INTERSENSORY REDUNDANCY GUIDES EARLY PERCEPTUAL AND COGNITIVE DEVELOPMENT

Lorraine E. Bahrick and Robert Lickliter
DEPARTMENT OF PSYCHOLOGY
FLORIDA INTERNATIONAL UNIVERSITY
MIAMI, FLORIDA 33199

Introduction: Historical Overview and Perspectives on Perceptual Development

The world provides a richly structured, continuous flux of multimodal stimulation to all of our senses. Objects and events can be seen, heard, smelled, and

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felt, and as we move around and interact with the people, places, and objects in our environment we produce continuous changes in proprioceptive and visual feedback from our exploratory activities. Our senses provide overlapping and redundant information for objects and events in our environment. Dating as far back as Aristotle's *De Anima* and *De Sensu,* scientists have been intrigued and challenged by issues arising from the specificity of stimulation from the different senses and the nature of the overlap among them. How are objects and events experienced as unitary when they stimulate receptors that give rise to such different forms of information? How are disparate forms of stimulation bound together? Aristotle postulated a "sensus communis"—an amodal or common sense—which he thought was responsible for perceiving the qualities of stimulation that were general and not specific to single senses ("common sensibles"). According to Aristotle, common sensibles included motion, rest, number, form, magnitude, and unity. These properties are remarkably similar to those characterized as amodal by contemporary perceptual theorists (Bahrick & Pickens, 1994; J. J. Gibson, 1966, 1979; Marks, 1978; Stoffregen & Bardy, 2001).

Centuries later, Locke (1690/1971) and Berkeley (1709/1910), among others, took a different approach to intersensory perception, proposing that perceivers must learn to interpret and integrate sensations before meaningful perception of objects and events could be possible. Following this "constructionist" approach, most modern theories of perception have been founded on the assumption that the different forms of stimulation from the various senses must be integrated or organized in the brain and therefore pose a "binding" problem for perception. It was thought that sensory stimulation had to be united by mechanisms that translate information from different codes and channels into a common language (Muller's "Law of Specific Energies," 1838).

The constructionist view permeated thinking about the development of perception during most of the 20th century (Birch & Lefford, 1963; Friedes, 1974; Piaget, 1952), with most investigators assuming that we must learn to coordinate and integrate the separate senses. From this view, information had to be integrated across the senses through a gradual process of association across development in order to perceive unified objects and events. This integration was thought to occur by interacting with objects, experiencing concurrent feedback from different senses, and associating, assimilating, or calibrating one sense to another. For example, according to Piaget (1952, 1954) not until well into the first half-year following birth do vision and touch begin to be integrated. Through acting on objects, tactile feedback gradually endows the two-dimensional visual image of an object with three dimensionality. The attainment of perceptual abilities such as size and shape constancy, visually guided reaching, and object permanence were thought by Piaget and his colleagues (e.g., Piaget & Inhelder, 1967) to be slow to emerge and to depend on the gradual development of sensory integration. Prior to this integration, the visual world of the infant was thought to consist of images shrinking, expanding, changing shape, and disappearing and then reappearing capriciously.

Until the activity-based achievement of sensory integration, infants were thought to perceive only unrelated patterns of visual, acoustic, or tactile stimulation, expressed by the well-known description of the world of the newborn infant by William James (1890) as a "blooming, buzzing confusion."

Not until J. J. Gibson's (1966, 1979) seminal work on the "ecological" view of perception was the integration perspective on perceptual development seriously questioned. In a sharp break from traditional views, Gibson recognized that the existence of different forms of sensory stimulation was not a problem for the perception of unitary events but instead provided an important basis for it. He argued that the senses interact and work together to pick up invariant aspects of stimulation and should be considered as a "perceptual system." One important type of invariant information is amodal information that is common across the senses. As pointed out by Aristotle, amodal information is not specific to a particular sensory modality but is information common to several senses. Temporal and spatial aspects of stimulation are typically conveyed in multiple senses. As a case in point, the rhythm or rate of a ball bouncing can be conveyed visually or acoustically and is completely redundant across the two senses. The sight and sound of hands clapping likewise share temporal synchrony, a common tempo of action, and a common rhythm.

We now know from a prolific body of research conducted over the last 25 years of the 20th century, inspired in large part by Gibson's ecological approach to perception, that even young infants are adept perceivers of amodal stimulation (see Bahrick & Pickens, 1994; Lewkowicz, 2000; Lickliter & Bahrick, 2000; Walker-Andrews, 1997). Infants detect the temporal aspects of stimulation such as synchrony, rhythm, tempo, and prosody that unite visual and acoustic stimulation from single events, as well as spatial colocation of objects and their sound sources, and changes in intensity across the senses (see Lewkowicz & Lickliter, 1994, for a review). These competencies provide the foundation for the perception of meaningful and relevant aspects of stimulation in social and nonsocial events, and they are described in more detail in subsequent sections of this chapter. In our view, detection of amodal information in early development provides a radical and efficacious solution to the so-called "binding" problem (see J. J. Gibson, 1979). That is, detection of amodal information in early development does away with the notion of perceivers having to coordinate and put together separate and distinct sources of information. By detecting higher order information common to more than one sense modality, even relatively naive perceivers can explore a unitary multimodal event in a coordinated manner. The task of development becomes to differentiate increasingly more specific information from the global array through detecting invariant patterns of both multimodal and unimodal stimulation (E. J. Gibson, 1969; J. J. Gibson, 1979; Stoffregen & Bardy, 2001).

Results from contemporary research on infant perception indicate that the fact that our senses provide overlapping and redundant information for certain properties of objects and events poses no problem for perception. Rather, as we argue later, this redundancy is a cornerstone of perceptual development, allowing optimal deployment of attention and the discovery of higher order perceptual structure. In this chapter we present a framework, the "intersensory redundancy hypothesis," that provides a way of conceptualizing the role of redundancy across the senses for promoting and organizing early perceptual and cognitive development. The intersensory redundancy hypothesis makes predictions about what aspects of stimulation will be attended to and processed more readily as a function of whether available stimulation for an object or event is multimodal or unimodal. Specifically, the intersensory redundancy hypothesis proposes that in early infancy information that is simultaneously available across two or more sensory modalities (amodal properties such as tempo, rhythm, and intensity) is highly salient and is therefore attended, learned, and remembered better than when the same information is presented in only one modality. Conversely, processing of some information is facilitated by unimodal stimulation. When modality-specific properties (such as pitch, color, pattern, or orientation) are presented in a single sensory modality, they are attended, processed, and remembered better than when the same properties are presented in the context of multimodal stimulation. We review a growing body of research that supports this framework and synthesize findings from human and animal as well as neural and behavioral studies that demonstrate the important role of intersensory redundancy in the development of perception, cognition, and communication.

II. Amodal Relations and the Multimodal Nature of Early Experience

The young infant encounters a world of richly structured, changing, multimodal stimulation through his or her interactions with objects, events, people, places, and the self. This stimulation is experienced through a unified perceptual system that is sensitive to invariant aspects of stimulation across the senses (E. J. Gibson, 1969; E. J. Gibson & Pick, 2001). Several researchers have argued that amodal information can initially guide infant attention and perceptual learning in a manner that is economical, veridical, and adaptive (e.g., Bahrick, 1992, 1994, 2001; E. J. Gibson, 1969; E. J. Gibson & Pick, 2001; Walker-Andrews, 1997). As we have already described, amodal information is not specific to a particular sense modality but is redundant or invariant across two or more senses. Across the visual and tactile modalities, shape, texture and substance are amodal and specifiable in either modality. Any changes in intensity and temporal and spatial aspects of stimulation are amodal, including temporal synchrony, common rhythm, and tempo of action, which unite the movements and sounds of most audible and visible events. If the perceiver detects amodal information, then attention is, by definition, focused on a unitary, multimodal event. By detecting these higher order relations that encompass multiple forms of sensory stimulation, the problem of how infants come to integrate stimulation across the senses is effectively eliminated. For example, detection of amodal temporal synchrony, rhythm, and tempo may focus an infant's attention on the sights and sounds of a person speaking or on the visual and acoustic impacts of a bouncing ball. Consequently, the person or ball would be perceived as a unitary entity. Sensitivity to amodal relations can also act as a buffer against forming inappropriate associations across the senses, as infants would not readily relate the sounds of speech with other objects that do not share the temporal structure of the speech sounds.

Researchers have demonstrated that infants perceive a variety of amodal relations across multiple senses (see Lewkowicz & Lickliter, 1994). For example, infants can perceive the relation between movements of a face and the sounds of a voice on the basis of temporal synchrony (Dodd, 1979), their common emotional expression (Walker, 1982; Walker-Andrews, 1997), and spectral information common to the shape of the mouth and a vowel sound (Kuhl and Meltzoff, 1984). Young infants can relate moving objects and their impact sounds on the basis of temporal synchrony (Bahrick, 1983, 1987, 1988; Lewkowicz, 1992, 1996), their common tempo of action (Bahrick, Flom, & Lickliter, 2002; Lewkowicz, 1985; Spelke, 1979), rhythm (Bahrick & Lickliter, 2000; Mendelson & Ferland, 1982), and collocation (Fenwick & Morrongiello, 1998; Morrongiello, Fenwick, & Nutley, 1998). They can also detect temporal information common to visual and acoustic stimulation specifying the substance and composition of moving objects (Bahrick, 1983, 1987, 1988, 1992) and the changing distance of moving objects (Pickens, 1994; Walker-Andrews & Lennon, 1985). In the area of visual–tactile perception, young infants can detect the common shape and substance of objects across vision and touch (E. J. Gibson & Walker, 1984; Hernandez-Reif & Bahrick, 2001; Meltzoff & Borton, 1979; Rose, 1994; Streri, 1993). Detection of these amodal relations guides selective attention and exploration of objects and events in the environment and promotes the perception of unitary multimodal events.

Infants not only detect amodal relations, they also participate in temporally coordinated, co-regulated interactions with adult caretakers. Much early perceptual and cognitive development emerges in the context of close face-to-face interaction with caretakers. Adults regularly scaffold infants' attention and provide a rich interplay of concurrent visual, vocal, tactile, vestibular, and kinetic stimulation. The movements and vocal rhythms of infants have also been shown to contain a burst–pause, turn-taking pattern that is intercoordinated with the temporal characteristics of adult communication (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Sander, 1977; Stern, 1985; Trevarthan, 1993; Tronick, 1989). This sensitivity to temporal, spatial, and intensity information in human interaction promotes affective attunement between caregivers and young infants (Stern, 1985) and provides a vehicle for the development of intersubjectivity and shared perspective (Rochat & Striano, 1999; Trevarthan, 1993). Infants thus create, participate in, and respond to amodal information in their interactions with adult caretakers in a mutually co-regulated manner. This lays the foundation for later milestones of social and communicative functioning.

Exploration of the self also provides one of the earliest and most potent and reliable sources of multimodal stimulation, as proprioceptive feedback always accompanies self-generated visual, vocal, and tactile stimulation (see Rochat, 1995). Infants engage in active, self-directed, intermodal exploration of their bodies (e.g., Butterworth & Hopkins, 1988; Rochat, 1993; Van de Meer, Van der Weel, & Lee, 1995) and the temporal and spatial contingencies between their movements and those of the multimodal objects and events in their environment (e.g., Bahrick, 1995; Bahrick & Watson, 1985; Rochat & Morgan, 1995; Schmuckler, 1995). In sum, a large body of converging evidence highlights the fact that infants are adept at perceiving, generating, and responding to a host of amodal relations uniting stimulation across visual, auditory, vestibular, tactile, and proprioceptive stimulation in the first months of life.

III. Unimodal–Multimodal Dichotomy in Developmental Research

Despite the fact that the infant's world is inherently multimodal, and that virtually all perception, learning, memory, and social and emotional development emerges in this multimodal context, the majority of research in developmental psychology has focused on development in only a single sense modality at a time (see Kuhn & Siegler, 1998, for an overview of this type of research). This state of affairs likely resulted from the historical concern with sensory integration, the apparent intractability of the binding problem, and a lack of appreciation of the complex interdependencies among the senses. Scientists have traditionally specialized in unimodal areas such as vision, audition, or olfaction research, with subspecializations within each sensory area. As a result of this "unimodal" approach, the development of a specific skill or competence has been typically investigated detached from the rich multimodal context in which it occurs. For example, theories of speech and language development have typically focused on the unimodal speech stream, detached from the moving face and person that produce the speech. Research on infant memory and categorization has often focused on responsiveness to a unimodal visual display. Theories of face perception have been primarily based on studies of a unimodal, visual facial display devoid of movement and speech. Studies of the development of joint attention typically present the visual behavior detached from the auditory and tactile stimulation that typically co-occur (for further discussion, see Lickliter & Bahrick, 2001, and Walker-Andrews & Bahrick, 2001).

The growth of the field of developmental psychology in general and the study of perceptual development in particular have tended to reflect this compartmentalization. Although research on the development of intersensory perception has grown more prominent, its theories and findings are for the most part segregated from research on the same questions explored with unimodal stimulation. Largely due to historical tradition, it has been placed alongside the other "senses" with "intersensory perception" constituting a separate area of inquiry (see Kellman & Arterberry, 1998, for an example). Thus, investigations of the development of a particular competence (e.g., aspects of memory, categorization, attention, speech perception) are likely to be conducted in separate studies of unimodal versus multimodal perception and to be undertaken by separate investigators. Consequently, research findings from the two areas are not well integrated and studies of unimodal and multimodal perception are difficult to compare, as they typically employ different methods and measures. Furthermore, few investigators actually compare responsiveness in one sense modality to responsiveness in two or more sensory modalities concurrently. Thus it is not known how perception of unimodal events such as the speech stream or moving faces generalizes to the multimodal world where speech occurs in the context of moving faces and vice versa.

Importantly, research findings are consistent with the view that the senses interact in complex ways (e. g., King & Carlile, 1993; Lickliter, 2000; Lickliter & Hellewell, 1992; Stein & Meredith, 1993) and that different results are obtained when perception and cognition are investigated in the context of multimodal as compared with unimodal stimulation (Lickliter & Bahrick, 2001; Walker-Andrews & Bahrick, 2001). Research from the areas of unimodal and multimodal perception needs to be integrated if we are to develop a unified, ecologically relevant theory of the nature of perceptual development. Studying the single sensory system alone can, in many cases, result in a distortion of normally occurring patterns of sensory experience and consequently result in findings of limited generalizability. More studies are needed with both humans and animals that examine the development of skills and capabilities in a multimodal context and directly compare responsiveness to unimodal versus multimodal events in single research designs. Furthermore, just as unimodal and multimodal research is not well integrated, neither is behavioral research well integrated with research in the neurosciences. The proliferation of research on multisensory functioning in the neurosciences (see Calvert, Spence, & Stein, 2002) makes findings in this area of central importance to a biologically plausible theory of the development of intersensory perception.

IV. Neural and Behavioral Evidence for Intersensory Interactions

Because the traditional view is that the different sensory modalities utilize separate and distinct neural pathways, neural "integration" of separate streams of sensory information has typically been viewed as necessary for adaptive perception and cognition. However, it has become increasingly clear that the separate senses are not so separate at the level of the nervous system (Knudsen & Brainard, 1995; Meredith & Stein, 1986; Stein, 1998; Stein & Meredith, 1993). This appreciation of the multimodal nature of the brain calls into question the long-standing view that higher order perceptual processing and cognition is needed to achieve successful binding or integration across the sensory modalities. Evidence obtained from neuroimaging studies reveals that many areas of the cortex and subcortex previously thought to receive input from only one sensory modality respond reliably to multisensory stimulation (see Calvert, 2001a, for a review). Furthermore, a number of empirical investigations have shown that both young and mature animals have well-organized inputs from different sensory modalities converging on the same target structure in the brain (e.g., Frost, 1984; Innocenti & Clarke, 1984). This body of evidence from the neurosciences has led investigators to a growing appreciation of the brain's sensitivity to multimodal information (see Calvert *et al.*, 2002; Stein & Meredith, 1993), but such an appreciation is not yet widely held by developmental psychologists and has yet to be incorporated into our thinking about the nature and direction of early perceptual organization. Here we briefly review some of the available neural evidence informing the study of perceptual and cognitive development.

The most investigated site of multimodal convergence is the superior colliculus, a midbrain structure known to play a fundamental role in attentive and orientation behaviors (reviewed in Stein & Meredith, 1993). Multisensory neurons have been found in the superior colliculus of cats (Meredith & Stein, 1983), monkeys (Jay & Sparks, 1984), and several species of rodents (Wallace, Wilkenson, & Stein, 1996). The multisensory neurons in the superior colliculus respond to input from several sensory modalities and provide a neural substrate for enhancing responsiveness to stimuli that are spatially and temporally aligned. For example, in guinea pigs, visual experience is required for the normal elaboration of the sensory map of auditory space in the superior colliculus (Withington-Wray, Binns, & Keating, 1990). Guinea pigs reared in darkness fail to develop an auditory map, supporting the view that normal development of a map of auditory space requires the coincident activation of neural activity deriving from the convergence of both auditory and visual input arising from common stimuli. The activity-based alignment of different sensory maps in the brain and the responsiveness of these areas to intersensory convergence is likely a critical feature of multisensory perception (Stein & Meredith, 1993). Sites of multisensory convergence have also been reported at the cortical level of the brain in cats (Wallace, Stein, & Meredith, 1992), monkeys (Mistlin & Perrett, 1990), rats (Barth, Goldberg, Brett, & Di, 1995), and humans (Calvert, 2001a; Giard & Peronnet, 1999), suggesting that the mammalian brain is inherently multimodal in structure and function.

Of particular interest to theories of intersensory functioning is the finding from a number of neuroanatomical and neurophysiological studies indicating that the temporal and spatial pairing of stimuli from different sensory modalities can elicit a neural response that is greater than the sum of the neural responses to the unimodal components of stimulation considered separately (the so-called "multiplicative or superadditive effect" reviewed in Stein & Meredith, 1993; Stein, Meredith, & Wallace, 1994). In other words, the activity of a neuron exposed to multisensory stimulation (i.e., simultaneous auditory and visual stimulation) differs significantly from the activity of the same cell when exposed to stimulation in any single modality (Meredith & Stein, 1986). Spatially coordinated and synchronous multimodal stimulus combinations have been shown to produce significant increases over unimodal responses in several extracellular measures of neural activity, including response reliability, number of impulses evoked, and peak impulse frequency. This superadditive effect of bimodal stimulation, in which the magnitude of neural effects resulting from bimodal stimulation consistently exceeds the level predicted by adding together responsiveness to each single-modality stimulus alone (i.e., neural enhancement) has also been reported in behavioral investigations. For example, Stein, Meredith, Honeycutt, and Wade (1989) demonstrated that the effectiveness of a visual stimulus in eliciting attentive and orientation behaviors in cats is dramatically affected by the presence of a temporally congruent and spatially collocated stimulus in the auditory modality. These findings provide further support for the notion of differential responsiveness to unimodal versus multimodal stimulation and indicate that spatially and temporally coordinated multimodal stimulation is highly salient at the level of neural responsiveness.

There is also compelling neurophysiological and behavioral evidence of strong intermodal linkages in newborns, young infants, and adults from a variety of species, including humans (e.g., Carlsen & Lickliter, 1999; King & Carlile, 1993; King & Palmer, 1985; Knudsen & Brainard, 1991, 1995; Lewkowicz & Turkewitz, 1981; Lickliter & Banker, 1994; Massaro, 1998; Mellon, Kraemer, & Spear, 1991; Withington-Wray *et al.,* 1990). Experimental manipulations with animal subjects that augment or attenuate sensory stimulation in one modality consistently lead to significant effects on the development of perception in other sensory modalities and on the development of intersensory functioning during both the prenatal and postnatal periods (Lickliter & Banker, 1994; Lickliter & Hellewell, 1992; Radell & Gottlieb, 1992; Sleigh & Lickliter, 1997). For example, Lickliter and Lewkowicz (1995) showed the importance of prenatal tactile and vestibular stimulation to the successful emergence of species-typical auditory and visual responsiveness in bobwhite quail chicks. Hein and colleagues (Hein, 1980; Hein & Diamond, 1983; Held & Hein, 1963) demonstrated that visual stimulation provided by young kittens' own locomotion was necessary for the development of eye–paw coordination and visually guided behavior. Eye–paw coordination was found to develop normally in kittens allowed to simultaneously walk and look at objects and events, but did not develop normally when kittens could only look at things while being moved passively. Kittens denied visual feedback from locomotion also consistently failed to develop visually guided reaching. Of course, under normal developmental conditions, convergence between multimodal visual and proprioceptive stimulation is a regular aspect of postnatal experience and such convergence appears to be an experiential requirement of normal perceptual development. Studies of neural and behavioral development have thus revealed strong intermodal interactions in newborns and infants, with stimulation in one sensory modality influencing and even calibrating responsiveness in other modalities in an ongoing manner.

Research with human adults has also provided compelling support for the salience of intersensory congruence. For example, Sathian (2000) found that the visual cortex can be involved in tactile perception in adult humans. In this study, PET scans of blindfolded subjects performing a tactile discrimination task (determining the orientation of ridges on a surface) revealed increased activity in the visual cortex. Furthermore, when function of the visual cortex was interfered with by means of transcranial magnetic stimulation, tactile perception was significantly impaired. In a similar vein, Calvert (2001b) scanned the brains of adults when they smelled odors, looked at colors, or did both simultaneously. Olfactory areas of the brain became particularly active when the colors and scents were congruent (i.e., a red strawberry) as compared with incongruent (i.e., a blue strawberry). Calvert concluded that multisensory congruence enhances neural responsiveness, whereas incongruence serves to suppress neural responsiveness (for a similar view, see Stein, 1998). The potent intersensory interactions present in early development appear to continue to affect perceptual responsiveness in adulthood.

Several perceptual illusions also underscore the existence of intersensory convergence and its role in guiding attention and perceptual discrimination. The well-known McGurk effect (McGurk & MacDonald, 1976), an auditory–visual illusion, illustrates how perceivers merge information for speech across the senses. When we view the face of a person speaking a speech sound such as "ga," while hearing a different speech sound, "ba," the perception is of another sound, "da," a blend between the concurrently presented auditory and visual stimulation. Infants also show evidence of this effect in the first half-year following birth (Rosenblum, Schmuckler, & Johnson, 1997), indicating that visual input has significant auditory consequences, even during early development.

Auditory input has also been shown to have dramatic consequences for visual perception. Scheir, Lewkowicz, and Shimojo (2002) demonstrated an audiovisual "bounce" illusion in young infants. Without sound, adults perceive two disks to be moving horizontally and passing through one another on a computer screen (streaming). When a discrete sound is added at the point of contact between the disks, adults report that the two disks appear to bounce against one another and change direction of motion. Young infants also appear to perceive the addition of sound to change the nature of the visual display from streaming to bouncing, indicating convergence across the modalities and demonstrating that sound can alter the perception of a visual event even during infancy. Shams (2000) reported a similar intersensory illusion in which sound can make adults see visual illusions.

Adults hearing two beeps while seeing one flash of light reported that they saw two flashes. Furthermore, neural activity in the visual cortex (thought to be specific to visual processing) was found to be essentially equivalent whether the participant actually saw two flashes (with no beeps) or just one flash accompanied by two beeps, suggesting that neural and behavioral consequences are operating in parallel.

These examples drawn from neural and behavioral studies indicate that intersensory convergence is integral to perceptual functioning. Inputs from our separate senses interact and influence one another more than we have acknowledged or appreciated for much of the 20th century. Furthermore, this influence results in the perception of emergent properties of stimulation qualitatively different from the perception of input from the separate sensory modalities. In our view, theories of behavioral development must be informed by knowledge of neural development and responsiveness, and vice versa. Simply put, our psychological theories of intersensory functioning must be biologically plausible. That is, they must be consistent with available findings on intersensory convergence from the neural level of analysis, the physiological level of analysis, and with the complex intersensory interactions known to exist in the very early stages of perceptual processing.

V. Intersensory Redundancy Hypothesis: Toward an Integrated Theory of Perceptual Development

Intersensory redundancy refers to a particular type of multimodal stimulation in which the same information is presented simultaneously and in a spatially coordinated manner to two or more sensory modalities. For the auditory–visual domain, it also entails the temporally synchronous alignment of the information in each modality. Only amodal properties (e.g., tempo, rhythm, intensity) can be specified redundantly because, by definition, amodal information is information that can be conveyed by more than one sense modality. Thus, the sights and sounds of hands clapping provide intersensory redundancy in that they are synchronous, collocated, and convey the same rhythm, tempo, and intensity patterns across vision and audition.

As depicted in Figure 1, intersensory redundancy is best viewed as arising from an interaction between the organism and its environment. Redundancy is not a property of the structure of the organism (its nervous system and sensory systems), nor is it a property of the structure of objects and events in the environment. Rather, it results from an interaction between a structured organism and a structured environment. Redundancy is experienced when an active perceiver explores multimodal events with multiple coordinated senses. For example, one might explore a person speaking by looking and listening. In this case, the perceiver would experience redundantly specified information for the tempo, rhythm, and intensity patterns of auditory–visual speech. However, when the perceiver looks away

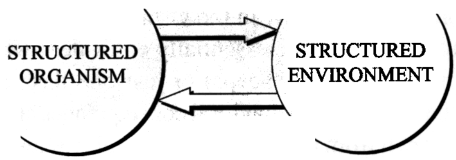

Fig. 1. Intersensory redundancy results from the dynamic relationship between a structured organism and a structured environment. Redundancy arises from exploration by a nervous system specialized for picking up different types of energy and their overlap and from unitary objects and events that provide a structured array of multimodal stimulation.

from the speaking person, or if the speaker leaves the room while talking, the perceiver no longer experiences redundantly specified information for tempo, rhythm, and intensity patterns. Rather, he or she perceives unimodal information for these speech properties. Thus, the perception of redundancy is dynamic in the sense that it can change from moment to moment as the relation between the nature of the organism's exploratory behavior changes and as the nature of the objects and events in the environment change. It is the convergence of information in two senses that makes amodal properties salient.

Redundancy thus relies on both a nervous system specialized for different types of energy and the ability of the senses to provide overlapping information about objects and events that are unitary in the world. Redundancy is only apparent across different forms of stimulation and in this sense requires specific forms of energy from the different sensory modalities. As we describe in more detail in the sections that follow, intersensory redundancy is highly salient and can direct selective attention and facilitate perceptual learning in early development.

In our view, intersensory redundancy is a particularly important and salient form of stimulation available to infants and plays a foundational role in early perceptual and cognitive development. Research with both animal and human infants indicates that different properties of stimuli are highlighted and attended to when *redundant* multimodal stimulation is made available to young organisms as compared with unimodal stimulation from the same events (see Bahrick, 2002; Bahrick & Lickliter, 2000; Lickliter & Bahrick, 2002). That is, young infants are especially adept at detecting amodal, redundant stimulation and detection of this information can organize early attention and provide a foundation for and guide and constrain perceptual development. We proposed an "intersensory redundancy hypothesis" to account for how this might be the case (Bahrick & Lickliter, 2000). The intersensory redundancy hypothesis describes how infants' attention will be allocated to different stimulus properties of objects and events as a function of the type of exploration (unimodal vs multimodal) afforded by the event. It also proposes consequences of this pattern of exploration for perception, learning, and memory.

One tenet of the intersensory redundancy hypothesis holds that in early development, information presented redundantly and in temporal synchrony to two or more sense modalities recruits infant attention and facilitates perceptual differentiation of the *redundant information* more effectively than does the same information presented to one sense modality at a time. From this view, detection of higher order amodal relations in multimodal stimulation from an object or event causes amodal stimulus properties to become "foreground" and other properties of the object or event to become "background." Thus, intersensory redundancy affects attentional allocation and this in turn can promote earlier processing of redundantly specified properties of stimulation (temporal and spatial aspects) over other stimulus properties. Because intersensory redundancy is readily available in the multimodal stimulation provided by our environment and our interaction with it, perception, learning, and memory of amodal properties likely precedes that for other stimulus properties. This "amodal processing precedence" in turn, can have long-range effects on perception, cognition, and social and emotional development. Because all our fundamental human capabilities emerge and develop in a multimodal context, rich with intersensory redundancy, these initial conditions can continue to influence the trajectory and organization of development. And because sensitivity to intersensory redundancy is present early in development and redundancy is so pervasive, it can create a cascading effect across development such that its consequences manifest in an ever-widening trajectory in a variety of domains (see Michel & Moore, 1995, and Moore, 1990, for examples of cascading effects in development).

However, not all exploration of the objects and events in our environment makes multimodal stimulation available. In fact, intersensory redundancy is often not available for a particular event, either because the perceiver is not actively exploring that particular event with multiple senses, or because the event that is the focus of attention is not providing redundant simulation at that moment in time to the senses through which the perceiver is exploring (e.g., the perceiver is just looking at, but not touching, a stationary or silently moving object). In this case, amodal information for the event may be unavailable or available only in a single sense modality. For example, one might experience the rhythmic sounds of speech from a neighboring room, or the sight of a light blinking at a regular rate on a nearby appliance. The amodal properties of rhythm and rate would then be specified unimodally rather than redundantly. In this case, the amodal information of rhythm and rate would not be salient and there should be no amodal processing precedence.

When only unimodal stimulation is provided for a particular property, there is no competition from intersensory redundancy. Therefore, attention is more likely to be recruited toward modality-specific properties of stimulation. Modality-specific properties are qualities specific to a particular sense modality. For example, color and pattern can only be perceived visually and pitch and timbre can only be perceived acoustically. According to a second tenet of the intersensory redundancy hypothesis, when only unimodal stimulation is available for a particular property, attention to modality-specific properties should be facilitated relative to other stimulus properties. Thus, we hypothesize that unimodal exploration enhances perceptual differentiation of modality-specific and nonredundantly presented properties, as compared with the same properties presented in the context of multimodal, redundant stimulation (Bahrick & Lickliter, 2000). Optimal differentiation of visible qualities of an object or event should occur when there is no competition from auditory stimulation, which creates intersensory redundancy and recruits attention away from the visible qualities. For example, in early development, differentiation of the appearance of a person's face would be optimal when the individual was silent, differentiation of the nature of their particular voice would be optimal when their face was not visible, and differentiation of the prosody, rhythm, tempo, and timing of language would be optimal when viewing a speaking person. This observation is consistent with observations of the early emergence of sensitivity to the prosody in speech (Cooper & Aslin, 1989; Fernald, 1984).

Thus, according to the intersensory redundancy hypothesis, the nature of exploration (unimodal vs multimodal) interacts with the type of property explored (amodal vs modality-specific) to determine the attentional salience and processing priority given to various properties of stimulation. As can be seen in Figure 2, bimodal exploration of amodal properties and unimodal exploration of modality-specific properties receive priority in processing. In contrast, processing is relatively disadvantaged for bimodal exploration of modality-specific properties (e.g., listening to the pitch and timbre of a voice while also seeing the speaking face) and for unimodal exploration of amodal properties (e.g., seeing a rhythm displayed visually without sound, or hearing a rhythm in sound without visual

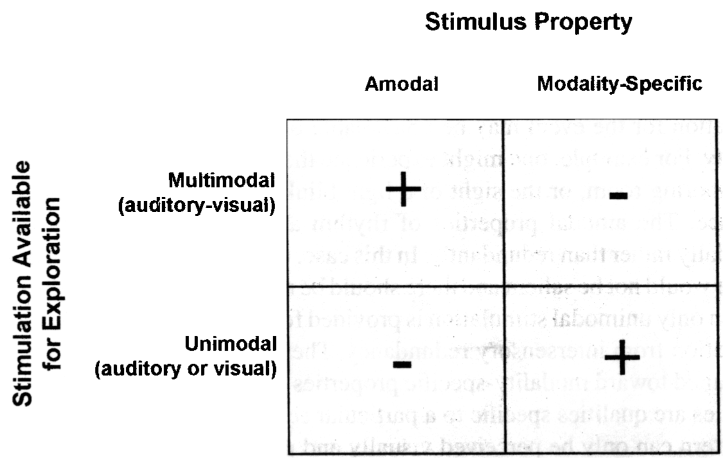

Fig. 2. Predictions of the intersensory redundancy hypothesis. Facilitation versus attenuation of attention and perceptual processing for amodal versus modality-specific properties of stimulation as a function of the type of stimulation (multimodal or unimodal) available for exploration.

accompaniment). Perceptual development is thus characterized by an intercoordination between exploration of amodal and modality-specific properties of events, and because of the prevalence of redundancy, detection of amodal information typically leads and constrains learning about modality-specific properties of stimulation.

The intersensory redundancy hypothesis makes predictions about multimodal and unimodal processing of objects and events. This is unusual in that predictions about and attempts to synthesize research from these areas that have previously been studied separately are uncommon. As we discussed in section III, the perception of multimodal and unimodal aspects of stimulation have typically not been studied together, making comparisons across studies that use different methods and stimuli difficult. The intersensory redundancy hypothesis promotes research investigating unimodal and bimodal perception of various properties of events in single designs. Further, it makes a priori predictions about the effects of different types of stimulation on perception of different properties and fosters comparisons across domains that have typically been segregated.

This model of selective attention is simplistic in the sense that it is based on the assumption that other contributing factors are held relatively constant. We acknowledge that factors such as goals, expectations, the intensity and amount of stimulation, and organismic factors (hunger, fatigue, arousal) also influence attention. The intersensory redundancy hypothesis is designed for the purpose of making predictions about which aspects of stimulation will be attended and processed as a function of whether the attended stimulation is unimodal or multimodal.

A. PREDICTIONS OF THE INTERSENSORY REDUNDANCY HYPOTHESIS AND THE IMPORTANCE OF INCREASING SPECIFICITY IN EARLY DEVELOPMENT

The intersensory redundancy hypothesis grew out of a synthesis of the neural, comparative, and human infant research on intersensory perception. Consequently, several fundamental aspects of the hypothesis are supported by existing research findings. Of particular importance, the prediction of amodal processing precedence is consistent with E. J. Gibson's (1969) differentiation view of perceptual development and with prior infant perception research showing that perceptual development proceeds in order of increasing specificity in early infancy. Bahrick (1992, 1994, 2001) demonstrated that global amodal relations (e.g., temporal synchrony between the sights and sounds of object impact) were detected developmentally prior to nested amodal relations (temporal microstructure specifying the composition of objects striking a surface), and this amodal information was detected prior to modality-specific aspects of the events (the color/shape of the object and the pitch of its impact sound). Detection of temporal synchrony was evident at even the youngest ages tested, whereas detection of nested composition information did not emerge until 7 weeks of age and increased dramatically across age. Detection of modality-specific pitch–color/shape relations in the same events did not emerge until 30 weeks of age.

Early detection of temporal synchrony is important because synchrony can specify the unitary nature of the audible and visible stimulation. Once infants attend to unitary audiovisual events, differentiation of other properties can proceed in a veridical manner. In contrast, if infants learned about arbitrary audiovisual relations prior to detecting amodal relations, generalization would not be appropriately constrained (e.g., all red objects do not produce high pitched, jingling sounds). Thus, detection of properties in order of increasing specificity acts as a buffer against learning inappropriate audiovisual relations (Bahrick, 2001).

Researchers have demonstrated that early detection of amodal relations can indeed guide and constrain perceptual learning about more specific arbitrary relations. For example, 7-month-old infants can learn the arbitrary relation between the appearance of an object and the speech sound paired with it when the object moves in synchrony with the sound, but not when amodal synchrony is absent (Gogate & Bahrick, 1998). Six-month-olds also learn to relate the color and pattern of an object and its tactually experienced shape in the presence of amodal shape information (available simultaneously to touch and sight) but not in its absence (Hernandez-Reif & Bahrick, 2001). Furthermore, 3-month-olds learn about the visual appearance of a single or compound object striking a surface and the particular sound it produced when synchrony is present (Bahrick, 1988, 1992, 1994). Even newborns show evidence of learning arbitrary audiovisual relations in the presence of amodal information, but not in its absence (Slater, Quinn, Brown, & Hayes, 1999).

Based on studies of a variety of events perceived through various sensory modalities, detection of amodal information such as temporal synchrony apparently can promote further differentiation of the unitary event and lead to learning about nested properties and finally about arbitrary, modality-specific relations. This developmental sequence whereby learning progresses in order of increasing specificity (from detection of amodal to arbitrary, modality-specific relations) is adaptive because it can promote learning about consistencies and regularities across the senses that are context independent prior to learning about more context dependent relations. Early detection of amodal relations fosters appropriate, veridical generalizations (e.g., voices go with faces; single objects produce single sounds) and minimizes inappropriate generalizations about relations that vary across contexts and are specific to certain events. In this manner, detection of amodal relations can guide and constrain learning about modality-specific relations such that general principles are well established prior to learning about more specific details of these events (see Bahrick, 2000, 2001).

This sequence of increasing specificity and amodal processing precedence observed across development is likely paralleled by a similar processing sequence that occurs within a given episode of exploration. If an event provides intersensory redundancy and captures attention, then, according to the intersensory redundancy hypothesis, attention will first be focused on global amodal relations, followed by nested amodal relations, and eventually, on modality-specific properties. Once the infant has explored the redundant amodal relations uniting the multimodal stimulation from an event, this promotes continued processing of the unitary event and guides attention to increasingly more specific levels of stimulation. Thus, just as perception appears to proceed from detection of global to specific aspects of stimulation across development, perceptual processing within a given episode of exploration may also proceed from global to specific aspects of stimulation at a given point during development.

Interestingly, a global processing precedence within an episode of exploration has been demonstrated for exploration of unimodal visual stimuli (see Freeseman, Colombo, & Coldren, 1993; Frick, Colombo, & Allen, 2000). Whether such a global processing precedence also holds for exploration of multimodal stimuli within an episode of exploration is an important empirical question and should be tested across a variety of domains. If the global-to-specific sequence previously described reflects a general pattern of multimodal processing, then the advantages of intersensory redundancy should be most evident and pronounced during early phases of exploration or processing of a particular event.

Similarly, our intersensory redundancy hypothesis predicts that the facilitating effects of intersensory redundancy on differentiation of amodal stimulus properties should be most apparent early in development when infants are first learning a skill and when detection of the information is difficult. Once the skill is mastered and/or perceptual discrimination becomes easier, the information in question (for example, a particular rhythmic sequence) can be detected rapidly and will likely be discriminated in both unimodal and bimodal stimulation. Thus, the effects of intersensory redundancy should be most apparent when the organism is first learning to differentiate novel or relatively unfamiliar information.

If the effects of redundancy are most pronounced in early development, this could have important implications for attention, perception, learning, and memory. Because these capabilities emerge primarily in a multimodal context, and initial conditions are known to have important influences on the trajectory and organization of subsequent development, the early effects of intersensory redundancy are likely to have a significant influence on the nature and course of later perceptual and cognitive development across a variety of areas. The intersensory redundancy hypothesis could thus potentially serve as a model to guide appropriate interventions for developmental delays in a number of perceptual, cognitive, and social domains as a function of the type of property in question (amodal vs modality-specific) and the likely basis of the particular developmental delay.

B. DIRECT EMPIRICAL SUPPORT FOR THE INTERSENSORY REDUNDANCY HYPOTHESIS

The intersensory redundancy hypothesis allows several a priori predictions regarding how young infants should attend to and discriminate different patterns of multimodal and unimodal sensory stimulation. First, perceptual processing and learning about amodal properties of objects and events (e.g., tempo, rhythm, duration) will be facilitated when the properties are presented across two sense modalities in a temporally coordinated manner relative to when the same properties are available to only one sensory modality. Conversely, perceptual processing and learning about modality-specific properties (e.g., color, pitch, orientation) will be facilitated when the properties are presented to only one sense modality relative to when the same properties are presented to two or more senses concurrently (see Figure 2). Thus, the rhythm or tempo of a unimodal event should be less likely to be noticed and remembered than the rhythm or tempo of a bimodal event.

The intersensory redundancy hypothesis also makes a developmental prediction. Because the facilitating effects of intersensory redundancy are likely most pronounced when infants are first learning a skill, we would expect differentiation of amodal properties to be extended more flexibly as infants become more competent perceivers. Specifically, we predict that in early development the detection of amodal properties should be facilitated by bimodal redundant stimulation when the information is novel or difficult, but detection of amodal properties will be extended to unimodal contexts in later development as infants become more skilled perceivers. Given the traditional dichotomy between research in the areas of unimodal and multimodal functioning, few studies in the existing literature relate directly to these predictions. Thus we have generated a body of research from our labs that tests these predictions of the intersensory redundancy hypothesis with both human and animal infants.

1. Human-Based Studies

Several studies with human infants provide support for specific predictions of the intersensory redundancy hypothesis. Bahrick and Lickliter (2000) assessed the ability of 5-month-old human infants to discriminate complex rhythmic patterns in bimodal, redundant stimulation as compared with unimodal stimulation. Infants were habituated to videos of a plastic hammer tapping out a distinctive rhythm under conditions of bimodal, redundant stimulation (they could see and hear the hammer), unimodal visual stimulation (they could only see the hammer tapping), or unimodal auditory stimulation (they could only hear the soundtrack of the hammer tapping). Infants were then presented test trials consisting of the same hammer tapping out a new rhythm. In this paradigm, following habituation (decreased interest in a familiar event), renewed interest (visual recovery) to a new event is taken as evidence of discrimination between the two events. Infants who received the bimodal, redundant stimulation showed significant visual recovery to the change in rhythm (discrimination), whereas those who received unimodal visual or unimodal auditory stimulation showed no visual recovery to the change in rhythm. In a further experiment we assessed infants' rhythm discrimination for bimodal, nonredundant stimulation (asynchronous films and soundtracks of the hammers tapping) and similarly found no evidence of rhythm discrimination. These results demonstrate that infants required redundancy in the form of temporal synchrony between the visual and acoustic stimulation to show a visual recovery to a change in rhythm (Bahrick & Lickliter, 2000). Thus, 5-month-olds discriminated complex amodal rhythms when they were bimodal and synchronous (seen and heard), but not when they were unimodal (seen or heard) or bimodal but asynchronous. This finding supports the first tenet of the intersensory redundancy hypothesis.

In a second study we replicated and extended the findings of Bahrick and Lickliter (2000) by assessing detection of a different amodal property with infants of a younger age. Bahrick, Flom, and Lickliter (2002) tested discrimination of tempo in 3-month-old infants, utilizing the same basic paradigm described earlier. Infants were habituated to films of a hammer tapping out a rhythmic sequence in one of two tempos (55 vs 120 beats per minute). The same tempo could be detected visually by watching the hammer, or acoustically, by listening to its impact sounds. Infants received bimodal, redundant, audiovisual stimulation, unimodal visual stimulation, or unimodal auditory stimulation during habituation. Then they received test trials presenting a novel tempo. Results paralleled those of Bahrick and Lickliter (2000), in that infants discriminated the change in tempo following bimodal, redundant audiovisual stimulation, but not following unimodal visual or unimodal auditory stimulation. These findings converge with those of rhythm discrimination and demonstrate the facilitating effects of intersensory redundancy for guiding attentional selectivity and fostering perceptual differentiation in infancy.

However, it is not clear to what extent the facilitating effects of intersensory redundancy persist across later stages of development. According to the intersensory redundancy hypothesis, the advantage of intersensory redundancy should be most pronounced when infants are first learning a skill and attenuated in later development. Once infants become proficient at detecting a particular stimulus property, perception of that property should become increasingly flexible and should no longer require redundancy. An amodal property may then be detected in unimodal stimulation.

Bahrick, Lickliter, and Flom (2002) tested this hypothesis. We assessed the ability of 8-month-old infants to discriminate complex rhythms in a task just like that experienced by the 5-month-olds in our prior study. As before, infants received videos of the hammer tapping out one of the two rhythms. Infants were habituated to the rhythmic sequences in bimodal, redundant audiovisual stimulation or unimodal visual stimulation. Test trials presented a novel rhythm. The 8-month-olds showed significant visual recovery to the change in rhythm in both the redundant audiovisual *and* the unimodal visual conditions. These findings contrast with those of the 5-month-olds in the Bahrick and Lickliter (2000) study and demonstrate that by 8 months of age, infants no longer required intersensory redundancy for discriminating the complex rhythmic sequences. This finding provides support for our developmental prediction that perception of amodal properties emerges in the context of redundancy and is later extended to nonredundant, unimodal contexts.

A few studies from related content areas have also provided unimodal and multimodal conditions to young infants and therefore provide converging evidence regarding the first prediction of the intersensory redundancy hypothesis—that discrimination of amodal information should be facilitated in bimodal as compared to unimodal presentations when performance is not at ceiling. Caron, Caron, and MacLean (1988) found that 7-month-old infants could discriminate happy from angry expressions spoken across different individuals when the face and voice were presented redundantly and synchronously, but not when the moving face was presented without the voice. Furthermore, discrimination of emotional expressions was significantly better in the bimodal compared with the unimodal condition, providing additional support for the salience of intersensory redundancy in a paradigm using social stimuli. Relatedly, Walker-Andrews (1997) comprehensively reviewed the literature on infants' affective discrimination and concluded that recognition of affective expressions emerges first in a multimodal context, and subsequently occurs on the basis of vocal and then facial expressions later in development. This developmental trajectory parallels the findings from our laboratory utilizing nonsocial stimuli.

Additional research has also focused on a second tenet of the intersensory redundancy hypothesis, namely the perception of modality-specific properties of events perceived in unimodal versus bimodal, redundant stimulation (the right-hand quadrants of Figure 2). According to the intersensory redundancy hypothesis, information experienced in one sense modality selectively recruits attention to modality-specific properties of events and facilitates perceptual differentiation of those properties at the expense of other properties. To evaluate this hypothesis, we again tested 5-month-old infants, this time assessing detection of orientation, a property available visually, but not acoustically (Bahrick, Lickliter, & Flom, 2000). We expected that infants would discriminate changes in orientation during unimodal visual, but not bimodal audiovisual stimulation. Infants were habituated to films of a hammer tapping out a rhythm. However, this time the movements of the hammer were depicted in one of two orientations (upward vs downward). Either the hammer hit downward against a wooden floor, or it hit upward against a wooden ceiling. Infants were habituated to videos of the hammers in one of the two orientations in the bimodal, audiovisual condition (where they could see and hear the hammer moving) or the unimodal visual condition (where they could only see the hammer moving). Infants then received test trials, under their respective conditions, where the orientation of the hammer was changed. Infants detected the change in orientation (i.e., significant increase in looking) following unimodal visual habituation, but not following bimodal audiovisual habituation (Bahrick *et al.*, 2000). Thus, consistent with predictions of the intersensory redundancy hypothesis, 5-month-olds successfully discriminated changes in orientation, a visual property, following unimodal visual exposure, but not following redundant, bimodal exposure.

The addition of the soundtrack apparently created intersensory redundancy and selectively recruited attention away from unimodally conveyed properties and toward redundantly specified properties of stimulation (as in Bahrick & Lickliter, 2000; Bahrick, Flom, & Lickliter, 2002). In contrast, the unimodal, visual stimulation promoted attention to visual properties of the event without competition from salient redundant properties. Thus, attention to modality-specific or nonredundantly specified properties is likely best fostered in the context of unimodal exploration when competition from concurrent redundantly specified properties is minimized. This suggests that unimodal exploration (of a face or voice, for example) is promoted when there is little competition from concurrent, amodal, redundant stimulation (face–voice synchrony, for example). Unimodal exploration likely fosters differentiation of increasingly more specific aspects of auditory or visual information, a process that is not initially promoted when redundant stimulation is available. Thus, differentiation of the appearance of a face would be best promoted when the face is silent and relatively still, whereas when the individual is speaking and moving, competition from audiovisual redundancy would be more likely to focus attention on amodal properties such as prosody, rhythm, tempo, affect, and intensity variations common to the speech and facial movement (Walker-Andrews, 1997; Walker-Andrews & Bahrick, 2001).

2. *Animal-Based Studies*

If the intersensory redundancy hypothesis relfects a general developmental principle, then redundancy should potentially be a potent contributor to perceptual responsiveness and learning at earlier stages of development and in other animal species. Studies of nonhuman animal infants and human infants have shown sensitivity to amodal stimulus properties in the days and weeks following birth (Bahrick, 1988; Lewkowicz, 2000; Mellon, Kraemer, & Spear, 1991; Slater *et al.*, 1999; Spear & McKinzie, 1994), but little is known about whether embryos or fetuses are sensitive to redundantly specified information during the prenatal period. Systematic manipulation of the human fetus's sensory experience during the prenatal period is, of course, prohibited and the use of such experimental methods is possible only with nonhuman animals. Lickliter, Bahrick, and Honeycutt (2002a) assessed whether redundant, bimodally specified information can guide attentional selectivity and facilitate perceptual learning prior to hatching in a precocial avian species. Precocial birds (such as domestic chicks, ducks, and quail) are particularly well suited for this type of research, as they develop in an egg (allowing ready access to the developing embryo during the late prenatal period) and can respond in behavioral tests immediately after hatching.

In the Lickliter *et al.* (2002a) study, bobwhite quail chick embryos were exposed to an individual maternal call for 6, 12, or 24 h, under conditions of unimodal auditory stimulation, concurrent but asynchronous auditory and visual stimulation, or redundant and synchronous auditory and visual stimulation. Redundant stimulation was provided by presenting a pulsing light that flashed in synchrony and with the same temporal patterning (rhythm, rate, and duration) as the notes of the maternal call. Quail embryos are able to perceive the call and the patterned light during the late stages of incubation, after they have moved their head into the airspace at the top of the egg in preparation for hatching. All chicks were then tested 24 h later (1 day after hatching) to determine whether they would prefer the familiar bobwhite maternal call over an unfamiliar variant of the maternal call. Chicks that received redundant audiovisual exposure preferred the familiar maternal call following all prenatal exposure durations, whereas chicks that received nonredundant audiovisual exposure prenatally showed no preference for the familiar call after any exposure duration. Chicks receiving the unimodal auditory familiarization prior to hatching preferred the familiar call only following the longest period (24 h) of prenatal exposure. Thus, bobwhite quail chicks show dramatically enhanced learning of the maternal call when amodal information (tempo, rhythm, duration) is presented redundantly across two sense modalities. Embryos exposed to redundant presentation of auditory and visual information learned the maternal call four times faster than embryos exposed to unimodal auditory information. These findings are the first to demonstrate the facilitating effects of intersensory redundancy during the prenatal period and in a nonmammalian species. Similar to the results from human infants reviewed earlier, avian embryos showed enhanced perceptual learning when amodal information was presented bimodally and in a temporally coordinated manner.

In a related study we also demonstrated that quail embryos provided intersensory redundancy prenatally show enhanced memory for the familiar maternal call in the period following hatching (Lickliter, Bahrick, & Honeycutt, 2002b). Specifically, chicks that received redundant audiovisual exposure as embryos were able to remember and prefer the familiar maternal call 4 days following hatching. In contrast, chicks receiving unimodal (auditory only) exposure prenatally failed to remember the familiar maternal call beyond 1 day following hatching. These results are the first both to provide evidence that redundantly specified information is remembered longer than the same information presented unimodally and to provide additional support for the facilitative effects of intersensory redundancy in the domains of perception, learning, and memory, even during the period prior to birth or hatching.

Although little if any research has focused on this issue, the human fetus likely experiences redundancy across auditory, vestibular, and tactile stimulation in utero. For example, when the mother walks, the sounds of her footsteps can be coordinated with tactile feedback as the fetus experiences changing pressure corresponding with the temporal patterning and shifting intensity of her movements as well as the accompanying and coordinated vestibular changes. In addition, the mother's speech sounds, laughter, heartbeat, or sounds of breathing may create tactile stimulation that shares the temporal patterning of the sounds as a result of changes in the musculature involved in producing the sounds. Research has suggested that fetuses can discriminate auditory stimulation on the basis of temporal patterning such as prosody (DeCasper, Lecanuet, Busnel, Cranier-Deferre, & Maugeais, 1994; DeCasper & Spence, 1991).

The infant may also experience self-produced intersensory redundancy between proprioceptive and tactile stimulation. Fetuses are known to engage in spontaneous motor activity of limbs and body (Robertson & Bacher, 1995), providing temporally organized cyclic stimulation. When the fetus moves in the uterus, the movement generates both proprioceptive feedback as well as temporally coordinated tactile consequences of the motion, such as changes in pressure on the skin. Additionally, the mother also responds with temporally coordinated movements to externally generated sounds. For example, she may dance or exercise to music, startle to a loud noise, or engage in conversation that has a distinctive turn-taking contingent structure—all of which produce movements that have tactile and/or vestibular correlates that share intensity and temporal patterning with the sounds. Thus, the developing fetus likely has ample opportunity to become familiar with and detect redundant stimulation during the late stages of prenatal development.

Taken together, converging evidence across species, developmental periods, and properties of events indicates the importance of intersensory redundancy for promoting attention and for fostering perceptual differentiation of amodal properties of events. Further, intersensory redundancy explains how, in a predominately multimodal environment, perceptual learning can initially be guided and constrained by detection of amodal relations. These findings also reveal conditions under which attention to amodal properties is not facilitated and attention to modality-specific properties and nonredundant aspects of stimulation are favored. That is, when a given event provides stimulation to only a single sense modality, attention and learning about unimodally specified properties of events is more enhanced. Modality-specific properties are likely best differentiated when competition from intersensory redundancy is not present. These findings highlight that in early infancy, perceptual development is characterized by a dynamic interaction between attention to amodal and modality-specific properties available in unimodal and multimodal stimulation.

C. ON WHAT BASIS DOES INTERSENSORY REDUNDANCY FACILITATE PERCEPTUAL DISCRIMINATION AND LEARNING?

Although the salience of intersensory redundancy for perception, learning, and memory is now documented in studies of both neural and behavioral responsiveness, the basis for its salience and facilitation of perceptual processing is not yet clear. Theorists have proposed several explanations of the perceptual facilitation found for multimodal stimuli over unimodal stimuli. One way of conceptualizing the nature and salience of intersensory redundancy is illustrated in "separate activation" models (e.g., Estes, 1972, 1974; Rumelhart, 1970; Shaw, 1978; Shiffrin & Schneider, 1977). This type of model has been used in information-processing studies of adults' attention to address why processing of redundant signals in separate channels is faster than processing single signals (the "redundant signals effect"; Kinchla, 1974). According to this model, when redundant information is available in two separate channels, activation does not combine across the channels to allow for faster processing. Rather, processing of the information is faster when redundancy is present because there are two different opportunities to detect the signal, one in each channel. The faster of the two signals is assumed to win out for attention and to influence the response (also called the "race model"; see Raab, 1962). Across multiple trials, the time of the "winner" will be less than the average time of either signal.

In the processing of multimodal redundant stimulation, such as rhythm or rate, presumably intersensory redundancy would be superior to unimodal processing because the perceiver could respond by detecting the information in either the auditory or visual channel. Thus, there would be a better chance of detecting the rhythm when it was redundantly specified. Available neural evidence and behavioral data on infant perception of intersensory redundancy do not provide support for the separate activation model and thus it is not the explanation we favor. As described in earlier sections, there appears to be considerable interaction among the sensory channels, even in early development, and information in one sensory modality significantly influences how information in other modalities is perceived, learned, and remembered.

Another way of conceptualizing the salience and facilitating effects of intersensory redundancy, also used in studies of divided attention, is seen in "coactivation models," where both components of a redundant signal are seen to influence responding together (e.g., Logan, 1980; Miller, 1982; Nickerson, 1973). According to this perspective, both stimulus components combine to influence activation. Activation builds gradually over time and when it reaches a threshold, a response (such as word recognition) occurs. From this view, responses to redundantly presented signals are especially fast because both signals independently produce activation. When applied to intersensory perception, redundant information would be thought to be particularly salient and to enhance learning because there would be more activation and stimulation from two sense modalities than from either sense modality alone. Thus, the difference between multimodal and unimodal stimulation is seen as one of quantity and is based on overall amount of stimulation.

The problem with this account is that the facilitation due to intersensory redundancy cannot be reduced to a simple quantitative benefit. Rather, as we reviewed earlier, there are multiplicative or superadditive effects in intersensory facilitation beyond what would be expected from adding together the effects of each modality alone (Stein & Meredith, 1993). Furthermore, how stimulation in the two senses is presented is also crucial for facilitation resulting from intersensory redundancy. For example, audible and visible stimulation must be temporally aligned (synchronous) for intersensory redundancy to be effective in guiding selective attention and perceptual responsiveness in infancy (Bahrick & Lickliter, 2000; Lickliter, Bahrick, & Honeycutt, 2002a,b). Thus, synchronous (but not asynchronous) presentations of auditory and visual stimulation results in the discrimination of changes in rhythm or tempo, even though the overall amount of stimulation is constant across the two conditions. Thus, the coactivation view, though consistent with some of the data from neural and behavioral studies, cannot account for reported qualitative differences between unimodal and multimodal stimulation.

A third view of the role of intersensory redundancy in facilitating attention and perception, which can be described as "intersensory convergence," fits best with existing evidence from neural, physiological, and behavioral studies and is consistent with E. J. Gibson's (1969) invariant detection view of perceptual development. According to this perspective, perceivers are sensitive to higher order, amodal patterns of stimulation across the senses. When attention is focused on this type of redundancy, the perceiver detects a whole that differs from the sum of its parts. Pick up of concurrent, redundantly specified information causes amodal properties of stimulation to become "foreground" and other properties to become "background." The resulting information is not only quantitatively different from that conveyed in each sense modality alone, but qualitatively different as well.

A metaphor from the area of visual perception may be useful in explaining this qualitative difference. The figure-ground segregation, or "pop out" effect for amodal properties of objects and events that results from detecting intersensory redundancy can be viewed in a manner similar to binocular convergence and resulting stereopsis (e.g., J. J. Gibson, 1950; Sekuler & Blake, 1990). The two eyes see objects and events from slightly different angles because of their different positions in the head. Consequently different patterns of stimulation reach each of our retinas. When two eyes converge properly on a target, we see depth from binocular disparity. Furthermore, the impression of depth differs qualitatively from each of the individual component patterns. Perceivers have no awareness of either individual pattern alone. Rather, from the interaction between the two patterns of stimulation, perception of three-dimensional space emerges. For example, when viewing a three-dimensional object of a particular shape, the component patterns to each retina differ in form, but contain information for the same object shape. To perceive the emergent three-dimensional shape, the two patterns must be spatially aligned. That is, binocular convergence allows the two patterns to overlap properly, creating the perception of depth.

We suggest that binocular convergence and stereopsis resemble the "pop-out" effect we experience for amodal stimulus properties when auditory and visual stimulation is redundant, concurrent, and temporally aligned. In the perception of multimodal events, the component patterns of stimulation to different sense modalities depict the same stimulus properties (e.g., rhythm, rate), but differ in their form (i.e., modality). To perceive the amodal properties of objects and events, the unimodal components must be temporally aligned. In other words, the convergence of different types of energy makes amodal properties of stimulation salient and fundamental for perception.

We favor this convergence perspective because it is most congruent with evidence of intersensory interactions across multiple levels of analysis. First, it is most consistent with evidence from the neurosciences regarding sensory interactions. For example, the findings reviewed earlier regarding the "superadditive" effects of concurrent bimodal stimulation on neural responsiveness (e.g., Stein & Meredith, 1993) point to the fact that the convergence of different types of sensory stimulation can result in outcomes that are greater and different from the sum of its parts (that is, responsiveness levels are seen that would not be predicted from adding together input to either sensory modality alone). Second, the convergence view is consistent with psychobiological studies demonstrating the functional distinction between unimodal and multimodal stimulation (e.g., Lickliter & Honeycutt, 2001; Reynolds & Lickliter, 2002; Sleigh, Lickliter, & Columbus, 1998). This body of work has shown the importance of type and timing (qualitative aspects) of sensory stimulation as well as amount (quantitative aspects) on developmental outcomes. Third, the convergence view provides a framework that easily accounts for auditory and visual illusions (e.g., McGurk effect, bounce illusion). Finally, the convergence view is most consistent with behavioral data from young infants described in earlier sections, including all direct evidence reviewed in support of the intersensory redundancy hypothesis. It also addresses why synchronous audiovisual stimulation is far better in promoting differentiation of amodal properties than are nonsynchronous pairings of the same audiovisual stimulation. The convergence view thus accounts for both qualitative and quantitative differences between effects of unimodal versus multimodal sensory stimulation.

VI. Summary and Directions for Future Study of Perceptual Development

Research on perceptual development reviewed in this chapter leads to several generalizations. These include:

- The brain is inherently multimodal in both structure and function
- There are superadditive effects in neural responsiveness to multimodal stimulation
- There are strong intersensory connections and interactions; auditory information influences how visual information is perceived, and vice versa (this allows for various intersensory illusions)

- The salience and facilitative effects of intersensory redundancy is seen across species, from avian to mammalian (including humans)
- Perception of amodal stimulus properties is promoted by concurrent, bimodally specified presentation of the same information in two or more sensory modalities (relative to unimodal presentations of the same information)
- Perception of modality-specific stimulus properties is promoted by unimodal presentations (relative to bimodal presentation of the same information)

Given the dramatic interconnections among the senses at all levels of analysis, from single-cell recordings to responses of neural populations, from attention to perceptual differentiation, learning, and memory, developmental psychologists can no longer ignore the importance of intersensory influences on basic processes of attention, perception, and cognition. Any account of development that aspires to be ecologically relevant and biologically plausible must be consistent with data from both the neural and the behavioral sciences regarding the basic role of multimodal stimulation in guiding and constraining individual development.

We have reached a point in the study of infancy where "what" questions are being replaced by "how" questions (Lewkowicz, 2000; Lickliter & Bahrick, 2000; Thelen & Smith, 1994). This shift in emphasis from descriptive to explanatory research requires convergence across levels of analysis, species, and methods. Given the explosion of data from the biological and behavioral sciences regarding the nature of intersensory functioning, increasing cooperation and coordination across disciplines will be needed to provide a unified theory of perceptual development. In this light, we conclude this chapter with several integrative themes that could contribute to the future study of perceptual development.

First, research on unimodal and multimodal perception needs to be better integrated. The current dichotomy between these approaches impedes progress toward a unified theory of perceptual development. Better integration could be achieved by incorporating unimodal and bimodal conditions into single studies where uniform methods allow for meaningful comparisons and avoid generalizing research findings beyond the context (unimodal vs multimodal) of investigation.

Second, research from the neural and behavioral sciences needs to be better integrated. Developmental psychology can no longer ignore findings from neural and physiological levels of analysis showing the interrelation of the senses at primary levels of processing and the implications of this insight for behavior. Specifically, our appreciation of the multimodal nature of the brain points out that higher order perceptual processing is not needed to achieve integration (binding) across the senses. Given that the integration issue has guided theory construction in the study of perceptual development for the better part of the 20th century, new frameworks are needed that move beyond these old ways of thinking and successfully incorporate findings from the biological sciences. Similarly, the neural sciences can benefit from cross-fertilization with the behavioral sciences. Data generated from the behavioral level regarding the nature of intersensory functioning can and should inform neural studies. For example, direct investigations for the basis of the observed behavioral effects described by the intersensory redundancy hypothesis (the role of redundancy and synchrony in guiding selective attention and facilitating perceptual learning) are needed at both the neural and the physiological levels of analysis.

Third, better integration of animal and human research is needed. The convergence of findings across different species will allow investigators to distill more fundamental developmental principles by highlighting invariant patterns of responsiveness that exist across species. Further, because we can experimentally manipulate the sensory experience of animals and thereby unpack the mechanisms of developmental change, the comparative approach can point to potentially fertile areas of investigation within the restrictions of human-based research (see Lickliter & Bahrick, 2000, for further discussion).

Fourth, the role of prenatal development in shaping and guiding young infants' attention and perceptual processing can no longer be overlooked. Birth is not an adequate starting point for explanations of perceptual development (Lickliter, 2000). The infant has already had a great deal of prenatal sensory experience at the time of birth, and the nature and type of this prenatal experience must be taken into account when addressing the origins of intersensory functioning. As a case in point, newborns' demonstrated sensitivity to amodal information (e.g., Slater *et al.*, 1999) likely has its roots in the detection of amodal stimulation in the prenatal environment.

Fifth, the important role of selective attention could be better emphasized in developmental research concerned with perception and cognition. All information for perception and cognition must pass through the lens of selective attention. The natural environment provides an array of dimensions of stimulation, including unimodal–multimodal, moving–static, social–nonsocial, affectively laden–affectively neutral, and self–nonself. Which aspects or poles of these dimensions will be perceived, processed, and learned at different points in development is determined in large part by selective attention. Research is needed to define the salience hierarchies and rules that govern infants' deployment of attention in the natural flux of sensory stimulation that typically varies along these important experiential dimensions. The intersensory redundancy hypothesis provides one testable example of such a hierarchy.

Sixth, further investigations of the interplay between the processing of modality-specific and amodal aspects of stimulation are needed. The world of natural events can be described as providing modality specific and amodal stimulus properties. When and under what conditions do infants attend to, perceive, or ignore each type of property and how does this affect learning and memory? The intersensory redundancy hypothesis described in this chapter provides one framework for guiding this type of research.

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