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Haptic processing by the left hemisphere in a split-brain patient

MARYSE BADAN* and ALFONSO CARAMAZZA†

*Faculty of Psychology and Educational Sciences, University of Geneva, 9, route de Drize, 1227 Carouge, Geneva, Switzerland; and †Department of Psychology, William James Hall, Harvard University, 33, Kirkland Street, Cambridge, MA 02138, U.S.A.

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Abstract—We report the case of a patient who suffered an ischemic accident resulting in damage to the anterior part of the corpus callosum and to the white matter in the posterior right hemisphere. Recognition of two-dimensional haptic stimuli explored with the right hand was severely impaired. The deficit was not specific to the type of stimuli, since letters, digits and geometrical shapes were not correctly recognized. Poor performance was not due to a specific mode of haptic exploration, since deficits were also observed without active manipulation of the stimuli. In contrast, the patient correctly named visual letters presented in the right visual hemifield (left hemisphere), and recognized three-dimensional common objects palpated with the right hand. Comparable results were observed in a surgical split-brain patient tested as a control. We conclude that (i) the construction of spatial representations of haptic stimuli, such as two-dimensional stimuli or three-dimensional block letters, cannot be fully realized in the intact left hemisphere, this ability requiring the contribution of both hemispheres, and (ii) tests for correct naming of common objects do not provide sufficient evidence to establish the integrity of the system involved in the identification of haptic information processed by the right hand of split-brain patients. © 1997 Elsevier Science Ltd.

Key Words: hemispheric specialization; hemispheric disconnection; left hemisphere; haptic recognition; single case study.

Introduction

The superiority of the right hemisphere for processing non-verbal stimuli is well established for spatial information, face and music [7, 13, 15, 19], and is also confirmed by a number of studies on haptic identification in normals. In right handers, a left-hand superiority has been observed in various haptic tasks, such as perception of lines varying in direction [3] and recognition of shapes presented in different orientations [10]. In a tactile letter-naming task, Hunt *et al.* [18] showed a left-hand advantage, although the effect remained significant only when novel stimuli were involved. Right hemisphere dominance has also been evidenced with the dichhaptic method, which requires the simultaneous exploration of two objects by both hands, without sight of the objects [27, 28]. Oscar-Berman *et al.* [25] reported a right-hand superiority in letter identification and a left-hand superiority for lines differing in orientation, whereas no differences were found for digits (see Summers and Lederman [26] for a detailed critical review of this issue).

Additional evidence for right hemisphere superiority in haptic manipulation comes from studies with brain-damaged patients. Bottini *et al.* [5] compared the performance of right and left hemisphere damaged patients in a haptic–visual matching task using objects and meaningless shapes. The performance of patients with right hemisphere damage was worse with meaningless shapes than with objects. Franco and Sperry [12] used two- and three-dimensional geometric shapes in a visuo-tactile matching task to test patients with either a partial (anterior) or a complete sectioning of the corpus callosum. The results showed a strong left hand–right hemisphere superiority for both two-dimensional (2-D) and three-dimensional (3-D) stimuli. By administering different visuo-spatial tasks (block design, cube drawing, wire figures, fragmented stimuli) to a callosal-sectioned patient, LeDoux *et al.* [22] observed superior performance of the left hand over the right hand.

Impairments in naming stimuli explored haptically (tactile aphasia or tactile anomia) have been mainly reported in split-brain patients for the left hand [6, 9, 15, 16]. The impairments can occur in the absence of any

* Address for correspondence: Faculty of Psychology and Educational Sciences, University of Geneva, 9, route de Drize, 1227 Carouge/Geneva, Switzerland; e-mail: badan@ibm.unige.ch.

other deficit in naming, and in the absence of tactile agnosia. These results have been interpreted as reflecting a disconnection between the right hemisphere and the cortical areas responsible for language in the left hemisphere. Few cases of bilateral tactile aphasia following left hemisphere damage have been described [2, 11]. These results, however, are difficult to reconcile with the absence of tactile anomia when the right hand of split-brain patients is tested with common objects, which suggests that the left hemisphere's capacities in haptic perception are not negligible.

The purpose of this study is to investigate further the left hemisphere's abilities in processing spatial information in the haptic modality. The ideal situation for doing so is to test patients in whom the contribution of the right hemisphere is prevented by an interhemispheric disconnection while the functionality of the left hemisphere is unaffected. We studied the recognition of 2-D stimuli by the right hand in a patient (AW) who suffered an ischemic accident resulting in damage to the corpus callosum and right posterior white matter. This patient, previously tested by Baynes *et al.* [1], showed clear evidence of interhemispheric disconnection. In particular, naming impairments occurred when AW explored objects with the left hand (15% correct). Remarkably, naming performance following right hand palpation was almost perfect (97% correct), suggesting a fully developed ability of the left hemisphere to generate an abstract representation of the explored objects. This paradoxically good performance of the left hemisphere, which is not supposed to be specialized for spatial processing, was investigated in depth by testing AW with an extensive battery of haptic tests.

Case report

AW is a right-handed woman born in 1938, who completed 10 years of formal education and was employed as a laboratory technician. In 1984, she underwent surgery for coronary artery disease. In August 1989, she was hospitalized following intermittent neurological symptoms, including the complaint that her left hand did not 'belong to her'. Oral language was normal, but she presented with left homonymous hemianopia, left hemiparesis, decrease in the cutaneous sensitivity on the left side of her body, decrease in proprioception in the left extremities and left tactile anomia. Medical examination revealed hypodensity in the right medial occipital and parietal lobes, and occlusion of the right internal carotid artery. A detailed neurological description and follow up is provided in Baynes *et al.* [1] and briefly summarized here.

At the time of testing, AW is reported to have presented with left apraxia, left homonymous hemianopia and left side sensory loss, but no left hemiparesis. Neuropsychological examination attested that verbal intelligence and memory were in the normal range, but that visuo-spatial skills were slightly impaired. Tested for signs of interhemispheric disconnection [4], the patient presented with unilateral left agraphia, unilateral left ideomotor apraxia, constructional apraxia, auditory suppression (left ear), lack of somesthesic transfer and left tactile anomia. In addition, AW also complained about the lack of control of her left hand, pointing out that, in some instances, her left hand acted inconsistently with the actions of her right hand. Brain imaging examinations (magnetic resonance imaging, MRI) showed an important thinning of the corpus callosum, extending from the anterior body to the splenium. There were also lesions in the right calcarine cortex, right hippocampal region and right posteromedial parietal lobe.

In February 1994, additional physical exams were performed on AW establishing the stability of her impairments. Moderate ataxia, hemianopia and alien left hand syndrome were confirmed. Given that some right visual field changes were experienced by the patient, additional brain imaging examinations were performed, but they failed to show any recent cortical damage in the left hemisphere. Clearly, one cannot rule out with absolute certainty that a residual deficit has eluded these controls. At the same time, we carried out new neuropsychological evaluations showing that the patient did not present major language impairments (comprehension, repetition, grammatical judgment and oral naming to visual stimuli, including picture of objects and actions, geometrical shapes, upper and lower case letters, and numbers). Performance on reading, and oral and written spelling of words and non-words was mildly impaired. Verbal fluency (naming of animals) was poor, but her spontaneous oral language was fluent. Number processing and calculation abilities were impaired. No clear signs of visuo-spatial neglect were observed. Deficits in drawing with and without a model were present, especially with the left hand. The patient showed constructional apraxia and left-hand ideational apraxia. Bucco-linguo-facial praxis were mildly impaired. Surface sensitivity of the right hand was mildly impaired, the deficits affecting mostly the thumb and the middle finger. Tactile anomia was observed only for the left hand: all of five three-dimensional objects were correctly named when explored with the right hand, whereas only one of six was correctly named when the left hand was used. Naming of manually explored 2-D stimuli (sandpaper) was mildly impaired for geometric shapes and markedly impaired for letters; in the latter case, the performance was 11% (1/9) and 25% (1/4) correct for the right and left hands, respectively.

Control subjects were five right-handed women who, as in other single case studies [8], were matched to the patient in age and educational level. Both AW and the control subjects signed a consent form before being tested, and were paid for their participation in the study.

In order to generalize the conclusions of the study, an additional brain-damaged patient (JW) was included in the study, and tested with some of the tasks used with

AW. JW is a right-handed man who underwent a complete section of the corpus callosum in 1979. At the time of testing (1994), he was 41 years old. He completed high school and 1 year of technical college. He was working as a freight handler in a dairy farm. For a detailed neurological and neuropsychological report on JW, including information about completeness of the interhemispheric disconnection, see Gazzaniga *et al.* [14].

Pretest

Before administering the experimental tasks, we performed a preliminary test to verify that, as suggested by Baynes *et al.* [1], the patient was indeed able to recognize 3-D objects palpated with the right hand. The experimenter simultaneously placed one object in each palm of the patient, for her to explore haptically and say whether they were the same or different. The task was performed in the absence of vision. The 16 trials included four with identical objects, four trials with objects of the same form but manufactured with different materials (e.g., plastic, metal), four trials with objects of different identity but sharing common features (e.g., length, shape) and four trials with objects that shared neither identity nor common features. AW had significant difficulties in performing the task. Stimuli in her right hand were actively and rapidly manipulated, whereas stimuli in her left hand were not even palpated or felt. As a result, the patient was unable to compare the stimuli (she performed correctly in only one of 16 trials). Instead, she attempted to name the objects; all stimuli explored with the right hand were correctly identified, whereas only one of 16 objects palpated with the left hand (6.3%) was correctly named. Thus, we confirmed the results of Baynes *et al.* [1] showing AW's difficulty in exploration and naming of objects held with the left hand. However, for our present purpose, it is worth stressing that these results also confirmed AW's intact abilities in naming 3-D objects explored with the right hand.

Experiment 1: Oral naming of haptic letters, digits and geometric shapes

The results of the screening suggested that AW may have a non-trivial impairment in the identification of 2-D haptic stimuli explored with her right hand. The experiment evaluated AW's abilities in naming 2-D letters explored haptically with the right hand, and investigated whether the deficit was specific to a class of stimuli or extended to other meaningful stimuli.

Methods

Stimuli. Stimuli included 2-D haptic letters, digits and geometric shapes that were presented in separate blocks. Letter stimuli were sandpaper upper case letters mounted on paperboard (10 × 10 cm). The letters were 8 cm high and their width ranged from 5 to 8 cm, depending on the letter. Every letter in the alphabet was used. Digit stimuli (from zero to nine) were similarly manufactured; their size was comparable to that of the letters. Finally, 10 sandpaper geometric shapes (star, cross, triangle, spiral, house, rectangle, diamond, oval, square, circle) were used. They were solid, except for the spiral. Their height ranged from 5.2 to 8.5 cm, and their width from 5 to 8 cm.

Procedure. AW sat with her right hand held in a prone position on a table, hidden by a screen. She received oral instruction specifying that she would have to explore a sandpaper stimulus with her hand and then name it. Letters ($n = 26$) were administered in different random orders in each of seven experimental sessions. They were displayed one at a time horizontally in the right hemispace and oriented so as to face the subject. The duration of the exploration was unlimited. No feedback on accuracy of responses was provided. Number of correct responses and exploration time were recorded. For digits, the subject was tested in eight different sessions; in the first five sessions, 10 stimuli were administered once, in a random order. In the three remaining sessions, each stimulus was presented twice for a total of 20 trials presented in random order. For geometric shapes, we first verified that the subject knew their name by presenting them visually at the beginning of the first two sessions. Five sessions of 20 randomized trials were performed in which each shape was presented twice.

Results and discussion

The percentages of correct responses for AW and the five control subjects (excluding self-corrected responses) are given in Table 1. Comparisons with control subjects were performed by taking into account only the data for the first five sessions.

For letters, AW's performance was poor compared to that of control subjects: on average she correctly named 62.3% of the stimuli, whereas control subjects performed 93.8% correct ($z = -13.65$, $P < 0.001$). AW's performance improved from the first (34.6% correct) to the fifth session (80.7% correct). However, in spite of this improvement, she still made more errors than control subjects in the fifth session, as well as in the two additional sessions.

AW differed from control subjects not only in naming accuracy, but also in the duration of the haptic exploration. AW's mean response time was 30.7 sec (S.D. = 14.0; $n = 86$). Correct responses were slightly faster (mean = 27.4 sec, S.D. = 13.8; $n = 55$) than incorrect responses (mean = 36.5 sec, S.D. = 12.7; $n = 31$). For control subjects, the mean response time was 8.1 sec (S.D. = 7.9; $n = 582$); the mean time for correct responses was 7.6 sec (S.D. = 7.0; $n = 551$) and the mean time for wrong responses was 16.7 sec (S.D. = 14.9; $n = 30$). The type of movements performed by AW to determine the letter identity seemed appropriate. Most of the movements corresponded to the exploratory procedures described by Klatzky and Lederman [20, 21], such as Lateral Motion and Contour Following.

Results for digits show that AW's performance was again poor relative to that of the control subjects; the

Table 1. Percentage of correct responses in haptic letter, digit and geometric shape oral naming

	AW (%)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Letters						
Session 1	34.6	92.3	92.3	92.3	84.6	100.0
Session 2	57.7	84.6	84.6	84.6	96.2	96.2
Session 3	69.2	96.2	92.3	96.2	96.2	100.0
Session 4	69.2	96.2	88.5	96.2	100.0	96.2
Session 5	80.7	96.2	100.0	96.2	92.3	96.2
Session 6	80.7					
Session 7	84.6					
Mean of five sessions	62.3	93.1	91.5	93.1	93.8	97.7
Mean of all sessions (AW): 68.1						
Digits						
Mean of five sessions	62.0	96.0	92.0	98.0	96.0	94.0
Mean of all sessions (AW): 73.6						
Geometric shapes						
Mean of five sessions	84.0	90.0	99.0	95.0	98.0	98.0

For the letter task, data are reported separately for AW and each control subject as a function of the different experimental sessions. For the digit and geometric shape tasks, the averaged performance across sessions is reported.

mean performance was 62.0% correct for AW and 95.2% correct for control subjects ($z = -14.56$, $P < 0.001$). AW's level of performance increased from 50.0% to 85.0% correct across testing sessions, whereas control subjects performed consistently across sessions. Mean response times were 35.9 sec (S.D. = 21.3; $n = 38$) for AW and 7.0 sec (S.D. = 5.7; $n = 235$) for control subjects. AW's correct responses were faster (mean = 28.65 sec, S.D. = 12.0; $n = 23$) than incorrect ones (mean = 45.6 sec, S.D. = 28.0; $n = 15$). A similar difference was observed in control subjects: 7.0 sec (S.D. = 5.7; $n = 226$) vs 9.0 sec (S.D. = 6.6; $n = 9$).

With geometric shapes, AW's performance was 84.0% correct and that of control subjects was 96.0% correct; this difference is significant ($z = -3.27$, $P < 0.001$). Except for one case in which the stimulus 'cross' was named 'octagon', the names given as answers were of shapes which are visually similar to the stimuli. For control subjects, confusion between ovals and circles, and between rectangles and squares were the most frequent errors ($n = 4$ each). AW's mean response time was 31.3 sec (S.D. = 28.0; $n = 96$); on average, correct responses were given after 26.7 sec (S.D. = 19.1; $n = 83$), whereas wrong responses were given after 60.9 sec (S.D. = 51.0; $n = 13$). For control subjects, the mean response time was 6.5 sec (S.D. = 8.0; $n = 493$); correct responses took on average 6.4 sec (S.D. = 8.0; $n = 475$) and incorrect responses took an average of 9.8 sec (S.D. = 5.3; $n = 18$).

The main conclusion from this experiment is that in spite of AW's ability to name haptically explored common objects, the haptic input from the right hand is not fully processed. The deficit is not specific to one class of stimuli, even though accuracy for shapes was slightly higher than for the other two types of stimuli (possibly because of a familiarization effect). Although AW received no feedback on her performance, it is plausible that the improvement across sessions reflected a learning process. In fact, she often made comments about the way she explored the stimuli, and during the last session she mentioned that, unlike the early ones, she was now looking for pertinent features (e.g., two holes for the letter 'B') to be able to identify the stimuli.

Several hypotheses can be entertained on the nature of the deficit responsible for AW's performance. Poor performance in the haptic letter-naming task may result from her mild sensory loss. Alternatively, AW's behavior may reflect a difficulty in accessing the stimulus name from a well-formed stimulus representation, or a difficulty in constructing a representation of the stimulus. These hypotheses were investigated in the following experiments. We began by testing whether AW's naming problems were due to impairments located at the output level, that is in the oral production of stimulus names.

Experiment 2: Oral and written naming of haptic letters

To ascertain whether AW's deficits in naming haptic letters orally would also be present in another response modality, we compared AW's naming performance under conditions where either oral or written responses were required.

Methods

Stimuli. The same haptic letters as in Experiment 1 were used.

Procedure. The presentation of the stimuli was as in Experiment 1. Four sessions were performed. In each session, two blocks of 26 randomized stimuli were administered; for one block AW had to name the stimuli and for the other block she had to write it. The order of presentation of the blocks was counterbalanced across sessions.

Results and discussion

Mean performance in oral and written naming did not differ significantly ($\chi^2 = 0.18$; n.s.): 86.6% (S.D. = 2.3) and 88.5% (S.D. = 8.3) correct respectively. Performance was slightly more accurate than in Experiment 1, this probably reflecting a learning effect analogous to the one already mentioned when discussing the results of that experiment. The results indicate that AW's performance was not dependent on the response modality. The fact that AW experienced difficulties in oral and written naming of haptic letters, as well as the fact that she was able to name visually presented upper and lower case letters (see Case Report), excluded the possibility that the impairment is located at the output level.

Since AW was impaired in 2-D letter, digit and shape naming, but not in common object naming, one should ask whether the deficit affected exclusively the processing of 2-D stimuli. If so, 3-D symbolic shapes should be named as easily as common objects. The next experiment addresses this question.

Experiment 3: Oral naming of three-dimensional block letters

Methods

Stimuli. Three-dimensional wooden upper case letters ($n = 26$) were used. The letters were 6.4 cm high, 1.8 cm thick and their width ranged from 1.6 to 5.9 cm.

Procedure. The subject sat in front of a table holding out her right hand supine. The experimenter placed a letter in her right palm so that the letter faced the subject. She had to explore the letter haptically and to name it without the help of vision. No time constraints were imposed, and no feedback was provided. If the subject flipped the stimulus, the experimenter reoriented it. Within each of five sessions, the 26 stimuli were presented in random order. Number of correct responses and exploration time were recorded.

Results and discussion

Table 2 shows the mean percentage of correct responses. AW correctly named 89.2% of the stimuli, whereas, on average, control subjects correctly named 94.1% of the stimuli. These scores are significantly different ($z = -2.23$, $P < 0.013$). AW's mean response time was 17.2 sec (S.D. = 9.5; $n = 126$). Correct responses were faster (mean = 16.5 sec, S.D. = 9.3; $n = 114$) than incorrect responses (mean = 23.7 sec, S.D. = 8.9; $n = 12$). The mean response time for control subjects was 4.29 sec (S.D. = 4.7; $n = 591$); the mean time for correct responses was 3.9 sec (S.D. = 4.0; $n = 556$) and the mean time for wrong responses was 10.6 sec (S.D. = 8.9; $n = 35$).

AW's naming performance with 3-D letters was far better than that with 2-D stimuli, but not quite as good as with common objects (see Case Report). Moreover, unlike the 2-D condition, her performance did not improve across sessions. The better results with 3-D stimuli cannot be explained by a familiarization effect, since 3-D and 2-D sessions overlapped partially. Thus, as also confirmed by the fact that exploration time with 3-D stimuli was considerably less than that with 2-D stimuli, the difference between conditions is likely to be real. The small difference between AW's performance with 3-D letters and common objects may be due to the fact that letters are much more similar to each other than the household objects used in the pretest, not only in terms of shape, but also of texture and weight. Thus, using block letters that can be confused more easily may have been sufficient to reveal a deficit in AW's haptic recognition which is masked with 3-D common objects that differ with respect to several of their properties. It is also possible that, over and above the distinction between 2-D and 3-D stimuli, the pattern of results reflects the existence of stored haptic templates for common objects, but not for letters and digits. Be this as it may, the significant (albeit small) difference between AW and control subjects suggests that the deficit does not exclusively concern the perception of 2-D stimuli.

Table 2. Mean percentage of correct responses in three-dimensional letter oral naming for AW and each control subject

	AW (%)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Mean of five sessions	89.2	91.5	94.6	92.3	96.9	95.4

Experiment 4: Haptic–visual matching of meaningless figures, letters and geometric shapes

Since verbal and meaningful stimuli were processed more accurately in the left than in the right hemisphere, and since the reverse pattern was observed for non-verbal materials, it might be supposed that AW's haptic performance with meaningless 2-D figures would be less accurate than with 2-D stimuli that can be named. To test this hypothesis, we designed a haptic–visual matching task involving meaningless figures, letters and geometric shapes. In this experiment, we were also interested in investigating whether the presence of a visual model would improve AW's haptic exploration performance.

Methods

Stimuli. Meaningless figures, letters and geometric shapes were used. Twelve meaningless sandpaper figures were mounted on paperboard (12.7 × 12.7 cm). The shapes were 8–10 cm high, 8–10 cm wide and included two to four strokes (either straight or curved lines of 1.5–2 cm width). The visual stimuli were reproductions of the haptic shapes. Two pairs of congruent copies of visual stimuli were mounted on white paper sheets. One pair corresponded to the shape of the haptic stimulus being presented; the second pair corresponded to a different haptic stimulus (distractors). The two members of each pair were displayed in different orientations: one member had the same orientation of the corresponding haptic stimulus, the other had a different orientation. The following procedure was adopted to create the list of pairs of stimuli. Each shape ($n = 12$) in each of four orientations was included in a list three times, for a total of 144 trials. The entire list was then randomized. The first 100 trials were used for the test. Five sets of 20 trials were administered in different sessions.

The haptic letter stimuli were the same as those used in the letter-naming task, except that not all the letters of the alphabet were used. Visual letter shapes were exact duplicates of the haptic letter shapes. These copies were drawn in black ink and mounted on white paperboards. Ten consonants (B, M, C, Y, F, L, W, J, V, K) and the five vowels (A, E, I, O, U) were used.

The haptic geometric shapes were identical to those used in the naming task. The visual stimuli were photocopies of the tactile shapes mounted on paperboards.

Procedure. Testing conditions were the same as in previous experiments. For meaningless figures, AW explored the stimulus (without being able to see it) for an unlimited time with her right hand. Then, she had to indicate with a right hand pointing movement the visual figure which corresponded to the haptic stimulus. The experiment was run under two conditions of presentation. In the condition 'with model', the visual stimuli were displayed in front of the subject concurrently with the presentation of the haptic stimulus. In the condition 'without model', the subject had first to identify the haptic stimulus and then, after a delay of 4–5 sec, the visual stimuli were administered. For both conditions, five sessions of 20 trials each were run for the 'with model' and for the 'without model' conditions. The subject received no feedback on her performance. Correct responses were recorded.

For letters, the subject had to indicate by means of a 'same/different' verbal response whether the stimuli she felt and saw were identical. Two sets of 40 trials were administered. In each set, half of the haptic stimuli were consonants and the other half were vowels. For consonants, in half of the trials the haptic and the visual stimuli were the same; in the other half of the trials they were different, but both stimuli were consonants. For vowels, the 20 trials were composed as follows: in five trials the haptic and the visual stimuli were the same; in five trials they were different but were both vowels; in 10 trials a vowel haptic letter was paired with a consonant visual stimulus. Thus, in each session, the numbers of 'same' and 'different' responses were 15 and 25 respectively. The experiment was replicated under the same conditions except that the subject had first to explore the haptic stimulus and then, after a delay of a few seconds, she was presented with the visual stimulus.

In the task using geometric shapes, AW had also to indicate with a 'same/different' verbal response whether the haptic and the visual stimuli were identical. Four sessions of 20 trials each were used in which every haptic shape was presented twice. In half of the cases, haptic shapes were paired with an identical visual shape, whereas in the other half of the trials they were matched with a dissimilar visual shape chosen randomly from the set of geometric shapes. Three sessions of 20 trials were administered in the 'without model' condition.

Results and discussion

Table 3 reports the mean percentage of correct responses for meaningless figures, letters and geometric shapes, in both 'with model' and 'without model' conditions. The results for meaningless figures are the following. In the 'with model' condition, AW's performance was 97.0% correct and the control subjects' performance was 97.2% correct ($z = -0.12$; n.s.); in the 'without model' condition, AW's and the control subjects' performances were 64.0% and 88.6% correct respectively—a significant difference ($z = -4.36$, $P < 0.001$). AW's performance was stable across sessions. The errors made by AW and the control subjects included roughly equal numbers of figure identity and orientation errors.

With letters, AW performed 97.5% correct and the control subjects 99.5% correct in the 'with model' condition; in the 'without model' condition, the corresponding values were 90.0% and 98.8%. In both conditions, the score difference between AW and the control subjects was significant ('with model': $z = -3.07$, $P < 0.002$; 'without model': $z = -9.9$, $P < 0.001$). For geometric shapes, AW responded correctly on 96.3% and the control subjects on 98.7% of the trials in the 'with model' condition; in the 'without model' condition, AW's performance was 96.7% and the control subjects 98.3% correct. The difference in the level of performance between AW and the control subjects was significant in the 'with model' condition ($z = -1.86$, $P < 0.032$), but not in the other condition ($z = -1.39$; n.s.)

The results with meaningless figures in the 'without model' condition show clearly that AW's impairment in recognizing haptic stimuli is not specific to a class of material. The contrast between the performances with and without model can be accounted for by considering that in the former, but not in the latter, condition correct identification can be achieved by comparing only a parcel

Table 3. Mean percentage of correct responses in tactile–visual matching of meaningless shapes, letters and geometrical shapes

	AW (%)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Meaningless figures						
With model	97.0	96.0	99.0	98.0	95.0	98.0
Mean of all control subjects: 97.2						
Without model	64.0	85.9	94.0	80.8	88.0	94.0
Mean of all control subjects: 88.6						
Letters						
With model	97.5	98.8	100.0	98.8	100.0	100.0
Mean of all control subjects: 99.5						
Without model	90.0	98.8	98.7	100.0	98.8	97.5
Mean of all control subjects: 98.8						
Geometric shapes						
With model	96.3	97.5	97.5	100.0	98.3	100.0
Mean of all control subjects: 98.7						
Without model	96.7	98.3	100.0	96.7	98.3	98.3
Mean of all control subjects: 98.3						

For both conditions, with and without model, data are reported separately for AW and each control subject.

of the haptic information with its visual counterpart. The fact that both AW and control subjects made identity and orientation errors supports the hypothesis that the construction of haptic representations involves at least two kinds of information: spatial information intrinsic to the object—i.e. the relative position of the different features, or strokes, that constitute a shape—and extrinsic spatial information concerning the relationships between the object, the environment and the observer.

The fact that the absence of the model proved detrimental to AW's performance only with meaningless figures may reflect the greater difficulty of generating and storing in memory a mental representation of these figures which, moreover, do not allow verbal encoding. One should also mention that the 'same/different' response task is intrinsically easier than the matching response used for meaningless shapes.

Experiment 5: Naming letters traced on finger and palm; naming finger-guided letters

Thus far, the tasks involved haptic explorations with fingers and wrist movements, i.e. cutaneous and proprioceptive information. In the following two experiments, we investigated whether other modes of haptic stimulation also resulted in impaired performance. Two traced-letter-naming tasks and one finger-guided letter-naming task were designed to test the subject in situations that did not require her to perform active exploratory movements.

Methods

Procedure. In the traced-letter task, the subject sat with her right hand held in a supine position on a table. The experimenter wrote with a pencil upper case letters on the tip of the index finger of the subject who was asked to name the letter. In a second version of the task, the stimuli were traced on the palm of the right hand. In the finger-guided task, the subject sat with her right hand in a prone position, her index finger touching the top of the table. By keeping the arm, hand and finger of the subject aligned, the experimenter moved the subject's hand so as to trace upper case letters. These passive movements involved mostly elbow and shoulder joints. In all cases, the letters faced the subject. The order in which the strokes of the letters were written was the same throughout all sessions. The subject was allowed to see neither the tracings nor the passive hand movements. No time constraints were imposed, and the subject could ask for the tracing or the hand guiding to be repeated. She received no feedback on her performance. In each session, the 26 letters of the alphabet were administered in random order; five sessions were performed for each task.

Results and discussion

The mean percentages of correct responses in the three conditions are reported in Table 4.

Table 4. Mean percentage of correct responses in the finger- and the palm traced-letter-naming tasks, and in the finger-guided letter-naming task

	AW (%)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Finger letter naming						
Mean of five sessions	62.3	80.0	92.3	94.6	93.8	96.9
Mean of all control subjects: 91.5						
Palm letter naming						
Mean of five sessions	70.0	86.2	96.2	94.6	94.6	98.5
Mean of all control subjects: 94.0						
Finger-guided letter naming						
Mean of five sessions	84.6	93.1	100.0	96.9	95.4	99.2
Mean of all control subjects: 96.9						

Data are reported separately for AW and each control subject.

In the fingertip version of the traced-letter-naming task, AW's performance was 62.3% correct, while the control subjects performed correctly on 91.5% of the stimuli ($z = -4.39$, $P < 0.001$). In the palm version of the task, the percentages of correct responses for AW and the control subjects were 70.0% and 94.0% respectively ($z = -5.23$, $P < 0.001$). In the finger-guided letter-naming task, AW correctly named 84.6% of the trials, while the performance of control subjects was 96.9% correct ($z = -4.38$, $P < 0.001$). None of the letter stimuli proved consistently more difficult, and no pattern emerged in the distribution of errors produced by the control subjects.

AW's lower performance in the two versions of the traced-letter-naming task and in the finger-guided letter-naming task is compatible with the performance observed with actively explored stimuli (Experiment 1). This suggests that the difficulty in recognizing 2-D haptic stimuli is not dependent on a specific mode of exploration of the stimuli.

It could be argued that the mild sensory (cutaneous) loss experienced by AW was at the origin of her difficulties in the traced-letter tasks. Indeed, the lower performance in the traced-letter task with respect to the finger-guided letter task indicates that some sensory loss may contribute to the decrease in overall performance. However, the fact that AW also experienced difficulties in naming letters presented through passive arm movements, which do not provide discriminating cutaneous information, implies that sensory deficits in AW's right hand cannot account fully for her difficulty in identifying haptic stimuli.

Thus far, we have shown that AW's haptic deficits are not material-specific and do not depend on the mode of exploration of the stimuli. These results invite the inference that shape identification is impaired because the patient is unable to generate an appropriate abstract representation of the stimuli. Pursuing this line of reasoning, the next experiment investigated whether this representational deficit is restricted to the haptic modality, or also affects the recognition of visual stimuli presented to the left hemisphere.

Experiment 6: Detection, naming and matching of visual letters

We have provided various evidence suggesting that AW's ability to process visual stimuli in the left hemisphere is quite adequate (e.g., the ability to read letters was unimpaired). The present experiment was carried out to determine whether AW was able to generate adequate representations of visual letters presented only to the left hemisphere, and to investigate the extent to which visual stimuli administered to the anoptic field (right hemisphere) could be processed.

Methods

Stimuli. Upper case letters ($n = 26$; font: Courier 24 pt, bold) were presented on a computer screen (diagonal 14 in.). Stimuli were displayed at mid-height, at a distance of 6 cm (6° of visual angle) either to the left or to the right of the center of the screen. To control for visual similarity, for the matching task, we used 10 letters and their corresponding distractors chosen on the basis of the confusion matrix reported by Gilmore *et al.* [17].

Procedure. The subject sat in front of a computer screen at a distance of 57 cm. She was asked to fixate a central reference (cross) presented for 1 sec. 17 msec after the offset of the central reference, a letter appeared either to the left or to the right of the fixation point for 83 msec. By pressing a key with the right hand, the subject had to indicate as quickly as possible whether a stimulus had appeared on the screen. Sixty-two trials were performed in a random order. They included 26 stimuli appearing on the right, 26 stimuli to the left and 10 catch trials where no stimulus was displayed. The stability of the fixation was monitored during the trials. In a second version of the task, the subject was also asked to name the letter. Stimuli were administered in different random orders in the two conditions.

In the matching task, the testing conditions and the presentation of the stimuli were the same as in the detection task. However, 200 msec after stimulus offset, two letters, one above the other, were displayed centrally. One was identical to the stimulus, the other was a distractor. In half of the trials, the target and the distractor were visually quite similar; in the other half, the letter pairs were not visually similar. The position of the target (top or bottom) was counterbalanced. The subject had to name the matching letter. Eighty trials were administered, 40 to the left and 40 to the right visual hemifield.

Results and discussion

The mean percentages of correct responses in the letter detection, the letter naming and the matching tasks are given in Table 5. AW was perfectly able to detect and to name visual letters presented to the left hemisphere (100% correct). In contrast, she only detected 42.3% of the stimuli presented to the right hemisphere, and she was not able to name the letters (1.9% correct). There were no false positives on catch trials. In the matching task, letters presented to the left hemisphere were always detected and performance was 100% correct. When stimuli were presented to the right hemisphere, AW adopted the strategy of always choosing the letter displayed in the upper position on the screen, except in one trial.

The results clearly confirmed the presence of left hemianopia. They also show that perception and recognition were intact in the left hemisphere. Thus, AW's impairments are limited to the haptic modality. The next experiment was designed to investigate the extent to which the deficit is due to the scanning mode implicit in the haptic modality.

Table 5. Mean percentage of correct responses in the visual letter detection task, the letter-naming task and in the visual letter forced matching task

		Left hemisphere (%)	Right hemisphere (%)
Letter detection			
Mean of two sessions		100.0	42.3
Letter naming			
Mean of two sessions		100.0	1.9
Letter forced matching			
Mean of two sessions	Top	100.0	100.0
	Bottom	100.0	5.0
	Mean	100.0	52.5

AW's results are reported separately for the left and right hemisphere presentations of the stimuli.

Experiment 7: Naming visual letters scanned sequentially

One factor that could account for the difference between haptic and visual performances is the different nature of these perceptual channels [23, 24]. In the case of 2-D stimuli, the haptic exploration is essentially sequential, whereas visual letters can be processed immediately as a whole. Because of the sequential nature of haptic exploration, perception of 2-D letters requires the integration of information over time, presumably in some sort of working memory. If this memory system were to be defective or overloaded by task demands, it could be at the origin of the deficit. To rule out the possibility that a modality-independent difficulty with the integration of information is responsible for AW's reduced performance, we used a procedure adapted from Loomis *et al.* [24].

Methods

Stimuli. Upper case letters drawn in black ink on white paper board (10 × 10 cm) were used. These letters ($n = 26$) were duplicated from the haptic letters used in the previous experiments.

Procedure. Stimuli were displayed on the table one at a time in the normal upright orientation. Unlike Experiment 6, stimulus presentation was not restricted to one visual hemifield. However, stimuli were partially hidden by a paperboard screen in which a window (1.5 × 1.5 cm) had been cut out. At the beginning of the trial, the window was positioned at the center of the stimulus. The task was to identify and name the letter by moving the window over the stimulus. No constraints were imposed on exploration time. No feedback was given to the subject. Five blocks of 26 randomized letters were administered in five sessions. Number of correct responses and response times were recorded.

Results and discussion

The mean percentage of correct responses for AW and the control subjects are reported in Table 6.

AW performed quite accurately, at a level comparable to normal control subjects (95.4% vs 96.8%, $z = -0.64$; n.s.), but her response times were considerably slower: 11.3 sec (S.D. = 4.0; $n = 127$) vs 3.9 sec (S.D. = 2.1; $n = 647$). A possible reason for AW's very slow performance is that hemianopia adversely affected her scanning strategy. At any rate, the fact that naming performance was not affected means that exploration time *per se* is not a good predictor of the response. Thus, the poor performance observed in Experiment 1 cannot be credited to the fact that in the haptic condition exploration took longer (30.7 sec). In conclusion, AW's unimpaired ability to identify sequentially scanned visual stimuli rules out the hypothesis of a modality-independent short-term memory deficit, or of a problem affecting the integration of sequentially processed information.

Table 6. Mean percentage of correct responses for sequentially scanned letter naming

	AW (%)	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)
Mean of five sessions	95.4	97.7	93.8	97.7	95.4	99.2
Mean of all control subjects: 96.8						

Data are reported separately for AW and each control subject.

Additional lesioned control

It could be argued that AW's performance reflects an idiosyncratic combination of partial disconnection of the corpus callosum and damage to the right hemisphere white matter. In order to generalize the conclusion reached so far on the functional capability of the left hemisphere, we briefly tested a split-brain patient (JW) with complete surgical interhemispheric disconnection documented by MRI [14].

When asked to read letters presented in free vision, JW performed correctly on 25 of 26 (96.2%) trials. In a haptic 3-D object-naming task, he was 100% correct (12/12) with the right hand and 41.7% (5/12) correct with the left hand. Tested a second time with 20 objects presented to the right hand, he was 95.0% correct. The right hand surface sensitivity was mildly impaired: he localized correctly 25 of 29 (86.5%) points of contact administered on the fingers and the palm. With the left hand, his performance was 14 out of 30 (46.7%) correct. Some of the haptic and visual tasks administered to AW were performed by JW under the same experimental conditions. The data are summarized in Tables 7–9. Overall, they show that JW was impaired in naming haptic stimuli, but not in identifying visual stimuli. Moreover, as was the case for AW, the presence of a visual model during the identification of haptic meaningless figures led to better performance than in the absence of the model. In the various tasks involving visual stimuli, JW was able to name and match lateralized letters. He showed a slight defect in naming sequentially scanned visual stimuli (90.4% correct); however, the level of the performance was much higher than that reached in the various haptic exploration tasks. The patterns of results observed in JW and AW were fully congruent, thus providing converging evidence in support of the idea that the left hemisphere's haptic perception ability is far from perfect.

Table 7. Percentage of correct responses in tasks with haptic stimuli

	Right hand (%)	Left hand (%)
Letter naming		
Session 1	53.8	38.5
Session 2	61.5	11.5
Mean	57.7	25.0
Digit naming		
Session 1	60.0	
Session 2	60.0	
Mean	60.0	
Geometric shape naming		
Session 1	70.0	
Session 2	55.0	
Mean	62.5	
3-D block letter naming		
Session 1	73.1	
Session 2	80.8	
Mean	77.0	
Meaningless figure matching		
With model	95.0	
Without model	60.0	

JW's results are reported as a function of the different tasks and of the different experimental sessions. In the haptic letter-naming task, the performances with both the right hand and the left hand are indicated.

General discussion

The recognition of haptic stimuli was investigated in a subject who suffered an ischemic accident resulting in damage to the anterior portion of the corpus callosum and to the white matter of the right posterior hemisphere.

Table 8. Percentage of correct responses in the tasks with visual letters

		Left hemisphere (%)	Right hemisphere (%)
Letter naming			
Session 1		91.2	7.7
Letter forced matching			
Session 1	Top/bottom	100.0	82.5
Sequentially scanned letters: free vision			
Session 1	88.5		
Session 2	92.3		
Mean	90.4		

JW's results are reported separately for the left and right hemisphere presentations of the stimuli and as a function of the different experimental sessions.

Table 9. Mean percentage of correct responses in the different tasks for AW, the control subjects and JW

	AW (%)	Controls (%)	JW (%)
Haptic stimuli			
Letter naming	62.3	93.8	57.7
Digit naming	62.0	95.2	60.0
Geometic shape naming	84.0	96.0	62.5
3-D letter naming	89.2	94.1	77.0
Meaningless figure matching			
With model	97.0	97.2	95.0
Without model	64.0	88.6	60.0
Letter matching			
With model	97.5	99.5	—
Without model	90.0	98.9	—
Geometric shape matching			
With model	96.3	98.7	—
Without model	96.7	98.3	—
Visual stimuli			
Letter detection	100.0	—	—
Letter naming	100.0		91.2
Letter matching	100.0		100.0
Sequentially scanned letters	95.4	96.8	90.4

For the visual stimuli, the performance includes only trials presented in the left hemisphere.

Testing was limited to the right hand because extensive test of the left hand had been carried out on the same patient by Baynes *et al.* [1], who concluded that, in spite of the naming deficit due to the disconnection with the language centers, AW was indeed able to generate spatial representations of common objects palpated with the left hand. Because of the etiology of this patient, the case of AW affords the rare opportunity to assess the capability of the isolated, intact left hemisphere to process haptic stimuli. Furthermore, the similarity between the performances of AW and JW provides the basis for extending our conclusions to the left hemisphere, more generally.

The results reported here suggest that the issue of the left hemisphere's capabilities in haptic tasks cannot be meaningfully addressed without considering the nature of the available information to the haptic system. In fact, as shown previously by Baynes *et al.* [1], AW was perfectly able to name haptically explored common objects. However, she was severely impaired when faced with 2-D stimuli and, to some extent, with 3-D symbolic shapes. This pattern of results is consistent with previous work demonstrating a deficiency of the isolated left hemisphere in tasks involving haptic perception of simple geometrical qualities [12]. AW's impairment was gradually circumscribed by showing that the difficulty in identification was not limited to a particular class of 2-D stimuli, since letters and geometric shapes, among others, were all poorly named (Experiments 1 and 3). It was also shown that naming errors occurred independently of the mode of haptic exploration, since AW performed poorly in both active and passive exploration tasks (Experiment 5). The simultaneous presentation of visual and haptic stimuli improved AW's recognition of letters, geometric shapes and meaningless figures (Experiment 4). Unlike haptic stimuli, visual letters were correctly identified by the left hemisphere, whether they were presented in free vision or in lateralized conditions, and even when they were sequentially scanned through a small window (Experiments 6 and 7).

The contrast between the recognition of common objects and 2-D stimuli suggests that the latter are recognized with more difficulty because they allow fewer exploratory procedures for discriminating haptic information [23]. The difference in performance between common objects on one side, and 2-D stimuli (and, to some extent, 3-D block letters) on the other, may reflect the fact that common objects afford multiple clues such as texture, shape, weight, etc. Even though some of these clues may not be fully processed, their conjunction may nevertheless converge on a unique solution to the identification process. By contrast, when shape is the only available clue (as for instance in 3-D block letters), even a mild impairment of the haptic system will lead to poor performance. In conclusion, the commonly adopted tests involving the naming of easily distinguishable household objects may not be sufficiently sensitive for assessing the integrity of the haptic system.

Another issue addressed in this study concerned the level of processing responsible for the observed haptic naming/recognition deficit. When AW was tested for surface sensitivity in her right hand, she showed some mild impairments in locating the points of contact (a similar impairment was also noticed in JW), indicating some amount of sensory loss. However, it is very unlikely that such a deficit is the cause of AW's and JW's inaccurate performance, since errors occurred independently of the mode of exploration of the stimuli. Furthermore, both AW and JW explored the stimuli with their index fingertip, where no loss of tactile sensitivity was detected.

The hypothesis that the impairment is at the level of the retrieval of the oral name of an otherwise well-formed representation of the stimuli is ruled out by the fact that a comparable percentage of errors occurred with written and oral responses. The same conclusion is suggested by the results in the delayed haptic–visual matching task: AW performed poorly even though this task did not require a naming response.

Because AW's deficits seem to be located neither at the input nor the output stage of the process involved in the haptic naming tasks, the likely locus of deficit is in processing spatial representations. Granting this conclusion, there remains the question of whether it is a central, amodal deficit or one restricted to the haptic modality. Our results show that AW and JW were both able to process visual representations of the stimuli when only the left hemisphere was activated, i.e. under the same conditions as the haptic recognition/naming task. Hence, we conclude that the deficit in these two patients is modality specific. Therefore, either 2-D shape recognition is truly a right-hemisphere process, or both hemispheres are needed for normal haptic recognition. At any rate, we can conclude with some confidence that the left hemisphere, isolated from the right hemisphere, is not capable of supporting the spatial representations necessary for dealing with the full range of haptic stimuli.

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