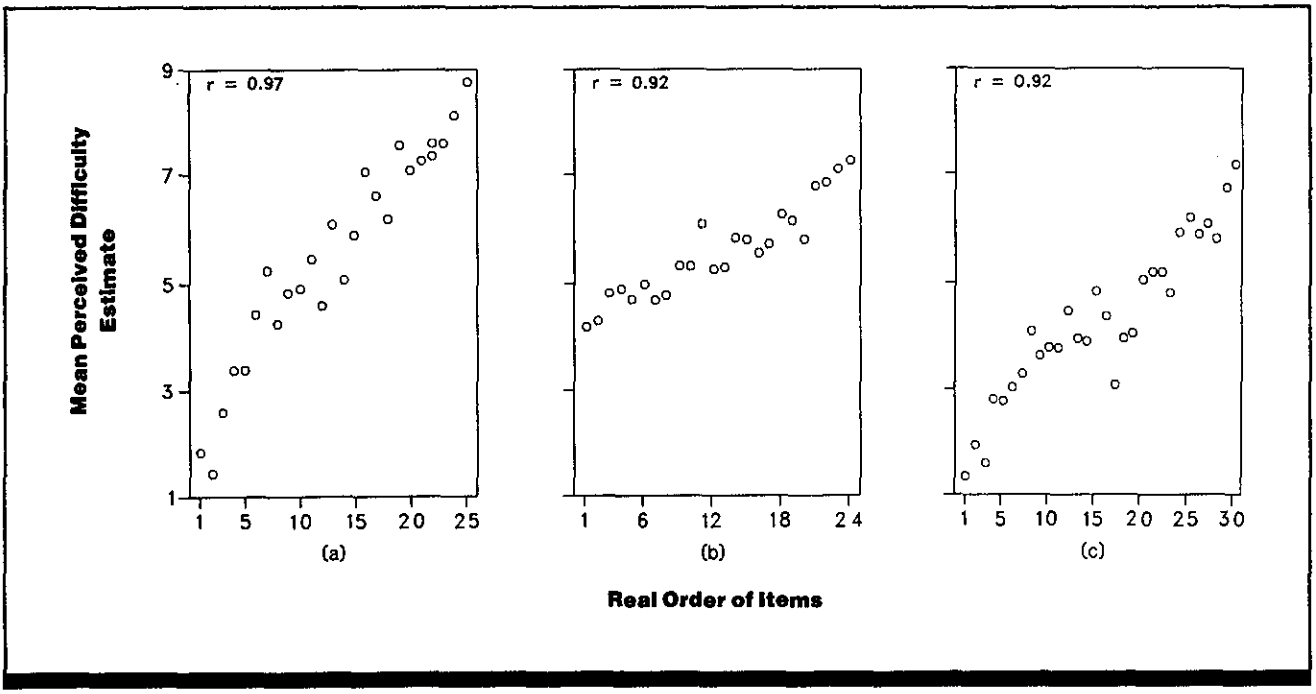


Figure 1. Mean estimates of perceived difficulty as a function of objective difficulty (which corresponds to the real order of items) for tests of (a) reasoning ability, (b) spatial ability, and (c) verbal comprehension. r = coefficient of correlation. (From *Handbook of perception and human performance*, adapted from Ref. 2)

Key Terms

Intelligence tests; mental workload; perceived task difficulty; reasoning ability; spatial ability; Stockholm 9-point scale; subjective workload; verbal comprehension; workload measures

General Description

A 9-point scale of "perceived difficulty" to measure the mental workload of items on an intelligence test has been developed at the University of Stockholm. The items are assumed to represent typical mental tasks, and they are already validated and arranged in order of difficulty on the tests. This makes it possible to determine the validity of the perceived difficulty rating by correlating it with the objective difficulty of the items. Less difficult items should yield lower ratings, and more difficult items should yield higher ratings. Figure 1 shows that the ratings are good predictors of objective task difficulty for items on (a) reasoning ability, (b) spatial ability, and (c) verbal comprehension, because the ratings increase with item order (objective difficulty) on these tests. *Rank-order correlation coefficients*, shown on the figure, are extremely high.

Applications

The scale could be applied to the measure of workload for any mental task, although some check on its validity for this purpose should be run, as it has been validated only on intelligence test items.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

• 79 items testing reasoning ability, spatial ability, and verbal comprehension taken from a standardized intelligence test battery; items arranged in order of increasing difficulty

• Tests administered to subjects under standard test-taking conditions, so that subjects would be thoroughly familiar with intellectual performance required

Experimental Procedure

• Independent variable: test item difficulty

• Dependent variable: subjects' rating of item difficulty on a 9-point scale

• After each test item, subjects were asked to rate the item on a scale in which 1 is very, very easy; 2 is very easy; 3 is easy; 4 is rather easy; 5 is neither easy nor difficult; 6 is rather difficult; 7 is difficult; 8 is very difficult; 9 is very, very difficult; short instructions given prior to the test

• 34 subjects with high school education participated, although not all completed all the tests

Experimental Results

• The ratings on the 9-point scale clearly rise with increasing objective test item difficulty.

• The correlations between real item difficulty and difficulty rating are 0.97 (reasoning ability), 0.92 (spatial ability), and 0.92 (verbal comprehension). These are extremely high coefficients, and are good evidence of rating validity.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The results were replicated in several studies from the same laboratory. In addition, test-retest reliability was extremely high ($r = 0.99$) in one of the studies.

Constraints

• The scale was validated on intelligence test items, and assumes that items are representative of many tasks. This assumption has not been tested.

• The relationship between difficulty rating and item order is slightly non-linear; it seems that increases in objective difficulty on the low and high ends of the scale yield smaller differences in subjective rating.

• Ratings of "perceived difficulty" may not be the same as ratings of "perceived effort"; thus the scale may not be a true measure of effort or workload.

Key References

1. Bratfisch, O. (1972). *Experienced intellectual activity and perceived difficulty of intelligence tests* (Report No. 30). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

*2. Bratfisch, O., Borg, G., & Dornic, S. (1972). *Perceived item difficulty in three tests of intellectual performance capacity* (Report No. 29). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

3. Hallsten, L., & Borg, G. (1975). *Six rating scales for perceived difficulty* (Report No. 58). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

Cross References

7.701 Criteria for selection of workload assessment techniques;

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.704 Measurements used in workload assessment;

7.709 Stockholm 11-point scale for subjective workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 2.2

7.709 Stockholm 11-Point Scale for Subjective Workload Assessment

Key Terms

Attention; mental effort; mental workload; problem solving; secondary task; Stockholm 11-point scale; subjective workload; target detection; workload measures

General Description

Mental effort may be considered a perceptual variable, in that it is experienced or perceived by an operator, and thus may be measured by a subjective scale, such as the 11-point scale for the assessment of mental effort developed at the University of Stockholm. Mental effort is different from, but related to, perceived difficulty (CRef. 7.708) of a task, but should be distinguished from attention and from spare mental capacity.

Some tasks (e.g., detection or discrimination of a target) may be perceived as requiring attention, even concentrated attention, but very little effort, even if they are very difficult. For other tasks (mainly information processing tasks such as mental arithmetic or problem solving), however, mental effort and attention are closely related.

Spare mental capacity available for a concurrent **secondary task** (CRef. 7.708) has often been used as a measure of the mental workload of a **primary task**. As the primary task uses more capacity, there is less capacity available for the secondary task; thus secondary task performance reflects capacity used by the primary task. With tasks that require concentrated attention but relatively little effort, spare capacity may be available but not momentarily accessible; on the other hand, there may really be no spare capacity with tasks that require both effort and attention. Thus the momentary *accessibility* of spare capacity is related to attention, and the *availability* of spare capacity is related to effort. Availability may be small for tasks requiring both effort and attention, but may be large for tasks requiring only attention. On the other hand, existent spare capacity may not be accessible for either type of task.

The University of Stockholm scale has been used to validate empirically the distinctions between attention and effort, and available and accessible spare mental capacity.

Applications

The scale can be used immediately after any task to measure the amount of expended mental effort.

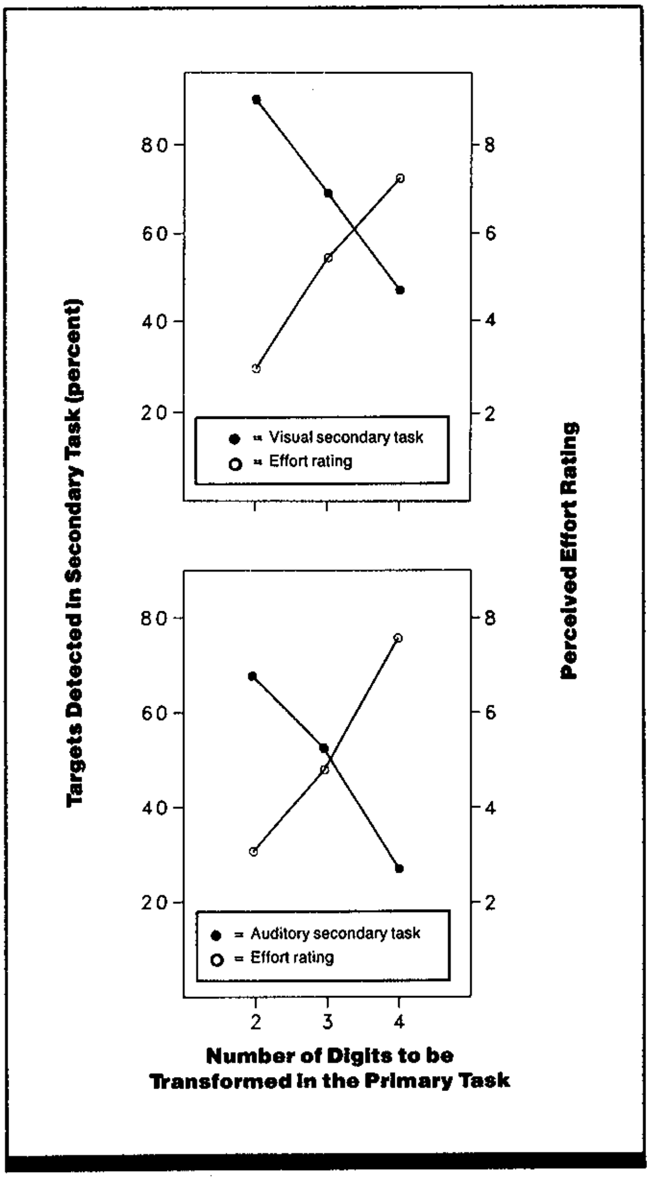


Figure 1. Performance on a secondary task and perceived-effort ratings as functions of primary task difficulty (i.e., number of digits to be transformed). (From *Handbook of perception and human performance*, adapted from Ref. 1)

Methods

Test Conditions

- Subjects performed a concurrent primary task and a secondary task to measure spare capacity
- Two experiments, each with a different type of secondary task
- Primary task required continuous mental digit transformations at three complexity levels (adding one to two, three, or four digits; e.g., 56 became 67); secondary task was either visual or auditory detection of letter pairs in a series of letters with, respectively, a manual or a verbal response

Experimental Procedure

- Independent variables: primary task difficulty, type of secondary task
- Dependent variables: secondary task performance, effort rating on primary task
- Subject's task: primary was digit addition; secondary was either visual or auditory detection of letter pairs
- 10 subjects, high school and college students

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• Secondary-task performance declined with increasing primary-task complexity, although primary-task performance was not affected (Fig. 1).
• Ratings of perceived effort rose with primary-task complexity, so there is a reciprocal relationship between perceived effort and spare capacity. The ratings are therefore sensitive to primary-task workload manipulation.

Repeatability/Comparison with Other Studies

Four studies from the same laboratory have reported similar sensitivity of the 11-point rating scale.

Constraints

• The scale seems valid and reliable, but more data are necessary before firm conclusions can be reached.
• Evaluations so far have been on perceptual or central processing tasks; the scale may not be as sensitive to other tasks, such as control of dynamic systems.

Key References

*1. Dornic, S. (1980). *Spare capacity and perceived effort in information processing* (Report No. 567). Stockholm, Sweden: University of Stockholm, Department of Psychology.

2. Dornic, S., & Andersson, O. (1980). *Difficulty and effort: A perceptual approach* (Report No. 566). Stockholm, Sweden: University of Stockholm, Department of Psychology.

Cross References

7.708 Stockholm 9-point scale for subjective workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 2.3

7.710 Workload Assessment Using Magnitude Estimation Techniques

Key Terms

Magnitude estimation; mental workload; psychological scaling; system operability; workload measures

General Description

Workload assessment measurements are designed to translate the subjective experience of mental workload into a numerical scale that represents the magnitude of that workload. Such a process is called psychological scaling, and a number of methods have been developed to scale various subjective experiences such as brightness, loudness, etc. One important scaling method is called magnitude estimation; it involves asking a subject to respond to a stimulus by giving a number that indicates the magnitude of the experience. Sometimes a standard stimulus is presented and assigned a numerical value, called the modulus, and other stimuli are judged in comparison to this value. Therefore, if a standard task is assigned a modulus of 10, then a task that requires half the workload of the standard should be given a value of 5, and one that requires double the workload should be given a value of 20. Subjects may also be asked to assign values of their own choosing without any standard stimulus or modulus, weighting the values only in comparison with other stimuli in the series. Not using a standard stimulus (modulus) is perhaps more common with many scaling tasks, but workload scaling has tended to use a standard.

Subjects can routinely assign numbers to stimuli with great consistency. The relationship between an objective measure of the stimulus and the subject's judgments follows a power function, such that

$$R = kS^P$$

where R is the subject's response and S is the judged strength of the stimulus. The constant (k) and the power (P) are peculiar to the stimulus continuum being judged.

This method has been applied to the judgment of perceived difficulty or workload of a task. Figure 1 shows the relationship between magnitude estimation judgments of perceived difficulty and some measurement of the actual difficulty level of the task. More difficult task levels produce higher judgments of perceived difficulty, and reported correlations between magnitude estimation judgments and objective workload indices range from 0.59-0.98, indicating that the judgments are a sensitive indicator of workload.

Applications

Magnitude estimation can be used to measure workload in perceptual, information-processing, motor, and communication tasks.

Methods

Details of the experimental methods are provided in Table 1.

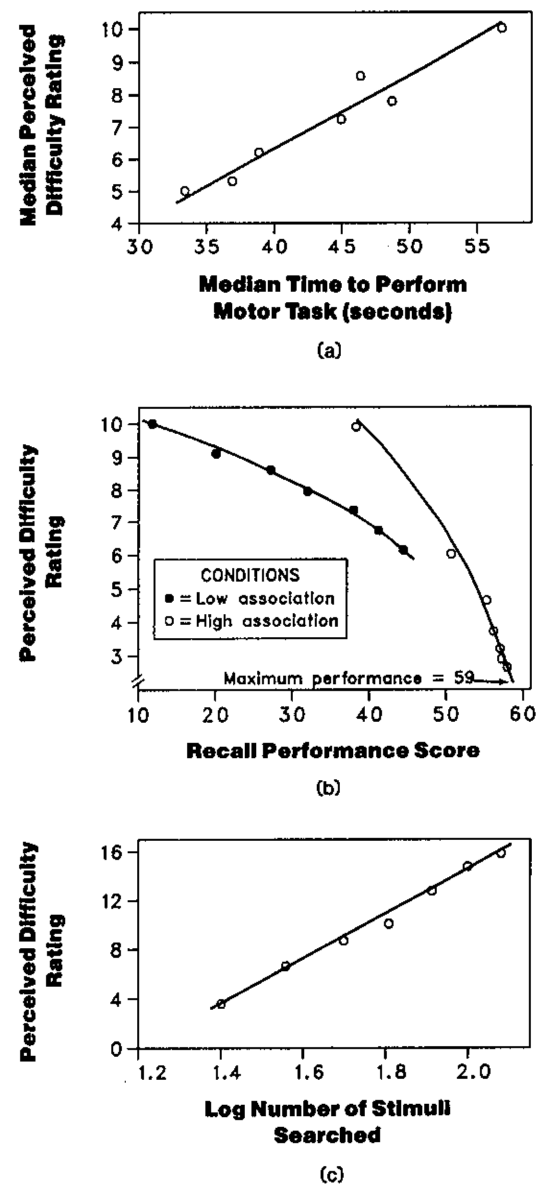


Figure 1. Ratings of perceived difficulty (obtained via magnitude estimations) as functions of several objective experimental variables. (a) Seven repetitions of a simple motor task; r = 0.96 (Study 1). (From Ref. 3) (b) Seven repetitions of recall of twelve-word lists for either difficult (left function) or easy (right function) word lists (Study 2). (From Ref. 4) (c) A visual-target search task (Study 3). (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Perceived task difficulty, as determined by the method of magnitude estimation, rises with objective measures of task difficulty.
- Measured correlations between perceived task difficulty and objective measures are extremely high.
- Figure 1b shows an easier task on the right and a harder one on the left; task positions further validate the perceived difficulty measure.

Repeatability/Comparison with Other Studies

At least five studies have confirmed the high correlations for tasks in various categories, as follows:

Motor skill task	0.96
IQ test item sequence	0.90
Correct word recall	−0.98
Rate of word recall	0.85
Perceptual task	−0.59
IQ test item solutions	−0.78

Constraints

- Not all subjects understand the method very well. Some instruction and training is usually required.
- Very high or very low numbers may be used by individuals, as subjects are not limited in the values they may use. Distributions of values are often non-Gaussian, and a geometric mean must be calculated.
- There may be long intervals between tasks in a practical situation, and subjects may not retain the same scale values over time.
- In experimental situations, the order of stimulus presentation is counterbalanced or randomized. This is seldom possible in practice, and biases due to order of presentation may affect the results.

Key References

*1. Borg, G., Bratfisch, O., & Dornic, S. (1971). *Perceived difficulty of a visual search task* (Report No. 16). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

2. Bratfisch, O., Borg, G., & Dornic, S. (1972). *Perceived item difficulty in three tests of intellectual performance capacity* (Report No. 29). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

*3. Bratfisch, O., Dornic, S., & Borg, G. (1970). *Perceived difficulty of a motor skill task as a function of training* (Report No. 11). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

*4. Dornic, S., Bratfisch. P., & Larsson, T. (1973). *Perceived difficulty in verbal learning* (Report No. 41). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

5. Dornic, S., Sarnecki, M., & Svensson, J. (1973). *Perceived difficulty, learning time, and subjective certainty in a perceptual task* (Report No. 43). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

6. Hallsten, L., & Borg, G. (1975). *Six rating scales for perceived difficulty* (Report No. 58). Stockholm, Sweden: University of Stockholm, Institute of Applied Psychology.

Cross References

7.701 Criteria for selection of workload assessment techniques;

7.702 Sensitivity requirements and choice of a workload assessment technique;

Handbook of perception and human performance, Ch. 42, Sect. 2.3

Table 1. Experimental studies of magnitude estimation for workload assessment.

Test Conditions	Experimental Procedure
Study 1 (Ref. 3)	
Simple motor task used as basis for subject's judgments Task resulted in rapid learning, so that performance time and, presumably, objective task difficulty decreased with practice 20-sec intertrial interval	Independent variable: time to perform task, which was, in turn, a function of trial number Dependent variable: magnitude estimation judgment of perceived task difficulty, with a modulus of 10 assigned to the first performance of the task Subject's task: move a small metal object through a "wire labyrinth" 7 male and 7 female subjects, ages 21-31
Study 2 (Ref. 4)	
Twelve lists of words of different degrees of difficulty, varying from a complete sentence to a chain of unrelated words with no associations among the words Tasks presented in random order Each list presented seven times, with a judgment of difficulty after each presentation	Independent variable: performance on recall task Dependent variable: magnitude estimation judgments of perceived task difficulty, with a modulus of 10 assigned to the first task Subject's task: learn 12 lists of 20 one- or two-syllable words 8 female and 5 male subjects, ages 17-26
Study 3 (Ref. 1)	
Matrices consisted of pairs of letters arranged in cells Number of cells varied from 5 x 5 to 11 x 11 Acoustic confusability was minimized	Independent variable: log number of stimuli detected in a visual search task Dependent variable: magnitude estimation judgments of perceived task difficulty, with a modulus of 10 assigned to the 8 x 8 matrix Subject's task: search for a target in a matrix of similar targets 8 male and 12 female subjects, ages 20-31

7.711 Mission Operability Assessment Technique (MOAT)

Key Terms

Conjoint measurement; mission operability assessment technique; multidimensional scaling; pilot workload; psychological scaling; workload measures

General Description

Operator workload in a particular system may be considered a unitary concept and given a single rating on an appropriate scale. In this case, each operator must combine such diverse aspects of workload as time stress or task difficulty according to individual understanding. Alternatively, several factors that contribute to workload may be rated at once on a single combined scale. This is called **multidimensional scaling. Conjoint scaling** is one type of multidimensional scale that has been applied to workload measurement.

In conjoint scaling, two (or more) aspects of a situation or stimulus are placed in a matrix. Each aspect has a number of levels, which are given verbal labels. The combination of each level with each aspect is then ranked (e.g., from 1 to 16 for the combinations for Table 1). Next, agreement among the rankings is tested by calculating a coefficient of concordance (W), a simple non-parametric statistical procedure. If there is high agreement, a common rank-order based on the mean rank-order for all the subjects is obtained. This is then subjected to one of several scaling solutions that yield an interval scale of values for the combination of the two aspects (i.e., the values are not rank orders but real numbers with meaningful intervals between them). In this way, two aspects or dimensions of a stimulus are rated at once. Subjects can readily perform this ranking task.

This conjoint measurement technique has been applied in several studies to the combined scaling of Pilot Workload/Compensation/Interference (PW) and Subsystem Technical Effectiveness (TE) to yield a measure of system operability, called the Mission Operability Assessment Technique (Table 1). A task analysis or task inventory is obtained for the system. The scales shown in Table 1 are then administered to pilots (or other operators in non-aircraft systems) and treated as described for various tasks in the system. An overall interval scale of system operability is then developed, in which pilot workload is included as a factor.

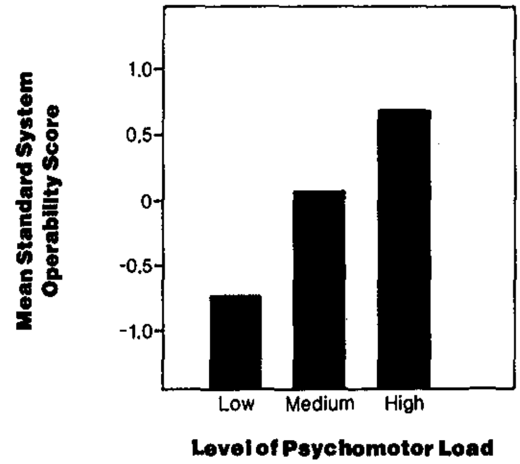


Figure 1. Mean standardized system operability scores for the Mission Operability Assessment Technique (MOAT) as a function of psychomotor load during simulated flight. (From Ref. 4)

Methods

Test Conditions

- Tests of PW/TE scale were conducted in a moving base simulator; 19 other workload measures were evaluated in the same study
- Low, medium, and high workload conditions, varied by aircraft pitch stability and random wind gust disturbance level
- Subjects flew nine familiarization flights in simulator, with different flight conditions but same instrument landing approach
- There were three data collection sessions, but only one in which PW/TE was evaluated

Experimental Procedure

- Within-subjects design
- Independent variables: workload condition, type of workload measure
- Dependent variables: PW/TE ratings, scores on 19 other workload measures
- Subjects: 6 male instrument-rated pilots, simulated flights and subsequent ratings with a mean of 1300 hr. flight experience

Experimental Results

- Ratings on the PW/TE rose with increasing imposed workload (Fig. 1).
- The differences in standardized scores between low and medium and between medium and high workload conditions were statistically significant.
- The PW/TE was one of five workload measures that demonstrated sensitivity to increasing workload.

Variability

Agreement among raters is high during scale development (i.e., in the matrix), but ratings of particular tasks show considerable variability.

Repeatability/Comparison with Other Studies

Two studies from different laboratories have demonstrated that the PW/TE is sensitive to increasing imposed workload.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Workload and system operability are not the same thing, and their relationship has not been demonstrated; only an indirect relationship can be assumed.
- Because of the variability among raters, it is recommended that as many raters as possible be used during implementation of the technique.

Key References

*1. Donnell, M. L. (1979). *The application of decision-analytic techniques to the test and evaluation phase of the acquisition of a major air system: Phase III* (TR-PR-79-691). McLean, VA: Decisions and Designs, Inc.

2. Donnell, M. L., Adelman, L., & Patterson, J. F. (1981). *A systems operability measurement algorithm (SOMA): Application, validation, and extensions* (TR-81-11-156). McLean, VA: Decisions and Designs, Inc.

*3. Nygren, T. E. (1982). *Conjoint measurement and conjoint scaling: A user's guide* (AFAMRL-TR-82-22). Wright-Patterson Air Force Base, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA122579)

4. Wierwille, W. W., & Connor, S. A. (1983). Evaluation of 20 workload measures using a psychomotor task in a moving-base aircraft simulator. *Human Factors, 25*, 1-16.

Cross References

7.701 Criteria for selection of workload assessment techniques;

7.702 Sensitivity requirements and choice of a workload assessment technique;

Handbook of perception and human performance, Ch. 42, Sect. 2.3

Table 1. Ordinal rating scales for pilot workload (PW) and subsystem technical effectiveness (TE) that are included in the "systems operability" measure of the mission operability assessment technique (MOAT). (From Ref. 2)

Pilot Workload/ Compensation/ Interference	Scale Values	Subsystem Technical Effectiveness	Scale Values
A measure of the degree of pilot workload/compensation/interference (mental and/or physical) required to perform a designated task	The Pilot Workload (PW)/Compensation (C)/Interference (I) required to perform the designated task is *extreme*. This is a *poor* rating on the PW/C/I dimension	A measure of the technical effectiveness of the subsystem(s) utilized in performing a designated task	The technical effectiveness of the required subsystem is *inadequate* for performing the designated task. Considerable redesign is necessary to attain task requirements. This is a *poor* rating on the subsystem technical effectiveness scale
	The Pilot Workload/Compensation/Interference required to perform the designated task is *high*. This is a *fair* rating on the PW/C/I dimension		The technical effectiveness of the required subsystem is *adequate* for performing the designated task. Some redesign is necessary to attain task requirements. This is a *fair* rating on the subsystem technical effectiveness scale
	The Pilot Workload/Compensation/Interference required to perform the designated task is *moderate*. This is a *good* rating on the PW/C/I dimension		The technical effectiveness of the required subsystem *enhances individual task performance*. No redesign is necessary to attain task requirements. This is a *good* rating on the subsystem technical effectiveness scale
	The Pilot Workload/Compensation/Interference required to perform the designated task is *low*. This is an *excellent* rating on the PW/C/I dimension		The technical effectiveness of the required subsystem *allows for the integration of multiple tasks*. No redesign is necessary to attain task requirements. This is an *excellent* rating on the subsystem effectiveness scale

7.712 Subjective Workload Assessment Technique (SWAT)

Table 1. Three-Point Rating Scales for the Time, Mental Effort, and Stress Load Dimensions of the Subjective Workload Assessment Technique (SWAT). (From Ref. 2)

Time Load	Mental Effort Load	Stress Load
1. Often have spare time. Interruptions or overlap among activities occur infrequently or not at all	1. Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention	1. Little confusion, risk, frustration, or anxiety exists and can be easily accommodated
2. Occasionally have spare time. Interruptions or overlap among activities occur frequently	2. Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention required	2. Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance
3. Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time	3. Extensive mental effort and concentration are necessary. Very complex activity requiring total attention	3. High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required

Key Terms

"SWAT"; conjoint measurement; mental effort; stress; subjective workload; time load; workload measures

General Description

The Subjective Workload Assessment Technique (SWAT) was designed specifically to measure operator workload in a variety of systems for a number of tasks. It uses the conjoint measurement technique (CRef. 7.711) to combine ratings on three different dimensions of workload: time load, mental effort load, and stress load. These dimensions are each represented on a three-point scale with verbal descriptions for each point (Table 1).

The set of descriptions in Table 1 is used in the development of a subjective scale of workload, during which a number of subjects are asked to place all possible combinations of the descriptions in rank order (from 1 to 27). The data obtained in this way are then subjected to some measure of agreement among subjects, usually a Kendall's coefficient of concordance, W, which is a simple non-parametric technique yielding a number from 0 to 1; 1 represents perfect agreement among all subjects. If $W = 0.75$ or higher, as is often the case, then the scale can be developed based on group data; otherwise, individual scales can be developed.

Because subjects are ranking combinations of three different dimensions, it is possible for them to combine the dimensions in various ways, according to different rules or models. For example, a simple additive model would yield

$$f(a_1, a_2, a_3) = f_1(a_1) + f_2(a_2) + f_3(a_3)$$

where f, f_1, f_2, and f_3 are each separate functions; the subscript indicates the dimension number. Several other models, such as distributive or dual distributive are possible, but the additive model seems to be the one employed by subjects in applications of SWAT. Once the model is determined, conjoint scaling is applied to the data. This is a process that transforms the rankings into an interval level scale, (i.e., a scale in which the values are not rank orders but numbers with meaningful intervals between them).

The procedure for determining which model is being used involves applying to the data a series of axiom tests developed for that purpose. This procedure, as well as the one for transforming the data, is quite complex, and a number of computer programs have been designed to carry them out.

Once the combinations have been scaled in this way, workload ratings on the individual dimensions may be obtained. Thus, if a subject gives a rating of 3 for time load, 2 for mental effort, and 2 for stress, these ratings may correspond to a value of 125 on the developed scale for the overall workload level.

The SWAT procedure has been evaluated in a number of studies, and is sensitive to workload increases in motor output, central processing, and communications tasks. It is also related to other measures of workload, such as performance on a secondary task.

Applications

The SWAT measure can be applied to workload in a number of settings, although cockpit evaluation has been most common.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The overall scale does not distinguish among various task types. It may be useful, in many circumstances, to follow scale development with further analysis of sub-scale data.
- Scale development requires approximately 1 hour of time per subject and a fairly complex analysis, although subsequent technique implementation is relatively easy.

Key References

1. Nygren, T. E. (1982). *Conjoint measurement and conjoint scaling: A user's guide* (AFAMRL-TR-82-22). Wright-Patterson Air Force Base, OH: Air Force Aerospace Medical Research Laboratory. (DTIC No. ADA122579)

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.711 Mission operability assessment technique (MOAT)

7.713 Subjective Workload Assessment Technique (SWAT) Ratings as a Function of Task Difficulty

Key Terms

SWAT; communications; memory; secondary tasks; subjective workload; workload measures

General Description

Generally, subjective workload increases as the difficulty of the task imposed upon an operator increases. The two studies described below illustrate this using subjective workload-assessment technique (SWAT) ratings. In Study 1, SWAT ratings distinguish difficulty levels in the critical tracking task and in secondary aircrew radio communications tasks. In Study 2, SWAT ratings distinguish among difficulty levels produced by number of information categories and presentation rate in a memory update task. The results validate the ability of SWAT ratings to index workload differences in both motor output and central nervous system information-processing types of tasks.

Applications

Subjective assessment of operator workload imposed by various tasks and design options.

Methods

Test Conditions

Study 1 (Ref. 4)

- Primary critical-tracking task, secondary aircrew-communications tasks
- Primary critical-tracking task with two levels of difficulty (high, low) defined as degree of control instability
- Secondary aircrew-communications tasks with eight workload levels (defined by number of bits as determined through information theoretical analysis, Ref. 5)
- 10 single task (2 primary, 8 secondary) conditions and 16 dual task conditions given to each subject; subjects completed SWAT rating after each trial
- Specific instrumentation not given, but probably included: CRT display of target and cursor, joystick to control display elements, control dynamics to produce instability requiring tracking in a single axis, and aircraft communication panels

Study 2 (Ref. 1)

- Letters of the alphabet presented sequentially, with letter duration of 500 msec; average sequence length was 20 letters; each sequence contained 2, 3, or 4 different letters repeated a variable number of times
- Auditory tone accompanied each letter presentation (frequency unspecified) to ensure subject attended letter display
- Interstimulus intervals of 0.5, 2.0, 3.5, or 5.0 sec determined level of task difficulty
- Presentation order of 12 memory conditions counterbalanced across subjects
- Letters presented on a 30-cm (12-in.) black-and-white video monitor one m from observer
- Trials presented in blocks of three, representing three repetitions of one of the 12 factorial combinations of the independent variables; SWAT ratings taken after each block

Experimental Procedure

Study 1

- Within-subjects design
- Independent variables: difficulty of tracking task; difficulty of radio communications task
- Dependent variable: mean SWAT ratings
- Observer's task: perform radio communications tasks alone or concurrently while attempting to keep cursor positioned over target in the tracking task
- 5 college students with extensive practice in tracking

Study 2

- Within-subjects design
- Independent variables: memory category size (number of different letters presented per trial), presentation rate (defined by interstimulus interval)
- Dependent variable: mean SWAT ratings
- Observer's task: indicate the number of times that each category (letter) occurred in the sequence (e.g., if the letter "Q" appeared eight times and the letter "T" 12 times, observers had to report eight Qs and twelve Ts to be correct)
- 10 male and 2 female paid volunteers with some practice on both memory task and SWAT ratings

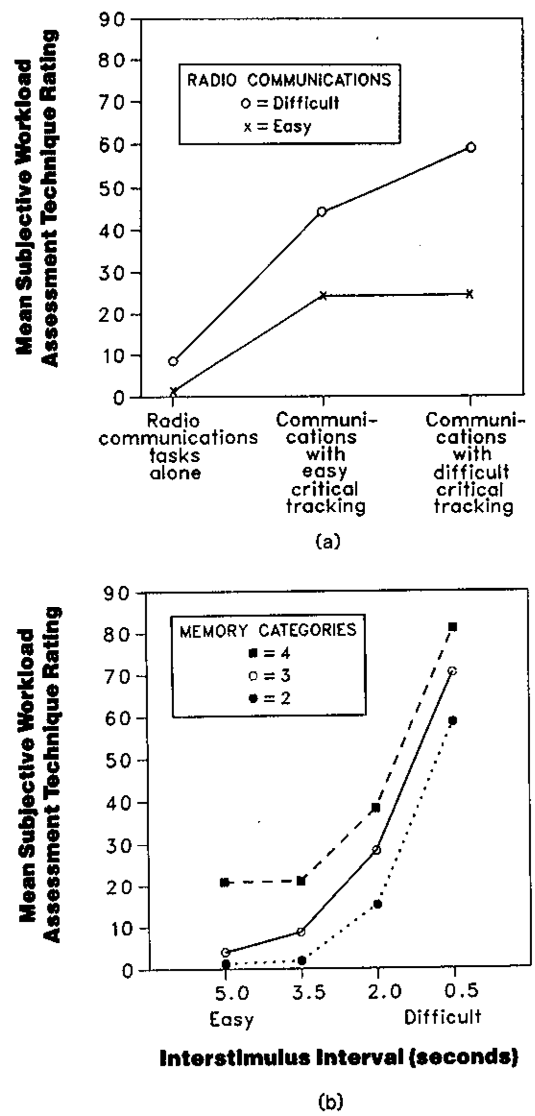

Figure 1. Mean subjective workload assessment technique (SWAT) ratings (a) as a function of task difficulty in radio communications tasks and a critical tracking task and (b) as a function of task difficulty in a memory update task that varied rate of presentation and number of memory categories. (Adapted from Refs. 1 & 4)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

Study 1

- SWAT ratings discriminate among the subjective workload differences in both the tracking task ($p < 0.01$) and the communications tasks ($p < 0.01$). SWAT ratings also measure subjective workload differences between single- and dual-task conditions ($p < 0.01$).
- SWAT ratings correlate reliably with bit values from the information-theoretical analysis of the communications tasks and with performance scores for the secondary communications task (both $p < 0.01$).

Study 2

- SWAT ratings discriminate among the subjective workload differences associated with presentation rate ($p < 0.01$) and number of categories ($p < 0.01$).
- SWAT ratings are more sensitive to both presentation rate and number of categories than the performance measure error scores on the memory task (CRef. 7.714).

Variability

In Studies 1 and 2, the Kendall coefficients of concordance (0.82 and 0.71, respectively, both $p < 0.01$) obtained during the scale-development phase of the study indicated significant agreement among observers in ranking all the possible combinations of work time, mental error, and stress measured by SWAT. In Study 2, observer strategies during scale development indicated varied weighting of work time, mental effort, or stress in determining rank orderings of the combinations of these factors. Kendall coefficients of concordance of 0.92-0.95 indicated significant agreement among observers employing the same strategy. Analyses of variance were used for both studies.

Repeatability/Comparison with Other Studies

The sensitivity of SWAT ratings has been demonstrated previously with radio communications tasks (Ref. 5; CRef. 7.723) and in a visual monitoring task (Ref. 2). SWAT ratings are also sensitive in high-fidelity flight simulations (Ref. 6).

Constraints

- While SWAT ratings are sensitive to workload at low load levels, SWAT is a non-diagnostic technique in that it will not distinguish among use of perceptual, central, or motor resources (CRef. 7.715).
- The scale-development phase of the technique can take up to 1 hr of observer time per subject. In addition, the proper axiom testing and scaling programs must be available (Ref. 3).

Key References

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2. Notestine, J. (1983). *Subjective workload assessment in a probability monitoring task and the effect of delayed ratings*. Unpublished master's thesis, Wright State University, Dayton, OH.

3. Nygren, T. E. (1982). *Conjoint measurement and conjoint scaling: A user's guide*. (AFAMRL-TR-82-22). Wright-Patterson Air Force Base, OH: Air Force Aero Medical Research Laboratory. (DTIC No. ADA122579)

*4. Reid, G. B., Shingledecker, C. A., & Eggemeier, F. T. (1981). Application of conjoint measurement to workload scale development. *Proceedings of the Human Factors Society 25th Annual Meeting* (pp. 522-526). Rochester, NY: Human Factors Society.

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6. Skelly, J. J., Reid, G. B., & Wilson, G. R. (1983). B-52 full mission simulation: *Subjective and physiological workload applications*. Paper presented at the Second Aerospace Behavioral Engineering Technology Conference, Long Beach, CA.

Cross References

7.701 Criteria for selection of workload assessment techniquies;

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.714 Comparison of normalized subjective workload assessment technique (SWAT) ratings and normalized mean error scores in a memory task;

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.723 Use of embedded secondary task in workload assessment;

Handbook of Perception and Human Performance, Ch. 42, Sect. 2.3.

7.714 Comparison of Normalized Subjective Workload Assessment Technique (SWAT) Ratings and Normalized Mean Error Scores in a Memory Task

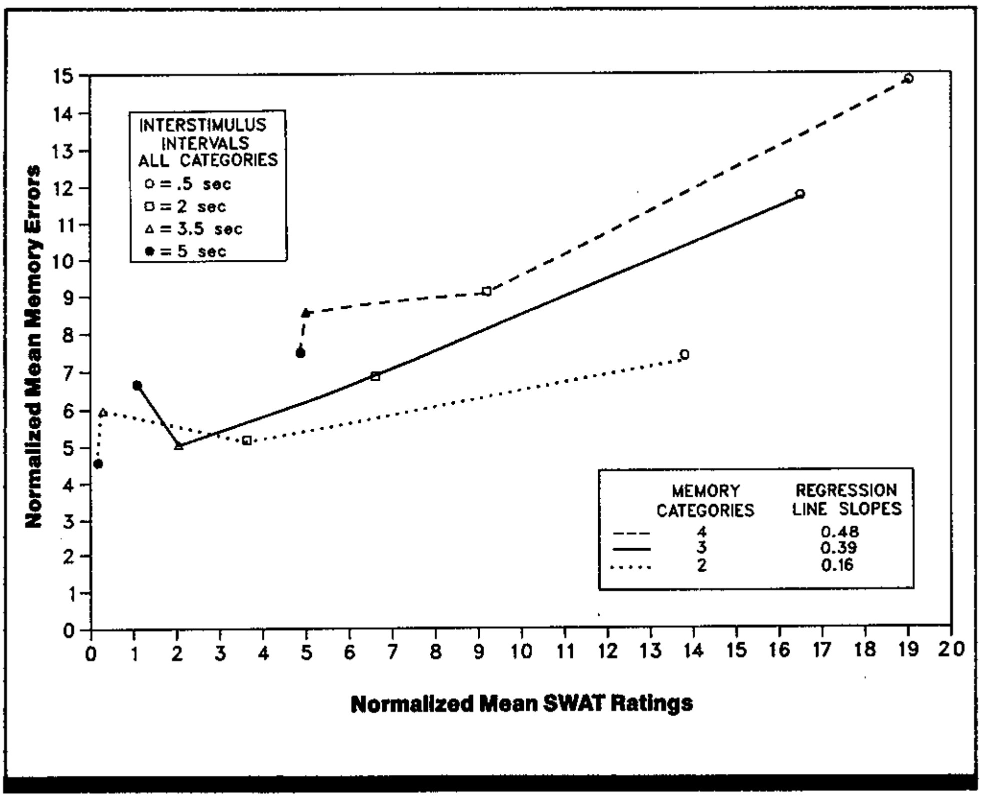

Figure 1. Normalized mean subjective workload assessment technique (SWAT) ratings and memory error performance as a function of number of memory categories and stimulus presentation rates (interstimulus intervals). A slope <1.0 indicates that the SWAT ratings are the more sensitive measures. (From Ref. 1)

Key Terms

SWAT; memory; subjective workload

General Description

Subjective workload assessment technique (SWAT) ratings are more sensitive to operator workload than are performance errors in a memory update task at low load levels. Increasing the number of categories that have to be held in memory and the presentation rate of items observers must process increases both performance errors and SWAT ratings (indicating greater subjective difficulty). However, increases in SWAT ratings are larger than increases in memory errors, indicating greater sensitivity of the SWAT ratings. This advantage is reduced with increased load levels. This finding is consistent with the theoretical position that subjective workload measures are a sensitive indicator of workload at load levels too low to produce performance decrements.

Applications

Assessment of workload associated with a particular task or design option when a low to moderate strain is placed on operator resources; specifically, in memory update situations, as in an air traffic controller's duties.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Letters of the alphabet presented sequentially, with letter duration of 500 msec; average sequence length was 20 letters; each sequence contained 2, 3, or 4 different letters repeated a variable number of times
- Auditory tone accompanied each letter presentation (frequency unspecified) to ensure subject attended letter display
- Interstimulus intervals of 0.5, 2.0, 3.5, or 5.0 sec
- Letters presented on a 30-cm (12-in.) black-and-white video monitor
- Trials presented in blocks of three, representing three repetitions of one of the 12 factorial combinations of the independent variables; SWAT ratings taken after each block

Experimental Procedure

- Independent variables: memory category size (number of different letters presented per trial), presentation rate (defined by interstimulus interval)
- Dependent variables: standard mean SWAT ratings (mean SWAT rating divided by the standard error of the mean SWAT ratings), standardized mean memory errors (mean square-root absolute deviation from correct divided by the standard error of the mean memory errors)
- Observer's task: indicate the number of times that each category (letter) occurred in the sequence (e.g., if the letter "Q" appeared eight times and the letter "T" twelve times, observers had to report eight Qs and twelve Ts to be correct)
- 10 males and 2 females with some practice on both memory task and SWAT ratings

Experimental Results

- Within each memory category condition, increases in presentation rate produce larger increases in SWAT ratings than in memory performance errors. The slope of the regression lines relating memory errors to SWAT ratings reflect this fact and index the relative sensitivity of the two measures. When the slopes of the regression lines are less than 1.0, SWAT ratings are the more sensitive of the two measures.
- The increase in regression-line slope with increase in memory-category size indicates a reduction in the sensitivity difference of the two measures with increasing workload. SWAT ratings are approximately six times more sensitive in the two-category condition, two to three times more sensitive in the three-category condition, and approximately two times more sensitive in the four-category condition. This is consistent with the assertion that subjective measures should be employed at low workload levels (i.e., when performance decrements do not occur).
- Similar analyses performed on the two measures as memory conditions varied within a presentation rate produce a similar trend. Regression-line slopes are 0.51, 0.61, 0.72, and 1.43 as presentation rate increases (interstimulus interval decreases from 5.0-0.5 sec). At the slowest rate (the lowest workload), SWAT ratings are twice as sensitive as the memory performance measure (slope = 0.51). This advantage is reduced and even reversed as workload increases (slope = 1.43 for fastest presentation rate).

Variability

Kendall coefficient of concordance $W = 0.71$ ($p < 0.01$) obtained during scale development phase of the study indicated significant agreement among observers in ranking all the possible combinations of work time, mental effort, and stress measured by SWAT. Observer strategies during scale development indicated varied weighting of work time, mental effort, or stress in determining rank orderings of the combinations of these factors. Kendall coefficients of concordance W of 0.92-0.95 indicated significant agreement among observers employing the same strategy.

Repeatability/Comparison with Other Studies

The sensitivity of SWAT ratings has been demonstrated with motor output tasks (critical tracking; Ref. 4; CRef. 7.713), radio communications tasks (Ref. 5; CRefs. 7.713, 7.723), and in a visual monitoring task (Ref. 2). SWAT ratings are also sensitive in high-fidelity flight simulations (Ref. 6).

Constraints

- While SWAT ratings are sensitive to workload at low load levels, it is a non-diagnostic technique, in that SWAT will not distinguish among use of perceptual, central, or motor resources (CRef. 7.715).
- The scale development phase of the technique can take up to 1 hr per observer. In addition, the proper axiom testing and scaling programs must be available (Ref. 3).

Key References

*1. Eggemeier, F. T., Crabtree, M. S. Zingg, J. J., Reid, G. B., & Shingledecker, C. A. (1982). Subjective workload assessment in a memory update task. *Proceedings of the Human Factors Society 26th Annual Meeting* (pp. 643-647). Seattle, WA: Human Factors Society.

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Cross References

7.713 Subjective workload assessment technique (SWAT) ratings as a function of task difficulty;

7.715 Subjective workload evaluation techniques: limitations and guidelines;

7.723 Use of embedded secondary tasks in workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 2.3

7.715 Subjective Workload Evaluation Techniques: Limitations and Guidelines

Key Terms

Mental workload; subjective workload; workload measures

General Description

Subjective workload evaluation techniques require operator assessment of the workload associated with a particular task or design option. For example, subjective workload can be assessed on the basis of a high, medium, or low rating on time load, mental effort load, and stress load (Refs. 4, 5). If workload can be conceived of experientially, then subjective measures can provide the most sensitive and reliable indications of load (Ref. 3). However, there are certain limitations and guidelines to this approach.

- Subjective workload measurement and primary-task performance may be differentially sensitive to different aspects of the task environment. For example, performance measures on a primary task are affected by increasing the difficulty of that task, whereas subjective workload evaluation techniques ratings are affected by addition of a concurrent task. It is therefore important to compare subjective workload evaluation techniques and primary-task measures to ensure that the measured task or design option is, in fact, the one that would result in optimal performance.
- Subjective workload evaluation technique ratings lack diagnosticity. They do not distinguish among perceptual, central processing, and motor loads. They can be considered as good indices of overall load assessment, but they do not pinpoint components of differential loading.
- A related point is that operators might not be able to distinguish mental load from physical load. If a global workload assessment is all that is required, this is not a concern. However, possible confounding of different load sources limits inferences about the resources being tapped by particular task components.
- It is crucial to determine what aspect or stage of the task (or portion of the design option) is to be related. The more specifically the variable of interest can be defined, the better. Operators should not be asked to make ratings on a global level because workload is determined by specific task components. This concern can be addressed by careful wording of the assessment instrument and specific instructions.
- Operators may confuse perceived difficulty of the task with perceived expenditure of effort. That is, an operator may believe more work is needed than is actually expended, which would lead to an inflated SWAT rating. This difficulty can be overcome, in party, by careful instructions and careful wording of assessment instruments.
- Because subjective techniques require ratings of an operator's perception of load, the approach assumes that processing is open to conscious introspection. However, an operator's awareness of physiological states, or the transduction of energy by the perceptual system, may be extremely limited. Furthermore, sensory awareness and proprioception is diminished under conditions of intense concentration, when workload might, in fact, be highest. The sensitivity of subjective measurements is limited to the extent that the range of subjective factors determining workload is in accessible to experience.
- The subjective measure should be administered immediately after task performance to limit the effect of distortions due to memory factors.
- Differences in operator experience may be a confounding influence.

Empirical Validation

The points enumerated above have been validated in a number of different ways. (1) In determining that perceived difficulty may differ from perceived effort expenditure, measures of both are taken and tasks are rank-ordered with respect to both types of ratings. The fact that the rank orderings differ significantly, depending upon the task aspect rated, supports the conclusion that external demand or perceived difficulty does not necessarily determine workload estimation (Ref. 1). (2) To establish that subjective workload measurement and primary-task performance are differentially sensitive, both measures are used in testing the task or design option of interest under both increases in primary-task workload alone and addition of secondary tasks. The result that subjective measures vary with the introduction of a secondary task whereas primary-task performance is a function of difficulty level of the primary task supports the point that the two measures do not index the same aspects of workload (Ref. 6). (3) Cautions about distortions due to memory factors are validated by work demonstrating that subjective ratings given even 15 to 30 minutes after task completion differ from whose given immediately after task completion (Ref. 2). The data available on this point are minimal, however, as subjective ratings are usually delayed after task completion.

Constraints

- The limitations mentioned above should be taken as constraints on the application of subjective workload evaluation techniques.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.712 Subjective workload assessment technique (SWAT);

7.713 Subjective workload assessment technique (SWAT) ratings as a function of task difficulty;

7.714 Comparison of normalized subjective workload assessment technique (SWAT) ratings and normalized mean error scores in a memory task

7.716 Primary Task Measures for Workload Assessment

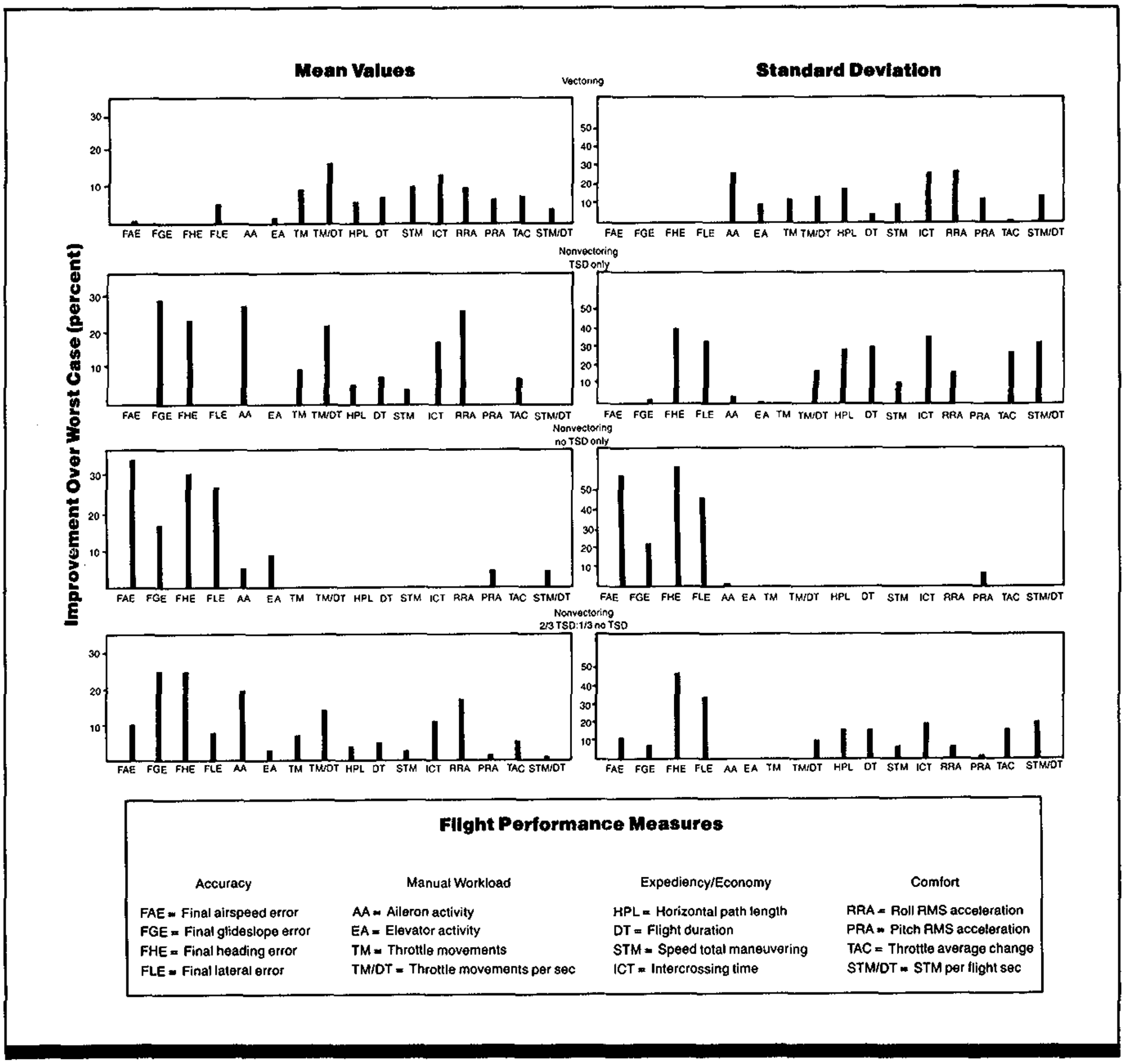

Figure 1. Air-traffic-control management profiles for four types of flights showing mean and standard deviation of percent improvement over worst case for 16 objective primary-task measures. Percentages shown are relative to the lowest value, which is not shown. (From Ref. 4)

Key Terms

Task sensitivity; workload assessment

General Description

Primary task measures attempt to assess workload by measuring actual performance on the task or design option of interest. It is assumed that as workload increases, the additional processing resources used will necessarily result in changes in operator performance. The approach and some problems inherent in it are illustrated through a study employing multiple primary-task measures to determine the impact of differences in situation displays on terminal-area air-traffic management. Various measures are insensitive to differences in workload, but it should not be assumed that performance is not affected by workload just because a single measure fails to reveal performance differences. The use of multiple primary-task measures is therefore recommended.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Vectoring and non-vectoring traffic-control management methods used; in vectoring condition three aircraft simulators lacked traffic-situation displays; in non-vectoring condition two of three aircraft simulators had traffic-situation displays (providing 360 deg traffic information) and the remaining one was without a traffic-situation display and thus had to be vectored.
- Ground protection map of the task area was available to each pilot
- Computer-generated aircraft introduced into the traffic-control situation every 2 min (on the average) with a 5-sec standard deviation
- Controllers could modify only speed of computer-generated aircraft; pilots had aileron, elevator, and throttle control of their craft; common voice circuit was used between all pilots and controllers
- Each replication consisted of a group of three pilots and two controllers; three runs in each of the two experimental conditions, 20-25 min per run
- Each group had 4-hr practice under each condition

Experimental Procedure

- Within-subjects, repeated measures design
- Independent variable: traffic-control management
- Dependent variables: 16 objective flight performance measures (Fig. 1), such as final airspeed, heading, glideslope, etc; verbal measures, defined as word rates, word counts, and content in verbal communications tape-recorded between simulator pilots and air traffic controllers; subjective measures, in the form of pilot and controller questionnaire after each trial and after experiment
- Observer's task: controller's task was to insert the three simulator aircraft between the computer-generated aircraft subject to a 1-nautical-mile or 60-sec spacing rule; pilot's task was to execute an approach to the terminal, employing either visual flight rules (for aircraft with a traffic-situation display) or instrument flight rules (for aircraft without a traffic-situation display)
- 15 observers, all current airline pilots or air traffic controllers

Experimental Results

- Of all the objective measures taken, only some are sensitive to primary-task workload in the different control situations (Fig. 1). For example, in the non-vectoring condition for pilots that have cockpit traffic-situation displays (TSD), final-airspeed error (FAE) does not indicate an improvement in performance over the worst possible case. However, with no cockpit display in the same condition, FAE indicates a 35% improvement, but TM shows no improvement.
- According to the results of multivariate analysis of variance and discriminate analysis, 8 of the 16 objective measures are useful in discriminating type of load being manipulated.
- Verbal measures show verbal workload for controllers is considerably reduced in both word rate and total word count when pilots use traffic-situation displays. Verbal workload for the pilot does not change between control situations.
- Subjective measures show that both pilots and controllers believe the non-vectoring condition is safer.

Variability

Standard deviations for the 16 objective measures are shown in Fig. 1. No information on variability was given for verbal and subjective measures.

Repeatability/Comparison with Other Studies

Several other studies have also found the primary-task measures are not equally sensitive to workload for all the indices used (Refs. 7, 8).

Constraints

- While primary-task measures possess high face validity, they may be insensitive to manipulations of load. Since it cannot be assumed that workload is not affecting performance just because one particular measure fails to reveal performance differences, the use of multiple task measures is recommended.
- Primary task measures may be sensitive only at certain levels of workload. For example, workload may be so low that there is no performance variation, or workload may be so high that the operator cannot deal with the load being imposed, and so performance does not vary (CRef. 7.702, Fig. 1, regions A and C, respectively). There are no a priori methods to determine into which region a workload level will fall.
- Even with the use of multiple primary-task measures, there is often a need to develop unique measures for each task situation, and consequently it is hard to measure workload across different situations.
- Secondary-task measures are often more diagnostic of workload effects on performance than are multiple primary task measures (CRefs. 7.717, 7.719, 7.723).

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Cross References

7.717 Use of the loading-task paradigm in workload assessment;

7.719 Major classes of secondary task;

7.723 Use of embedded secondary tasks in workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 1.1

7.717 Use of the Loading-Task Paradigm in Workload Assessment

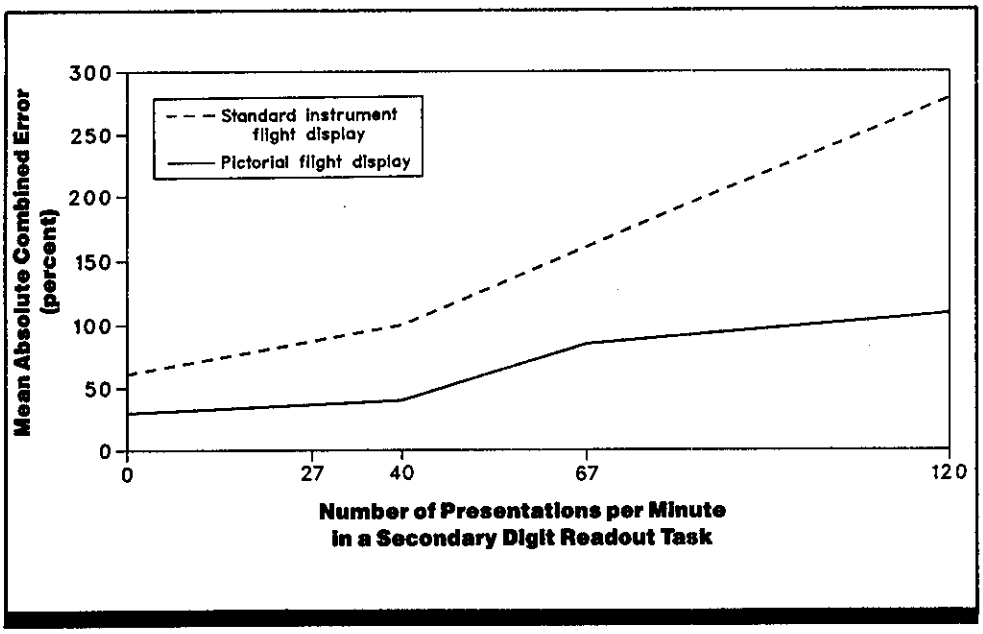

Figure 1. Mean absolute error of combined error scores (for altitude, heading, airspeed, and tracking) for standard instrument and pictorial (JANAIR) displays as a function of level of difficulty of a concurrent digit-reading task. An increased number of digit presentations per minute indicate increased task difficulty. (From Ref. 1)

Key Terms

Loading-task paradigm; secondary tasks; workload measures

General Description

In the loading-task paradigm, the subject is instructed to maintain performance on a secondary task, even at the expense of primary task performance. Under equal levels of secondary task loading, performance on more difficult primary tasks will deteriorate more rapidly than on less difficult tasks. The study described illustrates the method and shows that whereas single task performance may be insensitive to differences in primary task difficulty, secondary task loading can point out such differences.

Methods

Test Conditions

- Two displays present during testing. Display not being used was disengaged and panel lights turned off
- Standard helicopter instrument display with airspeed indicator, altimeter, compass, attitude indicator, rate of climb meter, and cross pointer position indicator
- Instrument display was contact analog vertical display (JANAIR), which provided a pictorial representation of the real world, without auxiliary instruments for quantitative flight information on standard display
- Numerical readout device (Burroughs "Nixie" tube) and display warning indicator (incandescent pilot lamp), placed 35.56 cm to the right and 35.56 cm below the center of each display array; numerical readout device placed to ensure subject shift of field of vision away from flight displays to read digits
- Digit presentation rates were 0.0, 0.4, 1.0, 1.75 sec between digit presentations of baseline condition of no digit presentations
- Nixie tubes were 1.27 cm (1/2 in.) in diameter and displayed 0.95 cm (3/8 in.) numerals, randomly generated
- Each subject trained in pre-test phase on tracking task to predetermined criterion on three successive 3-min trials on both displays

Experimental Procedure

- Independent variables: digit presentation rate, instrument display
- Dependent variable: mean absolute combined error of primary flight performance, defined as the combined error performance on four measures (altitude, airspeed, heading, and track)
- Subject's task: primary task was to fly a command altitude, heading, course, and airspeed; loading task was to read digits programmed to appear on the Nixie tubes
- 10 subjects, each either a helicopter pilot or fixed wing pilot or having extensive experience in simulator

Experimental Results

• There are significant error differences (between the two displays) in the single-task baseline conditions (no digit presentations) or at the two slowest digit-presentation rates. However, primary flight performance is better for the JANAIR display at the two fastest presentation rates (67 and 120 digits per min). This implies that the JANAIR display (pictorial) imposes less load on pilots than the standard display. Furthermore, this difference would not be revealed in a single-task investigation of the two displays.

Variability

Violations of the assumption of homogeneity of variance for the analysis of variance were ignored as possibly affecting the sensitivity of the analysis.

Repeatability/Comparison with Other Studies

The loading task paradigm has been used successfully in a variety of applications to evaluate the adequacy of displays, configurations, methods of task performance, and the effects of various types of stressors on primary task performance (Refs. 2, 3).

Constraints

• Some secondary tasks may possess low face validity if they are not part of the normal operating environment (CRef. 7.723).
• Since the loading-task paradigm stresses secondary task performance over primary task performance, the situation may seem artificial to subjects.

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.723 Use of embedded secondary tasks in workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 4.2

7.718 Use of the Subsidiary Task Paradigm in Workload Assessment

Key Terms

Environmental stressors; secondary tasks; subsidiary task paradigm; workload measures

General Description

The subsidiary-task paradigm employs a secondary task to assess the workload of a primary task. Operator instructions stress maintenance of performance on the primary task, and performance degradation in the secondary task indicates an inadequacy in reserve capacity that could not be measured with a single, primary task measure (CRef. 7.716). The technique is illustrated in the study described here. Noise and heat stress affect a subsidiary number processing task but do not affect performance in a primary pursuit-rotor tracking task. Hence the amount of reserve processing capacity employed in the presence of environmental stressors may increase, but this strain on processing resources may not be reflected in primary-task performance levels.

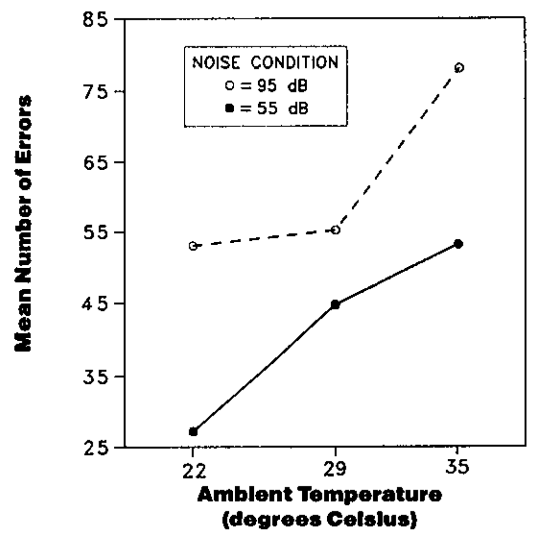

Figure 1. Errors in a subsidiary number-processing task as a function of ambient noise and temperature conditions. (From Ref. 2)

Methods

Test Conditions

- 55-dB(A) "normal" background noise or 95-dB(A) white-noise bursts 1-9 sec in duration occurring at random 1-9 sec intervals
- Room temperatures at 22°C, 29°C, or 35°C
- Primary tracking task with pursuit-rotor apparatus set at 60 rpm
- For secondary (subsidiary) task, two-digit numbers amplified to be heard over experimental noise levels, recorded on tape and presented at 2-sec intervals; subject pressed telegraph key once if current number was numerically lower than immediately preceding number and twice if current number was numerically higher
- Subjects given 15 min to adapt to noise and temperature conditions while they performed paper and pencil filler tasks
- Relative humidity of experimental room kept between 40% and 50%

Experimental Procedure

- Independent variables: ambient room temperature, noise level, gender of subject
- Dependent variables: time on target for primary task, defined as the amount of time per 60-sec trial subjects accurately tracked pursuit rotor target; number of errors for secondary (subsidiary) number-processing task
- Subject's task: for primary task, keep stylus on moving target on pursuit-rotor apparatus; for secondary task, press telegraph key once if auditorily presented number was numerically lower than previous number, twice if it was numerically higher than the previous number
- 72 male and 72 female college students, with no practice on either primary or subsidiary tasks

Experimental Results

- Exposure to high levels of noise or heat degrades performance on the subsidiary number-processing task ($p < 0.02$ and $p < 0.005$, respectively). According to a post-hoc analysis, there is a reliable difference only between the 22°C and 35°C conditions for the temperature variable ($p < 0.05$).
- Primary task performance is not sensitive to the effects of the heat and noise stressors.
- There are no gender differences in performance.
- These results imply that there are workload differences that cannot be directly measured by primary task performance (CRef. 7.716), as long as there is a reserve of processing resources not used up by the primary task. Higher-workload tasks draw upon an operator's reserve capacity of processing resources to a greater extent than lower-workload tasks. With the addition of a secondary task, differences in primary task expenditure are reflected in decrements in secondary task performance. This argument is depicted in Fig. 2. Another implication depicted in the figure is that the constituents of workload are linearly additive, with no intrusion of the secondary task on primary task requirements. Finally, an assumption implicit in the subsidiary task paradigm is that operator resources are undifferentiated, and this assumption is reflected in the ordinate of the figure (Ref. 6).

Variability

Standard deviations for the factorial combinations of heat and noise are 22°C/55 dB(A), 18.39; 29°C/55 dB(A), 42.49; 35°C/55 dB(A), 64.19; 22°C/95 dB(A), 24.03; 29°C/95 dB(A), 28.97; 35°C/95 dB(A), 48.83.

Repeatability/Comparison with Other Studies

Subsidiary task experiments employing noise stress to increase workload have produced results similar to those described here (Ref. 5). The subsidiary-task paradigm has also been successfully employed to investigate workload in a number of different settings (Refs. 1, 3).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Instructions for pursuit rotor were given prior to instructions for number processing task; aside from this and the fact that the pursuit rotor task was performed with the dominant hand, there was no other specification of pursuit-rotor tracking as the primary task.
• Subjects used dominant hand for pursuit rotor and non-dominant hand for number processing task.
• Use of the subsidiary-task paradigm requires careful choice of primary and subsidiary tasks. The subsidiary task should be one that is not likely to bias responding toward it in spite of contrary instructions; this limits the range of applicability of the technique.
• Pure stressing tasks used to increase workload have limited application. Mere occupation of a particular sensory or motor channel with a secondary task does not indicate the amount of processing resources in reserve for central processing (Ref. 3).
• The cross-adaptive technique may be used in situations similar to those described here (CRef. 7.722).
• Each of the implications and assumptions depicted in Fig. 2 have been questioned (Ref. 3).

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.716 Primary task measures for workload assessment;

7.722 Use of adaptive-task techniques to counter primary task intrusion in workload assessment;

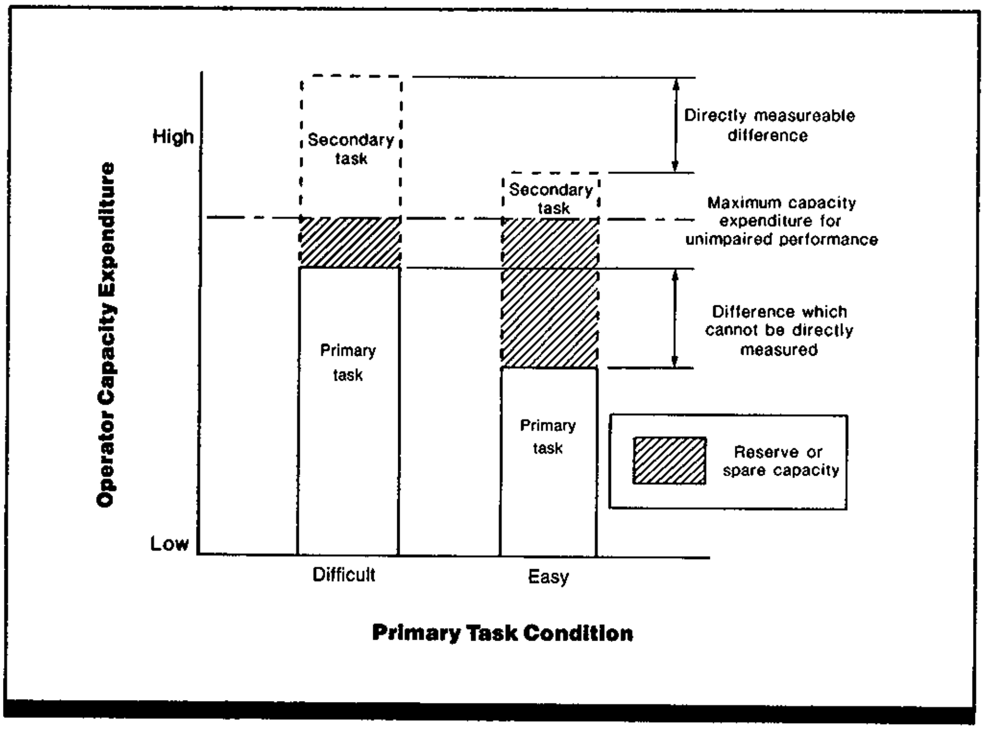

Figure 2. The use of a secondary task to measure workload differences in primary task conditions when operator processing capacity is not exceeded by either task alone. Differences in secondary task performance are interpreted as representing the spare capacity between performance of a difficult and easy primary task, which may be taken as a measure of relative workload of the two primary tasks. (From Ref. 3)

7.719 Major Classes of Secondary Task

Table 1. Types of secondary task used in workload measurement. (From Ref. 19)

Method	Description	Stage Loaded by Task	Application Examples
Simple reaction time	Subjects must respond to the occurrence of one discrete stimulus with a single response	Generally considered to draw upon perceptual resources and resources used for response execution. Used when the central-processing and response-selection aspects of a secondary task must be minimized	Refs. 4, 14, 21, 23
Choice reaction time	Usually involves presentation of more than one relatively simple stimulus and subject must generate a different response for each stimulus. Stimuli are often presented either visually or auditorily, and responses are usually manual	Generally assumed to impose greater central processing and response selection demands than simple reaction-time tasks	Refs. 5, 11, 17
Tracking	Employs visual stimulation and necessitates continuous manual response (e.g., stabilizing a cursor over a target on a video monitor by means of manual control). Task difficulty typically depends on the inherent instability of the control system	Depending upon the order of control dynamics, various degrees of central processing and motor demands are involved in tracking performance	Refs. 12, 13, 17, 24
Monitoring	Subject must detect the occurrence of a stimulus from among several alternatives. Stimuli can be presented in one or several modalities. Task difficulty can also be varied with the number and/or discriminability of alternatives	Generally considered to place a relatively heavy emphasis on perceptual processes	Refs. 3, 20
Memory	Short-term memory tasks are most common (e.g., subjects are given lists of information which must be searched or recalled at a later time). The primary task is performed while the information is being held in memory. A variety of different types of material and specific memory requirements have been employed; the Sternberg search task is often used	Generally considered to impose heaviest demands on central processing resources. The Sternberg task permits discrimination of central processing effects from stimulus encoding and response effects	Refs. 1, 10, 25
Mental mathematics	Requires subjects to carry out mathematical operations while performing a primary task. Different forms of addition tasks have been used, but subtraction and multiplication have also been used	Generally considered to draw most heavily on central processing resources	Refs. 7, 10, 17
Shadowing	Requires that subjects repeat sequences of verbal or numerical material as they are presented. Usually this is just mimicry and no transformations of the material are required	Generally considered to exert heaviest demands on perceptual resources	Refs. 2, 6, 15, 19
Time estimation paradigms	a. Interval production: requires that a subject generate a series of regular time intervals by performing a motor response at a specific rate. No sensory input is required, and the output modality can be chosen to reduce conflicts with the output modality of the primary task	a. Interval production probably places its greatest demands on motor output/response resources	a. Interval production: Refs. 18, 22, 27
	b. Time estimation: subjects either actively keep track of time during a specific interval (active estimation) or estimate duration of an interval at its conclusion without attending to time as it passes (retrospective estimation). Estimation has proven more acceptable to operators, is easy to score and implement, and minimizes learning effects	b. Active time estimation probably draws upon perceptual and central processing resources	b. Time estimation: Refs. 8, 9, 27

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Choice reaction time; memory; mental workload; monitoring; primary tasks; secondary tasks; shadowing; simple reaction time; time estimation; tracking; workload measures

General Description

Assessment of the workload imposed upon an operator by a particular task (usually called the primary task) has often been accomplished through the use of another task (the secondary task) which is performed concurrently with the primary task. The logic employed by these studies of workload is that varying degrees of task difficulty will produce varying performance decrements on the two tasks (assuming both tasks draw upon the same pool of operator resources). This dual-task interference can be taken as an index of the demands placed on operator resources by the two tasks. This can be achieved by manipulation of primary-task difficulty and observation of variations in secondary-task performance, or by varying secondary-task difficulty and observing concomitant changes in primary-task performance.

The table provides a brief description of each secondary-task method and tells at what stage the task is presumed to operate. There is extensive literature associated with each of the methods, and examples of studies in which a specific method was successfully employed are included.

Constraints

- Most of these secondary tasks will possess low face-validity in the context of the operator workload situation being assessed, and will seem artificial to the operator. Also, implementation of these tasks may require equipment not normally found in the situation being assessed. The use of embedded secondary tasks overcomes these problems (CRef. 7.723).

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Cross References

7.723 Use of embedded secondary tasks in workload assessment

7.720 Choice of Secondary Task: Application of a Multiple-Resources Model

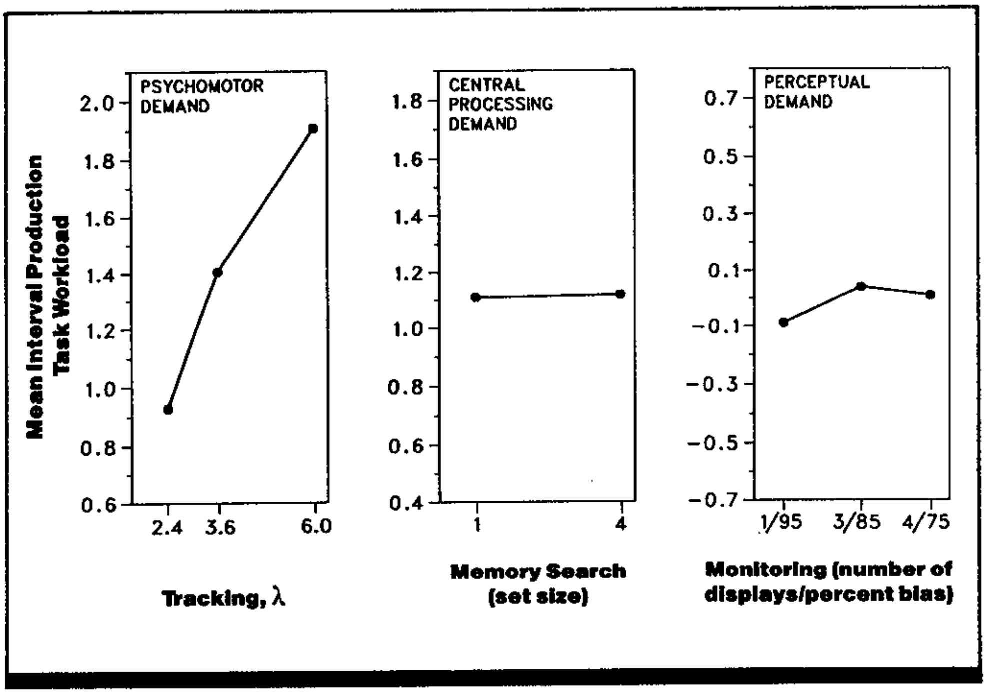

Figure 1. Mean interval production task (IPT) workload as a function of difficulty level in three primary tasks. (From Ref. 3)

Key Terms

Flight control; interval production task; memory search; monitoring; multiple resources model; secondary task; tracking; workload measures

General Description

A secondary task measure that draws upon processing resources different from those used by a concurrently performed primary task will be insensitive to the workload associated with the primary task. For example, scores on the interval production task (IPT) approximate a linearly increasing function of instability tracking task difficulty, but do not vary with workload in either a memory search task or a probability monitoring task; thus the IPT is sensitive to loading on a motor response task, but not to loading on tasks requiring perceptual input or central processing resources. This result can be interpreted in terms of a multiple resources model, which holds that the human operator possesses distinct resource pools for the performance of input, central processing, and output components of a task. Selection of an appropriate secondary task depends, in part, upon the resource pool drawn upon by the primary task.

Applications

Assessment of workload associated with a particular operator task or design option; specifically, workload assessment in manual response tasks, such as flight control or switch activation.

Methods

Details of the experimental methods are provided in Table 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Primary tasks used to establish context for secondary task.

Primary Task	Test Conditions	Experimental Procedure
Probability monitoring	CRT displays with cursors whose location at each of six display positions could randomly change One display 95% signal bias, three displays 85% signal bias, four displays 75% signal bias	Independent variable: level of task demand, defined by the number of displays with signal biases as specified Dependent variable: response time (manual response) Observer's task: detect bias in cursor movement Signals appeared once per min on the average 4 observers
Memory search task	Memory set size of one or four letters Average interstimulus intervals of 2 or 4 sec	Independent variables: memory set size, average interstimulus interval Response time (manual response) Observer's task: decide whether a presented letter was a member of a previously memorized set Number of observers not specified
Instability tracking	CRT display of fixed target and moving cursor Control dynamics magnified operators' errors, which were then fed back to influence cursor movement, producing an unstable system	Independent variable: system instability, defined as the rate of exponential increase in the system's outputs Dependent variable: tracking performance, defined as the distance between target and cursor Observer's task: control the cursor by means of joystick to minimize error (distance between target and cursor) Number of observers not specified
Secondary task	**Test Conditions**	**Experimental Procedure**
Interval production (IPT)	Subjects generate continuous series of time intervals by emitting a motor response at a consistent rate within the limits of one to three responses per second	Independent variable: Subjects performed one of three primary tasks concurrent with IPT; subjects instructed to perform as well as possible on both tasks, but to confine errors to the IPT (subsidiary task paradigm; CRef. 7.718) Dependent variable: IPT workload measure based on differences between variability in intervals produced under single-task and dual-task conditions; variability is calculated by the following equation: IPT score = $(N/T) \sum_{i=1}^{N} \lvert\Delta t_i\rvert$ where N is the total number of generated intervals and T is the total time for data collection. Δt represents difference between two successive intervals

Experimental Results

- IPT workload is a roughly linearly increasing function of tracking difficulty. The effect of task demand is significant, and differences between each loading level are also significant (both $p < 0.01$). In addition, the IPT does not interfere with tracking performance.
- Memory loading does not affect IPT performance ($p < 0.05$). In addition, the IPT does significantly interfere with memory search performance, yielding an average increase in search time of 35 msec ($p < 0.05$). This interference is uniform across memory load levels.
- Reducing the average interstimulus interval in the memory search task significantly increases IPT workload ($p < 0.05$).
- Probability monitoring does not affect IPT performance ($p > 0.10$). In addition, the IPT does not interfere with monitoring performance ($p > 0.10$).
- All results taken together imply that there are separate resource pools for input, central processing, and output functions. IPT performance is sensitive only to loading in the motor (tracking) task, implying that the IPT draws upon output resources more than input or central processing resources. Because this sensitivity is apparent even when the IPT does not interfere with primary task performance, the

IPT can be considered useful in operational as well as laboratory settings.

Variability

IPT workload measure is an index of variability in the duration of intervals produced. No other information on variability was given.

Repeatability/Comparison with Other Studies

The primary tasks employed here have all been used before in the assessment of workload (Refs. 1, 2). The multiple resources model can be used as a guide to the choice of secondary task methodology. However, there are also other criteria for workload assessment techniques (CRef. 7.701).

Constraints

- The data on IPT performance paired with the probability monitoring task are from a partially completed study.

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Cross References

7.701 Criteria for selection of workload assessment techniques;

7.718 Use of the subsidiary task paradigm in workload assessment;

Handbook of perception and human performance, Ch. 42, Sect. 4.4

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Notes

7.721 Guidelines for the Use of Secondary Task Measures in Workload Assessment

Key Terms

Secondary tasks; tracking; workload measures

General Description

Operator workload can be measured by requiring performance of two concurrent tasks, and then comparing performance in the two-task situation to baseline single-task performance. Two major categories of secondary task measures are the loading-task paradigm (CRef. 7.717) and the subsidiary-task paradigm (CRef. 7.718). The table highlights guidelines for implementation of these paradigms. The major purpose of the guidelines is to ensure that the secondary-task methodology provides maximum sensitivity to workload measurement.

Empirical Validation

The principles described in Table 1 are the result of much work on the topic of secondary-task sensitivity. E.g.:

- The principle of employing a continuous secondary task can be validated by comparative evaluations of secondary tasks. Tasks that require sustained operator attention of processing are more sensitive to workload than those that require only momentary allocations of attention (Ref. 2).
- The concept of multiple resources and the need for a task to tap the proper resource pool has been validated by work that demonstrates differential sensitivity of workload measures in various types of task. For example, an interval-production task requires regularly timed finger tapping that can be presumed to draw heavily on psychomotor response resources. This measure is sensitive to workload differences in a critical-tracking task, but not to workload differences in memory search or display monitoring. The critical-tracking task is a psychomotor task, whereas memory search and display monitoring are presumed to draw upon central and perceptual processing resources, respectively (Ref. 6).
- The need to reduce peripheral interference while at the same time tapping the appropriate resources is validated by work on the P300 spike as a workload measure (CRef. 7.725). This measure is sensitive to the imposition of a tracking task, but insensitive to varying degrees of workload of the task. The peripheral motor processing increases overall workload. However, the P300 spike and the tracking task draw upon different resource pools; consequently, P300 is insensitive to varying degrees of tracking difficulty (Ref. 3).

Constraints

- Practicing the secondary task to reach asymptotic performance carries with it the problem that such practice will result in automatization of the secondary task. This minimizes the capacity demands of the task and makes it less sensitive to variations in primary-task workload. Furthermore, practice on a primary-secondary task combination may result in improved ability to perform two tasks concurrently, which also reduces sensitivity to workload.

Table 1. Guidelines for the use of secondary task measures in workload assessment. (From Ref. 5)

- The secondary task chosen should impose a continuous demand on the operator; this is particularly crucial when the demands of the primary task might vary widely over time. A non-continuous secondary task could then possibly be imposing a demand on operator resources at times when primary task demand is low. This would reduce the sensitivity of the secondary task to short-term loads in the primary task.
- Sufficient practices should be given on the secondary task to stabilize performance prior to using the task concurrently with the primary-task. This allows reliable estimation of primary-task workload. This guideline is especially crucial if the secondary task is to be used repeatedly with the same operators in different situations.
- The secondary task must require the same resources as the primary task. Failure to do so will reduce the sensitivity of the secondary-task measure to primary-task workload because two different aspects of performance will be measured. Examples of dimensions that define separate resources include information processing stages, stimulus modalities, and representational codes and response methods (Ref. 7).
- When employing a secondary task measure such as the event-related potential (CRef. 7.725), it is important that the task require subjects to process the stimulus eliciting the potential while at the same time requiring no overt response to the stimulus. This avoids the peripheral interference associated with response competition, but ensures the use of appropriate processing resources.
- Baseline measures of single-task performance on both the primary and secondary task must be taken. This is done for different reasons in the loading- and subsidiary-task paradigm. Primary-task baselines in the loading-task paradigm monitor changes that occur in primary-task performance under concurrent task situations, and secondary-task baselines ensure maintenance of secondary-task performance at the experimenter-determined criterion. Primary-task baselines in the subsidiary-task paradigm help evaluate intrusion effects, and secondary-task baselines are needed to determine the degree of single to concurrent task decrements.
- In the loading-task paradigm, maintenance of secondary-task performance at single task levels under concurrent conditions must be emphasized.
- In the subsidiary-task paradigm, maintenance of primary-task performance at single task levels under concurrent conditions must be emphasized.
- Several levels of secondary-task difficulty should be employed, because higher levels of secondary-task difficulty may distinguish workload differences not apparent at lower levels of secondary-task difficulty. This concept is illustrated in Fig. 1 (CRef. 7.718). Figure 2 shows the theoretical basis for employing several levels of secondary-task difficulty. Lower levels of secondary-task difficulty may not be sufficient to shift the total operator workload to the most sensitive portion of the curve (Region B), while higher levels may produce an overload that results in a lack of sensitivity of the secondary task (CRef. 7.702).
- Since the subsidiary-task paradigm stresses primary-task performance, the operator may not adhere to the resource allocation policy required by the experimenter; this could result in primary-task intrusion. Either an adaptive or embedded secondary-task technique can be employed to avoid this. The adaptive technique maintains primary-task performance by varying secondary-task loading. The embedded secondary-task technique employs a secondary task that is normally part of the operator environment, and therefore does not seem artificial to the operator.

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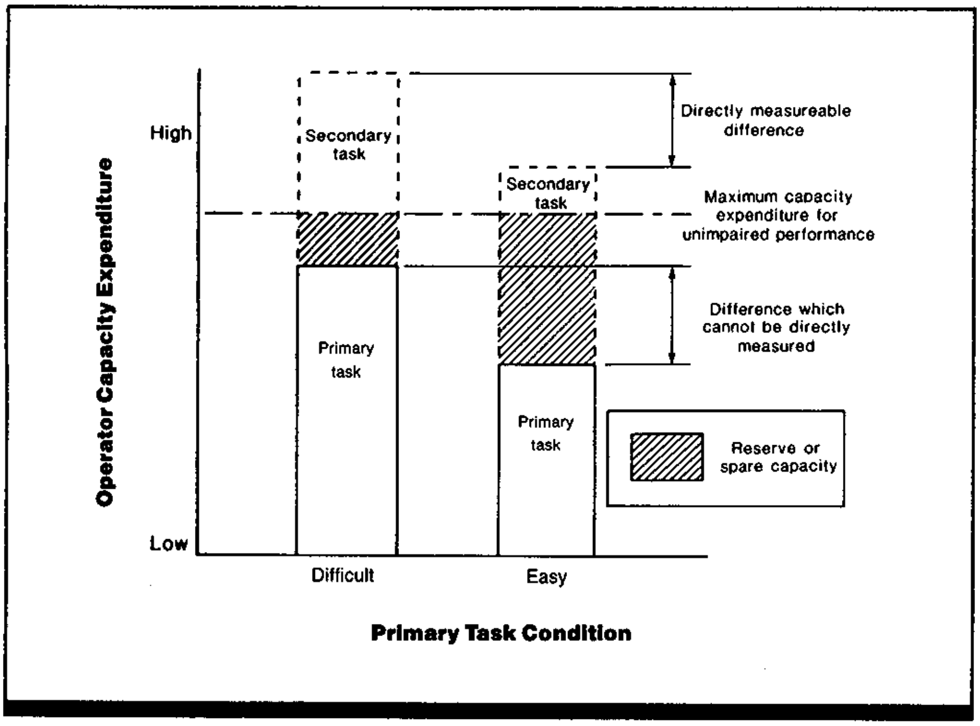

Figure 1. Representation of secondary-task measurement of operator reserve processing capacity. (From Ref. 1)

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Cross References

7.702 Sensitivity requirements and choice of a workload assessment technique;

7.717 Use of the loading-task paradigm in workload assessment;

7.718 Use of the subsidiary task paradigm in workload assessment;

7.725 Use of the P300 spike with a secondary task

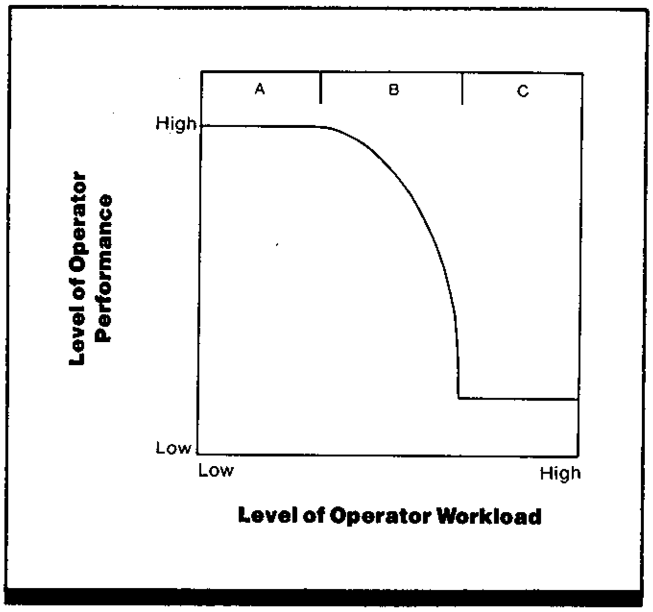

Figure 2. Hypothetical relationship between workload and operator performance. Regions A, B, and C are areas where different workload measures may be appropriate. (From Ref. 5)

7.722 Use of Adaptive-Task Techniques to Counter Primary Task Intrusion in Workload Assessment

Key Terms

Secondary tasks; workload measurement

General Description

Adaptive-task techniques stabilize primary-task performance through manipulation of secondary-task loading. Such stabilization is critical in workload assessment because primary-task performance measures do not necessarily measure the amount of effort expended by an operator. For example, if an operator sets a particular criterion for acceptable performance, much effort will be used to maintain that level of performance when the task is first being learned, but with practice much less effort may be required to maintain the same performance level. The cross-adaptive technique is a method used to maintain experimenter-specified criterion levels on a primary task by varying the secondary-task load in response to primary task performance; as primary-task performance levels begin to improve, secondary-task loading is increased, preventing the operator from ever reaching the target criterion. The amount of secondary-task loading imposed without intrusion on the primary task then gives a clear measure of primary task workload. Because primary-task performance levels are standardized, interpretation of secondary task decrements is made more straightforward than if primary-task performance varied.

The cross-adaptive technique is illustrated in the study described here. A secondary task was turned on or off in order to keep scores on a primary tracking task near an experimenter-determined criterion. Loading scores in the cross-adaptive condition proved more sensitive to differences in tracking-display gain than scores obtained either through use of an independent loading task or a primary task alone.

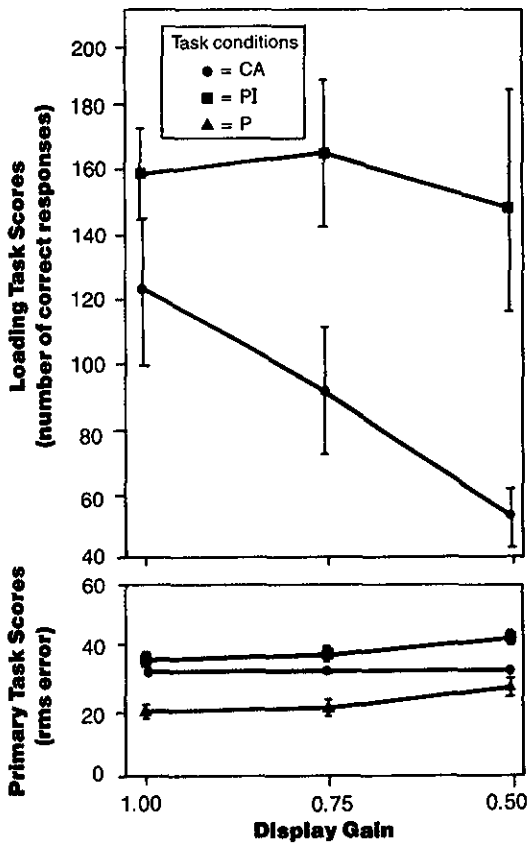

Figure 1. Primary and loading task scores as a function of gain of primary-task display. Error bars represent plus or minus one standard deviation. (P = Primary task only, PI = Primary plus independent loading task, CA = Primary plus cross-adaptive loading task). (From Ref. 6)

Applications

Situations in which it is necessary to choose between design options on the basis of workload, especially when testing for workload would occur over a period of time so as to promote practice effects or when experimenter control of subject variables is not always possible.

Methods

Test Conditions

- For primary acceleration-tracking task, two compensatory-display meters, one in the vertical axis and one in the horizontal axis; two-axis hand controller (if the entire display range is given a plus or minus 1.00, the hand-controller range was plus or minus 0.28 units/sec^2); display gain was 1.00, 0.75, or 0.50
- Forcing function generator entered step-function disturbances into each tracking-task axis every 4 sec; disturbances rectangularly distributed with mean of zero and range of 0.20 display scale units/sec^2
- Secondary task was to extinguish one of two illuminated neon bulbs, spaced 2.54-cm (1-in.) apart and 91.44-cm left of the tracking displays; lights randomly programmed so that one would go on 440 msec after subject extinguished previous light; illuminance not specified
- Entire display panel 45.72 cm from subject's eyes
- Loading task conditions: primary task only, primary task plus fixed loading and primary task plus cross-adaptive loading
- In the cross-adaptive condition, the loading task was turned on whenever rms vector error fell below 33.3 and turned off when it rose above 33.3
- Subjects instructed to perform as well as possible at all times and to not neglect one task for the other

Experimental Procedure

- Independent variables: display gain, loading-task condition
- Dependent variables: primary-task scores, defined as root-mean-square (rms) vector error with continuous scoring for each 5-min run; loading-task scores, defined as the number of correct responses to lights
- Subject's task: for primary tasks, move the controller in two dimensions to keep the needles centered in both displays; for loading task, press thumb switch on controller in appropriate direction to extinguish light
- 2 subjects with extensive practice

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Experimental Results

- Cross-adaptive loading-task scores are highly sensitive to small differences in display-gain conditions. The ability of the primary-task scores to detect differences in display-gain conditions in this study is optimized by adaptive adjustment of the forcing-function amplitude on practice runs, and, in any event, the primary-task-only scores are not nearly as sensitive as the cross-adaptive loading-task scores. The fixed loading task is ineffective in increasing sensitivity to differences in display gains.
- The cross-adaptive technique maintained primary-task scores within a narrow range; in the two other conditions primary-task scores varied substantially.

Variability

Error bars (Fig. 1) represent plus or minus one standard deviation.

Repeatability/Comparison with Other Studies

The cross-adaptive technique has been used by other investigators with varying degrees of success. For example, when adapting a visual secondary task to maintain primary-task performance on an arithmetic task, primary-task performance was nearly the same as with a self-paced secondary task (Ref. 1). Another adaptive technique ("cross-coupled critical tracking"; Ref. 5) has used a two-axis critical-tracking task, with performance on one axis serving to maintain performance on the other axis, and therefore serving as a "secondary task." This methodology, in which one component of a multicomponent task is used as a secondary task, has the advantage of high face validity. It has been used successfully to discriminate between several display types (Refs. 2, 3), to evaluate workload in a manual control task (Ref. 4), and to evaluate workload in control devices involving different levels of kinesthetic information (Ref. 7).

Constraints

- Adaptive techniques must employ a continuous measure of primary-task performance to be maximally effective in stabilizing primary-task performance.
- Very little work has been done to provide general rules of application with discrete-task and complex-task environments.
- Adaptive techniques may have little applicability outside of laboratory environments, due to implementation problems resulting from the instrumentation necessary in these techniques.

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Cross References

7.716 Primary task measures for workload assessment

7.723 Use of Embedded Secondary Tasks in Workload Assessment

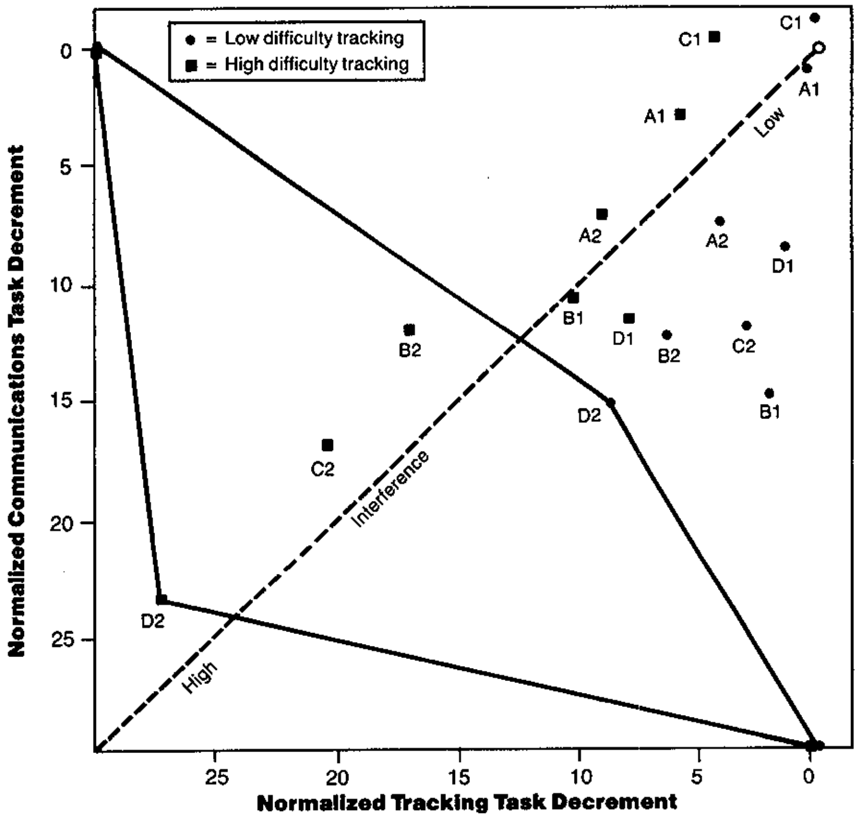

Figure 1. Combined dual-task decrement for each pair of communications and tracking tasks, which is equivalent to a performance operating characteristic. The labels on the points refer to various communications tasks. (From Ref. 1)

Key Terms

Embedded tasks; task sensitivity; workload measures

General Description

Assessment of operator workload through use of a secondary-task measure can be subject to problems of primary-task interference, artificiality of the assessment technique, and the need for additional equipment at an operator workstation. An embedded secondary task overcomes these problems because it is normally part of the operator's duties.

Realistic radio-communication activities produce significant dual-task interference in a single-axis tracking task. The interference is correlated with a priori workload scaling techniques and indicates that analytically derived estimates of workload can be used to develop additional secondary tasks.

Applications

As a general methodology, workload assessment in situations where high face validity of secondary tasks is crucial; specifically, crew task workload assessment through use of radio communication activities of differential task sensitivity.

Methods

Test Conditions

- A-10 aircraft instrument-panel mockup containing 12.7 cm (5 in.) black-and-white TV monitor and digital clock with 1.27 cm lighted LCD; actual A-10 communication panel with IFF, VHF, UHF, FM, INTERCOM, and antenna panels
- Mockup simulated threat-warning display with subminiature light bulbs at 3, 6, 9, and 12 o'clock on each of two concentric circles corresponding to 3- and 6-mi ranges; ninth bulb at center of display
- Simulated stationary throttle with push-to-talk three-position microphone switch; standard Air-Force headset with boom microphone; 60.96-cm control stick 30.48 cm in front of pilot seat with useful travel of 45 deg side to side
- 1 x 2 cm fixed target centered on TV monitor
- System in tracking task was inherently unstable because of positive feedback controlling cursor position; operator had to compensate for the instability
- Two levels of tracking task diffi-

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culty (high or low) are defined as maximum level of instability in the control system at which subjects could maintain control of the task (multiplied by 0.95 for high difficulty and by 0.60 for low difficulty)
• Communication-task workload defined in three ways: (1) number of bits based on number of perceptual and manual/verbal action decisions in each task assuming equiprobability of alternatives and independence of sequential actions, (2) weighting factors derived for paired comparisons of task difficulty by A-7 and A-10 pilots, and (3) ranking of task workload by 30 pilots
• In dual-task trials, tracking began as soon as radio chatter began; communications task presented after 10-20 sec foreperiod; tracking task recorded only during communications task (10-100 sec); baseline tracking recorded over a 60-sec period

Experimental Procedure

• Independent variables: tracking-task difficulty; communications-task workload
• Dependent variables: primary-task (tracking) performance, defined as the ratio of the number of control losses to total tracking time; secondary-task (communications) performance, defined as (1) response time from message onset to occurrence of first switch action, (2) response time from termination of instructions to completion of requested activity, and (3) time from onset of input to final switch action; dual-task decrement, defined as the absolute number of time-averaged control losses that occurred in combined-task conditions
• Observer's task: (1) primary task, keep cursor on the video monitor centered over target by making inputs with the control stick; (2) secondary-task, carry out instructions presented as a communications task
• 4 male and 2 female civilian subjects with extensive practice

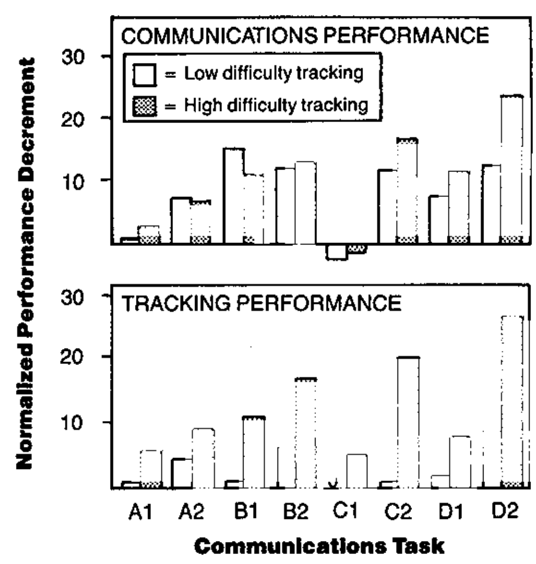

Figure 2. Histogram of dual-task performance decrements for communications and tracking tasks. (From Ref. 1)

Experimental Results

• Measure of request-to-response time varies significantly with concurrent task load in six of the eight communication tasks. However, since total-task time is a more common measure and is redundant with request-to-response time, total-task time was selected to assess the sensitivity of workload measurement obtainable with communications-task methodology.
• Combined dual-task decrement can be illustrated as a single point in a mutual-interference space, equivalent to a point on a performance operating characteristic (Fig. 1). Relative locations of points along the negative diagonal indicate resource allocation policies adopted by subjects. Points along either axis indicate resource allocation favoring that task. Dual-task points near the upper right corner show little combined decrement, and are therefore associated with secondary tasks unlikely to be sensitive to workload. As data points are shifted toward the lower left corner, the secondary tasks associated with them can be expected to provide reliable workload measures.
• Mean tracking control losses are affected only by communications-task demands. However, dual-task decrement in communications-task duration is sensitive both to tracking demand and communications demand (Fig. 2). Hence the communications task tends to be more sensitive to manipulations of task loading, indicating that performance on secondary communications task can provide a common univariate index of workload.
• Information theoretical analysis is the only a priori estimate of communications task loading that significantly correlates with secondary task performance. In addition, there are high correlations between communications-task performance decrements and subjective measures of time loading, mental effort, and psychological stress.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The results reported here represent a novel approach to the assessment of primary task workload. To the extent that older methodologies are plagued by problems of face validity (artificiality), primary-task interference, and the need for additional equipment at operator workstations to collect data, the embedded secondary task method is preferred.

Constraints

• The results clearly apply to a specific primary and secondary task. However, the general methodology is applicable to a wide range of workload assessment situations.

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Cross References

7.721 Guidelines for the use of secondary task measures in workload assessment

7.724 Transient Cortical Evoked Responses as a Physiological Measure in Workload Assessment

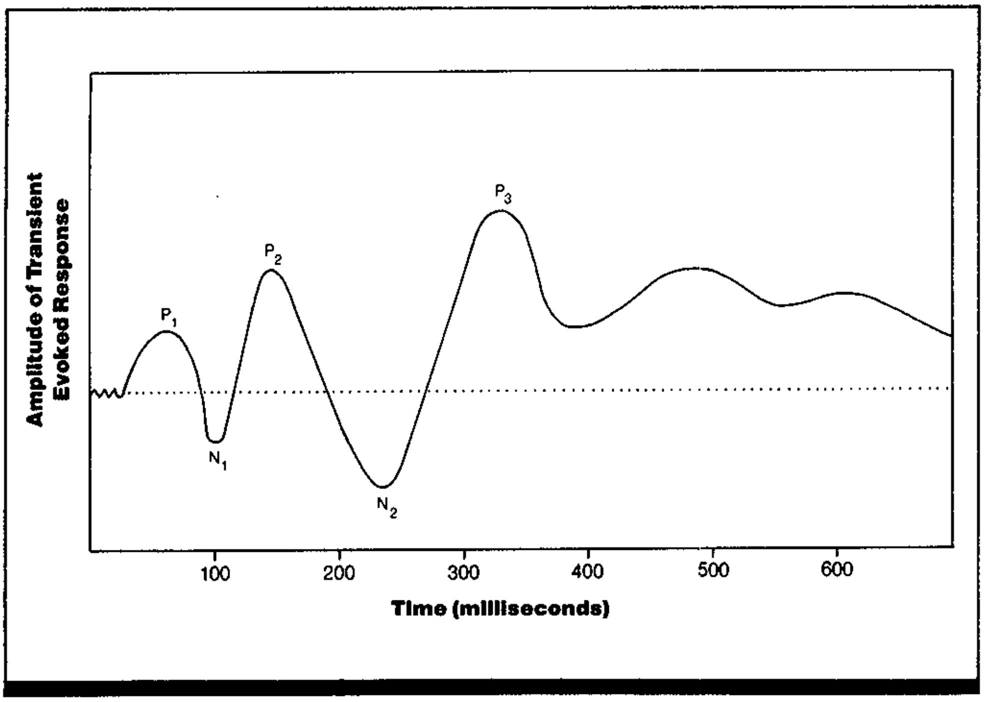

Figure 1. Idealized components of a typical transient visual-evoked response. P and N indicate positive and negative components, respectively. (From *Handbook of perception and human performance*)

Key Terms

EEG; evoked potential; P300; workload measurement; workload measures

General Description

The transient cortical evoked response is a series of voltage oscillations originating in the cortex of the brain in response to the occurrence of a discrete event. It can be recorded from the scalp of an awake subject and requires no overt action by the subject. The response is usually divided into components that are labeled *P* or *N*, depending on the positive or negative polarity of the component. A component is further specified by its minimal latency in msec from the onset of the eliciting event. In Fig. 1, P_3 (P300) represents a positive component occurring at least 300 msec after the eliciting stimulus.

Certain components of the transient evoked response are related to various aspects of the stimulus situation. Specifically, the amplitude and latency of the P300 peak are sensitive to aspects of the stimulus situation that can be interpreted as contributing to workload. The P300 amplitude is inversely proportional to the predictability of a stimulus (Refs. 3, 7). The latency of the P300 peak has been interpreted as an index of the time taken to evaluate a stimulus (Ref. 1). The P300 latency is correlated with reaction time, but does not include the time for selection and execution of a response (Ref. 2). To the extent that task predictability and difficulty in stimulus evaluation contribute to workload, P300 amplitude and latency may be used to assess workload (Ref. 6; CRef. 7.725).

Applications

Situations in which engineers must choose between design options on the basis of operator workload, especially when it is important to gauge workload in a manner that is relatively non-disruptive of the primary task; situations in which it is necessary to determine the locus of inference of two time-shared tasks.

Method of Application

The technique requires instrumentation for the recording of the electroencephalogram (EEG) and computer facilities for the analysis of the EEG signal. As a control measure, the electrooculogram (EOG) is often recorded along with the EEG, so that evoked potentials contaminated by eye movement artifacts may be excluded from analysis.

The technique uses a stimulus presentation to evoke the P300 while an operator is performing the task of interest; in this case, whatever processing is required of the eliciting stimulus may be regarded as a secondary task (Ref. 6; CRef. 7.725). The technique can also be used to directly assess evaluation time and expectations associated with a primary-task stimulus (Ref. 4).

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Constraints

- The P300 technique requires EEG sampling over a large period of time, so that momentary fluctuations in workload may be averaged into the measurement. This results in a reduction of the sensitivity of the measure to workload.
- The diagnostic limitations of P300 amplitude and latency in assessing workload have yet to be defined.
- The transient response to primary-task stimuli has been tested primarily at lower levels of memory and processing load and has not yet been examined at higher loading levels.
- It is crucial that operators engage in some processing of the eliciting stimulus while performing the primary task in order for the P300 to be used as an index of workload (Ref. 5). However, there will be a loss of face validity to the extent that the eliciting stimulus is not normally a part of the operating environment.

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Cross References

7.725 Use of the P300 spike with a secondary task;

Handbook of perception and human performance, Ch. 42, Sect. 5.2

7.725 Use of the P300 Spike with a Secondary Task

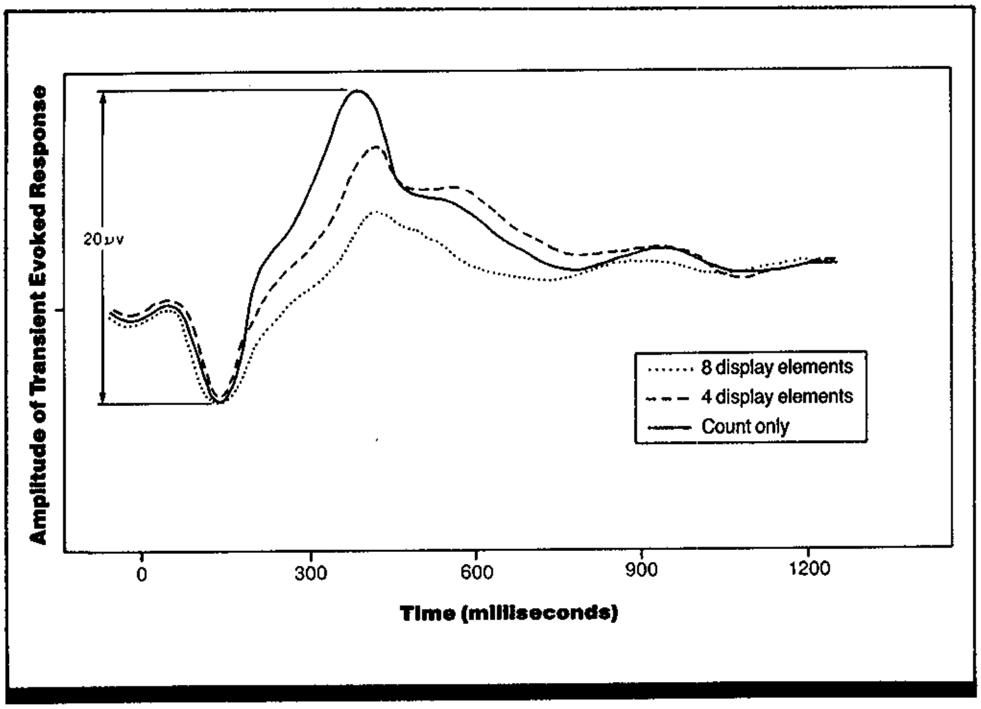

Figure 1. Amplitude of transient evoked response (P300) to course changes of elements in displays containing zero (secondary task only), four or eight moving elements. (From Ref. 3)

Key Terms

EEG; P300; secondary task; workload measurement; workload measures

General Description

The event-related brain potential, P300, can be used to assess primary-task workload. When workload in a simulated air-traffic-control task is increased by increasing the number of targets the operator must monitor, the amplitude of the P300 spike elicited by a secondary task decreases. The P300 amplitude decrease is accompanied by poorer response time and poorer accuracy in monitoring as the number of targets increases, which lends validity to the P300 spike as a workload index. An added advantage of the technique is that the secondary task used to elicit the P300 (counting auditory tones played concurrently with the primary task) does not disrupt primary-task performance.

Applications

As a general methodology, situations in which designers must decide among systems or design options on the basis of the workload placed upon the operator by each system, and in which disruption of primary-task performance by a secondary task must be minimized.

Methods

Test Conditions

- Target events were changes in continuously moving geometrical forms (squares and triangles) ~4 mm in diameter, displayed on a 10.5 x 13 cm oscilloscope located ~70 cm from observer; every 6-10 sec luminance of one form increased for 200 msec (flash) and one form changed direction by ±60 deg (course change); squares and triangles were equally likely to display an event, determined randomly, as long as the form was not within 2 cm of display edge or 1 cm of another form
- Number of forms were 0, 4, or 8 where no forms indicates secondary task only
- Two secondary tasks performed separately with primary task; secondary task was either one of two button-press responses to high- or low-pitched auditory tone, or count the number of high-pitched tones as they occur in each block of trials and report total
- Forms entered display asynchronously from random locations on the left or right halves of the upper and lower edges of the screen, and linearly traversed screen at 25 mm per sec in a random direction that was between 10 and 170 deg (relative to 0 deg vertical); forms re-entered screen when they reached display edge
- During flash detection, flashes of triangles and all course changes were irrelevant; during course change detection, triangle course changes and all flashes were irrelevant

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• Electroencephalogram (EEG) and electrooculogram (EOG) sampled for 1280 msec on each trial, beginning 100 msec prior to stimulus onset
• Ambient lighting intensity adjusted to observer's preference
• 1200-Hz tones (low-pitched) and 1400-Hz tones (high-pitched), 65 dB sound pressure level (SPL re 20μN/m^2) delivered via TDH-39 earphones against a constant background of white noise 58 dB SPL; 60-msec tones (including 10 msec rise/fall) presented every 2 sec: 0.67 probability of low tone on any trial and 0.33 probability of high tone
• Instructions stressed accuracy on secondary task, provided primary-task accuracy did not fall below average single-task level; monetary reward given for this level of performance

Experimental Procedure

• Within-subjects repeated measures design
• Independent variables: monitoring task, display-load level, type of secondary task, and secondary-task stimulus
• Dependent variables: amplitude of the P300 spike in traffic-control management condition; response time and accuracy for the response-time secondary task
• Observer's task: primary task was to monitor course changes or flashes in squares on the visual display; secondary task was either to count tones or discriminate between high and low tones
• 6 female and 2 male right-handed observers with correctable 20/20 vision and some practice (mean age = 24.4 yrs)

Experimental Results

• Amplitude of the P300 spike decreases as display load increases when observers perform the secondary counting task. This decrease is seen over each load level in the course change condition, but only from a load level increase of zero to four elements in the flash detection condition (a load of eight target elements produces no further change). The effect is statistically reliable ($p < 0.01$).
• Response time for the secondary task increases as display load increases for each load level in the course-change primary task. In the flash detection task, response time increases only from a load level zero to four elements (a load of eight target elements produces no further response time increase). These effects are statistically reliable ($p < 0.05$). Accuracy data are positively correlated with response time data. Both of these results lend validity to the use of P300 amplitude as a workload index.
• Neither secondary task has a significant effect upon the percentages of course changes and flashes detected. Hence using the event (tone occurrence) that produced the P300 spike as a workload index does not itself disrupt primary-task performance.
• Since the counting task that elicits the P300 requires no overt responding, the task probably draws on central and perceptual resources rather than response-related resources. Because the P300 is influenced by workload, the primary task also probably draws upon central and perceptual resources.

Variability

P300 spike latency variability increased monotonically across all three load levels for the course change task ($p < 0.01$), but only from zero to four element load levels in the flash detection task ($p < 0.05$).

Repeatability/Comparison with Other Studies

Earlier studies using the P300 amplitude to measure workload in a secondary-task situation found decreases in amplitude when two tasks were performed, but the decrease did not continue under progressively higher load levels (Refs. 2, 4). Those studies employed a tracking task as the primary task, which may have drawn heavily upon response-related resources rather than central resources. A study employing only a primary task found decreasing P300 amplitude with increasing workload under some conditions (CRef. 7.726).

Constraints

• To successfully employ the P300 amplitude as an index of workload, the resources drawn upon by the event eliciting the P300 spike must be the same as those drawn upon by the primary task.
• Even when the above constraint has been met, the P300 eliciting event must be processed so that the amplitudes of the P300 spike will be related to primary task performance (Refs. 1, 3).
• Use of P300 requires EEG equipment and thus is difficult to implement outside of the laboratory.

Key References

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Cross References

7.726 Use of transient cortical evoked response in the primary task situation;

Handbook of perception and human performance, Ch. 42, Sect. 5.2

7.726 Use of Transient Cortical Evoked Response in the Primary Task Situation

Key Terms

Memory search; P300; primary tasks; reaction time; workload measurement; workload measures

General Description

Visually evoked **brain potentials** can be used as an index of operator workload in a single-task situation. As the number of target items in a memory search task is increased (i.e., as memory load is increased), the latency of the P300 spike increases linearly. The P300 spike latency increase with increasing memory load shows much less of a deviation from linearity than **reaction-time** measures. The results demonstrate the use of the evoked potential as an index of high-level cognitive activity rather than simply gauging workload in low-level perceptual tasks.

Methods

Test Conditions

- Electroencephalographic activity recorded at vertex and referred to right mastoid with Beckman silver/silver chloride electrodes; scalp abraded each day to keep impedence between electrodes <1.5 K ohms
- Each AE8 composite of 96 responses, 730 msec in duration
- Set of 1, 2, 4, or 6 letters given to observer for memorization
- Probe item was a white letter 0.8 cm in height, centered on a 2.5 x 2.2 cm background; letter front illuminated by mercury-argon lamps and presented tachistoscopically within a 7.0- x 11.4-cm diffuse ambient field; letter luminance was 37.32 cd/m^2; surround luminance was 4.80 cd/m^2
- Probe-letter duration was 2 sec with a fixed 3-sec interstimulus interval
- Viewing distance of 120 cm; letters subtended 22 min of arc of visual angle
- Stimulus presentation order randomized for each subject
- Observers instructed to respond quickly, but to try to maintain error-free performance; auditory feedback given on correct responses (2.9 kHz tone, 70 dB SPL)
- Probe-letter was a member of the memory-set on one-half the trials

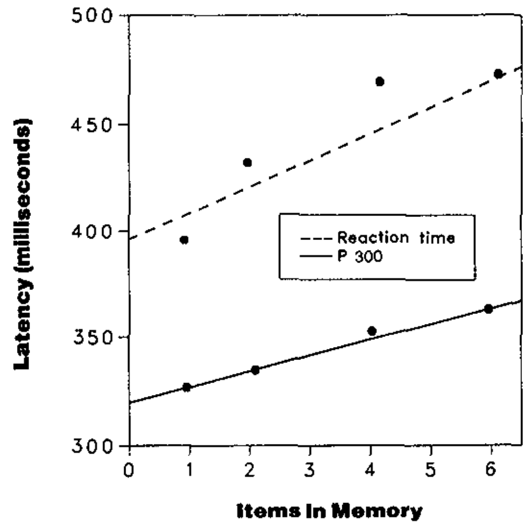

Figure 1. Reaction time and P300 latency in a memory scanning task. (From Ref. 4)

Experimental Procedure

- Memory search task, within-subjects, repeated measures design
- Independent variables: size of memory set, presence or absence of probe item in memory set
- Dependent variables: reaction time, latency of P300 spike
- Observer's task: indicate if a visually presented letter was one of those held in the memory set feedback provided
- 6 observers (4 men, 2 women), ages 21-37, all with normal or corrected vision and some practice

Experimental Results

- Latency of the P300 spike increases significantly as the size of the memory set increases ($p < 0.01$). This implies that P300 latency can be used as a workload index, since increasing memory-set size increases memory load (i.e., the number of items that must be searched to perform the task).
- Reaction time also increases as a function of memory set size ($p < 0.01$). However, trend analyses shows that there is a significant deviation from linearity in response time data; in contrast, the P300 latency exhibits a strong linear trend. This again implies that the P300 spike is a sensitive index of workload imposed by the memory search task.
- Amplitude of the P300 spike is significantly affected by the stimulus. Letters in the memory set produce a higher P300 amplitude than letters not in the memory set. Furthermore, the amplitude produced by positive items remains fairly constant with memory set size increases, whereas the amplitude produced by negative items decreases as set size increases.

Variability

99% of the variation on P300 latency across memory set size is attributed to the linear trend; 20% of the variation in reaction time across memory set size is accounted for by significant deviation from linearity.

Repeatability/Comparison with Other Studies

Many earlier studies used only relatively low-level pure tones, noise bursts, or light flashes to determine how P300 is affected (Refs. 1, 2, 3). The idea that the P300 is a useful index of workload at higher processing levels is consistent with other more recent research (CRef. 7.725). The finding that response time increases with memory set size is a very robust one (Ref. 5).

Constraints

- The sensitivity of the P300 latency to workload in many tasks has not yet been determined.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

7.725 Use of the P300 spike with a secondary task;

Handbook of perception and human performance, Ch. 42, Sect. 5.2

7.727 Resource Reciprocity Between Primary and Secondary Tasks Reflected in P300 Spike Amplitude

Key Terms

Evoked potentials; P300; resource reciprocity; tracking; workload measurement; workload measures

General Description

Amplitude of the P300 brain potential can be used as an index of workload. As the difficulty of a primary step-tracking task increases, amplitude of the P300 spike elicited by a stimulus relevant to a secondary task decreases. However, amplitude of the P300 spike elicited by discrete changes in spatial position of the tracked target increases with increasing difficulty of the tracking task. This is a demonstration of resource reciprocity between concurrently performed tasks.

Methods

Test Conditions

- CRT display of target and cursor in pursuit step tracking task; joystick to control cursor
- First-order (velocity) and second-order (acceleration) joystick control dynamics
- These primary task conditions: first-order control with predictable input, first-order control with unpredictable input and second-order control with unpredictable input
- Horizontal target displacement sequence either predictable (regular right-left shifts) or unpredictable; magnitude of target displacement was random; displacements occurred at 3-sec intervals
- Each of three secondary tasks involved counting: count low tones in Bernoulli sequence of high- and low-pitched tones; count dimmer flashes in Bernoulli sequence of brighter or dimmer 100-msec flashes (as horizontal bar along target path); count number of times target moved in a given direction; control condition had no secondary task
- Counting task for number of target changes to the left embedded the secondary task within the primary task; that is, observers did not have to attend to a different stimulus from that used in the tracking task, as they did in the visual and auditory conditions

Experimental Procedure

- Pursuit step-tracking primary task, secondary counting task; within-subjects design
- Independent variables: tracking-task difficulty, defined as the combination of control dynamics with target-position-sequence predictability; nature of secondary task
- Dependent variables: P300 amplitude, root-mean-square tracking error, subjective estimates of task difficulty
- Observer's task: primary task was to move cursor onto moving target by means of joystick; secondary task was to count specified events (low-pitched auditory tones, dimmer light flashes, number of target step changes to the left)
- 12 observers (8 males, 4 females), with an unknown amount of practice

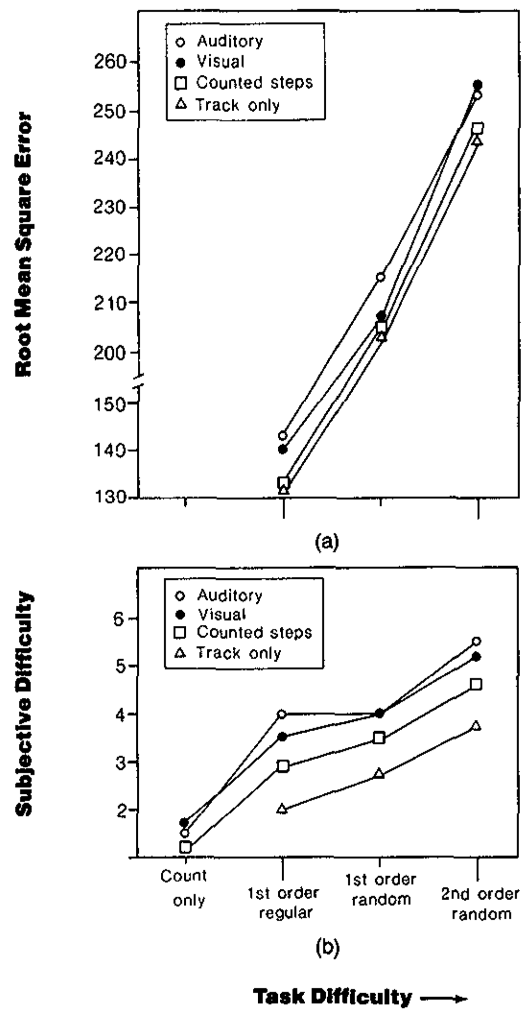

Figure 1. (a) Average root-mean-square error and (b) subjective difficulty ratings for each level of tracking difficulty. The parameter for the curves is type of secondary task. (From Ref. 6)

Experimental Results

- Root-mean-square tracking error increases as presumed difficulty of tracking task increases. That is, as combination of control dynamics with predictability progresses from first-order-regular to first-order-random to second-order-random, the root-mean-square error of the tracking task also increased.
- Subjective difficulty estimate also increases as presumed difficulty of tracking increases. Note the difference in subjective ratings (Fig. 1) between the secondary task that employed an embedded stimulus (stepcounting) and those that did not (auditory and visual). Situations in which observers must attend to different sources of information should draw more heavily on processing resources.
- Increases in tracking-task difficulty produce decreases in P300 amplitude for potential elicited by auditory stimuli. Introduction of a secondary task using visual stimuli also produces a decrease in P300 amplitude, although no further decreases occur with increases in tracking-task difficulty. In the step-counting condition, increases in tracking difficulty produce increases in the P300 amplitude elicited by an

embedded stimulus event. Taken together, these results suggest resource reciprocity. Processing resources diverted from secondary task performance are used for primary task performance.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The findings that P300 amplitude decreases with introduction of a secondary task and P300 decreases with increased workload have been demonstrated in other studies (Refs. 1, 2; CRef. 7.725). Furthermore, root-mean-square error and subjective estimates have been used in other studies as indices of workload in tracking tasks (Refs. 3, 4; CRefs. 7.713, 7.722).

Constraints

- The use of P300 amplitude as a workload index requires instrumentation that limits the settings in which it can be used.

Key References

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Cross References

7.713 Subjective workload assessment technique (SWAT) ratings as a function of task difficulty;

7.722 Use of adaptive-task techniques to counter primary task intrusion in workload assessment;

7.725 Use of the P300 spike with a secondary task;

Handbook of perception and human performance, Ch. 41, Sect. 3.9

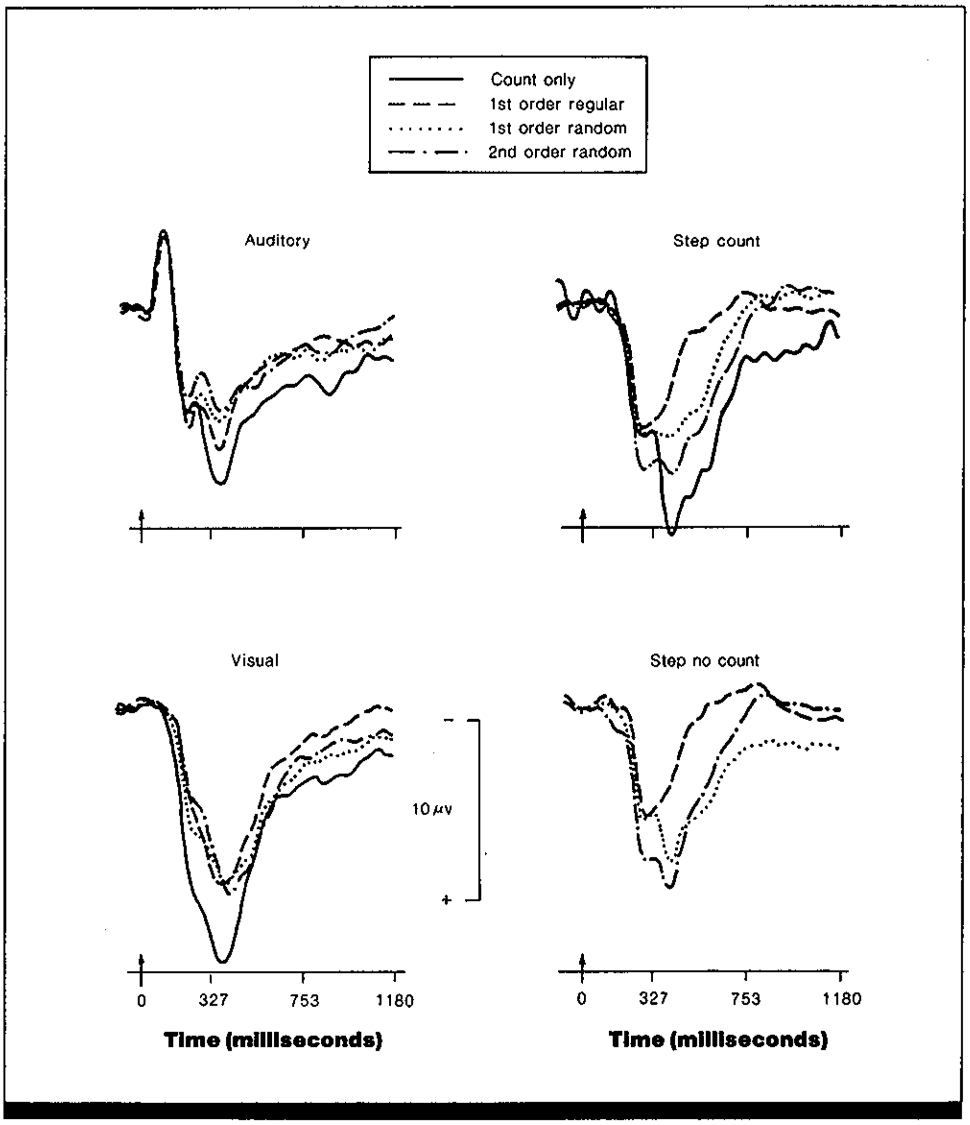

Figure 2. Average parietal event-related potential elicited by visual, auditory, and spatial probes presented concurrently with the pursuit step-tracking task at each level of difficulty. An increase in P300 amplitude is indicated by the minimum of the curve approaching the scale at the bottom of the panel. (From Refs. 4 and 6)

7.728 Pupil Diameter as an Indicator of Workload

Key Terms

Auditory discrimination; memory; pupillometry; reasoning ability; workload measurement; workload measures

General Description

Pupil diameter can be used as an index of operator workload. When operators engage in information processing, pupil size increases over baseline levels. Furthermore, as presumed workload on a particular type of processing increases, pupil diameter also increases. The results obtained are usually small but very consistent, making pupil diameter one of the most sensitive indices of workload. The technique is difficult to implement in non-laboratory settings, but it is valuable as a laboratory-based technique.

The table summarizes the results of a number of studies that employed measurement of pupil size to assess workload. The studies are grouped with respect to the general process studied. The results indicate a reasonable ordering of pupil diameters as a function of workload, not only across different tasks, but also distinguishing workload levels within a particular task. All pupillary responses reported are with reference to baseline diameters.

Applications

Laboratory assessment screening of workload levels for particular tasks or design options.

Constraints

- Factors such as ambient lighting, eye movements, and emotional states may cause pupillary responses large enough to obscure those due to workload alone (Ref. 8). Because it is difficult to control these factors in non-laboratory settings, this technique is very difficult to implement in applied settings.
- Because the technique is sensitive with so many different tasks, it is not specific to a particular type of resource. Therefore it should be considered a global measure of workload without reference to measurement of a particular type of load.
- Lengthy stimulus presentation at close distances (e.g., <3 m) will tend to result in constriction of the pupil. This effect is called the "near-vision pupil reflex" and is quite variable among subjects (Ref. 9). This is the type of effect that can impede the use of pupillometry in a monitoring or vigilance situation.
- Pupils of eyes with blue or light irises are generally larger and respond with larger dilations than pupils of eyes with dark irises. Generalizations from studies that did not control for this variable must be guarded (Ref. 9).
- Pupillary diameter is highly variable, varying as much as 10-20% over a period of several seconds when stimulus conditions are not changing. Repeated measures designs or many observations per subject can overcome this difficulty (Ref. 9).

Table 1. Experimental studies using pupil diameter to assess workload. (After Ref. 3)

Processes Studied	Subject's Task	Results	Source
Memory—digit span	Repeat strings of three to seven digits 2 sec after they were aurally presented	Average pupil diameter increases 0.2-0.5 mm with increasing memory load. Pupil diameter increases with each new digit presentation (for a given memory load), reaching maximum in the 2-sec pause between the end of the presentation and the beginning of the response (when memory load is highest)	Ref. 10
Memory—digit span	Report aurally presented strings of five to thirteen digits	Pupil diameter increases by 0.1-0.7 mm with presentation of each digit up to seven digits. Diameter increase reaches asymptote with a load of seven digits, suggesting that further increases in task demand no longer yield pupillary increases when short-term memory limits are reached	Ref. 12

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Processes Studied	Subject's Task	Results	Source
Language—grammatical language	Decide whether a sentence of the form "A follows B" or "B precedes A" is exemplified by a stimulus such as "AB" or "BA"	Pupil diameter increases by 0.4-0.5 mm once both sentence and stimulus pair have been presented. More complex sentences yield a larger pupillary dilation	Ref. 2
Language—semantic categorization	Judge pairs of words as similar or different in meaning; first word of the pair was either the easiest or most difficult of one of three psychometric vocabulary tests	Pupillary dilation of 0.1 mm follows presentation of easy word, whereas dilation of 0.2 mm follows presentation of hard word. Second dilation of 0.30 and 0.35 mm follows presentation of comparison word after easy and hard word, respectively. This second dilation occurs during the judgment period	Ref. 2
Language—sentence encoding and reproduction	Listen to and repeat six-word sentences that were either standard (meaningful English), anomalous (standard syntax, no semantic organization), or scrambled (neither syntactic nor semantic organization)	Pupillary dilation reaches 0.20 mm, 0.25 mm, and 0.40 mm, for standard, anomalous, and scrambled sentences, respectively. The greater the strain on verbal resources due to lack of syntactic and semantic organization, the greater the pupillary response	Ref. 6
Language—sentence encoding	Either repeat complex sentences or answer a question about them	Repetition produces a maximum pupillary dilation of 0.30 mm; question answering produces a maximum pupillary dilation of 0.40 mm. The deeper the processing required by the task, the greater the pupillary response	Ref. 13
Language—letter matching	Decide whether a pair of visually presented letters have the same name or not; letters could either be in the same case or in different cases; former situation requires only analysis of physical features, second situation requires name code extraction in addition to physical features analysis	Same-case pairs produce maximum pupillary dilation of 0.08 mm; different-case pairs produce maximum pupillary dilation of 0.14 mm. The deeper level of processing produces a greater pupillary response	Ref. 5
Reasoning—arithmetic	Multiply pairs of numbers; problem difficulty had three levels, ranging from pairs of one-digit numbers to pairs of two-digit numbers between 11 and 20	Encoding and storage of the multiplicand produces a 0.15-mm pupillary dilation. Peak dilation occurs after presentation of the multiplier, reaching 0.30 mm, 0.45 mm, and 0.50 mm, for the easy, medium, and difficult problem levels, respectively	Ref. 1
Perception—auditory discrimination	Judge whether comparison tone is higher or lower in pitch than a standard; difficulty of discrimination inversely related to difference in frequency between standard and comparison	Pupillary dilation varies from 0.10 mm-20 mm from the easiest to the most difficult discrimination	Ref. 11
Perception—auditory detection	Detect a weak 100-msec 100 Hz sinusoidal signal against a white noise background; subjects rated their certainty about signal presence or absence	Signal present responses yield maximum pupillary dilation of 0.20 mm; signal absent responses yield maximum pupillary dilation of 0.10 mm	Ref. 4
Perception—visual	Detect brief increments in luminance on a uniform visual field; magnitude of the intensity increment adjusted to yield 50% correct detection	Maximum pupillary dilation of 0.10 mm only if actual luminance change is detected	Ref. 7

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Cross References

7.701 Criteria for selection of workload assessment techniques

Notes

7.729 Surface Electromyography as an Index of Physical Workload

Key Terms

Electromyogram; muscle activity; workload measurement; workload measures

General Description

The electromyogram (EMG) is a record of electrical activity in muscles that can be used to index physical workload. The amplitude of the EMG is a linearly increasing function of the force exerted by a muscle, as well as the tension level of the muscle. Furthermore, the EMG spectrum changes as a muscle fatigues, showing an increasing dominance of lower frequencies. These two findings allow use of the EMG to assess physical workload by determining the absolute force necessary for system operation and by assessing workload over time.

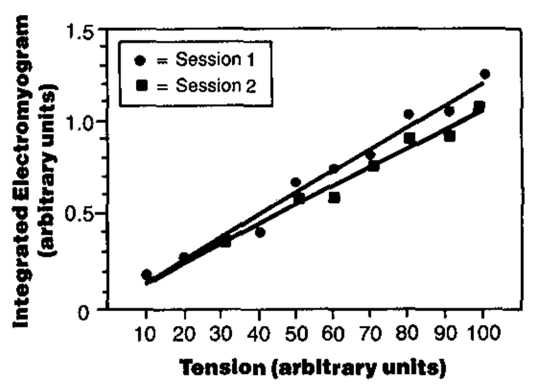

Figure 1. Linear relationship between electromyogram and muscle tension for a single subject on two different occasions. (From Ref. 1)

Methods

Test Conditions

- **Dynamometer** measured only forces resulting from foot rotating about the ankle
- Full deflection equivalent to a force of 125 kg; calibration of instrument linear over entire range of forces employed
- Measurement of pressure made by hydraulic system and Bourdon gauge
- EMG recorded from the gastrocnemius-soleus (calf muscle) of the right leg
- Ten tensions from 4.5-45 kg in 4.5 kg steps; maximum pressure well within capabilities of all subjects
- Electrodes were three small brass suction cups 0.64 cm in diameter and 0.64 cm deep; action potentials recorded from oscilloscope on 70-mm bromide paper travelling at 100 cm/sec

Experimental Procedure

- Independent variable: force exerted by calf muscle, of 4.5-45 kg in ten equal increments
- Dependent variable: integrated electromyogram, defined as the mean integrated area of three randomly selected areas of EMG recording integrated over a period of 0.5 sec
- Subject's task: increase pressure smoothly to the required level (by rotating the foot at the ankle) and hold it for 5 sec
- 30 subjects with an unknown amount of practice

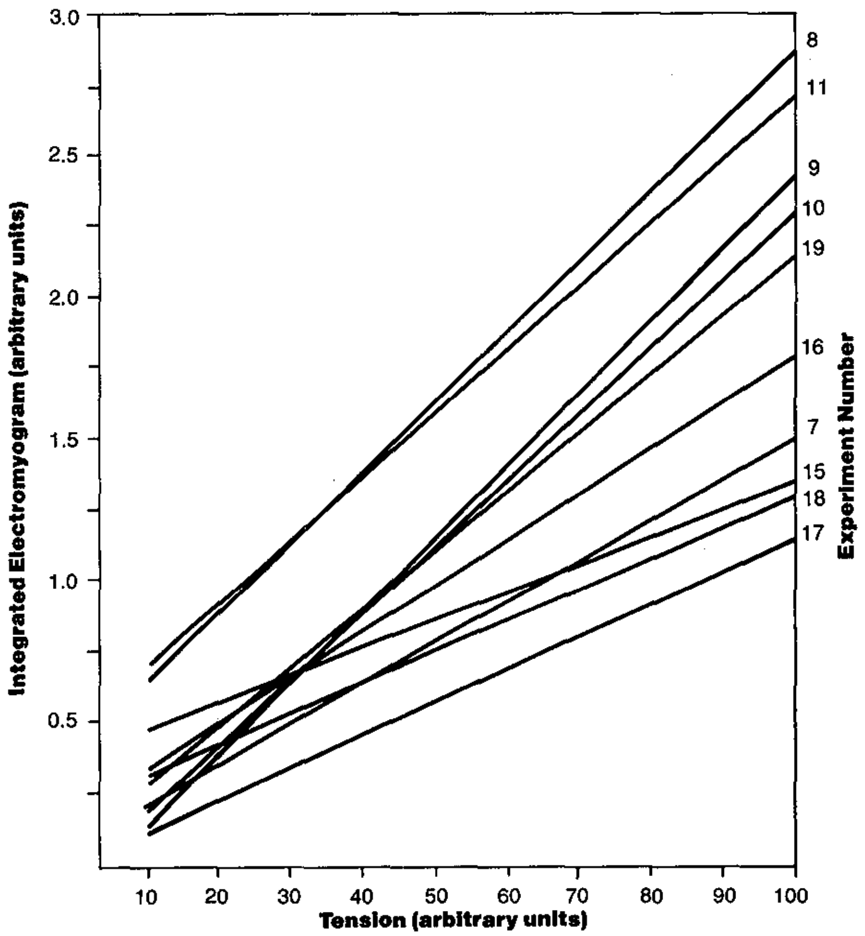

Figure 2. Regression lines between electromyogram and muscle tension for ten different experiments. Numbers at right of figure indicate experiment number, which corresponds to the data in Table 1. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Integrated EMG is an increasing linear function of muscle tension. Figure 1 shows this relationship (lines of best fit) for a single subject on two different occasions approximately 5 months apart. Figure 2 shows this relationship for ten different experiments. The regression coefficients associated with the functions in Fig. 2 are shown in Table 1; they tend to be characteristic of a subject on different occasions.
- Similar experiments show that the linear relationship holds throughout the contraction range of a particular subject up to a maximum. Furthermore, the linear relationship holds for isotonic contractions as well as for the isometric contractions employed in the study described here.
- Related experiments for arm muscles (biceps) show that the EMG spectrum changes as fatigue increases within a muscle. The synchronization of motor neurons results in lower frequencies becoming more dominant (Ref. 3).

Variability

Standard deviations and residual variances of regression lines in Fig. 2 are given in Table 1. Residual variance was probably due to inaccurate measure of tension resulting from lack of muscular skill in the subjects and tremors. Residual variance decreased as the period of integration was lengthened, reaching a minimum with periods of 0.5-1.0 sec, and then increasing again with longer integration periods.

Habitually large residual variance of some subjects could be reduced to normal range by administering quinal barbitone prior to experiment.

Scatter of EMG values increased at near-maximal contractions due in part to subject difficulty in maintaining a constant pressure reading.

There is considerable variability among subjects.

Repeatability/Comparison with Other Studies

Some earlier work with animals failed to find a quantitative relationship between EMG and muscle tension (Ref. 2). However, indirect stimulation with electrical induction did produce results similar to those described here (Ref. 1). Changes in EMG spectrum with fatigue of the type described here have been obtained by several other studies (Refs. 4, 5).

Constraints

- The linear relationship between EMG and muscle tension described here does not hold under supramaximal stimulation of the motor nerve to a muscle (Ref. 1).
- Instrumentation requirements may limit use in certain operational situations.

Key References

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Cross References

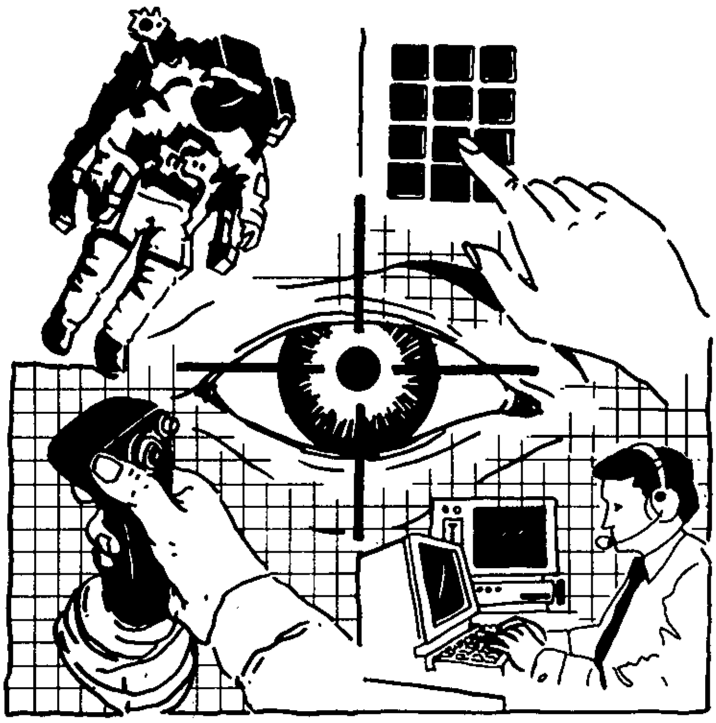
7.701 Criteria for selection of workload assessment techniques

Table 1. Regression coefficients and variability data for regression lines in Fig. 2. (From Ref. 1)

Exp. No.	Product moment correlation	Regression coefficient	Ratio of variances residual/total	Ratio of standard deviations
7	+0.991	0.0118	0.018	0.134
8	+0.964	0.0197	0.070	0.265
9	+0.935	0.0202	0.126	0.355
10	+0.971	0.0189	0.057	0.238
11	+0.942	0.0187	0.114	0.338
15	+0.994	0.0099	0.012	0.110
16	+0.995	0.0131	0.010	0.100
17	+0.977	0.0103	0.045	0.212
18	+0.922	0.0102	0.016	0.127
19	+0.970	0.0166	0.059	0.243

Notes

Section 7.8 Motivation and Personality



7.801 Effect of Incentives on Performance

Table 1. Effect of incentives on task performance.

Task Dimension	Incentive Level	Effect of Incentive	Source
Duration:			
Short	Moderate/high	None	Ref. 1
Long	Low/moderate	Improves performance; can abolish decrement	Ref. 1 Ref. 2
Interest:			
Low	Low/moderate	Improves performance	Ref. 1
High	Moderate	None	Ref. 1
	High	Improves performance	Ref. 3
Complexity:			
Simple	Low/moderate	Improves performance	Ref. 1
Dual	Moderate	Causes selective focus on central or important aspect	Ref. 1
	High	Impairs performance on central as well as peripheral task	
Memory load:			
Small	Moderate	Improves performance	Ref. 1
Large	Moderate	Improves or impairs	Ref. 1
Pacing:			
Self-paced	Moderate	Improves speed; either shows no change or impairs accuracy	Ref. 1
Experiment-paced	Moderate	Improves accuracy (depends on pace)	Ref. 1
Other stressors:			
Noise	Moderate	Intensifies impairment	Ref. 1
Sleep loss	Moderate	Counteracts impairment	Ref. 2

Key Terms

Arousal; incentive; memory; motivation

General Description

Incentives generally improve performance. However, the number of variables in studying the effect of incentives on performance is so large that research results are often contradictory. One variable is the nature of the incentive itself. Because incentives are so varied (e.g., large rewards of assistantships, small monetary payments, avoidance of shock, knowledge of results, social approval, or being given more interesting tasks), incentives are classified here as low, medium, or high in level.

Incentive level and type interact with the task, which can also vary in many dimensions, with the performance measure used and with individual differences in mood, state, or semipermanent personality characteristics, such as extroversion/introversion or anxiety. Most studies of the effect of incentives on performance control for only one or two of the variables, so the table should be viewed as the general result when the task dimension listed is combined with the level of incentive in the second column.

Constraints

- Because so many variables are involved, many of the results specified here have been reversed under certain conditions.
- For exceptions and other variable levels, see especially Ref. 1.

Key References

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Cross References

7.803 Effect of anxiety on performance;

10.101 Theories of arousal and stress;

10.103 Classification of factors influencing the stress state;

10.104 Arousal level: effect on performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance;

10.708 Incentive and introverted/extroverted personality: effect on the diurnal rhythm of performance;

10.805 Five-choice serial response task: effect of different stressors on performance

7.802 Situational Stress: Effects of Personality Type and Threat

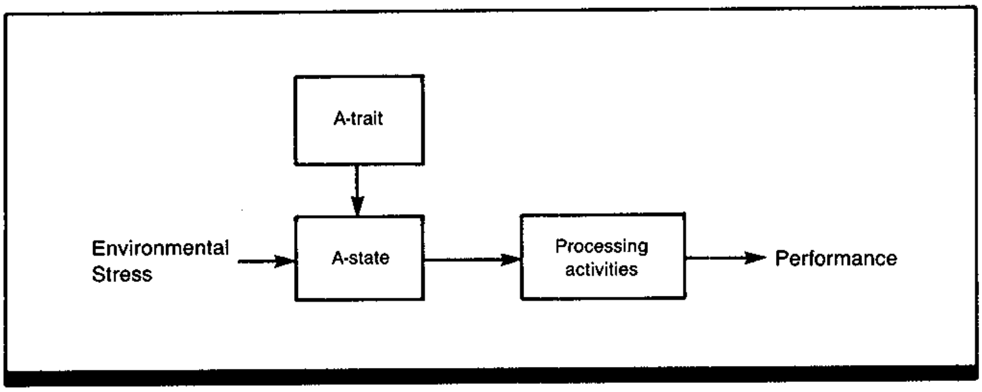

Figure 1. Schematic representation of the relationship of trait anxiety (A-trait) and environmental stress with state anxiety (A-state). (From Ref. 1)

Key Terms

Individual differences; personality; stress

General Description

Trait anxiety (A-trait) refers to a relatively stable individual level of anxiety proneness; state anxiety (A-state) is characterized by subjective, consciously perceived feelings of tension and apprehension and heightened autonomic nervous system activity. Both A-trait and environmental stress are thought to contribute to A-state, as shown schematically in Fig. 1. The increase in Affect Adjective Check List (AACL) scores from rest to test periods significantly differentiates high and low A-trait subjects under failure-threat conditions, but not under shock-threat or no-threat conditions (Fig. 2a). The increase in heart rate from rest period to test period did not significantly differ over anxiety level (Fig. 2b). Whereas failure-threat appears to increase A-state through A-trait, shock-threat increases A-state as a direct environmental stress (Fig. 1).

Methods

Test Conditions

- A-trait (anxiety) level of subjects determined after completion of Taylor Manifest Anxiety Scale (MA) during subject screening process
- Experiment divided into three periods: rest, performance, test; all subjects received equal rest and performance treatments; 18 high anxiety (HA) and 18 low anxiety (LA) subjects assigned to one of three threat conditions: failure-threat, shock-threat, no threat
- Each subject tested individually in small cubicle, with one of two experimenters in adjoining room; communication with subject through large open window
- Ring plethysmograph attached to measure heart rate (HR); subject relaxed for 8 min, without communicating with experimenter (rest period)
- Two experimenters administered treatment conditions separately to separate groups of subjects
- Memory task: Digits Backward Test, in which subject repeated backwards a string of digits (performance period); strings of increasing length given to determine subject's limit (level at which a specific number of digits was twice failed); subject then tested with eight strings which were one digit shorter than the subject's limit
- Threat condition established after maximum performance on digit string task was determined; failure-threat and no-threat conditions produced by verbal instructions; for shock-threat conditions, verbal threat followed by attaching electrodes to subject's ankle; then six multi-digit strings presented
- Measures of A-state: the Affect Adjective Check List (AACL), administered before digit task was begun and at end of digit series following threat; and heart rate (HR), analyzed for the last 15 sec of rest period, just prior to first administration of AACL, and for the first 15 sec of digit performance immediately after threat administration

Experimental Procedure

- Independent variables: A-trait level, type of threat condition, experimenter conducting study, time period (resting or test)
- Dependent variables: A-state, measured by mean AACL and HR values
- Subject's task: complete Digits Backwards Test and AACL
- 108 male undergraduate subjects; 54 high A-trait (HA) (score ≥ 18 on Taylor Manifest Anxiety (MA) scale) and 54 low A-trait (LA) (score ≤ 11)

Experimental Results

- Of 16 tests involving the experimenter variable, none significantly affects results, so data for both experimenters are combined.
- The mean AACL scores of HA and LA groups in the three threat conditions (Fig. 2a) are directly affected by A-trait ($p < 0.01$) and time period ($p < 0.001$). The interactions of threat condition by time period ($p < 0.001$) and threat condition by A-trait by time period ($p < 0.05$) also significantly affect the mean AACL scores.
- The A-trait by time period interaction is significant for failure-threat ($p < 0.05$), but not for shock-threat or no-threat conditions, indicating that the AACL scores of HA subjects in the failure-threat condition increase more than those of LA subjects in the same condition.
- The mean HR scores for HA and LA groups all increase from resting to test periods (Fig. 2b). Time periods are statistically significant, but data are not given.
- HR scores increase the most in the shock-threat conditions. Condition by time period interaction is significant, but data are not given.
- The condition by A-trait by time period interaction is not significant, nor is the main effect of A-trait, indicating the

effects of experimental condition are essentially the same for HA and LA groups.

Variability

Significance was determined by analysis of variance.

Repeatability/Comparison with Other Studies

Failure feedback impairs performance for high A-trait, but not for low A-trait subjects (Ref. 4; CRef. 7.803).

Constraints

- The AACL measure which differentiates HA and LA subjects in the failure-threat condition, but not in the shock-threat condition, could not be run until the test period was over, at which point subjects knew that they had or had not failed the final six series of digits and knew that they had not been shocked.
- No information about effect on performance is given.

Key References

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Cross References

7.803 Effect of anxiety on performance;

10.101 Theories of arousal and stress;

10.104 Arousal level: effect on performance;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement

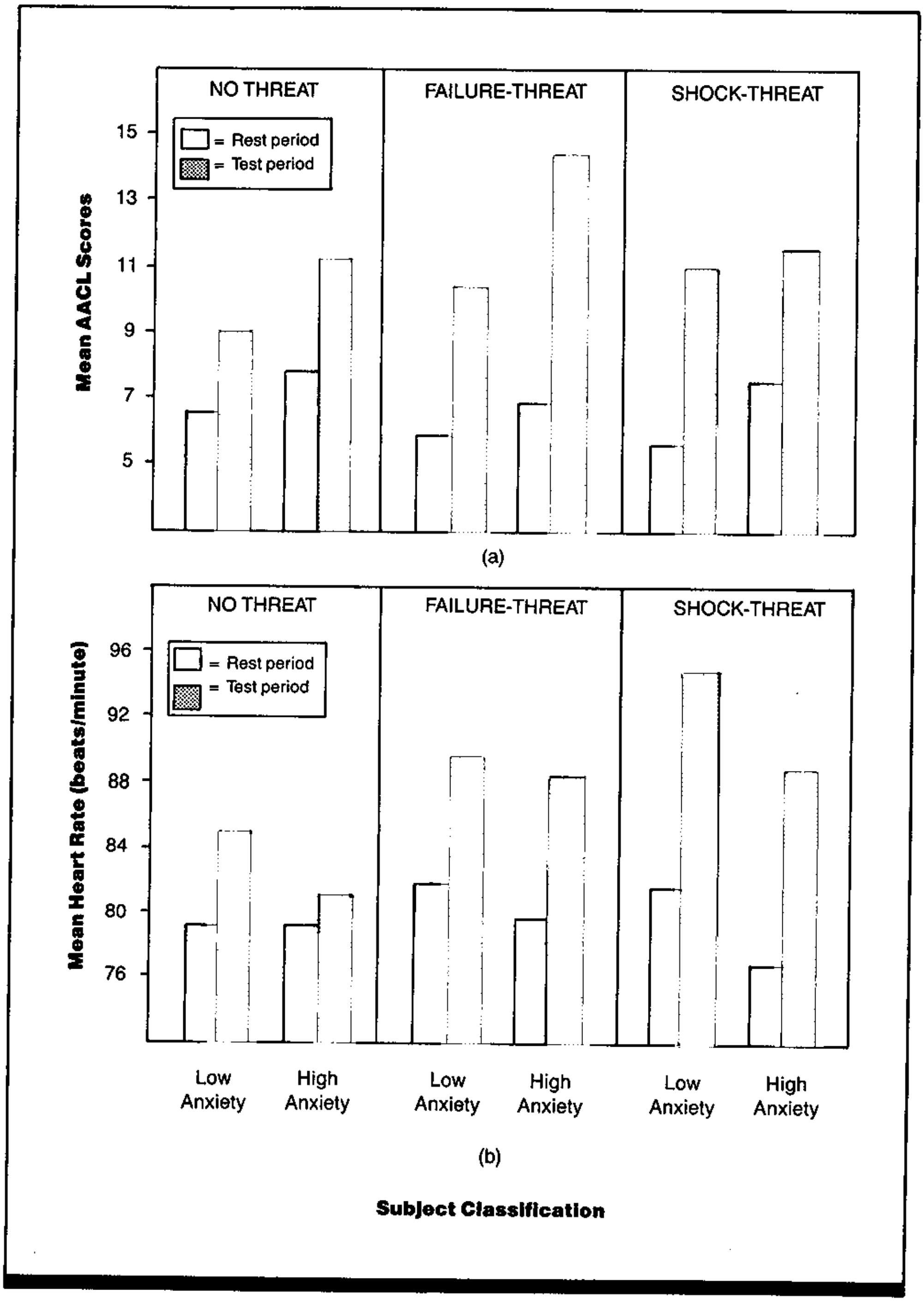

Figure 2. Mean Affect Adjective Check List scores (a) and heart rates (b), reflecting state anxiety, at resting and test periods for subjects differing in anxiety and threat condition administered. (Adapted from Ref. 2)

7.803 Effect of Anxiety on Performance

Task	Independent Variables	Effect of High Anxiety	Source
Digit span	Varied	Very robust effect—in 11 out of 12 studies, span reduced	Ref. 4
	High/low intelligence	High intelligence—anxiety positively related to digit span Low intelligence—anxiety negatively related to digit span	Ref. 7
Recall	With and without relaxation	Low-anxiety subjects respond faster when relaxed	Ref. 13
Paired associates	With success/failure feedback	Low-anxiety subjects learn faster under failure High-anxiety subjects learn faster under success	Ref. 15
Anagrams	Direction of gaze	Cause poorer performance and more time spent in off-task glancing	Ref. 10
	With high-low stress	High anxiety with high stress subjects spending 60% of time on task; all other groups estimated at 80% of time on task	Ref. 2
Letter transformation	With high/low memory load (number of items stored)	Minimal effect with low memory load; significant effect with high memory load	Ref. 6
Nonsense syllables	Easy/difficult list	No effect on easy list; negatively related to speed of learning on difficult list	Ref. 11
Dual	Varied	No effect on primary task; impairment on secondary task	Ref. 3
Exam	Separated worry/emotionality	Worry scores show a negative and significant correlation with grade; emotionality shows a negative, nonsignificant correlation with grade.	Ref. 9
Grade point average (GPA)	Separated worry/emotionality	Worry correlated with GPA: Males: −0.47, females: −0.35 Correlations of GPA with emotionality also negative, but much lower	Ref. 12

Key Terms

Anxiety; personality; stress

General Description

Anxiety is a response to a situation perceived as threatening or dangerous. Whether the experience of anxiety is a sustained stressor, a semipermanent personality characteristic of an individual (trait anxiety), or a temporary situation-related stressor (state anxiety), anxiety affects performance. Scores on self-report scales are usually used to measure an individual's anxiety level in studies of the effect of anxiety on performance. Some scales measure both a worry and an emotionality component of anxiety, which associate differently with performance measures. The subjectively labelled emotionality component is explained, in one theory, as the cognitive response to autonomic changes.

The effect of anxiety depends on the nature and difficulty of the task. In general, anxiety, like noise, produces an increase in the selectivity of attention, especially in dual-task situations. Unlike noise, however, anxiety produces no improvement in main-task performance, while both noise and anxiety reduce secondary-task performance. The absence of central-task improvement suggests that, for anxiety, the increase in selectivity is coupled with a reduction in information processing capacity, perhaps due to added task-irrelevant processing caused by the worry component of anxiety. For very simple tasks, such additional processing may cause minimal performance deficits, but when greater processing demands are made by the task, greater deficits result.

The table lists the tasks in which anxiety, either state or trait, affects performance and describes the effects of high anxiety.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Effect of anxiety can be reduced or eliminated by "cognitive therapy" (Ref. 8), by the provision of success feedback (Ref. 15), or by providing individuals with appropriate coping strategies (Refs. 1, 14). Unfortunately, it may not always be possible to use these techniques in a practical situation.
- Anxiety level is usually assessed by self-report measures of several types, which can only be administered before or after the task.

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Cross References

7.802 Situational stress: effects of personality type and threat;

7.804 Effects of stress on performance for introverts and extroverts;

10.101 Theories of arousal and stress;

10.103 Classification of factors influencing the stress state;

10.104 Arousal level: effect on performance;

10.202 Effects of different stressors on performance

7.804 Effect of Stress on Performance for Introverts and Extroverts

Table 1. Effects of various stressors on the performance of introverts and extroverts.

Stressor	Arouser/ De-arouser	Task and/or Conditions	Dependent Variable	Results	Differences Between Introverts and Extroverts	Source
Noise	Thought to be an arouser	Visual vigilance task (signal detection) in quiet or in 90-dB white noise	Mean number of correct detections	See Fig 1.	Intense noise eliminates vigilance decrement in extroverts; little effect on introverts	CRef. 10.302
Caffeine	Considered a stimulant drug and thus an arouser. Interaction effects of caffeine, intro/extroversion, time of day, and practice are reported	Auditory vigilance task (signal detection) with caffeine or with placebo	Percentage of correct detections	See Fig. 2	Caffeine eliminates vigilance decrement in extroverts; little effect on introverts	Refs. 6, 7 CRef. 10.708
Dual task	Secondary task can be considered an arouser or a distractor. Extroverts cope better with distraction than introverts	Primary auditory vigilance task (signal detection) with or without secondary task	Number of primary signals omitted	See Fig. 3	Addition of secondary task significantly improves performance of extroverts; minimal impairment of introverts' performance	Refs. 1, 4
Signal frequency and time-on-task	High signal probability improves vigilance performance because it is thought to be an arouser. Time-on-task is thought to be a de-arouser	Visual vigilance task (signal detection) with low or high signal frequency	Mean number of correct detections	See Fig. 4	High signal rate improves performance for both; time-on-task impairs extroverts' performance more than introverts'	Ref. 3 CRef. 10.708
Incentive (knowledge of results)	Usually improves performance of extroverts; their performance with incentives is less variable across the day	Letter cancellation task (self paced)	Number of lines of prose processed in 15 min; results expressed as percentage of daily output	See Fig. 5	Incentive has greater effect on extroverts' diurnal performance rhythm	Ref. 4 CRef. 10.708
	Positive incentives tend to affect extroverts, while punishment or threat of punishment has a greater effect on introverts					Ref. 5

Key Terms

Alertness; arousal; caffeine; concurrent tasks; extroversion; incentive; introversion; stress; vigilance

General Description

On simple vigilance tasks, introverts perform better than extroverts; in particular, they show less decrement over time on task. In general, extroverts show greater changes in performance in response to variations in the parameters of the task, such as signal frequency or uncertainty, distractors, and task load, and to stressors, such as noise, drugs, sleep loss, and incentives. Performance of extroverts is usually improved by stressors considered to be arousers and impaired by stressors considered as de-arousers, such as sleep loss or time on task.

Although these differences have been explained as a uniform difference in arousal level (with introverts having the higher arousal), such an explanation does not apply to effects which show variation with time of day. For example, introverts achieve their highest level of temperature and performance efficiency earlier in the day than do extroverts. Some differences in the effects of stressors on introverts and extroverts may be phase, rather than overall, differences.

The table shows the effects of stressors and stressful variations of task parameters on the performance of introverts and extroverts.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

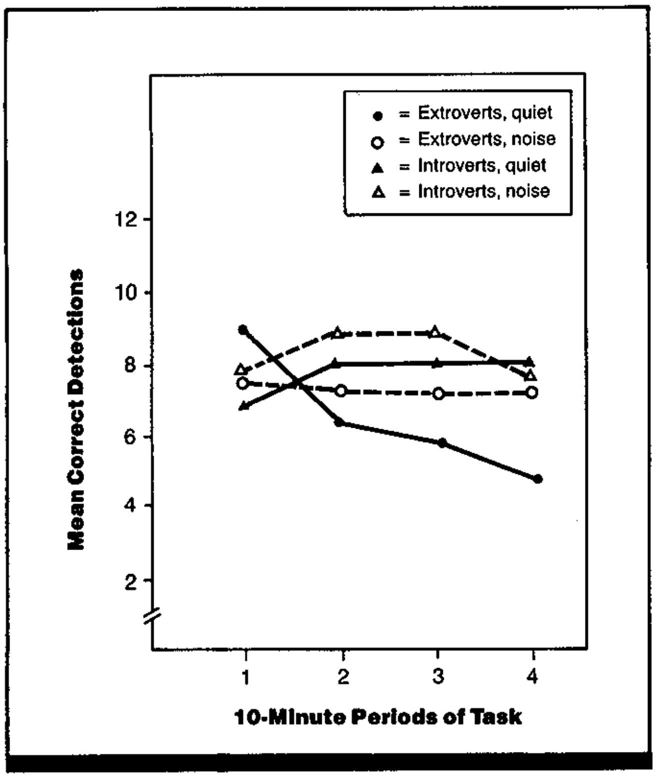

Figure 1. Number of correct detections on a visual vigilance task for introverts and extroverts in noise and in quiet over 10-min periods of task. (From Ref. 3)

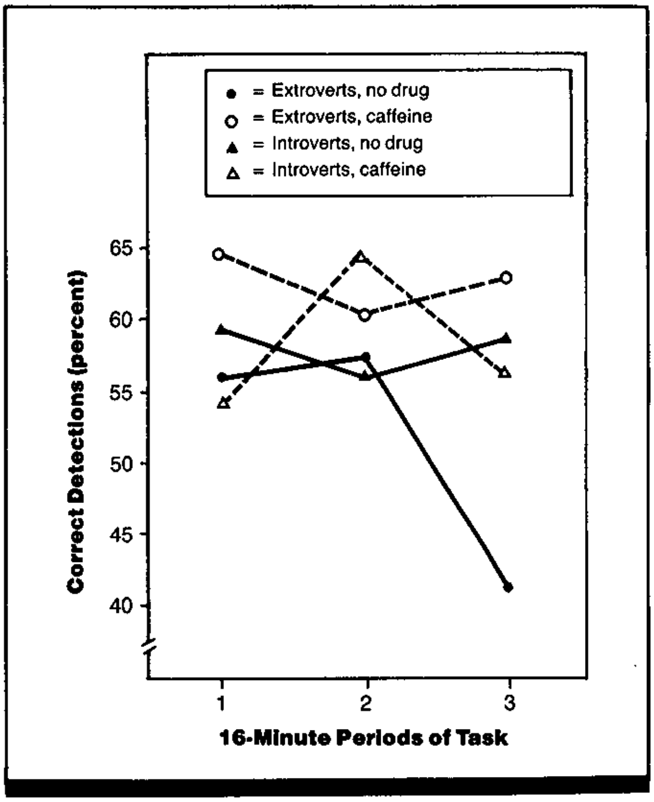

Figure 2. Number of correct detections on an auditory vigilance task for introverts and extroverts under caffeine and no drug conditions as a function of 16-min periods of task. (From Ref. 6)

Constraints

- These effects are found with simple vigilance tasks in a laboratory environment. The basic complexity or interest of the task itself is considered to be an arouser and to interact with other stressors and with introversion/extroversion.

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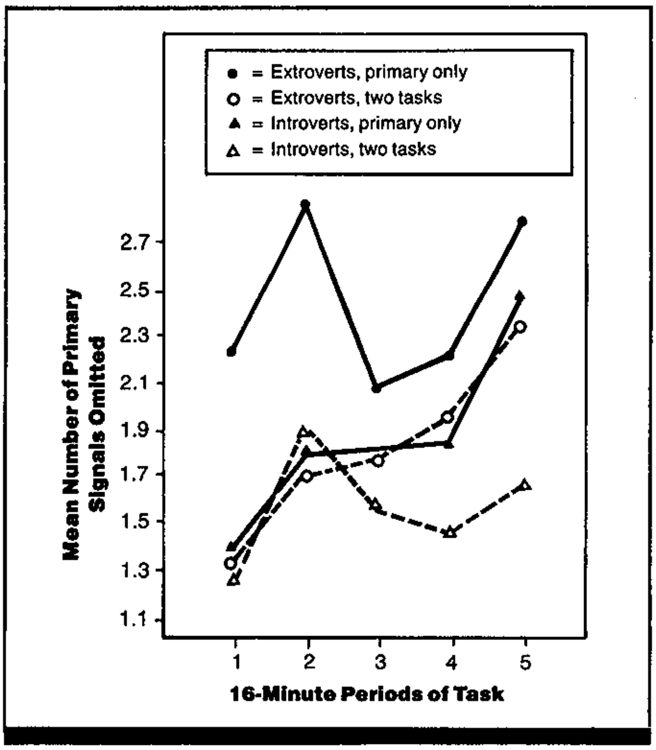


Figure 3. Comparison of signal detection performance for introverts and extroverts when a secondary task is added. (From Ref. 1)

Cross References

1.925 Optokinetic nystagmus: effect of instructions;

7.803 Effect of anxiety on performance;

10.101 Theories of arousal and stress;

10.104 Arousal level: effect on performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.302 Continuous broadband noise: effect on task performance;

10.708 Incentive and introverted/extroverted personality: effect on the diurnal rhythm of performance;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement;

Handbook of perception and human performance, Ch. 44, Sect. 7.2

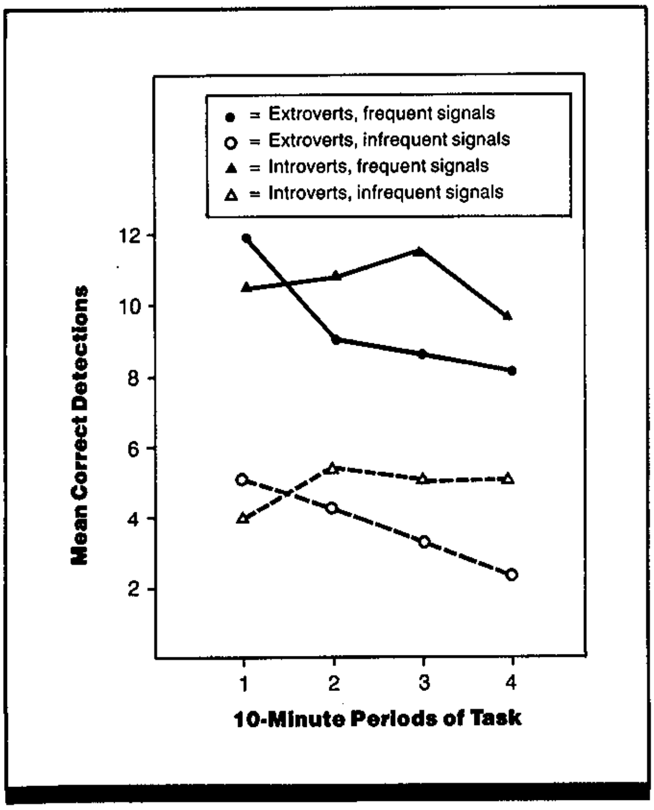


Figure 4. Number of correct detections on a visual vigilance task for introverts and extroverts under high or low signal probability conditions as a function of 10-min periods of task. (From Ref. 3)

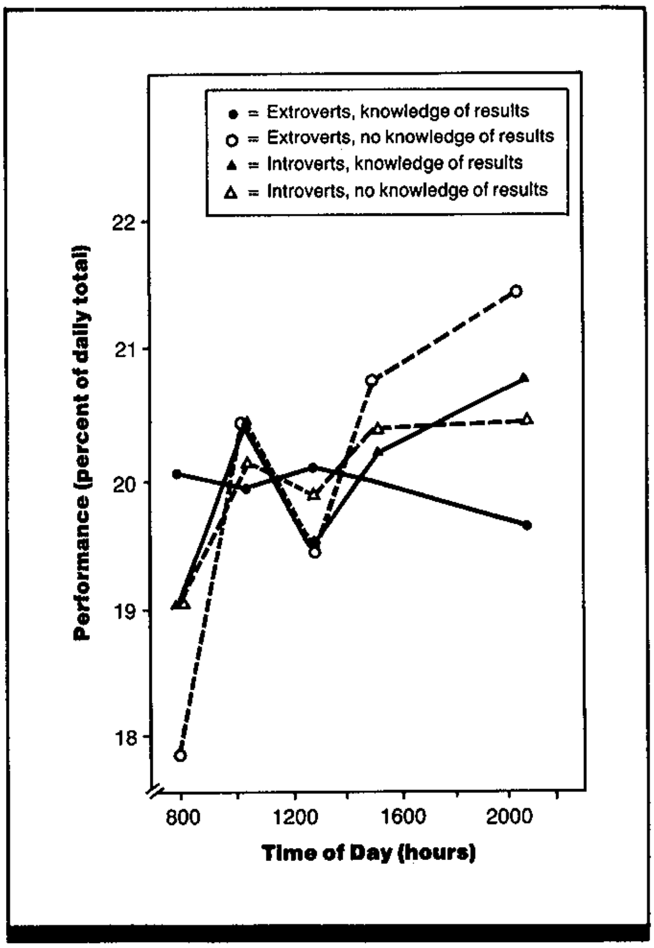
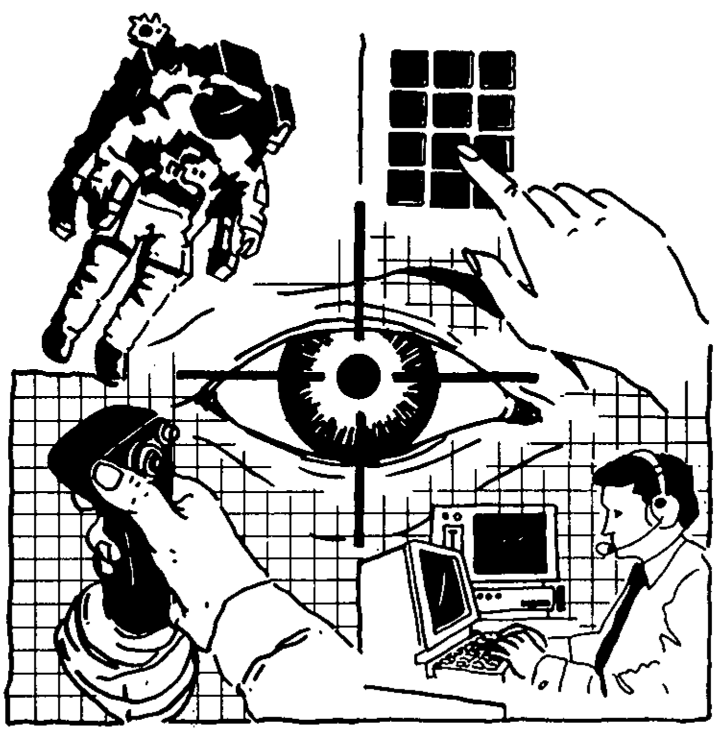


Figure 5. Performance of introverts and extroverts on a letter cancellation task with and without knowledge of results as a function of time of day. (Adapted from Ref. 2)

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Section 7.9 Decision-Making Skill



7.901 Characteristics of Humans as Decision Makers

Key Terms

Battlefield management; decision making; monitoring; problem solving; process control; situation diagnosis; supervisory control

General Description

The efficacy of human decision-making behavior varies as a function of many different factors including statistical estimation requirements, memory of variables preset by the operator, extent of operator practice, and whether skill-based or problem-solving behavior is involved. As statistical decision makers, humans are generally inefficient at making estimates of either descriptive or inferential statistics. Conversely, humans are effective decision makers when they have had input into the situations they are monitoring, and when they are highly practiced. Table 1 compiles the results of various laboratory studies of human decision behavior for a variety of decision tasks.

Table 1. Human decision-making characteristics.

Type of Decision-Making Task	Characteristic Decision-Making Behavior	Source
Estimates of descriptive statistics	Good at estimating means	Ref. 3
	Good at estimating proportions, but shows some tendency to underestimate high proportions and overestimate low proportions	Ref. 3
	Poor at estimating sample variance and usually underestimates it	Refs. 3, 4, 5
Statistical inferences from samples	Very conservative in making probability estimates, probably due to misunderstanding of sampling distributions	Ref. 3
	Believes small samples to be more typical of populations than is warranted	Ref. 3
Understanding and use of probability statistics	Good at understanding and using probability statements not based on frequency, e.g., "The probability of rain today is 0.7"	Refs. 3, 4
	Tends to overestimate probability of favorable outcomes, and underestimates probability of unfavorable outcomes	Ref. 4
Problem change recognition	Too conservative in recognizing changes in problem conditions; delays too long in response to those changes	Refs. 5, 6
Situation diagnosis	Poor at making diagnosis of complex situations entailing complicated interpretations of configural cue patterns	Refs. 2, 6
Formulation and selection of action alternatives	Not sufficiently inventive and tends to adopt the first solution developed	Refs. 2, 6
	Forms hypotheses early, then tries to confirm rather than test them; does not consider enough hypotheses	Ref. 5
Identification and use of decision criteria	Finds it difficult to use more than one or two criteria at a time; tends to identify only those criteria favorable to selected action	Refs. 2, 6
Use of available information	Tends to use only concrete, high confidence facts and prefers to ignore ambiguous or partial data	Refs. 2, 6
	Asks for more data from sources of good-quality information	Refs. 5, 6
	Requests more evidence than is necessary for a decision	Ref. 5
	Poor at combining evidence to update probability estimates	Ref. 5
	Gives undue weight to early events and is reluctant to change an erroneous commitment in light of new evidence	Refs. 1, 5
Detection of change(s) in statistical properties of monitored process(es)	Exhibits near optimal behavior in optimal estimation and optimal control experiments, even though sophisticated interpretation of dynamic probabilities is involved	CRefs. 7.310, 9.512

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- In field studies and in daily "real life" control situations, humans exhibit much more sophisticated and optimal decision-making behavior than would be predicted from the results of laboratory experiments (CRef. 7.312). The on-the-job behavior of air traffic controllers and process control operators indicates that they have far more extensive knowledge and understanding of the complex dynamic systems they control than laboratory experiments would lead one to believe. The evidence suggests that operators find it easier to remember many variables when they have set the variables to their values rather than merely observed them (CRef. 7.312).
- All of the reported laboratory studies used relatively unpracticed subjects who were obliged to make statistical decisions consciously. On the other hand, highly practiced, automatically performing operators attain optimal decision behavior by using skills that require no conscious reflection. Accordingly, skill-based behavior is far more effective and optimal than problem-solving behavior. Optimal human decision making requires prolonged practice to the point that automaticity of behavior is achieved (CRefs. 7.303, 7.312).

Key References

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Cross References

7.303 Hierarchically structured control models;

7.310 Optimal estimation model;

7.312 Comparison of different research settings for study of supervisory control;

9.512 Modeling of the human operator: the optimal control model

Notes