



Isolation of a right hemisphere cognitive system in a patient with anarchic (alien) hand sign

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Abstract—We report evidence of isolated conceptual knowledge in the right hemisphere of a woman with chronic anarchic hand sign after ischemic infarction of the central four-fifths of the corpus callosum. Limited visual information was available to the right hemisphere, access to medial temporal structures subserving memory was disrupted and disconnection from left hemisphere language structures was complete. Still, the right hemisphere could build mental representations of objects via tactile input and use them in cross-modal matching. These representations were not accessed consistently in auditory comprehension or naming tasks. This functional specificity and its pathoanatomical correlates demonstrate that the study of anarchic hand sign can illuminate not just motor control issues but may inform our understanding of the representation and lateralization of conceptual knowledge as well. Published by Elsevier Science Ltd

Key Words: tactile anomia; agraphia; corpus callosum; disconnection syndrome.

Introduction

Over the last three decades, the study of commissurotomy patients has yielded increasingly specific information regarding the role of the corpus callosum in the integration of lateralized cognitive functions. Whereas the classic studies of Gazzaniga, Sperry and colleagues relied on surgical reports to ascertain the extent of callosal transection (e.g., [18, 45]), magnetic resonance imaging (MRI) has since provided a means for the localization of partial callosal damage caused by naturally occurring lesions as well as therapeutic surgical ones. This capacity for *in vivo* localization, combined with the careful assessment of cognitive processes using tasks akin to those developed in experimental psychology, has, in turn, allowed a better understanding of structure–function relationships underlying interhemispheric transfer (for review, see [16]).

Studies of patients with partial (posterior) callosotomy or posterior cerebral artery stroke have established that the splenium mediates visual transfer [1, 16, 19, 23, 27,

36]. Direction-specific transfer of somesthetic information has been observed in one patient (EB) with a posterior section of the corpus callosum [16]. With respect to auditory transfer, MRI and dichotic tests of speech sound recognition in partial callosotomy patients and in a stroke patient indicate that the posterior body mediates the interhemispheric integration of phonemic and orthographic information [42, 47]. Preservation of transfer of semantic information in the absence of somesthetic transfer has also been documented after posterior section in one patient [43]. Another patient with inadvertent sparing of a limited amount of callosum has demonstrated very specific additive transfer of phonemic and orthographic information [19]. The present study of a patient with a naturally occurring lesion of the body of the corpus callosum that spares a portion of the splenium and the entire genu and rostrum presents an unusual opportunity to learn more about specific patterns of transfer and to confirm observations made with patients with a long history of neurological disease on a patient with normal neurological development.

This case of chronic anarchic hand syndrome was investigated 2.5 years post-onset. The patient suffered multifocal ‘watershed’ infarcts of the callosum and right hemisphere involving medial gray and white matter struc-

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tures in the frontal, posterior parietal, posterior temporal and occipital lobes. The extent of the callosal and hemispheric lesions are detailed via MRI, and specific perceptual and cognitive functions are examined using a variety of tasks to take advantage of this opportunity to learn more about interhemispheric transfer. Data reported here were gathered in a 6-month period in which AW was neurologically stable. Neuropsychological assessment and pilot naming experiments were initiated in October 1991. Experiments 2 and 3 were carried out in November 1991. Experiment 1, an elaboration of the pilot studies, was completed in March 1992. Experiment 1 examines the patient's ability to name objects based on a right hemisphere representation generated from tactile input. Experiment 2 examines her ability to use that information for cross-modal matching. Finally, Experiment 3 compares the patient's naming, auditory comprehension, tactile matching and memory ability using stimuli that are free of cues identified in prior experiments.

Case report

Neurological history

AW, a right-handed female born 22 October 1938, was admitted to the hospital on 7 August 1989 following a 2-week history of fluctuating neurological symptoms, including right occipital headache, unformed visual hallucinations (flashing white and colored lights), paresthesias and weakness of the left face and upper extremity, and dizziness. Her chief complaint on the day of admission was, "My left hand is not feeling like my own". The past history was notable for coronary artery disease requiring three-vessel bypass surgery in 1984, hypertensive vascular disease, hypercholesterolemia and heavy cigarette smoking. AW was employed as a laboratory technician prior to her stroke. She had completed 10 years of formal education.

On admission, neurological examination revealed a clear sensorium with normal speech and language functions, a left homonymous hemianopia without hemi-inattention, a mild left hemiparesis affecting face, arm and leg, decreased pin prick sensation in the left hemibody, decreased proprioception in the left extremities, and inability to name objects placed in the left hand. Computerized X-ray tomography revealed a hypodensity in the right medial occipital and parietal lobes. Electroencephalography showed diffuse right hemisphere slowing and no paroxysmal activity. Cerebrospinal fluid analysis was normal. Carotid ultrasound revealed occlusion of the right internal carotid artery.

On her most recent follow-up at the clinic (8 October 1991), the patient's chief complaint was that her left hand did not obey her. For example, on several occasions while driving, the left hand reached up and grabbed the steering wheel from the right hand. The problem was persistent and severe enough that she had to give up driving. She reported instances in which the left hand closed doors the right hand had opened, unfolded sheets the right had folded, snatched money the right had offered to a store cashier, and disrupted her reading by turning pages and closing books. She stated that she could get her left hand to do things only after she watched the right hand do them. Neurological examination showed no left hemiparesis, severe left hand apraxia, which was worse with the eyes closed but still evident with the eyes open, a left homonymous hemianopia and left hemisensory loss. Her medications at the time of the present

experiments included atenolol, diltiazem, triamterene, lovastatin, aspirin, dipyridamole and alprazolam.

Neuropsychological test battery

Standardized testing demonstrated average intelligence and memory skills. On the Wechsler Intelligence Scale (Revised), there was a 16-point advantage of verbal IQ over performance IQ, with mild motor slowing and difficulty with visual integration (FSIQ 93; VIQ 100; PIQ 84). Memory skills were in the average range on the Wechsler Memory Scale (Revised), but the Verbal Memory Index score was significantly above AW's Visual Memory Index score (General Memory 97; Verbal Memory 109; Visual Memory 87). Likewise, although her combined Attention and Concentration score was in the average range (104), Verbal Span was much easier for her than Visual Span (Forward 94th percentile, backward 90th percentile and forward 34th percentile, backward 36th percentile, respectively). The California Verbal Learning Test scores were generally at or above the mean for her age group. She did make many perseverative errors, however. In contrast, her performance on the Benton Visual Retention Test was in a range suggestive of impairment. She made many errors of rotation and distortion, but they were equally distributed over the right and left sides of the page. AW's score on the Benton Facial Recognition Test would place her in the borderline range. In summary, AW's verbal intelligence and memory are in the average range, but visuospatial skills, particularly visual memory function, were mildly impaired.

Signs of interhemispheric disconnection

AW continued to complain of an inability to control her left hand, the symptom that Brion and Jedynak [7] suggested was a clue to look for signs of callosal disconnection. Like most alien or anarchic hand patients, as pointed out by Della Sala *et al.* [11], AW recognized her left arm as her own, but complained that she could not control its actions. Her early report that her left hand had to observe the actions of her right to carry out commands is similar to behaviors reported in callosally sectioned patients [34]. This inability to control her left hand was intermittent and incidents occurred more frequently when she was fatigued. She found this symptom disturbing and irritating. In several sessions of standardized psychometric testing, the only evidence of left hand interference in activities was observed in the Picture Arrangement subtest of the WAIS-R, in which her left hand attempted to arrange the cards differently from the right hand.

Use of tasks known to elicit signs of interhemispheric disconnection in split-brain patients readily demonstrated her difficulties. Of the clinical features enumerated by Bogen [6] as potential callosal signs, AW demonstrated five. Left ear suppression on dichotic listening was demonstrated. She was mildly apraxic with her left hand. Her left hand was also agraphic (see Fig. 1). She was unable to consistently name common objects placed in her left hand despite having been tested extensively on those objects earlier. Each hand showed mild constructional apraxia on Kohs Blocks. AW's drawings also demonstrated some left-hand constructional apraxia, as well as perseveration (see Fig. 2). AW was unable to transfer somatosensory information between her right and left hands.

Brain imaging and lesion localization

On 6 November 1991, magnetic resonance images were acquired in the sagittal and coronal planes using a 1.5-Tesla

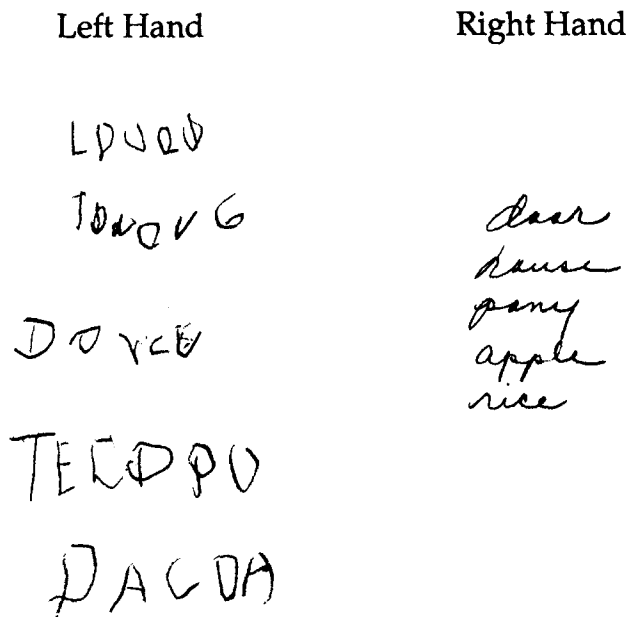


Fig. 1. Left hand agraphia was easily demonstrated when AW was asked to write five common nouns and sign her name with her right and left hands. Her right hand attempt is normal, demonstrating a clear hand and accurate spelling. Her left hand attempts to produce the same words result in awkward illegible letters. Letters are so poorly formed that it is difficult to judge spelling, but words clearly contain the wrong number of letters.

General Electric Signa system. T1-weighted sagittal sections were 3.0 mm thick and separated by 1.0 mm gaps (TR/TE = 600 msec/20 msec; acquisitions = 2). Corresponding T2-weighted sagittal sections were also 3.0 mm thick with 1.0 mm gaps (TR/TE = 2000 msec/30 msec, 2000 msec/85 msec; acquisition = 1).

T1-weighted coronal images were 3.0 mm thick with no gaps (flash sequence, TR/TE = 50 msec/15 msec). T2-weighted coronal images were 5.0 mm thick, separated by a 1.0 mm gap, and sectioned so that each T2 image corresponded to every other T1 image (TR/TE = 2000 msec/30 msec, 2000 msec/85 msec; acquisition = 1). Lesion localization was defined in accordance with the coronal atlases of Matsui and Hirano [31] and Kreig [29], and the vascular distribution of the lesions was determined using the templates of Damasio and Damasio [10].

There is marked thinning of the corpus callosum extending from the anterior body to the splenium (Fig. 3). Areas of abnormal signal are scattered throughout the body, sulcus and splenium, and extend into the intrahemispheric white matter on the right. The ventral extreme of the splenium appears to be spared. The thinning of the callosum and the intracallosal and right pericallosal lesions is likewise evident on the coronal sections (Fig. 4), which also demonstrate the extent of right hemisphere involvement. There is abnormal signal emanating from the right cuneus, lingual gyrus and hippocampal region consistent with ischemic infarction in the distribution of the lateral branch of the posterior cerebral artery. The lesion involves almost the entirety of the right calcarine cortex (Fig. 4c, c'), sparing only a few millimeters of its posterior extreme. There is atrophy of right medial temporal structures with compensatory dilatation of the temporal horn extending from the section just behind the anterior commissure to the isthmus of the cingulate gyrus (Fig. 4b); the lesion involves the entorhinal cortex, parahippocampal gyrus, dentate gyrus and amygdala. The anterior portion of the amygdala, which typically lies in the territory of the anterior choroidal artery, is spared. The subcortical extension of the lesion near the posterior aspect of the right temporal horn may involve the tail of the caudate nucleus, but there are no signal abnormalities involving the basal ganglia in the region of the frontal horn. There is abnormal signal in right posterior parietal structures, namely, the precuneus, cingulate gyrus and white matter of the ventromedial superior parietal lobule. with com-

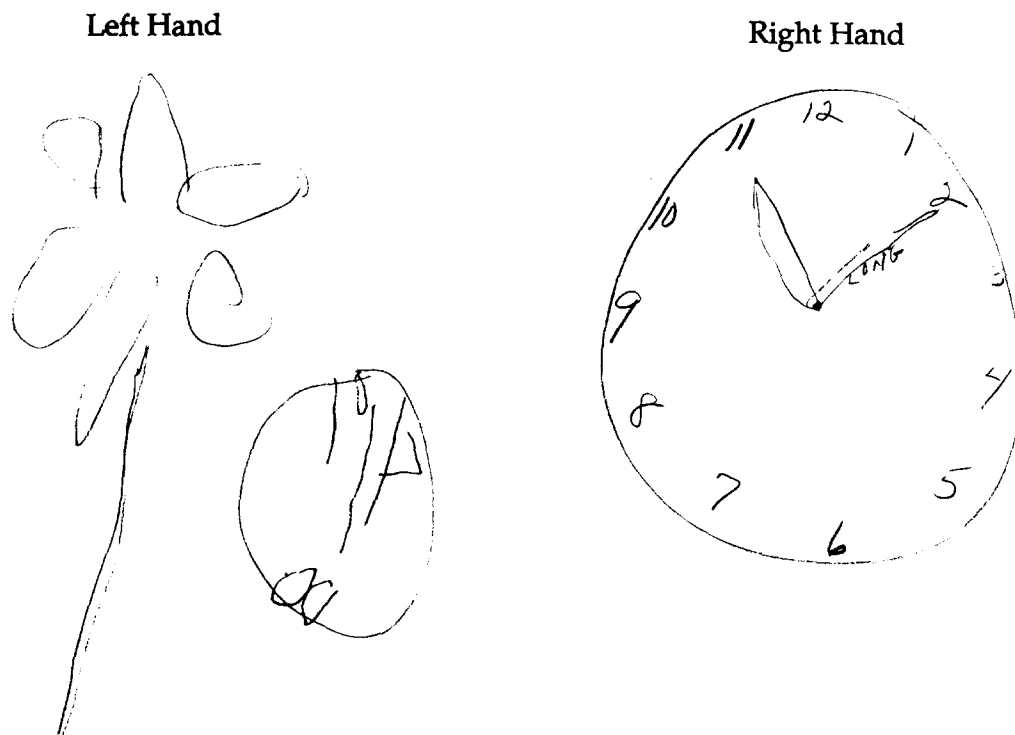


Fig. 2. Right and left hand attempts to draw a clock face demonstrate left hand constructional apraxia. The right hand draws a primitive but normal clock. The left hand first perseverates the flower drawn immediately prior to the clock and when asked again produces a poorly formed clock without numerals.

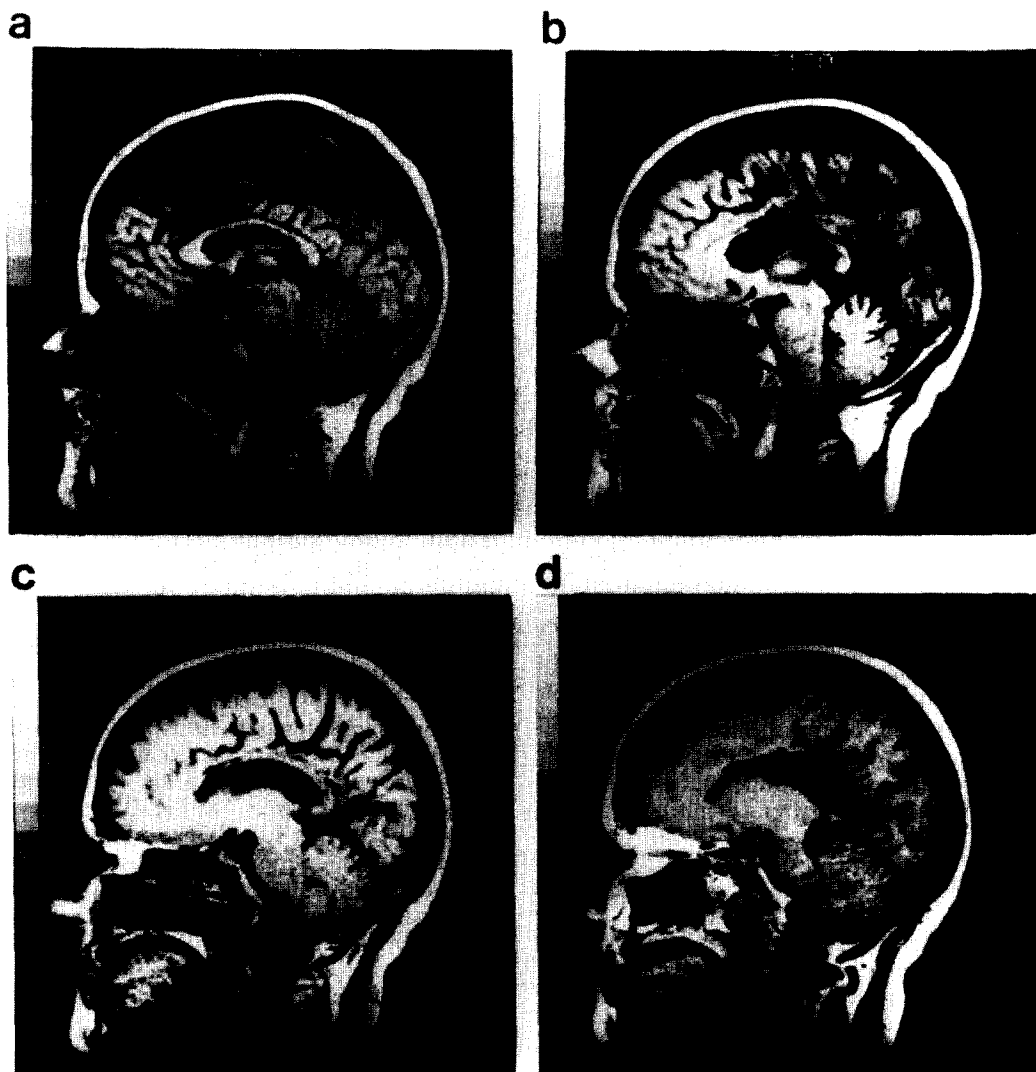


Fig. 3. Serial T1-weighted sagittal magnetic resonance images demonstrating the extent of the callosal infarction in patient AW. Mid-sagittal section (a) and parasagittal sections (b–d), each 4.0 mm to the right of the previous section. Note the marked atrophy of the body of the callosum in b, and the areas of decreased signal emanating from the body, sulcus and splenium in c and d. In addition, c and d illustrate the right medial occipital lobe lesion.

compensatory dilatation of the atrium (Fig. 4b, b'), consistent with ischemic infarction in the distribution of the inferior internal parietal branch of the anterior cerebral artery. Pericallosal white matter lesions are seen in sections passing through the level of the hippocampal commissure.

The infarcts lie at the distal reaches of the right posterior and anterior cerebral arteries, including their watershed area. The diffuse periventricular hyperintensities in the left as well as right hemisphere seen on the T2-weighted sagittal and coronal images are consistent with ischemic demyelination secondary to diffuse small vessel disease; given AW's long history of vascular disease, these likely predate her presenting neurological signs and symptoms.

Summary

AW demonstrated anarchic hand sign with otherwise mild neuropsychological impairment. Her left hand was mildly apraxic and markedly agraphic. AW demonstrated tactile anomia for items presented out-of-view to the left hand. She also reported and displayed intermanual conflict. Her neuroimaging results demonstrated the partial interruption of callosal fibers

and lesions of the right calcarine cortex, right hippocampal region and right posteromedial parietal lobe. The experiments presented below investigated the limits of her right hemisphere's ability to identify objects.

Experiment 1

Experiment 1 was designed to gather a broad sample of AW's verbal responses to tactile stimuli from eight common categories. If a less well-specified or diffuse right hemisphere representation contributes to semantic naming errors, we might expect to see semantic paraphasias, particularly many within-category errors. That is, the right hemisphere may support a 'fruit-like' or 'tool-like' representation that lacks the specific feature information needed to differentiate apples from oranges or pliers from wrenches. Experiment 1 tested that hypothesis.

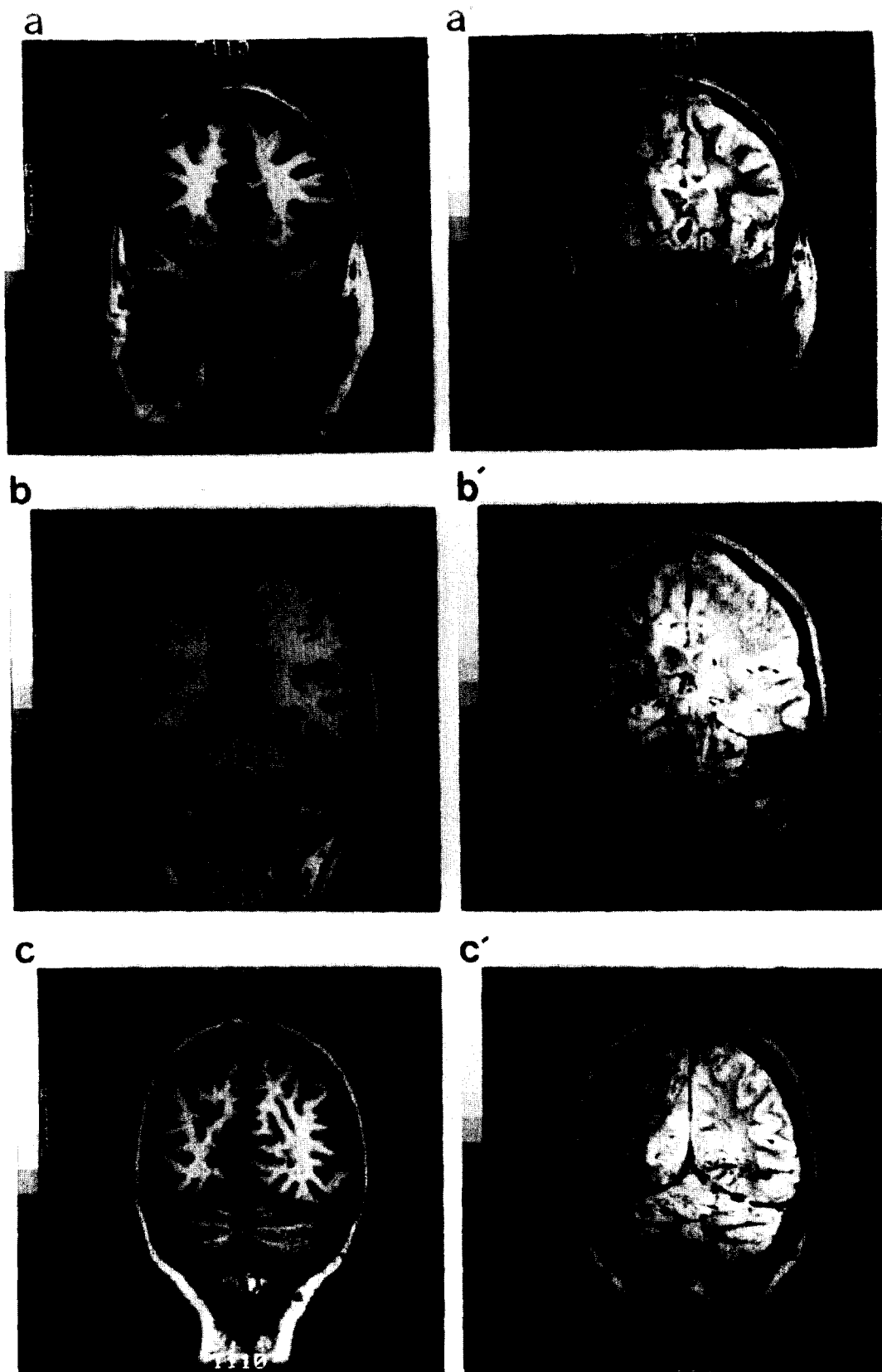


Fig. 4. T1-weighted (a–c) and corresponding T2-weighted (a'–c') coronal magnetic resonance images demonstrating regions of infarction within the right hemisphere. a and a' show the anterior extreme of the lesion approximately 15 mm posterior to the tip of the genu; signal abnormalities are seen in the right cingulate gyrus, subjacent white matter and body of the callosum. b, which lies approximately 6 mm anterior to the splenium, demonstrates the involvement of the posterior hippocampal region and compensatory dilatation of the right temporal horn. The extension of the lesion into the white matter of the superior parietal lobule is evident in b'. c, which lies approximately 18 mm posterior to the splenium, illustrates decreased signal in the ventral cuneus and dorsal lingual gyrus along the upper and lower banks, respectively, of the calcarine fissure. The dorsal extension of the lesion into the precuneus is shown in c'. Diffuse periventricular hyperintensities are seen in all three T2-weighted images.

Materials

A flexible testing screen was assembled using a plastic frame draped with an opaque terry cloth towel in order to obscure a 20-in by 24-in area. AW could place either hand or both hands under the skirt formed by the towel but had no view of her hands or the activities of the examiner. Eight easily manipulable items were chosen from each of the following eight categories: cosmetics, tools, toys, vegetables, fruits, office supplies, kitchen utensils and jewelry. Items were chosen for ease of manipulation and availability without regard to frequency or concreteness. Of necessity, they were all concrete items regardless of the concreteness rating of their names. However, there is no way to estimate their frequency of occurrence in the world at large. Nonetheless, a *post-hoc* attempt to ascertain the frequency and concreteness of the names of the items used was made. From most to least frequent, the mean Francis and Kucera [14] frequencies by category are 64.5 for toys (eight of eight), 49 for cosmetic items (six of eight), 34.4 for kitchen utensils (seven of eight), 18.1 for office supplies (seven of eight), 14.9 for jewelry (seven of eight), 10.3 for fruit (seven of eight), 8.7 for vegetables (seven of eight) and 8.4 for tools (seven of eight). From most to least concrete, Paivio *et al.* [32] concreteness ratings are 7.00 for office supplies (one of eight), 6.98 for fruit (three of eight), 6.98 for vegetables (two of eight), 6.96 for toys (three of eight), 6.92 for cosmetics (four of eight) and 6.90 for kitchen utensils (one of six). No concreteness score was found for items in the tool or jewelry categories. Frequency does not appear to predict success. Little can be said about the concreteness scores as many items were not found. However, all names that were found were in the range usually considered to indicate high concreteness.

Procedures

AW was seated in a quiet room with one hand resting out of view under the apparatus described above. A pseudo-randomly chosen item was placed in her hand and she was encouraged to actively palpate it until she recognized it. She was encouraged to attempt to name the item before making any other vocalization. After naming the item, she was instructed to explain why she had chosen that name. A total of 64 items were presented out of view to the left hand for naming responses. The procedure was repeated with the right hand.

Results

Overall accuracy was strikingly different for the left and right hands. Stimuli palpated by the left hand were named correctly only 15% of the time. In contrast, the right hand was correct 97% of the time. Of the left hand responses, 15% were names of items in the same category

Table 1. Number correct on left hand tactile naming

Category	Correct	Same category	Other
Cosmetics	4	2	2
Tools	0*	3	3
Toys	2	1	5
Vegetables	0	0	8
Fruits	1	1	6
Office supplies	2†	2	3
Kitchen utensils	0	0	0
Jewelry	0	0	8
Total	9 (15%)	9 (15%)	43 (70%)

*One item was accidentally exposed to view and identified by sight; a second was identified by smell.

†One item was accidentally exposed to view and identified by sight.

(‘hammer’ for a pair of pliers, ‘banana’ for an apple). The two errors made on right hand stimuli were both out of category (‘bobby pins’ for an earring, ‘ruler’ for a paint stick). Of the rest of the left hand responses (70%), many were neither related nor physically similar (see Tables 1 and 2).

If the responses had been restricted to the eight categories used, the percentage of within-category errors expected by chance would have been 12.5%. The number of category errors actually made was at this level. However, as there was no experimenter-imposed restriction on the responses, they could have come from any category. Despite this apparent freedom, AW’s responses only included two items that were not from the categories tested. One response, ‘coin’, was from a category previously used with her. The other response, ‘clothespin’, was a common household item, but not strictly speaking a kitchen utensil or a tool. Therefore, either because of AW’s self-imposed restrictions or because of real limitations on the categories of easily available manipulable items, it is warranted to assume that this rate of same category errors represents chance performance.

AW was able to name some items presented to her left hand out of view. Her speed and accuracy on these tasks is in stark contrast to that of her right hand. Items palpated by her right hand were identified quickly and accurately. In contrast, verbal identification of items palpated by the left hand was slow and indefinite. AW was routinely asked why she had chosen a name. Her responses were frequently confabulatory and based upon the characteristics associated with the item she had named not the item she had palpated (see her responses to ‘paintbrush’ and ‘comb’), a phenomenon frequently observed in commissurotomy patients [16].

Discussion

It is not clear what mechanism guides the correct naming (15%). AW could be correctly identifying items in her

Table 2. Examples of tactile naming responses

Object	Response	
	Right hand	Left hand
Responses in naming only trials		
Block	Block...wooden	I don't know... almost like a block...I don't know
Car	Car	Straw...kind of round and can bend
Pepper	Pepper	Banana...it feels long and mushy
Watch	Wristband...watch	Toothbrush...feel the bristles
Pineapple	Pineapple	Oh, wow. I smell something...like fruit...smell apple...no, of course not...it feels like a basket
Bobby pin	Bobby pin	Small, but not smooth, not round, not square
Responses following tactile matching		
Apple	Apple	Cotton?
Screw	Screw	Screw...felt the grooves
Nailpolish	Nailpolish	Soggy carrot
Asparagus	Asparagus	Asparagus...has to be...felt long
Paintbrush	Paintbrush	Hammer...it's heavy
Cotton	Cotton	Paintbrush...felt hard end and something soft
Comb	Comb	Nailpolish...didn't feel big...felt hard

right hemisphere but failing to transfer that information consistently to her left hemisphere for speech production. Alternatively, she could be transferring somatosensory information about the items into her left hemisphere, which then guides the choice of items. It is also possible that ipsilateral somatosensory information may be providing partial cues on which to base left hemisphere guessing. Gazzaniga [15] has reported that the hemisphere ipsilateral to tactile stimulation does receive some somatosensory information. For example, information regarding the presence or absence of a stimulus, the presence or absence of edges and amount of weight is available to the ipsilateral hemisphere of commissurotomy patients and can provide the basis for left hemisphere guessing. It is therefore difficult to be certain if the naming errors made in response to left hand tactile stimulation were the result of some partial or faulty assembly of information within the right hemisphere; if the correct item was identified by the right hemisphere, but transfer to the left hemisphere was not sufficiently detailed to select the appropriate phonological code; or if the errors originated in the left hemisphere based on ipsilateral sensory information.

Having established that AW has limited naming of left hand palpated items, we wished to determine if her ability to match these items to a visual representation was superior to her naming ability. Greater accuracy on this task would indicate that her right hemisphere was indeed generating an abstract representation of the items palpated and could use it to perform the matching task.

Experiment 2

To generate a set of palpable items for tactile-visual matching, we selected items from six categories:

cosmetics, geometric shapes, tools, toys, vegetables and fruits. In each of five categories, four items corresponded to those used in Experiment 1. Two items in those categories were different. The geometric shape category was new.

Materials

Six items from each category were chosen based on subjective ease of naming by palpation as determined by the examiner. As in Experiment 1, items were chosen for ease of manipulation and availability without regard to frequency or concreteness. As there is no way to estimate their frequency of occurrence in the world at large, a *post-hoc* attempt to ascertain the frequency and concreteness of the names of the items used was made. From most to least frequent, the mean Francis and Kucera [14] frequencies by category are 73.16 for toys (six of six), 44.3 for geometric shapes (six of six), 24.8 for tools (four of six), 15.2 for cosmetic items (five of seven), 6.83 for vegetables (six of six) and 9 for fruits (six of six). From most to least concrete, Paivio *et al.* [32] concreteness ratings are 7.00 for fruit (one of six), 6.96 for toys (four of six), 6.90 for cosmetic items (one of seven), 6.44 for tools (one of six) and 6.21 for geometric shapes (three of six). No concreteness score was found for items in the vegetable category. Frequency does not appear to predict success. Concreteness scores for many items were not found, but names that were found were in the range usually considered to indicate high concreteness. A computer image of each item was created and used to generate a black and white image of the item for AW to use for pointing responses.

Procedures

AW was seated in a quiet room with her left hand resting on the table. She preferred not to wear a blindfold and was reliably able to keep her head turned away and her eyes closed. A pseudo-randomly chosen item was placed in her hand and she was encouraged to actively palpate it until she was satisfied that she knew what it was. AW was encouraged to try to form a picture of the item in her mind, but not to think about the name of the item. When she indicated that she was finished, the item was taken away and six pictures were placed on the table in front of her. One picture was the correct item, two were other items in that same category, and three were pictures randomly selected from the rest of the stimulus set. Before making any comments aloud, AW was instructed to point to the item that she had been holding with her left hand. After she had made her selection, she was asked why she had chosen that item. This and subsequent sessions were videotaped and performance was scored from the tape.

Results

AW was able to match the picture to the palpated item with above-chance accuracy, despite the difficulty she had previously demonstrated naming objects by palpation (see Table 2). Her accuracy at matching was greater than her naming ability (59% in 37 trials vs 15% in 61 trials). Since response choices were selected from other items in the set of tested materials, it was possible that the familiarity gained over the course of the experiment might have made later items easier for AW to identify. This possibly was ruled out by showing that there was no significant difference in the percentage correct from the first 18 items tested compared with the percentage correct from the last 19 items tested (61% vs 58%, $z = 0.26$, n.s.). When AW failed to match an item, it did not appear that she had category information available, as the number of within-category errors did not differ from chance ($z = 1.33$, n.s.). Therefore, the difference between AW's ability to perform cross-modal matching and to name palpated items appears to be real.

Discussion

These results demonstrate that AW was able to visually recognize items palpated by the left hand. The discrepancy between her left hand cross-modal matching and left hand anomia confirm that although the right hemisphere does not easily support naming, it is able to build an abstract representation from left hand somatosensory information. These results are compatible with those observed by Risse *et al.* [36] in a group of seven patients with incomplete anterior transections of the corpus callosum. Two of these patients were able to correctly make visual-tactile matches for items they could

not name in their left hand. They both had sparing of only the posterior one-third of the splenium on MRI. Patients with sections that did not extend as far posteriorly were able to name items placed in either hand. Delouche *et al.* [12] observed left hand tactile anomia in a patient with a large hemorrhagic lesion of the isthmus portion of the corpus callosum and some general callosal atrophy, confirming the importance of this region of the callosum in naming of stimuli identified by the non-dominant hemisphere.

Although these results indicate that the right hemisphere is able to assemble an abstract representation based on tactile information, the question of where the naming errors originate remains unresolved. It has been established that the right hemisphere seldom generates speech [15, 52]; therefore, it is unlikely that naming responses can be attributed to the right hemisphere. In view of the high likelihood that the left hemisphere controls speech, incorrect responses must be based on (i) semantic information from the right hemisphere based upon its own identification of the item and transferred to the left hemisphere; (ii) somatosensory cues transferred from the left to the right hemisphere; or (iii) ipsilateral tactile or somesthetic information from the left hand stimulation. It is also possible that variable amounts of information from all of these sources is available to the left hemisphere. If we assume that the semantic information supplied is category information, the failure to make a significant number of within-category errors on Experiments 1 and 2 argues against the first hypothesis. However, we cannot rule out the use of somatosensory information transferred from the right hemisphere or ipsilateral sensory information to inform verbal responses. Because visual information cannot be lateralized to this right hemisphere due to the right occipital lesion, it is not possible to test the extent of AW's right hemisphere lexical and semantic abilities with respect to visual language.

In summary, the results of Experiment 2 indicate that AW was able to abstract features of objects in the tactile modality and form percepts of them that could be used to recognize representations of the objects generated in a different modality. As visual field testing suggested that she had too little functional vision in the left visual field (LVF) to have accurately recognized the pictures even with a free field display [3], we suspect that the spared splenial fibers (Fig. 3) allowed her to use right visual field (RVF) information to make above-chance selections. On occasion, the right and left hemispheres differed over the correct choice (see Table 3, asterisk footnote), which would suggest that they were making separate use of the available visual information. It is unclear whether the right hemisphere was able to identify items uniquely (i.e. to gain either complete or partial semantic access without phonological information, and transfer that information into the left hemisphere for a verbal response) or if a representation was assembled that only supported cross-modal matching but did not provide semantic access.

Table 3. Number correct matching pictures with palpated objects: left hand only

Category	Correct	Same category	Other
Cosmetics	6	1	0
Geometric shapes	2	1	3
Tools	3	2	1
Toys	4	0	2
Vegetables	5	0	1
Fruits	2*	1	3
Total	22 (59%)†	5 (14%)‡	10 (27%)‡

Note: one extra item from the cosmetics category was administered by error. That data point was retained.

*After palpating the orange, AW's left hand clearly selected the picture of the orange, but she verbally rejected that choice and used her right hand to point to the cross. When it was pointed out to her that her left hand seemed to want to make a different choice, she reiterated that it was the cross she intended to select. This trial was counted as a correct left hand choice.

†Above chance performance, $z = 5.84$, binomial $P < 0.001$, two-tailed.

‡Not significantly different from chance.

AW's use of cues to aid identification and possible transfer of higher-order information limited the interpretation of the results of Experiments 1 and 2. Examining her responses, her descriptions became more precise and often further from the actual physical properties of the palpated object after she had verbalized an incorrect response (see Table 2). This suggests that her left hemisphere was guessing and confabulating about its own response. It was also observed that when she was unable to identify a picture immediately, she often could not identify it at all. This raised the question of whether her right hemisphere performance was further hampered by an inability to remember items identified by palpation.

Experiment 3

A comparison of AW's ability to identify, remember, retrieve and generate names of palpated items was needed. The next series of manipulations was designed to provide a direct comparison across identical sets of items that could not be differentiated by weight, texture or sound, but only by building a mental representation from the tactile information about edges and angles.

Materials

Four wooden geometric shapes were selected from the Halstead-Reitan Tactile Form Board items. The forms chosen were a circle, a cross, a diamond and a triangle. The wooden apparatus utilized to administer Tactile Form Recognition clinically was used to assure that the hand being tested was out of view. These same materials

were used for each of the manipulations described below, but the procedures differed.

Procedure

Before tactile testing was initiated, the four forms were presented for visual naming to ascertain that AW recognized them and knew their names. Following free-field naming, her hand was placed through the Tactile Form Recognition board. The right hand was always tested first to give her a maximum left hand advantage. *Naming*: the wooden shapes were placed in her right hand one at a time for her to name aloud. Forms were presented in a random order until each form had been presented five times for a total of 20 trials. The left hand was tested in an identical fashion. *Auditory comprehension*: AW was asked to place her right hand through the Tactile Form Recognition Board. The four shapes were placed within easy reach of her hand. The examiner then named one of the forms for her to pick up. AW was encouraged to palpate each form in turn until she was satisfied that she recognized the item requested. After she made her selection, the examiner then replaced that item with the other forms and scrambled their order. AW was not informed whether her choice was correct or incorrect. This procedure was repeated until she had been asked to retrieve each shape five times. The procedure for the left hand was identical. *Matching*: this procedure was identical to that for auditory comprehension, except instead of hearing the name of the target item, AW was given one shape to palpate until she indicated that she was satisfied that she recognized it. That form was then removed from her hand and placed with the other forms. The search procedure was identical to that of auditory comprehension. *Matching with delay*: this procedure was identical to that of matching, except that a 30-sec delay was introduced between removing the target shape from her hand and allowing her to initiate a search for the item.

Results

AW was able to match shapes, i.e. retrieve the blocks that she had just palpated with her left hand at above-chance levels (see Table 4). She was unable to use her left hand to retrieve blocks that had been named aloud nor could she accurately identify palpated blocks by name.

Her ability to match a palpated block was disrupted by the introduction of only a 30-sec delay. In contrast, her right hand performed at above-chance levels in all of these conditions.

Discussion

AW's left hemisphere was able to use the tactile information from her right hand to form a mental rep-

Table 4. Percentage correct recognizing wooden geometric forms by palpation

Condition		Right hand	Left hand
Tactile naming		86%	38%*
	<i>n</i>	(21)	(21)
Auditory comprehension		90%	35%*
	<i>n</i>	(20)	(20)
Tactile matching, immediate		92%	70%†
	<i>n</i>	(20)	(20)
Tactile matching, 30-sec delay		80%	40%*
	<i>n</i>	(20)	(20)

Note: in all conditions, four geometric forms, a circle, a square, a diamond and a cross, were available for the hand being tested to palpate while concealed by a wooden device designed for that purpose. All right hand performances were above chance levels.

*Not significantly different from chance performance (chance = 25%), $z = 1.29, 0.98$ and 1.45 , respectively.

†Above-chance performance, $z = 4.51$, binomial $P < 0.001$, two-tailed.

resentation of the object that she can match, remember, retrieve and name. In contrast, her right hemisphere was able to use the tactile information from her left hand to construct a representation for intramodal matching, but this representation was not available for cross-modal matching, i.e. to name or to match with spoken words. This suggests that (i) AW's right hemisphere lacks a reliable auditory lexicon and (ii) her left hemisphere cannot use its lexicon to control the selection, presumably because of the callosal infarct.

AW's right hemisphere manifests a deficit in tactile memory that is apparent with only a 30-sec delay. It is not clear whether this problem is related to the putative absence of a right hemisphere lexicon that would otherwise support a mnemonic code and/or if it is due to damage to right medial temporal lobe structures.

Proponents of right hemisphere language might argue that the difference between the occasional accurate naming in Experiment 1 and the failure to name at above-chance levels with a restricted set of items in Experiment 3 was due to the more abstract, infrequent nature of the stimuli. The tactile stimuli from Experiment 1 were all concrete objects which are generally expected to be represented in the right hemisphere lexicon [9]. Although frequency and concreteness ratings were not available for the names of all of the items tested, there was little difference in the rated frequency or concreteness of those items that could be found. Moreover, AW did not fail to name objects in Experiment 3, nor did she respond with more concrete object names. Therefore, a more plausible interpretation is that the right hemisphere is not responsible for naming responses in either case, but that the left hemisphere was guessing aloud using whatever cues it had available, including tactile information from ipsilateral pathways. These results are most consistent with the view that the right hemisphere lacks the ability to generate or to decode phonological information consistently, but is

able to generate mental representations from tactile information.

General discussion

Isolated cognitive systems

AW's functional dissociations correlate well with her anatomical lesions. AW is able to transfer sufficient visual information into the right hemisphere for cross-modal matching (tactile-visual) via the splenium. Tasks that require naming responses were not accurately performed. The scarcity of paraphasic errors and chance number of category errors argues against transfer of category information from a right hemisphere lexicon. Likewise, the nature of many of her responses suggests that the left hemisphere is confabulatory, perhaps operating on partial or inaccurate somatosensory information. In contrast, patient JW, when interrogated shortly following the posterior callosotomy which severed his splenium, demonstrated increased naming accuracy and narrowing of his responses around the correct verbal identification of LVF stimuli [41, 43]. This patient with intractable epilepsy had an intact anterior callosum and was presumably accurately transferring higher-order semantic information, although the section of the posterior callosum disrupted the transfer of visual information presented to the LVF. AW, if she names an item incorrectly, is captured by her own verbal response and reports the sensory evidence appropriate to that response. Her descriptions became more precise but often further from the actual physical properties of the palpated object after she had verbalized an incorrect response (see Table 2).

However, she did sometimes indicate a conflict between the verbal label and sensory information. Upon being presented with a whole pineapple to palpate out of view, AW first commented on the fruit-like odor, but could not integrate this with her tactile impression that she was palpating a basket. In this case, the left hemisphere was apparently identifying the odor but failing to integrate that information with the 'feel' of a basket (which it did rapidly and easily when the same item was presented to the right hand). Although this response raises the question of whether her right hemisphere may sometimes be able to make a unique identification that becomes available to the left hemisphere, it may also be an indication that the left hemisphere does not make its normal integrative use of somatosensory information transmitted through the ipsilateral pathways.

Right hemisphere lexicon

The inability to name objects placed in the left hand of callosally sectioned patients is one hallmark of the disconnection syndrome [15]. When tested using tactile

matching tasks, split-brain patients demonstrate that they can form a mental representation of palpated objects, but are unable to access the speech production mechanisms of the left hemisphere to verbally label them. As many of these patients have some right hemisphere auditory comprehension and some of them can read tachistoscopically despite the inability to generate verbal names, it is generally agreed that the right hemisphere can support an independent lexicon. The prevalence and utility of this lexicon, however, is a matter of dispute (for review, see [2]). The presentation of a patient such as AW confirms the validity of the data obtained from split-brain patients and suggests this patient population may be useful in further understanding the semantic or conceptual organization of the right hemisphere.

The idea that the right hemisphere might support a distinct language system has inspired a variety of proposals regarding the possible role of the right hemisphere in normal language and in recovery from aphasia and alexia. One view is that the right hemisphere lexicon plays a role in the semantic reading errors made by patients with deep dyslexia [8, 9, 37, 38], which is characterized by semantic, morphological and visual paralexias, sensitivity to part of speech and concreteness of lexical items, and difficulty reading non-words. These symptoms, particularly the presence of semantic paralexias, or substitution of semantically related words when reading out loud (a patient might read the word 'chair' as 'table' for example), have been attributed to a "more diffuse or undifferentiated" right hemisphere lexicon [30]. A similar argument has been made for the occurrence of semantic paralexias in aphasic patients [39]. If there are distinctive properties of the right hemisphere lexicon, the utility of such a lexicon should be considered in constructing models of normal language processing.

Support for this position in the split-brain literature has been inconsistent. Zaidel [51, 53] reported semantic errors in response to LVF exposures in the West Coast splits. In contrast, Gazzaniga and colleagues [17, 20, 21, 41, 44] have demonstrated great variability in the sophistication of the right hemisphere's lexical knowledge and rare semantic errors [4, 17].

If and when semantic errors do occur, it is not necessarily the case that they arise because of a distinctively different semantic representation in the right hemisphere. A different mode of right hemisphere access, such as serial rather than parallel processing of letter strings [35], might result in a distinctive error pattern. It is also possible that such errors could arise as a result of faulty callosal transfer. For example, after posterior callosal section, patient JW seemed to have access to higher-order, non-specific semantic information about words and pictures presented to the LVF [43]. Prior to first stage commissurotomy, he did not demonstrate this kind of behavior nor did it persist after the second stage of commissurotomy was completed. It seems possible that the crucial factor in JW's case was the alteration in the ability of the corpus callosum to transmit information.

However, these experiments were of necessity carried out close to the time of surgery; therefore, intrahemispheric dysfunction secondary to diaschisis cannot be ruled out.

Beauvois *et al.* [5] suggest a different cause for the tactile aphasia of a patient with alexia without agraphia and bilateral tactile anomia, and no evidence of damage to the corpus callosum or the right hemisphere. Following removal of a left parietal-occipital angioma with evacuation of a hematoma, their patient RG correctly named palpated items 71% of the time with the right hand and 64% of the time with the left hand. The majority of the errors were semantic paraphasias. In contrast, callosotomy patients can seldom name items palpated by the left hand and naming errors are often unrelated to the targets. Beauvois *et al.* suggest that the errors of the callosotomy patients occur after an initial correct tactile recognition by the right hemisphere fails to be transferred into the left hemisphere. In contrast, the semantic paraphasias of their patient arise as a result of a pre-linguistic sorting of objects into categories that is accomplished before specific names are selected.

The view of Beauvois *et al.* may be compatible with the category-specific deficits reported in the aphasia literature [48, 49], but is at odds with the view that semantic errors arise in the right hemisphere because of some difference in the semantic representation. The errors reported by Beauvois *et al.* were attributed to a failure of processing that could arise within either hemisphere. In contrast, the paralexias attributed to the right hemisphere have been attributed to failure of left hemisphere inhibition of right hemisphere semantic processing. If the latter account were general, such errors should have been demonstrated in AW's relatively isolated right hemisphere. Moreover, split-brain patient JW, whose right hemisphere was originally mute, can now initiate vocal responses to both LVF and RVF words and pictures. His errors include semantic paraphasias following stimulation in either hemifield [4].

In the discussion above, we are assuming an amodal semantic or conceptual system with varied access routes. However, it is possible that the right hemisphere has visual and tactile semantic systems that are normally organized (i.e. like the language system of the left hemisphere) and a verbal semantic system that has a different organization. Because of AW's left homonymous hemianopia, we cannot directly test visual representations of palpated objects in her right hemisphere, but do not believe multiple, modality-specific semantic systems to have been adequately demonstrated. Although it is certainly logically possible for there to be tactile, visual and verbal semantic systems that are differently organized (see Shallice [39, 40] for defense of such a position), it is difficult to understand why the left hemisphere would harbor a verbal semantic system that matches the right hemisphere's visual semantic system at the same time that the right hemisphere has its own differently organized verbal semantics.

Methodological limitations

Because much of the callosum is intact and because there is some ipsilateral representation of somatosensory information, it is not possible to be entirely certain whether some responses are driven by transfer of information from the right hemisphere, partial ipsilateral information received by the dominant left hemisphere, or whether they are driven by the non-dominant and damaged right hemisphere. Verbal responses to left hand stimuli in particular probably involve the left hemisphere speech mechanisms, which may be guessing randomly or formulating responses based on partial information. In general, the left hemisphere responds normally to both verbal and visual language tasks (AW's verbal IQ is 100) and AW rarely made errors when naming items palpated by the right hand. When naming items palpated by the left hand, AW is often grossly inaccurate in her report of both the name and the attributes of the item, which we attribute to left hemisphere guessing based on partial or inaccurate information. If her right hemisphere were initiating these responses, it would appear to be generating incorrect verbal labels for items it can identify. Although this seems unlikely, we cannot rule out that possibility. Alternatively, it is possible that the left hemisphere could be mediating some of the accurate left hand matching responses. However, it is difficult to understand why this would introduce a memory deficit in the intact left hemisphere or why the language dominant hemisphere would do better at matching than naming. We therefore believe that, despite the possibility of left hemisphere participation, the most reasonable explanation of our data must invoke a right hemisphere cognitive system.

Anarchic hand syndrome

We consider the 'alien hand syndrome' or '*la main étrangère*' in the light of these observations. Brion and Jedynak [7] originally reported the syndrome soon after the callosal disconnection syndrome was reported by Sperry *et al.* [45]. They interpreted the errant behavior of the left hands of their patients as a pathognomonic sign of callosal involvement. They reported four patients who demonstrated a variety of signs of interhemispheric disconnection, two of whom had pathological verification of the extent of the damage. The deficits included difficulty naming items placed out of sight in the left hand, difficulty executing gestures with the left hand to verbal command, constructional apraxia, left hand agraphia, left hemi-inattention, and difficulty transferring somesthetic information from one hand to the other. Brion and Jedynak expected that the alien hand syndrome would be observed only in the non-dominant hand.

Brion and Jedynak were correct that close observation would result in the report of more alien hand cases with signs of disconnection. However, Goldberg *et al.* [26]

reported two cases with alien right hand syndrome as well. Both patients had left medial frontal lesions, suggesting that the syndrome is not adequately explained as a disconnection of the dominant motor programs from executive control of the non-dominant hemisphere. Goldberg and Bloom [25] proposed that damage to the medial frontal cortex, most particularly the supplementary motor area, was necessary to cause the emergence of the alien hand syndrome in the hand contralateral to the damage, due to the unyoking of the medial premotor system and the lateral premotor system. They argued that both systems contribute to voluntary motor control, but the lateral premotor system is organized to respond directly to external information in a 'reactive' mode (p. 233) and the medial premotor system is newer and more involved in "internal mnemonic sources of information" (p. 234). Goldberg and Bloom concluded that the medial system yields the feeling of voluntary control over action, and damage to that system yields the disruption of balance that results in the contralateral alien hand.

In contrast, Feinberg *et al.* [13] suggest that there are two distinct alien hand syndromes, a frontal type and a callosal type, that are the result of different mechanisms and have different characteristics. The frontal type usually involves the dominant hand, is accompanied by a grasp reflex, compulsive movements, restraining action by the non-dominant limb and compulsive manipulation of tools. The callosal type involves the non-dominant hand, is activated by dominant hand action, involves intermanual conflict and is often accompanied by left apraxia. The former requires both disruption of the left frontal lobe and release from right hemisphere inhibition to emerge. The latter requires only hemispheric disconnection.

Tanaka *et al.* [46] reported three cases with a variety of abnormal motor movements of the non-dominant hand, including movements antagonistically, randomly and symmetrically related to the dominant hand movements. There was also a failure to move the non-dominant hand at will on some occasions. The authors suggest that these movements are subsequent to lesions of the ventral part of the body of the corpus callosum, which normally connects the superior parietal lobules. As the left superior parietal lobe dominates in the selection of motor movement, the separation produces a loss of voluntary control of the left hand.

As part of a case report, Della Sala *et al.* [11] reviewed the literature and presented a summary of the data from 35 patients demonstrating alien or anarchic hand syndrome and intermanual conflict. They emphasized that the cardinal manifestation of the syndrome is the loss of voluntary control over one hand and that it does not include autotopagnosia. Patients do not deny that the recalcitrant limb is their own and do not neglect the limb, but are dismayed by the inability to assume voluntary control over its action. For this reason, Della Sala *et al.* suggested that the syndrome might better be called 'anarchic' rather than 'alien' hand, and we have followed

that suggestion in this paper. They also point out that few cases have been followed longitudinally and that although the syndrome has been described as fleeting, particularly after callosal disconnection [50], the patient they report continues to display the syndrome 3 years post-onset. They suggest that bihemispheric damage may be requisite to chronicity. In contrast, Papagno and Marsile [33] suggest that the extent of the callosal lesion is most crucial. The subject they report with a discrete lesion and transitory anarchic hand did not display disconnection signs such as left agraphia and left tactile anomia.

Anatomical considerations

The presence of anarchic hand sign has been associated with damage to the corpus callosum from the earliest reports of Brion and Jedynak [7]. AW has damage to the body of the callosum that spares much of the splenium and the genu. Of the 10 symptoms of callosal disconnection listed by Bogen, AW exhibits five. Two symptoms, verbal anosmia and spatial acalculia, were absent and two, double hemianopia and hemialexia, could not be tested due to her field cut. The remaining symptom constructional apraxia is predicted by Bogen to be present in the right hand. However, in AW some constructional apraxia was observed bilaterally using Kohs blocks. She was able to draw and copy adequately with her right hand, however. In contrast, her left hand was impaired on drawing tasks. The bilateral constructional apraxia is consistent with Gazzaniga's [16] observations that these skills depend upon interhemispheric integration in some patients and therefore can be observed to decline for either hand after callosal section in these patients.

Although Goldberg *et al.* [25, 26] suggested that medial frontal damage is necessary for the sign to emerge, in AW the frontal lobe structures are not infarcted, but extensive involvement of the medial temporal, posterior parietal and occipital lobes is observed. Thus, AW demonstrates intermittent intermanual conflict and disruptive left hand behaviors without evidence of medial frontal damage. These findings indicate that an intrahemispheric lesion of the medial frontal lobe is not a necessary condition for the production of the anarchic hand syndrome. AW may represent what Feinberg *et al.* [13] term the callosal type of anarchic hand syndrome. AW's lesion encompasses the area of the callosum described by Tanaka *et al.* [46], but extends both anteriorly and posteriorly. She exhibits both antagonistic movements and the occasional inability to move her left hand at will seen in Tanaka *et al.*'s cases. She also appears to support Papagno and Marsile's [33] contention that chronic anarchic hand sign is accompanied by other disconnection signs. However, extracallosal damage may contribute to her presentation as well.

AW's lesions serve to isolate her right hemisphere from

verbal output and from direct visual input. She does process tactile information from her left hand and receives useful visual information from her left hemisphere via the intact splenium. However, she corroborates the observation that the anterior one-third of the splenium may be crucial for naming of items palpated by the left hand [36]. In a systematic investigation of the clinical signs associated with callosal transfer, Giroud and Dumas [24] noted alien hand in only two of eight patients with callosal lesions gleaned from a 12-month review of 282 new cases of cerebral infarction. One had an anterior right infarction of the corpus callosum and the other a large corpus callosum lesion with a small infarction of the centrum semiovale. The latter patient (Case 7) was the only case with tactile anomia and had the most posterior callosal lesion, including the anterior one-third of the splenium.

In view of the above, the positive but unwilling motor activity of the left hand may be related to the specific lesion described by Tanaka *et al.* [46]. Geschwind *et al.* [22] also reported a case of anarchic hand without evidence of callosal apraxia, tactile anomia or loss of somatosensory transfer. This patient had a lesion in the posterior two-thirds of the body of the corpus callosum, sparing the splenium. These anatomical considerations suggest that an extensive callosal lesion may be necessary to produce a full disconnection syndrome. Jason and Pajurkova [28] stress the intermittent nature of the loss of 'metaccontrol' in a patient with lesions of the genu and body of the corpus callosum and bilateral inferomedial frontal lesions. AW's control of her left hand was intermittent and this appears to have been true of Geschwind *et al.*'s patient as well. This inconsistency of behavior and localization may indicate that the mechanisms of conscious control are not entirely dependent on any one fiber pathway.

Beyond the anatomy of the alien hand syndrome, AW demonstrates a right hemisphere cognitive system that can assert its independence when given an appropriate mode of expression. She also demonstrates specific cognitive deficits that are consistent with her neurological damage: in particular, a right hemisphere memory deficit for tactile information. The nature of the right hemisphere representation that supports AW's judgments may be more accurately characterized as conceptual rather than semantic, but that question awaits further investigation. Her normal verbal IQ and memory argue that her left hemisphere continues to function well, with no apparent loss in verbal intelligence related to absence of right hemisphere support. Most importantly, the right hemisphere cognitive system, with limited memory and language, can use tactile and visual information to demonstrate its ability to formulate an abstract representation and to act independently on its own judgment. It is this independence that leads to the perceived 'anarchic' hand in this patient.

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