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Tactile agnosia
Underlying impairment and implications for normal tactile object recognition

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Summary

In a series of experimental investigations of a subject with a unilateral impairment of tactile object recognition without impaired tactile sensation, several issues were addressed. First, is tactile agnosia secondary to a general impairment of spatial cognition? On tests of spatial ability, including those directed at the same spatial integration process assumed to be taxed by tactile object recognition, the subject performed well, implying a more specific impairment of high level, modality specific tactile perception. Secondly, within the realm of high level tactile perception, is there a distinction between the ability to derive shape ('what') and spatial ('where') information? Our testing showed an impairment confined to shape perception. Thirdly, what aspects of shape perception are impaired in tactile agnosia? Our results indicate that despite accurate encoding of metric length and normal manual exploration strategies, the ability tactually to perceive objects with the impaired hand, deteriorated as the complexity of shape increased. In addition, asymmetrical performance was not found for other body surfaces (e.g. her feet). Our results suggest that tactile shape perception can be disrupted independent of general spatial ability, tactile spatial ability, manual shape exploration, or even the precise perception of metric length in the tactile modality.

Keywords: tactile agnosia; somatosensory perception; object recognition; touch; tactile

Introduction

Although the recognition of objects through touch cannot rival visual object recognition in its speed or accuracy, normal humans are nevertheless able to recognize most common objects after a few brief palpations. Furthermore, tactile object recognition plays a regular, if not highly frequent, role in everyday life. Whenever we retrieve keys or lipstick from the bottom of a pocket or purse, or awake at night to switch on a lamp or answer a phone, we must identify by touch the desired objects as distinct from other objects on which our hands might alight.

Despite our proficiency at tactile object recognition and our reliance on it in everyday life, the programmatic study of tactile object recognition is a recent development in cognitive psychology (e.g. Klatzky and Lederman, 1987). Similarly, although neuropsychology has devoted considerable attention to the visual agnosias and their implications for the neural basis of visual object recognition (for review, *see* Farah, 1990), there has been little work reported on tactile agnosia (Delay, 1935; Hecaen and David, 1945; Caselli, 1991*a*, *b*; Endo *et al.*, 1992; Reed and Caselli, 1994). Indeed, the very existence of tactile agnosia has been the subject of controversy (Semmes, 1965; Teuber, 1965*a*, *b*).

In this paper, we report a series of experimental investigations on a subject with a unilateral selective disturbance of tactile object recognition, or tactile agnosia, resulting from a small, anatomically well-defined cerebral infarction. We have three main goals in these studies. The first is to establish the existence and selectivity of tactile agnosia. It has been suggested that tactile object recognition failure invariably results either from impaired basic somatosensory acuity, or from supramodal impairment of spatial perception and, thus, does not represent a true impairment of tactile object recognition *per se*. We hypothesize, instead, that tactile agnosia results from dysfunction of the high level, modality specific, shape perception process analogous to that which is believed to underlie visual agnosia (e.g. Farah, 1990). The choice between these explanations of tactile agnosia has implications for our understanding of the perceptual and cognitive systems underlying normal tactile object recognition, in that it can support or deny the existence of a neurally distinct system for modality specific tactile shape perceptions. Our second goal is to determine what aspects of high level tactile shape perception are impaired. We contrast tactile shape perception with tactile spatial perception to assess whether there is a tactile analog of the visual 'what' versus 'where' distinction. In addition to delimiting the shape specificity of tactile agnosia, we assess the degree to which it is specific to the hand (the major tactual exploratory organ) compared with other body surfaces. Our third goal is to elucidate which aspects of tactually mediated shape perception processing are impaired in tactile agnosia. We will assess the role of exploratory hand movements and try to determine the specific spatial properties of objects which can and cannot be tactually perceived by a patient with tactile agnosia.

Case report

E.C. is a 65-year-old, right-handed, hypertensive woman with a high school education. In December, 1989 (4 years prior to testing) she sustained a left inferior parietal infarction which impaired her ability to recognize objects tactually with her right hand. Nine months later she abruptly developed a left homonymous hemianopia which resolved incompletely, due to a right mesial occipitotemporal infarction. The MRI scan and the corresponding anatomical template analysis (Damasio and Damasio, 1989) reveals lesions of left Brodmann areas 39 and, to a lesser degree, area 40; and right areas 17, 18 and 36 (Fig. 1).

Neurological examination in April 1991 revealed a left superior quadrantanopia without clinically detectable hemiachromatopsia, normal hand movement and language, but impaired right hand tactile object recognition. At the time, E.C. complained of a feeling akin to numbness in her right hand and an inability to recognize objects in her pocketbook using her right hand. Clinical cognitive assessment included the short test of mental status (score 38 out of 38) (Kokmen *et al.*, 1987), the complex figure test (normal copy, but defective recall) (Taylor, 1969), and clinical language assessment (normal sentence writing, spelling words, visual and tactile naming, reading aloud and spontaneous discourse). Intellect, language and motor skills in particular were normal. Thus, her only impairments reflected visual memory presumably due to the right mesial temporal infarction (complex figure test) and tactile agnosia presumably due to the left inferior parietal infarction.

Altogether, the left inferior parietal damage was highly focal, and did not substantially involve subcortical white matter tracts. The right hemisphere lesion involved mesial occipital (visual) and mesial temporal (memory) cortices. Historically, the somatosensory disorder predates the right hemisphere lesion and, behaviourally, it could not be expected to contribute to the right hand disorder. Apart from a small, crescentic residual left superior quadrantanopia, and mild impairment of visual memory (recall of the complex figure test), no abnormality of visual perception was found (judgement of line orientation, facial recognition and complex figure tests). For both anatomical and behavioural reasons, therefore, we do not feel the right hemisphere lesion contributed to the somatosensory disorder.

She returned 1 year later for more extensive somaesthetic testing. Tactile object recognition was assessed in both April 1991 and April 1992. She was asked to identify 40 common items unimanually. If an incorrect or ambiguous name was given for the object, she was asked to describe the object and its use. On both occasions, she demonstrated impaired tactile object recognition with the right hand (20 out of 40 in 1991, 25 out of 40 in 1992) compared with her unimpaired left hand (36 out of 40 in 1991, 37 out of 40 in 1992).

When the subject guessed the identity of an object, the majority of her errors were structural in nature. For example, she mistakenly identified a pine cone as a brush, a ribbon as a rubber band and a snail shell as a bottle cap. Other errors were descriptions of the object material. For example, a disposable razor was identified as plastic. Exploratory hand movements were also analysed. Normal object exploration patterns were employed and reiterated with the agnosic hand when the object's identity was not immediately recognized. The exploratory strategies of the agnosic right hand were similar to those executed by normal subjects for unknown objects (Lederman and Klatzky, 1987). The unimpaired hand recognized objects quickly, often just by grasping the object without requiring further exploration.

Clinical examination of basic somatosensory function exonerated this level of processing as the cause of her tactile object recognition impairment. Light touch, pinprick, temperature, proprioception, kinaesthesia, two point discrimination and vibratory sensation were normal for both hands (Reed and Caselli, 1994). Computerized sensory examination (Dyck *et al.*, 1993) confirmed normal and symmetric vibratory detection thresholds in the hands bilaterally.

Intermediate somatosensory function was also intact. E.C. displayed no extinction to double simultaneous stimulation in tactile, visual or auditory modalities. Her weight perception (discriminating differentially weighted plastic eggs of equal size), size perception (discriminating blocks of different dimensions) and texture perception (discriminating four grades of sandpaper) were normal with each hand in 1991 and 1992. Perception of substance and simple familiar geometric shape, however, appeared mildly impaired. E.C. had mild difficulty discriminating different materials (e.g. metal, wood, wax, rubber). Although she correctly identified all stimuli with her unaffected left hand, she made some errors with her right hand in 1991 and 1992. While E.C. could identify common geometric shapes (square, circle, triangle, cylinder, sphere and rectangle) with each hand in 1991, she missed one shape with her right impaired hand in 1992. Somatosensory and visual knowledge about objects and mental imagery were normal (Reed and Caselli, 1994). No

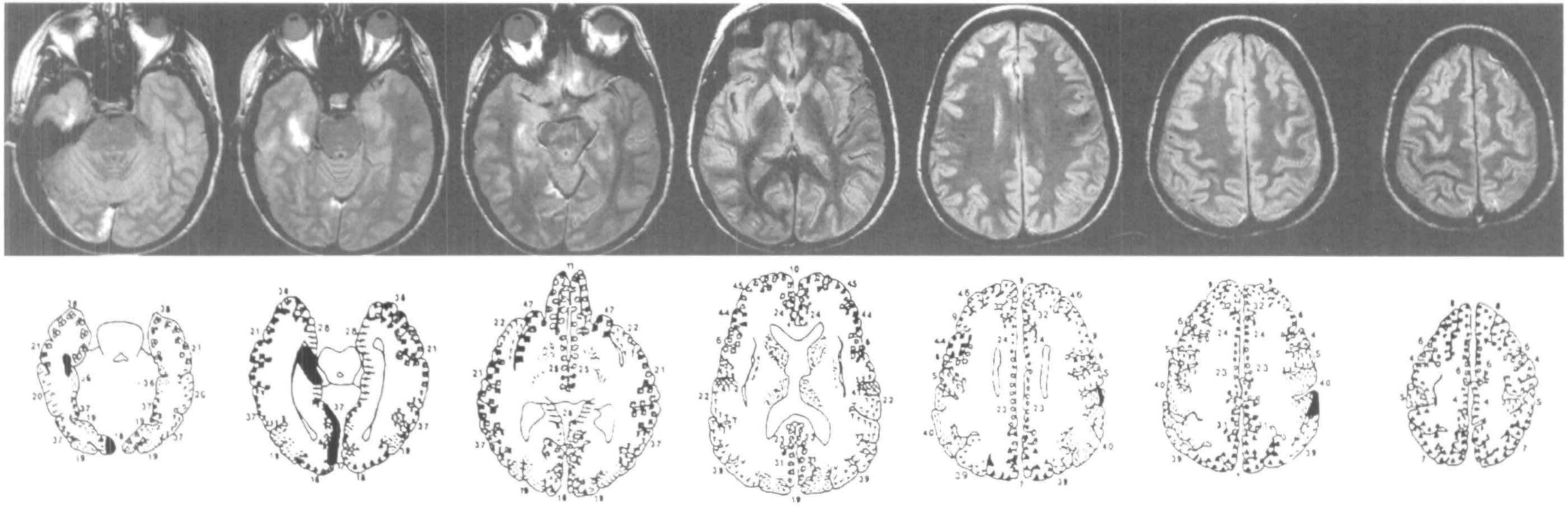

Fig. 1 MRI and anatomical templates in the top row show the proton density weighted MRI transverse sections depicting two discrete areas of infarction. The relevant lesion is located in the left inferior parietal lobe, and involves part of Brodmann area 40 and to a lesser degree area 39. The second and larger area of infarction involves right mesial temporal, retrosplenial, and mesial occipital cortices. (Permission has been obtained to reproduce this figure from Elsevier Science Ltd, 1994.)

other factors that might adversely influence performance on tests of tactile object recognition, including apraxia, aphasia or hemiparesis, were present.

Thus, E.C. has normal sensory function in both hands, is mildly impaired at recognizing substance and simple geometric shape, and has a significant impairment of tactile object recognition which affects her right hand only. In other words, she has a unilateral tactile agnosia. The left hand is unimpaired and thus may act as a control for assessing right hand performance. Further, her tactile object recognition impairment appears to be bracketed somewhere between elementary sensation and object memories.

E.C. and all normal control subjects gave their informed consent to participate in the experiments reported in this paper.

Part I. The role of general spatial impairment in tactile agnosia

Does tactile agnosia result from a general impairment in the processing of spatial information from any modality? Alternatively, does it result from the loss of modality specific representations in the somatosensory system, which encode the spatial structure of touched and grasped objects? These two interpretations of tactile agnosia correspond to two different views of normal tactile shape perception. In the first case, tactile shape perception would involve the registration of relatively elementary tactile features of the object, which are synthesized to enable recognition using a general purpose (as opposed to tactile) spatial faculty. In the second case, there would exist higher level tactile representations that synthesize the elementary percepts for purposes of tactile object recognition.

If one were to reason by analogy with visual agnosia, one would conclude in favour of the second hypothesis. It is clear that patients with visual agnosia have a modality specific impairment, and indeed the well-established dissociation between disorders of visual recognition and disorders of visual–spatial orientation implies that visual object recognition involves representations distinct from those required for so-called 'spatial' tasks (Ungerleider and Mishkin, 1982). However, the analogy between tactile and visual recognition is not necessarily a valid one. In the words of De Renzi (1982, p. 154) 'the relevance of spatial factors in tactile perception is likely to be greater than in vision, since the identification of the spatial arrangement of a haptically scanned stimulus requires the subject to build up a synthesis of elements perceived in successive steps, a process considerably slower and more complex than the global and simultaneous perception which occurs in vision'. The relatively heavy demands on spatial synthesis or integration in tactile shape perception relative to visual shape perception, along with the frequent association between tactile shape perception deficits and other spatial processing deficits, has led several authors to conclude that tactile agnosia is secondary to a more general spatial impairment (Ettlinger *et al.*, 1957; Semmes *et al.*, 1960, 1963; Teuber, 1965*a*, *b*; Corkin *et al.*, 1970; De Renzi, 1982).

Semmes (1965) can be credited with conducting the first systematic study of a large number of patients, aimed at discriminating between the two hypotheses about tactile object perception. She tested a large group of brain injured men (penetrating missile wounds) and control subjects on a variety of tests of tactile and spatial function. Tactile object recognition was assessed using novel two-dimensional and three-dimensional patterns. Tactile sensation was assessed by point localization, two-point discrimination, and sense of passive movement. Spatial ability was assessed by a map-following task, in which subjects had to walk within a three by three array of discs on the floor, following paths specified by a map. Semmes found that when tactile object recognition was impaired without concomitant sensory deficit, spatial ability was also impaired. From this she concluded that tactile agnosia was secondary to a more general impairment in spatial cognition.

The goal of our initial studies was to test the hypothesis of Semmes with Case E.C. Specifically, we used four different tasks to determine whether E.C.'s difficulty in tactile object recognition was due to a general impairment of spatial ability as measured by map following tasks, or to a difficulty in integrating separately perceived elements of an object.

Experiment 1

We assessed E.C.'s spatial ability using the map following test developed by Semmes and her colleagues for assessing spatial ability in her subjects. We also administered a second test of map following ability, the Money Road Map Test.

Methods

Extrapersonal Orientation Test (Semmes et al., 1955). E.C. was given a series of five maps depicting pathways to be followed among nine disc markers on the floor. She was instructed not to turn the map as she walked along the path. North was marked on the wall and on the map. The five maps had a total of 35 turns. Each correct turn was scored for each map and the total was summed over the maps for a total of 35 possible points. The instructions and test conditions replicated those described in Semmes *et al.* (1955, 1963) and Weinstein *et al.* (1956).

Standardized Road Map Test of Direction Sense (Money, 1976). E.C.'s task was to watch the experimenter trace a dotted pathway on a map with her pencil and to say whether a person walking on the path would turn left or right at each corner. E.C. was not allowed to turn her head, body or map.

Results

E.C. performed the Extrapersonal Orientation Test quickly and with confidence, scoring 31 out of 35 correct. Her performance was considerably better than the average performance of the control subjects tested by Semmes: in the same task, 17 male non-brain damaged controls with peripheral nerve damage in the legs or injuries to the radial or ulnar nerves scored an average of 26.5 (Semmes *et al.*, 1955). E.C. clearly does not have a general spatial impairment affecting performance on this task.

On the Road Map test, E.C. responded quickly and scored 30 out of 32. Impaired performance is considered to be to $\leqslant 22$ (Lezak, 1995). Thus, E.C. is within the normal range and has no left–right disorientation.

Experiment 2

Although the ability to interpret and use a map is a paradigm example of a spatial ability, on the surface it does not have much in common with the form of spatial ability thought to be required in tactile object recognition. A more direct way of testing for a supramodal deficit of shape integration in a subject with tactile agnosia is to assess the ability to integrate separately perceived parts of shape in the visual modality. We assessed this ability in three ways with E.C.

Methods

Hooper Test of Visual Organization (Hooper, 1958). E.C. recognized pictures of objects that have been cut up and rearranged, thus taxing the ability to integrate separately perceived parts of an object.

Direct test of integration in picture recognition. Some of the items in the Hooper test may be recognized on the basis of single object piece or feature, thereby eliminating the need for visual integration. We therefore developed a second test of visual integration in which the pictures have been cut up so that no individual piece can lead to recognition. In a validation study, normal subjects were shown single picture pieces and asked to recognize the depicted object on the basis of the single piece. Only those pictures that could not be recognized by any of their single pieces were included in the test. The two or three pieces of a picture were placed on separate cards and arranged vertically in front of E.C.. E.C. had to integrate the pieces to recognize the object. The pictures of the objects are a subset of the Snodgrass and Vanderwart (1980) set.

Peephole Visual Object Recognition. In order to test E.C.'s ability to recognize real objects visually with a need for integration comparable to that required by tactile object recognition, E.C. recognized real objects by viewing them through a peephole. A cardboard mask with a peephole the size of a fingertip was held at arm's length so that the board obscured most of object. The dimensions of the peephole were 2.0×2.5 cm, with 0.95° of visual angle. The dimensions of the stimuli ranges from 2.54×0.64 cm (safety pin) to 20.32×8.89 cm (bottle), with a range of 2.43–19.22° of visual angle. E.C. viewed the object by gazing through the peephole and moving it around. She was instructed not to move her eye up to the peephole, bring the peephole up to her eye, or expose the object. The object set was chosen from a set of common objects that E.C. could not previously recognize by touch (e.g. ribbon, tweezers, key chain).

Results

E.C. scored 27 out of 30 correct on the Hooper Test. Normal control subjects score between 25 and 30 (Hooper, 1958). E.C. is therefore within the normal range.

E.C. scored 18 out of 24 correct on the picture integration test. Normal control subjects (n = 8; mean age = 59.13 years) scored between 11–25 correct (mean = 18.13), suggesting that E.C. is within the normal range.

E.C. recognized all 29 objects that she viewed through the peephole, indicating that she can integrate separately viewed pieces of real objects to permit recognition in the visual modality.

Discussion of experiments in Part I

E.C. performs normally on a variety of tests of spatial ability, including tests designed to tax the ability to integrate separately perceived parts of visual shape, and the same test that Semmes (1965) used to detect an impairment of spatial ability in her subjects with tactile shape perception deficit. This implies that E.C.'s difficulty with tactile shape perception does not result from a more general problem with spatial ability. Additional confirmation may be found in Part II, Experiment 4 which tests E.C.'s performance at a tactile spatial task. The fact that E.C.'s tactile agnosia is confined to one hand is also difficult to reconcile with a generalized spatial impairment.

What is the underlying nature of the impairment? As mentioned in the case description, we have already reported that E.C.'s sensory processing is intact in both hands. Therefore, the breakdown in tactile object perception is bracketed at some level of processing between elementary sensation at one end and supramodal spatial representation and tactile memories at the other. In the following experiments we assessed further the intervening processing of objects perceived through touch by E.C.'s agnosic hand, and attempt to specify the spared and impaired abilities.

Part II. Delimiting the agnosic impairment: shape specificity and hand specificity

In an earlier study (Reed and Caselli, 1994), we hypothesized that E.C.'s impairment in tactile object recognition lies in some aspect of modality specific tactile perception. We demonstrated that her tactile agnosia is post-sensory and pre-mnemonic in that her sensory function was intact in both hands and she performed well at a tactile mental imagery task. The preceding experiments show that her spatial ability is also intact, as operationalized by good performance on the test used by Semmes to argue that a spatial impairment underlies tactile agnosia, and on other tests taxing shape integration. By a process of elimination, this suggests that the cause of E.C.'s tactile agnosia lies in some aspect of modality specific tactile perception. In the next set of experiments we obtain direct evidence for this hypothesis from drawing and matching tasks, and further delimit the impairment by distinguishing tactile shape perception from tactile spatial perception, thereby demonstrating an analogue of the visual 'what' versus 'where' distinction in the tactile modality. We also delimit the agnosic impairment in terms of body surfaces affected.

Experiment 3

In this experiment we asked E.C. to recognize objects by touch, and to draw those objects she failed to recognize. This provides a rich (albeit difficult to quantify or normalize) source of evidence on her tactile object perception.

Methods

E.C. identified a set of 28 common objects by touch using her agnosic hand (e.g. combination lock, cassette tape, umbrella). For those objects she could not identify within 2 min, E.C. was immediately handed a sheet of paper and a pencil and asked to draw a picture of what she had felt.

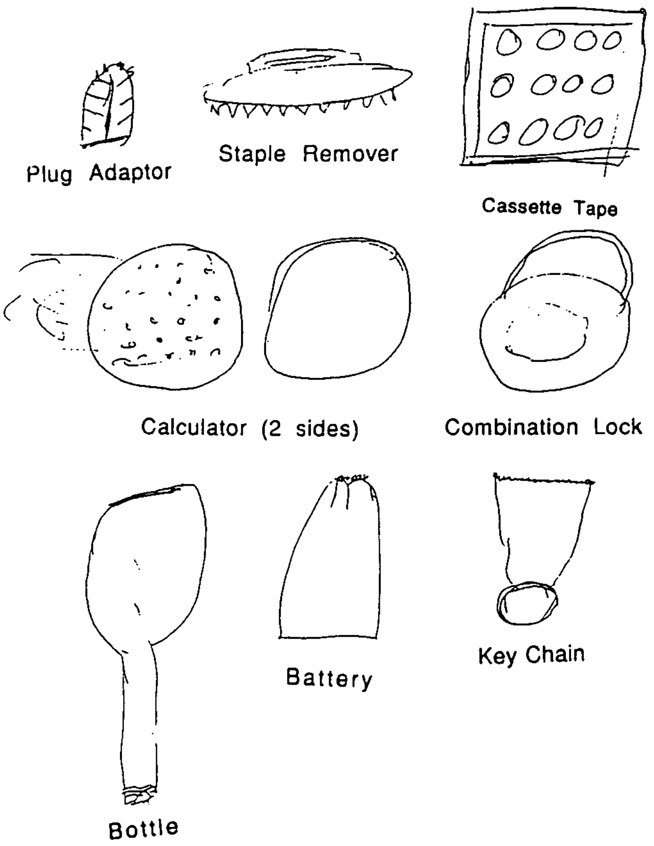

Fig. 2 Experiment 3. E.C.'s drawings of objects she failed to recognize when exploring them tactually with her agnosic right hand. The identity of each object is indicated beneath each drawing.

Results and discussion

E.C. failed to recognize 15 of the 28 objects with her agnosic hand. A selection of her drawings of these objects are illustrated in Fig. 2. Note that in many of these drawings various aspects of object shape are not accurately represented. If one examines the drawings of the staple remover, calculator, cassette and plug adapter, the pictures suggest that while E.C. was able to extract the basic contour or outline of the object in general, she tended to miss the internal details or she includes too many instances of a particular detail. In contrast, her drawing of the bottle, battery and key chain demonstrate a roughly correct form, although still unrecognizable. Taken together, these drawings suggest that E.C. has some difficulty acquiring a representation of an object's shape from tactile apprehension.

Experiment 4

Evidence for dual streams of cortical visual processing, the 'what versus where' pathways, has become widely accepted. Anatomically, a ventral system interconnects striate, prestriate, and inferior temporal areas, and is required for the visual identification of objects, and a dorsal system interconnects striate, prestriate and inferior parietal areas, and is involved in the visual localization of objects (Mishkin *et al.*, 1983; Van Essen and Maunsell, 1983). Anatomical and behavioural studies in both monkeys (Mishkin, 1979; Friedman *et al.*, 1986) and humans (Caselli, 1993) has led to the hypothesis that an analogous 'what/where' distinction may exist in the cortical somatosensory system.

In this experiment, we tested the hypothesis that E.C.'s unimanual tactile impairment was confined to shape perception ('what'), and does not affect spatial perception ('where'). A series of experiments by Horwitz, Grady, Haxby and colleagues (Haxby *et al.*, 1991; Horwitz *et al.*, 1992) were designed to show functional differentiation among human posterior extrastriate brain regions during object and spatial vision. We modified their tasks to create tactile versions of these experimental paradigms. In the Horwitz *et al.* (1992) study, a variation of the Test of Facial Recognition (Benton and Van Allen, 1973) was used to assess object recognition. This test requires subjects to match faces whose superficial appearance is transformed by changes in lighting and perspective. We created a tactile test to maintain the flavour of the transformation required in the face recognition test. Because tactile face recognition is not feasible, our recognition task required subjects to identify a capital letter and match it to a lower case version of it. The localization task required subjects to match the spatial position of a dot within a box, exactly as in the Horwitz *et al.* (1992) study except the stimuli were palpated rather than viewed.

Methods

Tactile object recognition was assessed with a two alternative, match to sample task. The sample stimulus was a capital letter and the two choice stimuli were lower case letters. E.C. pointed to the choice that matched the sample stimulus.

Tactile spatial processing was assessed using a two alternative, match to sample localization task. A sample square was placed next to two alternatives. The sample stimulus consisted of a dot in a square on one side of which was a double raised line. The choice stimuli were rotated either 0, 90 or 180° relative to the sample. E.C. determined which choice square had the dot in the same location relative to the double line as the sample stimulus. The square was 2.54×2.54 cm and was constructed from toothpicks; the double raised line was a two layer, double row of toothpicks.

Results

For the object recognition task, there was a significant asymmetry between performance for the agnosic hand, 59.6% (31 out of 52) correct, and the control hand, 96.2% (50 out of 52) correct [$\chi^2(1) = 20.15$, $P < 0.0001$]. In contrast, control subjects ($n = 3$, mean age = 63 years) were 92% and 90.67% correct for left and right hands, respectively, and showed no asymmetry [$\chi^2(1) = 0.22$, $P > 0.10$].

For the location task, no difference was found between the performance of the agnosic hand, 87.5% (105 out of 120) correct and of the control hand, 93.3% (112 out of 120) correct [$\chi^2(1) = 2.408$, $P > 0.10$]. Control subjects also showed no asymmetry in performance between the two hands, 95% (57 out of 60) versus 90.56% (54.3 out of 60) [$\chi^2(1)= 1.08$, $P > 0.10$]. The asymmetry of errors between the two hands for E.C. is also not significantly different from that of the control group [$\chi^2(1) = 0.053$, $P > 0.10$]. Thus, E.C. has preserved localization ability. She was able to perform mental rotation and spatial localization of tactile stimuli.

In summary, there is a dissociation between tactually mediated shape recognition and localization functions in our tactile agnosic, supporting the existence of a tactile 'what/where' distinction in the human brain.

Experiment 5

Tactile shape perception is normally a function of the hand. This suggests that a disorder of tactile shape perception could be specific to the hand. In the next two experiments, we address the question of whether E.C.'s tactile agnosia is specific to the hand or whether the deficit affects other parts of the body as well. In the present experiment, we examine passive shape identification on the hand (the part of the body commonly used for tactile object recognition), on the arm (the part of the body used for positioning the hand) and on the cheek (a part of the body rarely used for shape recognition).

Methods

The experimenter traced numbers (1–9), letters (A, B, C, F, J, R, S, W, Z) and common shapes (star, triangle, heart, flower, arrow, circle, square, moon, diamond) on E.C.'s palms, forearms and cheeks using a blunt pointed instrument. Given that different parts of the body surface have different frames of reference (Parsons and Shimojo, 1987), care was taken to draw the letters in the proper orientation from the point of view of the subject.

Results and discussion

The results suggest that tactile agnosia is restricted to the hands. E.C.'s performance on passive palm identification showed a significant difference between her agnosic 77.8% correct (42 out of 54) and control hands 92.6% correct (50 out of 54) [$\chi^2(1) = 4.70$, $P < 0.03$]. In contrast, no asymmetries were found for passive forearm identification [right 70.4% (38 out of 54) correct, left 70.4% (38 out of 54) correct], nor for passive cheek identification [right 72.2% (39 out of 54) correct, left 75.9% (41 out of 54) correct]. Control subjects showed no reliable asymmetries for passive identification on the hand (right 79.6%, left 83.3%), forearm (right 66.7%, left 70.4%) or cheek (right 64.8%, left 66.7%). Thus, E.C. showed an abnormal asymmetry only in her hand identification. In addition, her overall performance deviated from normality only with her hand; E.C.'s forearm and cheek identification was as good as that of the normal subjects.

Experiment 6

The previous experiment involved passive tactile recognition. In this experiment, we examined the question of effector specificity for tactile agnosia. We investigated whether asymmetries in tactile object recognition extended to another part of the body that can also explore and manipulate objects, namely the feet.

Methods

E.C. was given a set of 25 common objects to recognize tactually using her feet. The objects were selected to be recognizable using a single foot as an exploring effector (e.g. sock, shoe, comb). The objects were presented in random order, one at a time to a foot so that at the end of the experiment, each foot had felt each object. No time or exploration restrictions were imposed with the exception that the subject could only use one foot to explore the object.

Results

E.C.'s object identification performance with her feet produced no asymmetry between her left foot (12 out of 25) and her right foot (15 out of 25) [$\chi^2(1) = 0.73$, $P > 0.10$]. Control subjects ($n = 5$, mean age 61.6 years) also showed no asymmetry between left (12 out of 25) and right (12.75 out of 25) feet [$\chi^2(1) = 0.8$, $P > 0.10$].

Discussion of experiments in Part II

The experiments in Part II suggest that our tactile agnosic's deficit is specific to shape *per se*. Her drawings of palpated objects show misperceptions of various aspects of shape. Our experiments indicating a dissociation between 'what' and 'where' tactile processing also support this finding, demonstrating impairments in shape perception but not localization.

Our findings also provide some evidence that tactile agnosia may be specific to the hand. No asymmetry of graphaesthesia or tactile object recognition could be demonstrated in any other bodily region except the palmer surface of the hands.

Part III. Specifying the tactile shape perception impairment

In the next set of experiments we systematically test various aspects of shape perception in order to specify what aspect or aspects are impaired in tactile agnosia. These tasks progressively increase in the complexity of shape information required, and also assess the role of exploratory hand movement.

Experiment 7

We investigated whether basic metric information was accurate by asking E.C. to tactually estimate the lengths of eight wooden dowels [0.5 inch (1.27 cm)–7 inch (17.78 cm)] to the nearest 0.25 inch (0.64 cm). With eyes closed, E.C. felt the dowel with one hand and verbally stated its length. There were no restrictions to exploration with the exception that it be unimanual. Trials were blocked by condition: agnosic hand, control hand, and vision. There were four trials for each dowel for a total of 32 trials per condition. The dowels were presented in random order.

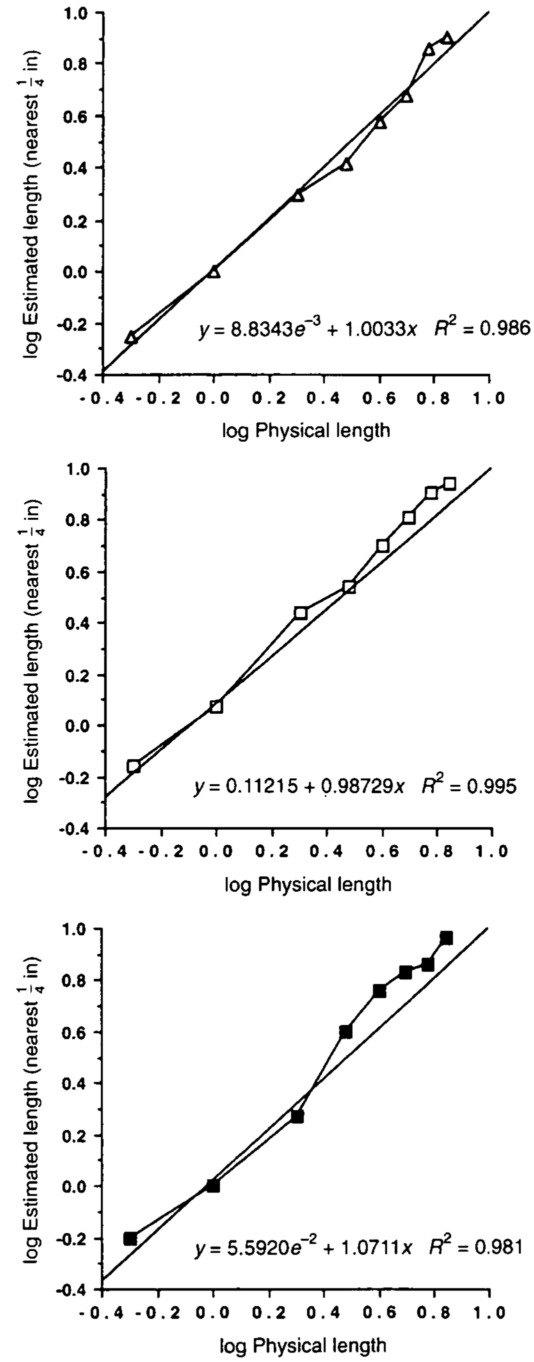

Fig. 3 Experiment 7. Lengths of dowels were estimated by E.C. using her left control hand (filled squares), her right agnosic hand (open squares) and vision (open triangles). Length estimates are plotted against the actual lengths in log–log coordinates.

Results

Length estimates were plotted against the actual lengths in log–log coordinates (Fig. 3). No difference was found between length estimates made with her agnosic hand, her control hand and vision. Converging evidence is found with a test of length estimation error (the difference between actual length and estimated length) which revealed no asymmetry between hands [$t(61) = 1.66$, $P > 0.10$]. Additional evidence that basic metric information is accurate can be found in her performance on the localization test in Experiment 5: E.C. could accurately judge the distance of a raised dot from the side of a box. Thus, basic metric information is accurately registered, at least for simple length judgements.

Experiment 8

Shape, however, requires more than the perception of a single length. It depends on the simultaneous apprehension of spatial extent in multiple dimensions. The next test assessed E.C.'s ability to make simple ordinal judgements of two dimensions of a shape: which dimension of a complex polygon was the longest. Stimuli were eight asymmetrical polygons constructed from foamcore. Exploration was not restricted with the exception that it be unimanual. Trials were blocked by condition: agnosic hand, control hand and vision.

Results

E.C. demonstrated perfect performance using her agnosic hand (24 out of 24), her control hand (24 out of 24) and vision (24 out of 24). Thus, E.C. is not impaired in her ability to perceive the relative length of different dimensions of a complex shape.

Experiment 9

Shape perception requires more than an appreciation of ordinal relationships, such as 'longest' among the dimensions of the shape. It requires the simultaneous perception of the precise metric relationships among the shape's dimensions. Furthermore, perception of shape is not psychologically a simple summation of the perceptions of the shape's individual dimensions (Shepard, 1964). To assess E.C.'s ability to perceive relative length to width ratios of an object, we constructed a tactile version of a task developed for the analogous purpose with visual agnosia by Efron (1968). E.C. compared pairs of rectangular stimuli with equivalent surface areas but different length to width ratios. The seven rectangles varied in proportion from 1:1 (squares) to 1:12.5. In Efron's visual test, two rectangles were compared simultaneously on the basis of their proportions and a same/different response was required. In the tactile version, pairs of rectangular foamcore stimuli were compared sequentially, using only the agnosic hand, the control hand or vision. There was a total of 48 trials, with an equal number of same and different trials.

Results

With the tactile stimuli, normal control subjects ($n = 4$, ages 50–61 years) are, on average, 100% accurate using vision (24 out of 24), and 89.6% (43 out of 48) accurate using touch. There is no significant difference in performance between left and right hands [$\chi^2(1) = 0.67$, $P > 0.10$]. E.C. also demonstrated little difficulty with visual comparisons, making only one error in the 1:1 rectangle comparison condition. In contrast, E.C. demonstrated a significant asymmetry in performance between her two hands [$\chi^2(1) = 5.315$, $P < 0.02$]. With her control hand, E.C. was 89.6% (43 out of 48) accurate. Errors occurred only on the 'same' rectangle comparisons (three out of 24) and most similar comparison (two out of four). With her agnosic hand, E.C. was 70.8% accurate (34 out of 48). The majority of the errors were for the 'same' rectangle comparisons (nine out of 24) and for the most similar comparison (four out of four). Only one error was made for comparisons of greater detectability. Thus, this more demanding discrimination of relative proportion produces an asymmetry in performance between agnosic and control hands. E.C.'s performance is analogous to the performance of patients with visual apperceptive agnosia, also called visual form agnosia, in that the impairment affects the perception of aspect ratio of fairly simple shapes.

Experiment 10

In the next two experiments, we investigated whether E.C. could integrate shape with other object properties. In order for an object to be recognized, perceptual information regarding its particular properties must be combined or integrated to form an object representation (Garner, 1974). Shape and size are highly integrated in normal perception, i.e. people involuntarily process information about both properties simultaneously (Reed *et al.*, 1990).

We first established that E.C. could tactually discriminate stimuli on the basis of shape and size alone. Stimulus objects were planar (1.25 cm thick), hand sized, corduroy covered, balsa wood shapes (for a more detailed description, *see* Klatzky *et al.*, 1989). The shapes were oval, hourglass-shaped, and clover-shaped (three-lobed) and the sizes were small (surface area = 17.4 cm^2), medium (32.9 cm^2) and large (52.9 cm^2). E.C. was told which value of a property was classified as an 'A', 'B' or 'C' category. All properties (e.g. size, hardness, texture) but the classification property (shape) were held constant. E.C. then classified the set of objects as As, Bs and Cs.

Results

With either hand, E.C. could discriminate and classify the stimulus set on the basis of both shape and size at relatively high levels of performance and without a significant asymmetry. When categorizing by shape, E.C. was 83.3% (20 out of 24) accurate with her agnosic hand and 95.8% (23 out of 24) accurate with her control hand [$\chi^2(1) = 2.01$, $P > 0.10$]. When categorizing by size, E.C. also showed little difference between the two hands (24 out of 24 for agnosic hand, 23 out of 24 for control hand).

Experiment 11

A sensitive task to determine whether E.C. normally and simultaneously processes (i.e. integrates) shape and size is the withdrawal task (Klatzky *et al.*, 1989; Reed *et al.*, 1990; Lederman *et al.*, 1993). The withdrawal task is a speeded classification task in which there are initially two possible ways to classify objects (e.g. shape and size: A = oval and small, B = hourglass and medium, C = clover and large). In this task, the subject focuses her attention on one dimension (e.g. shape) but she is not informed that another dimension (e.g. size) is also relevant to the classification decision.

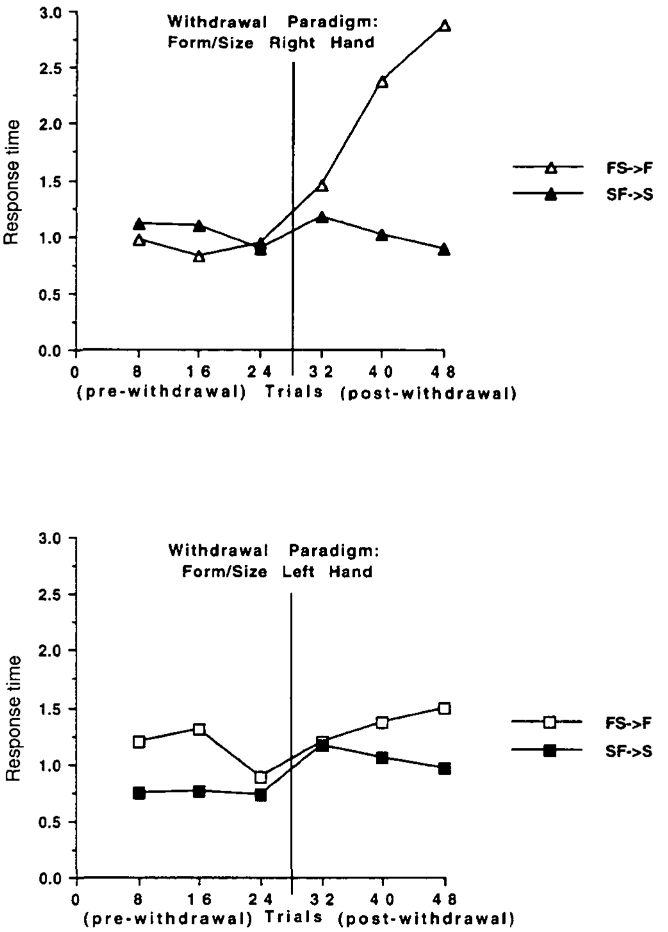

Fig. 4 Experiment 11. E.C.'s response times for the withdrawal task using her left control hand and right agnosic hand. Data points to the left of the line are part of the pre-withdrawal period in which two sources of information can be used for classification; data points to the right of the line are part of the post-withdrawal period in which only one source of information can be used for classification. FS→ F: shape (form) and size are redundant and size is withdrawn; SF→ S: shape (form) and size are redundant and shape (form) is withdrawn.

After a series of trials, the implicitly relevant dimension is withdrawn from classification and made constant (e.g. A = oval and medium, B = oval and medium, C = clover and medium). We examine the effect of this withdrawal on response time performance using the stimuli described in Experiment 10. According to Garner (1974), if two dimensions are being integrated or processed together, response times before withdrawal should be significantly faster than response times after withdrawal because the subject is able to make use of both types of relevant information. Thus, if E.C. were using both dimensions to classify the objects, then the withdrawal of the implicit dimension should impair performance.

Results

Response times for the withdrawal task are illustrated in Fig. 4. Response times for the control hand mirror normal performance. After an initial decrement in performance after the implicit property is withdrawal, there are indications of a relearning curve. *t* test comparisons for the response times of the eight trials before and eight trials after withdrawal show significant decrements in performance post-withdrawal [$t(14) = 2.31$, $P < 0.03$ for size/shape; $t(14) = 2.53$, $P < 0.03$ for shape/size]. Response times in the shape/size for the agnosic hand also show significant decrements in post-withdrawal response times [$t(14) = 3.90$, $P < 0.0001$]. What is unusual about the performance with the agnosic hand is that in the shape/size condition, E.C. relied primarily on size information, even though she was told to focus on shape information. Thus, when size was removed from categorization there was a large withdrawal effect from which E.C. never recovered. There was no re-learning curve or subsequent decrease in response times. In addition, there was a corresponding increase in categorization errors. However, in the size/shape condition there was no withdrawal effect [$t(14) = 1.23$, $P > 0.10$]. It appears that E.C. relied exclusively on size information.

In summary, E.C. can categorize simple shapes with her agnosic hand. Although the withdrawal task suggests that she is aware of the correlation between shape and size information, E.C. avoided using shape information when possible. It appears that E.C.'s tactile object recognition deficit is not a result of integrating object properties *per se*. Instead, her performance suggests a problem with shape processing in particular.

Experiment 12

Increasing shape complexity further, we assessed E.C.'s ability to recognize overlearned, familiar two-dimensional and three-dimensional shapes. The two-dimensional shapes (square, rectangle, parallelogram, diamond, circle, oval, triangle, pentagon, hexagon, heart, star) were constructed from foamcore. The three-dimensional shapes (cube, sphere, cone, egg, triangular form, rectangular form, cylinder, pyramid, dome) were either bought or constructed out of Styrofoam. All objects were hand sized. E.C. either named or described the object. Trials were blocked by stimulus type (two-dimensional, three-dimensional) and condition (agnosic hand, control hand and vision).

Results

In the two-dimensional shape recognition task, E.C. was 33.3% accurate (12 out of 36) with her agnosic hand and 83.3% (30 out of 36) accurate with her control hand. Two shapes, the parallelogram and hexagon, were eliminated from the analyses because E.C. could not name them when presented visually. Despite this elimination of unknown shapes, there was a large asymmetry in performance between the two hands [$\chi^2(1) = 18.51$, $P < 0.0001$]. In the three-dimensional shape recognition task, E.C.'s performance was markedly better. With her agnosic hand she was 88.9% (34 out of 38) accurate and with her control hand and vision she was 100% accurate. Although there was still a significant asymmetry between the two hands [$\chi^2(1) = 4.22$ $P < 0.04$], it was much less. Comparing performance for two-dimensional and three-dimensional shape recognition, two-dimensional objects were more difficult to recognize for both the agnosic hand [$\chi^2(1) = 24.771$ $P < 0.0001$], and the control hand [$\chi^2(1) = 5.15$, $P < 0.03$]. The ease of tactually extracting three-dimensional shape information is also seen in control data for which recognition performance is superior for three-dimensional familiar shapes [$\chi^2(1) = 10.48$, $P < 0.002$]. Control data showed no asymmetry between hands.

These results indicate that E.C. has an asymmetrical impairment in recognizing familiar shapes. However, her performance is better for three-dimensional than two-dimensional shapes. This finding may seem counter-intuitive because one might think that three dimensions would add complexity, especially in terms of depth and increased variation. However, response times from normal studies in which subjects classify either planar or volumetric stimuli by shape shows that three-dimensional stimuli can be identified in approximately half the time of two-dimensional stimuli (Reed, 1994).

Experiment 13

We next examined E.C.'s ability to distinguish between unfamiliar complex shapes. On this task, she could not derive clues to recognition from previous knowledge (top down processing). E.C. compared pairs of complex planar shapes and made same/different responses. The stimuli were constructed out of balsa wood and were hand sized (6×4.5× 0.7 cm). The shapes are illustrated in Fig. 5; distracters were made by eliminating the checked portions. E.C. was given no restrictions of time or exploration. She was permitted to re-sample the stimuli. Performance was compared for her agnosic hand, control hand and vision.

Results

Although her visual discrimination was 100%, E.C. was at chance 54% (13 out of 24) with her agnosic hand. In contrast, she was 92% correct (22 out of 24) with her control hand [$\chi^2(1) = 8.55$, $P < 0.004$]. These results indicate that E.C. has difficulty forming a tactile representation of a object with a complex shape.

Experiment 14

Is the impairment of shape secondary to a faulty exploration strategy? Exploration can affect shape perception in two ways. First, E.C.'s impairment may be a problem of extracting the information simultaneously instead of a faulty representation of shape. The sequential nature of touch places an extreme load on integrating processes necessary for the representation of shape. In addition, larger objects require more integration of contour than smaller items. Second, E.C.'s impairment may be a problem of incomplete exploration. She may not contact those critical details that distinguish the two objects. The next two experiments address these questions.

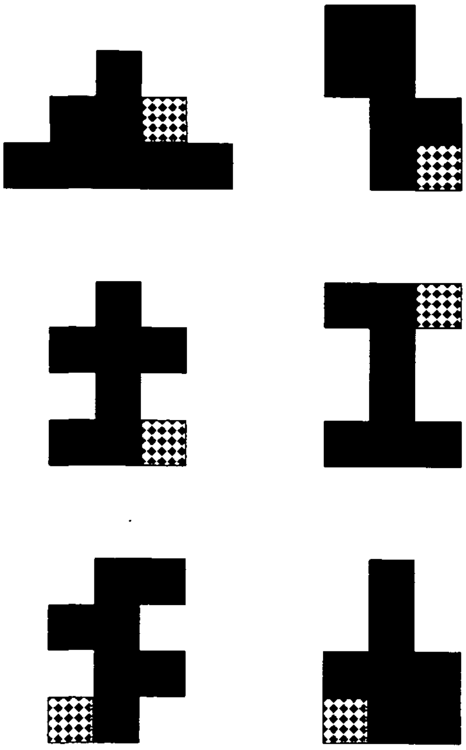

Fig. 5 Experiment 13. Illustration of unfamiliar complex shapes. Patterned region indicates the piece that was removed to construct the distractor stimuli.

Shape discrimination performance for simultaneous and sequential information acquisition was compared. For the simultaneous information condition, E.C. compared small balsa wood shapes (4×3 cm) which could be felt in a single grasp. For the sequential information condition, E.C. compared large balsa wood shapes (11.5×8 cm) which required multiple grasps or a dynamic tracing of the stimulus' contour. The shapes were the same as those in the previous task. Same/different judgements were made. Again, E.C. was given no restrictions in exploration, no time limits and was allowed to re-sample the stimuli.

Results

As with the hand sized stimuli of the previous task, E.C. was at chance for both sizes of complex shapes with her agnosic hand [54% (13 out of 24) small, 58% (14 out of 24) large]. However, with her control hand she was 87.5% (21 out of 24) and 96% (23 out of 24) accurate for small and large stimuli, respectively. Clearly, her performance with her control hand surpassed her performance with her agnosic hand for both small stimuli [$\chi^2(1) = 6.45$, $P < 0.02$] and large stimuli [$\chi^2(1)=9.55$, $P < 0.002$]. Thus, the exploration manipulation had little effect. Larger objects that forced E.C. to follow the contours and acquire information sequentially, induces no difference in performance compared with small objects for which information can be acquired simultaneously [agnosic hand, $\chi^2(1) = 0.085$, $P > 0.10$; control hand, $\chi^2(1) = 1.09$, $P > 0.10$].

Experiment 15

In this experiment, we tested the possibility that E.C.'s shape impairment was a result of a failure to explore the complete object. To ensure complete object exploration, we compared a guided exploration condition with the free exploration condition. E.C. compared two complex polygons and made same/different judgements. From the above medium-sized stimulus set, we chose a subset of eight stimuli. For the free exploration condition, E.C. was allowed up to 20 s to explore the first object. Unlike the previous tasks, she was not permitted to re-sample the stimuli. In the guided exploration condition, E traced E.C.'s finger around the perimeter of the shapes twice. E.C. was told when one tracing was completed. Trials were conducted using an ABBA design.

Results

E.C.'s performance with her agnosic hand was 57.8% (37 out of 64) accurate for free exploration and 68.8% (44 out of 64) accurate for guided exploration. No significant effects of exploration were found for her agnosic hand [$\chi^2(1) = 1.62$, $P > 0.10$]. Her performance with her control hand was 87.5% (56 out of 64) accurate for free exploration and 85.9% (55 out of 64) accurate for guided exploration. Again there were no effects of exploration [$\chi^2(1) = 0.068$, $P > 0.10$]. However, performance with the control hand was significantly better than the agnosic hand in both the free exploration condition [$\chi^2(1) = 14.20$, $P < 0.002$] and the guided exploration condition [$\chi^2(1) = 5.40$, $P < 0.03$]. Visual performance was 100%.

In summary, her performance with her agnosic hand was inferior to that of her control hand under the same conditions. Her performance improved only slightly with externally guided exploration. Thus, this difference between performance on agnosic and control hands cannot be accounted for by incomplete exploration. Further support for this claim can be found above in the passive shape recognition task of Part II, Experiment 5. Although shapes were drawn on her palm and no exploration was required, her shape recognition with her agnosic hand was still impaired.

Experiment 16

In the final experiment, we investigated whether E.C.'s impairment was a problem of keeping track of multiple features. In particular, would E.C.'s performance be affected by an increase in the number of parts in a pattern? E.C.'s drawings of the staple remover, cassette tape and plug adapter in Experiment 3 suggested this possibility. We constructed one, two and three element stimuli using clay and clay tools. The stimuli were flat, rectangular pieces, approximately 6×4×1.5 cm. Feature types and positions were varied. The elements were basic shapes, triangles, circles, and squares. They were placed in various locations within the rectangular area. Stimuli could be different in terms of shape or location. E.C. compared two stimuli and made same/different judgements. Visual performance was 100%.

Results

Our results indicate that E.C.'s deficit, or asymmetrical performance between agnosic and control hands, increases as the number of features or shapes increases. For one-shape stimuli, there was no significant difference between the agnosic hand [88.9% (24 out of 27) correct] and the control hand [96.3% (26 out of 27) correct] [$\chi^2(1) = 1.08$, $P > 0.10$]. However, there was a significant difference between the agnosic hand [77.8% (21 out of 27) correct] and the control hand [96.3% (26 out of 27) correct] for two shape stimuli [$\chi^2(1) = 4.10$, $P < 0.05$]. The difference increased between the agnosic hand [66.7% (18 out of 24) correct] and the control hand [92.6% (25 out of 27) correct] for three shape stimuli [$\chi^2(1) = 5.59$, $P < 0.02$]. Thus, the deficit increased with the complexity of the stimuli.

Discussion of experiments Part III

E.C. clearly has a problem with shape perception. With a series of shape perception tasks, we increased task difficulty by increasing shape complexity and decreasing familiarity. Although she was able to process metric distance, ordinal dimensions and simple overlearned shapes, her deficit became more pronounced the more complex the shape or stringent the judgement. This deficit cannot be attributed to disorganized exploration. Further, it appears that E.C. has a particular problem of keeping track of object parts.

General discussion

E.C. has a unilateral tactile agnosia, that is, a unilateral impairment of tactile object recognition that is not attributable to impaired sensation. In the foregoing experiments, we addressed a series of questions about tactile agnosia, starting with its very existence as a selective impairment of tactile object recognition. In contrast to the predictions of the alternative hypothesis of Semmes and others, that tactile agnosia is secondary to a general impairment of spatial ability, E.C. showed no general spatial impairments. She performed well on the tests of spatial ability originally designed to tax the same spatial integration process assumed to be taxed by tactile object recognition. We therefore conclude that E.C.'s impairment is specific to tactile perception.

Within the realm of high level perception, we separately assessed her ability to derive shape ('what') and spatial ('where') information from touch, and found her impairment confined to shape perception. Shape perception was further explored in a series of experiments varying the precision of the information demanded, and the role of exploratory hand movements in the encoding of shape. Despite accurate encoding of metric length, two-dimensional and three-dimensional shapes posed a problem for this subject, the more so the more complex they were, and faulty exploration was not responsible for this impairment. The asymmetry of E.C.'s performance with her hands was not found with other body surfaces. However, given the poor level of normal subjects' performance with foot mediated object recognition it is likely that tactile object recognition is a specialized function of the hand, and therefore not surprising that E.C.'s impairment is apparent primarily in hand mediated object recognition.

Our results suggest that tactile agnosia can result from an impairment of shape representation specific to the tactile modality, distinct from impairments of earlier sensory tactile perception. This could be caused by a loss of modality specific tactile representations of shape or high level shape features, or by a disconnection between early somatosensory representations of her right hand and higher level representations that are not modality specific. Note that such a disconnection would have to be quite specific, undercutting the efferents to shape representations and not to spatial representations, but such a disconnection is, in principle, possible, and therefore remains a possibility for explaining tactile agnosia, just as it does for explaining visual agnosia. Nevertheless, whether caused by a disconnection from amodal shape representations or a loss of modality specific shape representations, E.C.'s tactile agnosia supports the existence of a system specialized for tactile shape recognition, in contrast to amodal spatial perception or even modality specific spatial perception.

In comparing tactile agnosia to visual agnosia, the most analogous form of visual agnosia would appear to be apperceptive visual agnosia (for review, *see* Farah, 1990). Whereas in associative visual agnosias, shape perception is grossly intact, in apperceptive visual agnosia the perception of shape is impaired despite good elementary sensory function (e.g. Efron, 1968; Benson and Greenberg, 1969). An apparent difference, however, between E.C. and patients with apperceptive visual agnosia is that E.C.'s impairment is unilateral. However, unilateral visual agnosia has occasionally been reported (Mazzucchi *et al.*, 1985; Charnallet *et al.*, 1988).

Another difference between the visual and tactile agnosia is their impact on daily functions. E.C. can sometimes recognize even complex objects by touch, whereas apperceptive visual agnosia precludes object recognition. In part, this may be simply a matter of the severity of E.C.'s agnosia. Another explanation, however, may reflect the different roles of shape perception in tactile and visual object recognition. Klatzky *et al.* (1987) found that when classifying objects on the basis of several equally discriminable object properties, visually classified objects were grouped primarily by shape in contrast to tactually classified objects which were grouped by texture, hardness and, to a lesser extent, shape. Thus, evidence from the normal tactile object recognition literature supports the idea shape plays a different role in tactile and visual object representations.

Finally, the clear somatosensory nature of E.C.'s deficit and the location of her parietal lesion strongly suggests that inferior parietal cortices have a somatosensory function in humans. Homologies with subhuman primates are unclear for this neuroanatomical region. In monkeys, the inferior parietal lobule comprises Brodmann area 7 which has well-known visual and somatosensory functions. In humans, however, Brodmann area 7 is entirely above the intraparietal sulcus. Our studies show that at least some somatosensory functions are retained by inferior parietal substrates in the evolutionary leap to the human brain.

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