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Let not thy left hand know what thy right hand knoweth

The case of a patient with an infarct involving the callosal pathways

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Summary

Following a cerebral vascular accident, a patient showed a classical disconnection syndrome: left-hand tactile anomia, apraxia and dysgraphia and right-hand constructional apraxia. What made the case unusual was the presence of hand asymmetry in the performance of some matching-to-sample tasks carried out in foveal vision. The left hand committed significantly more errors than the right hand when it was not possible to identify on a perceptual basis the stimulus that was to be matched, because it was removed (memory condition) or was indicated verbally (verbo-visual matching), or had the same name but not the same physical appearance as the match (capital and lower-case letter matching). No hand difference emerged when the stimulus remained in full view throughout the matching task (perceptual condition). The hand effect, however, was limited to colours and letters. Objects, geometrical shapes and unfamiliar faces were matched with equal proficiency by both hands under every condition of presentation. Left-hand errors also significantly outnumbered right-hand errors in sorting colours according to hue and colouring drawings. MRI showed an infarct in the left cingulate white matter that ran parallel to the trunk of the corpus callosum, and an infarct of the splenium. However, the latter did not prevent the transmission of colour and letter information between the two hemispheres, as shown by the performance on perceptual equivalence tasks and by the correct right-hand responses to stimuli projected to the left visual field. We propose that this pattern of deficit is contingent upon the specific role that the left hemisphere plays in categorizing a given colour patch as belonging to a definite colour region (red, blue, etc.) and in grapheme recognition. Without the assistance of the left side the right hemisphere lacks the benefit provided by meaning identification. In our patient the left brain did receive information from the right brain and was able to process it, but was prevented by the paracallosal lesion from transmitting what it knew to the right motor area. No hand effect emerged for objects and geometrical shapes, because their semantic memory is bilaterally represented.

Keywords: hemisphere disconnection; letter recognition; colour recognition; limb apraxia

Introduction

Complete section of the commissures results in two isolated hemispheres that are no longer able to carry out tasks dependent on information processed in the other half of the brain. Accordingly, neither hand can match-to-sample an object presented visually or tactually to the ipsilateral hemisphere. In addition, the isolated right hemisphere fails tasks involving language, such as reading words and naming objects projected to the left visual field, naming objects held in the left hand and performing gestures with the left hand on verbal command. A question still under debate is whether or not the right brain has the lexical competence to comprehend nouns. While some authors (Zaidel, 1990) claim that this ability is represented in the minor hemisphere, others (Gazzaniga, 1983) argue that there is wide variability across patients. All agree, however, that the right brain can interpret the meaning of the visual representation of an object, as shown by the left hand's ability to match a palpated object or an object that has been presented to the left visual field with a semantically related object (Cronin-Golomb, 1986; Trevarthen, 1990).

In patients who have undergone surgical section of the callosum, the disconnection syndrome is contingent upon the

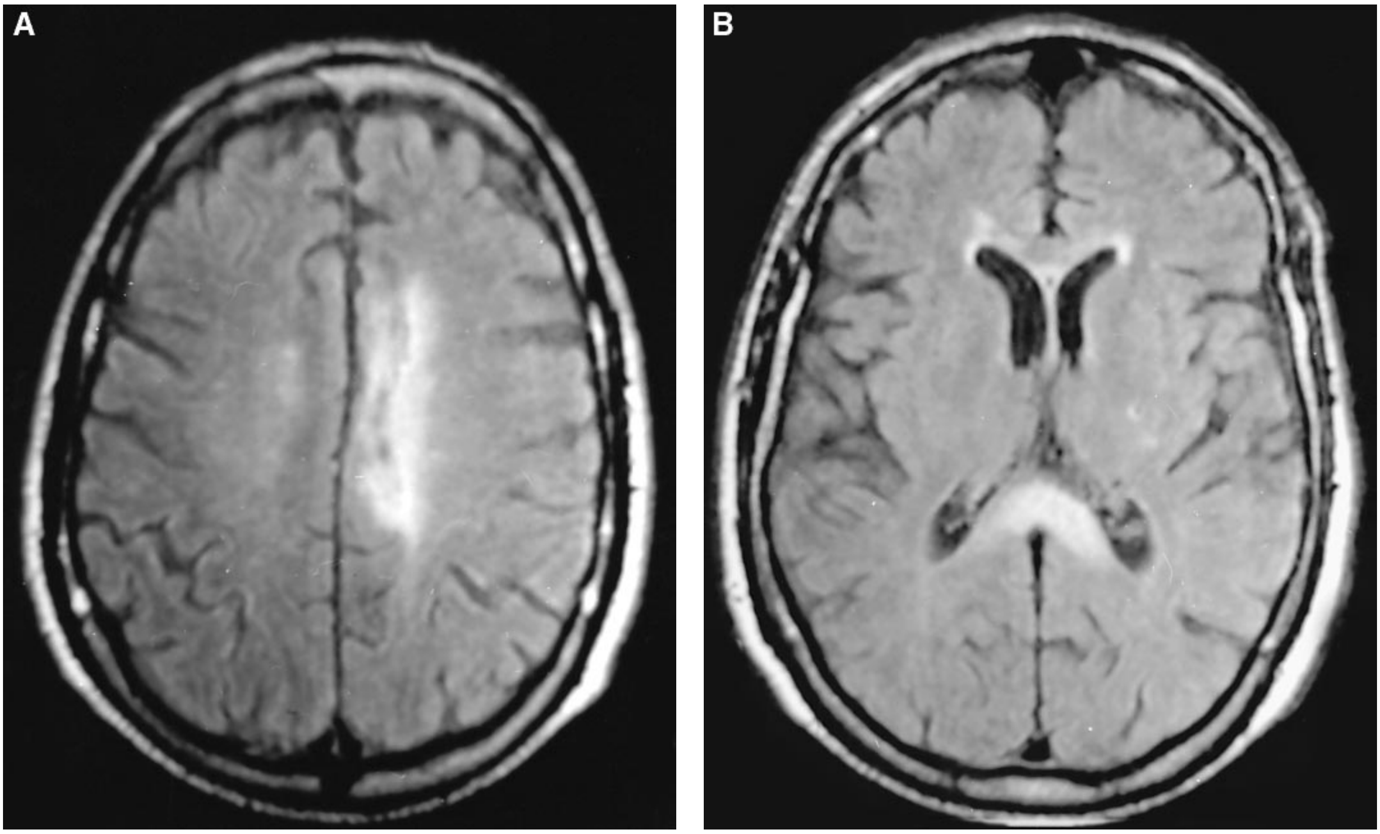

Fig. 1 MRI horizontal sections showing in **A** the paracallosal infarct and in **B** the splenial infarct.

complete interruption of splenial fibres. If they are partially spared, no deficit appears (Bogen, 1987). Indeed, this was the interpretation of Goldstein and Joynt (1969) of the absence of interhemispheric transfer deficits in the patients reported by Akelaitis (1944). Rather more positive were cases of spontaneous pathology, such as the patient reported by Geschwind and Kaplan (1962), who showed definite signs of hemispheric disconnection following an infarct damaging the anterior half of the trunk. The most widely accepted account (Gordon, 1990) of this contradiction is that most, if not all, of the symptoms are due to diaschisis.

We report a patient who showed, under certain experimental conditions, a striking inferiority of his left hand in performing matching-to-sample tasks carried out in full vision, as a sequel to a paracallosal lesion of the left hemisphere. This patient made many more errors with his left hand than with his right hand, even when visual stimuli were processed by the right hemisphere and could reach the right motor centre. We think that this pattern of impairment throws new light on the hemispheric specialization of function.

Case report

Antonio (a fictitious name) was an 82-year-old man whose medical history was unremarkable except for arterial hypertension over the previous few years. On December 7, 1996, the patient presented with right hemiparesis and aphasia, from which he made a partial recovery. He came to our attention in January 1997. Neurological examination showed a mild paresis, marked grasping and sensory deficits of the right hand. The results of visual field examination (Goldman perimetry) were normal. His speech was halting and laborious, with some phonological distortions, reminiscent of those found in Broca's aphasia.

Neuroradiological findings

An MRI, carried out on February 18, 1997, showed a lesion located in the left cingulum (areas 23 and 24), involving the roof of the lateral ventricle, from the anterior margin of the frontal horn to the level of the paracentral lobule, parallel to the corpus callosum (Fig. 1A). It probably interrupted the callosal pathways of the trunk within the left hemisphere, with the possible exception of a few posterior fibres. In addition, there was evidence of a small lesion of the genu and a wide lesion of the splenium (Fig. 1B). It is uncertain whether the latter was an extension of the callosal infarct or a separate infarct. Punctiform lesions were seen in the left temporal lobe and the white matter of both hemispheres.

Neuropsychological examination

Formal language examination (Ciurli *et al.*, 1996) was carried out in January 1997 and repeated in March 1997, when a

Table 1 *Performance on language tests*

	Number of correct responses/ number of test items
Token test	
Right hand	29/36
Left hand	14/36
Visual naming	
Objects	16/20
Visual naming	
Colours	4/10
Tactile naming	
Right hand	6/20
Left hand	11/20
Tactile equivalence	
Right hand	12/20
Left hand	19/20
Reading words	19/20
Reading non-words	9/20
Writing object names	
Right hand	13/20
Left hand	0/20
Writing to dictation	
Right hand	11/20
Left hand	0/20
Imitating movements	
Right hand	54/72
Left hand	36/72

moderate improvement was observed in the results of all tests. Here we will focus on the scores of the second examination (Table 1), which was carried out at the same time as the experimental investigations to be reported below. It should be pointed out, however, that the hand effect was already present at the time of the first examination, when it was fortuitously discovered whilst the patient was performing the token test. Since the performance of the right hand was sometimes hampered by grasping, the examiner asked the patient to point to the tokens with his left hand and was amazed to find that the number of errors increased remarkably: the number of correct responses was 26 out of 36 with the right hand and 7 out of 36 with the left hand. Table 1 shows that the hand asymmetry on the token test was replicated in March ($\chi^2 = 12.99$, $P < 0.001$). It was also apparent in writing. When Antonio used his right hand to write the names of 20 visually presented objects, he gave 13 correct responses, five responses with one spelling error and two responses with more than one spelling error. On writing to the dictation of the same words, he gave 11 correct responses, eight responses with one spelling error and one response with more than one spelling error. By contrast, on both tests his left-hand writing was characterized by the perseveration of the same ill-formed letters. No improvement was observed when the patient attempted to write in block letters: with his right hand he made a few omission errors and with his left hand he perseverated in selecting the same letters, unrelated to the target. Object visual naming was within the normal range, while colour naming was impaired. Tactile naming (tested with the same 20 objects used in visual naming) revealed an apparent inversion of the hand asymmetry, the number of correct responses being 6 out of 20 with the right hand and 11 out of 20 with the left hand. However, it seems likely that the patient's right- and left-hand errors did not share the same origin. Those produced using the right hand stemmed from the somaesthetic deficits found on neurological examination. In keeping with this hypothesis, the patient performed poorly with his right hand in a test in which he had to feel two objects in succession and to decide whether they were same or different. When the task was carried out with the left hand, the performance was almost flawless. Thus the impairment he showed with his left hand in tactile naming cannot be attributed to stereognosic deficits. Colour discrimination was assessed by means of the Ishihara and Farnsworth test, and was found to be normal. A striking difference between the hands was also apparent on a gesture imitation test (Table 1). According to the norms provided by De Renzi *et al*. (1980), the patient's score was at the borderline level with the right hand and definitely pathological with the left hand ($\chi^2 = 9.60$, $P < 0.001$). On the contrary, constructional apraxia (copying drawings) was more impaired with the right hand than with the left hand.

The unexpected finding that the patient's performance on the token test was worse with the left hand than with the right hand provided the impetus for the following experiments that were carried out in the period from March to June 1997, during which the patient's deficit remained unchanged. The patient's co-operation throughout the tasks was good and he never showed signs of fatigue or lack of concentration. He gave informed consent to participate.

Experiment 1. Perceptual and mnestic matching to sample

This experiment was carried out to verify whether the ability to match-to-sample various types of visual stimuli was contingent upon the hand used. Two paradigms were used, both of which required the patient to match the presented stimulus with the identical one from among eight alternatives. One made demands on perceptual skills only (the stimulus and the alternatives were present throughout the task), while the other also had a mnestic component: the stimulus was presented for 3 s, during which the alternatives were covered with a piece of cardboard which was removed after a further 3 s unfilled delay. The following sets of stimuli were used: (i) drawings of objects; (ii) geometrical figures; (iii) unfamiliar faces; (iv) coloured cards (red, green, yellow, pink, brown, blue, black and white); and (v) letters. For each type of stimulus, blocks of 48 trials were performed first with the right and then with the left hand.

The results showing correct responses made with either hand in the two tests are shown in Table 2. Unsurprisingly, the memory task proved to be more difficult than the perceptual task for all categories, except objects, in which

Table 2 *Correct responses in the perceptual and memory matching-to-sample tasks*

	Number of correct responses/number of test items			
	Perceptual task		Memory task	
	Right hand	Left hand	Right hand	Left hand
Objects	48/48	48/48	48/48	45/48
Geometrical shapes	45/48	45/48	39/48	34/48
Faces	40/48	40/48	30/48	23/48
Colours	46/48	45/48	40/48	17/48
Letters	48/48	46/48	45/48	30/48

Antonio's performance was at ceiling in both conditions. More interesting was the finding that, on the perceptual task the patient had a similar performance with either hand, whereas on the memory task his performance was worse with the left hand than the right hand. The scores (successes/failures) of the memory task were converted to natural logarithms (1n) and were analysed by means of a factorial analysis of deviance with five tests and two hands (Ross, 1990). The hand factor was significant ($\chi^2 = 30.56$, $P < 0.001$), because of the patient's poorer performance with the left hand. The hand × test interaction showed a trend towards significance [$\chi^2(4) = 8.50$, $P < 0.10$]. When the hand factor was analysed within tests, it was significant for colours [$\chi^2(1) = 20.26$, $P < 0.001$] and letters [$\chi^2(1) = 5.37$, $P < 0.02$] but not for objects, geometrical shapes or unfamiliar faces. In matching colours and letters to sample, Antonio's performance with the left hand was 65% and 37% inferior, respectively, to that with the right hand.

Comment

It seems that the hand effect, found for colours and letters, was contingent upon the absence of the stimulus during the matching task. Would the same effect occur if the information about the target were provided verbally?

Experiment 2. Verbo-visual matching

To answer the above question, a verbo-visual matching test was given. Antonio viewed an array of eight stimuli and selected from these the stimulus named by the examiner. Only objects, colours and letters were tested, given the impossibility of assigning verbal labels to unfamiliar faces. Blocks of 40 trials per hand were administered for objects and colours and blocks of 48 trials for letters.

Again the patient's performance was 100% correct with either hand when the stimuli were objects. When they were colours or letters, his correct responses with the right hand were 31 out of 40 (78%) and 40 out of 48 (83%), respectively, while those with the left hand were 22 out of 40 (55%) and 20 out of 48 (42%) ($\chi^2 = 4.53$, $P < 0.05$ for colours and 17.78, $P < 0.001$ for letters).

In order to rule out the possibility that the absence of a hand effect with objects was contingent upon the patient's ceiling performance, a more difficult verbo-visual test was devised. An abstract noun was given orally and the patient had to select from an array of eight to 10 drawings of objects the one that was related to it (e.g. he had to point to the drawing of a church in response to the word spirituality). No significant hand effect emerged, although his performance was far from perfect: he scored 35 out of 48 with the right hand and 30 out of 48 with the left hand.

To compare Antonio's verbo-visual matching of objects and colours, we devised a further test, in which the same stimuli were used. The patient viewed arrays of different coloured drawings of objects and attempted, in separate blocks, to match-to-sample either the name of the object or the name of the colour. The selective impairment of the left hand for colours was confirmed. On object pointing, his performance was almost perfect (right hand 48 out of 48, left hand 46 out of 48), while on colour pointing his performance with the left hand showed a 68% decrement compared with that of the right hand (right hand 37 out of 48, left hand 12 out of 48; $\chi^2 = 26.05$, $P < 0.001$).

Comment

The foregoing experiments provided evidence that neither hemisphere was able to guide the left hand correctly in pointing to colours and letters when the matching task demanded a mental representation of the target and not merely its perception. This finding is surprising, if one considers that Antonio processed the stimuli with both visual areas and that the pathways linking the right visual cortex with the right motor cortex were apparently viable, as shown by his good performance with objects.

Given the damage of the splenium, we decided to investigate whether the interhemispheric transfer of visual information was effective and whether the hand asymmetry would persist if the stimulus were to be projected to one visual field, such that the visual field and the hand effect could be examined separately.

Experiment 3. Same-different judgements on the perceptual equivalence of laterally projected stimuli

Only stimuli that had yielded a hand effect, i.e. colours and letters, were used in a memory paradigm. The procedure was as follows. Stimuli were presented on the screen of a computer 4° to the right or left of the fixation point for 100 ms. The patient viewed the screen from a distance of 57 cm. and was requested to fix his gaze on a central cross. A second examiner checked that he maintained fixation throughout the test. After a 'ready'

Table 3 *Correct responses in the memory matching-to-sample task with laterally presented stimuli*

	Number of correct responses/number of test items			
	Right hand		Left hand	
	Right visual field	Left visual field	Right visual field	Left visual field
Objects	29/36	23/36	27/36	22/36
Geometrical shapes	31/36	30/36	26/36	28/36
Colours	35/36	36/36	16/36	20/36
Letters	36/36	30/36	23/36	22/36

signal, a stimulus was flashed to either visual field and, after a 3 s delay, a second stimulus was projected to the same or the opposite field. The patient said whether the two stimuli were 'same' or 'different'. Forty-eight pairs were presented for each category: half were the same and half were different. In half of the trials the first stimulus was projected to the left visual field and in the other half to the right visual field. Antonio gave correct responses to 96% of the pairs of colours (46 out of 48) and 88% of the pairs of letters (42 out of 48).

Comment

When the left hemisphere gave the response, stimuli projected to one field could be successfully compared with those projected to the other field.

Experiment 4. The hand effect in delayed responses to laterally projected stimuli

A closer assessment of the patient's ability to transmit interhemispheric visual information in the memory paradigm was carried out by studying all the possible combinations of hand with visual field. A single stimulus was flashed in the right or left visual field for 100 ms. Following a 3 s delay, six alternatives were presented in full view and the patient was requested to point to the match, using the right hand in half the trials and the left hand in the other half. Thirty-six trials were given for each field by hand combination in separate blocks. Objects, geometrical shapes, colours and letters were tested. The patient's scores are presented in Table 3.

Data (success/failures) were converted to natural logarithms (1n) and were analysed by means of a factorial analysis of deviance with four tests, two hands and two visual fields (Ross, 1990). The significant effects were test [$\chi^2(3) = 11.64$, $P < 0.01$], hand [$\chi^2(1) = 12.93$, $P < 0.001$] and the hand × test interaction ($\chi^2 = 16.38$, $P < 0.001$). To study this significant interaction, the hand factor was compared within each test. It was not significant in the object and geometrical shape tests, even when error rates were controlled experiment-wise (Miller, 1981), while it was significant in the colour test ($\chi^2 = 16.99$, $P < 0.005$) and the letter test ($\chi^2 = 14.77$, $P < 0.01$), even when the error rates were controlled family-wise.

Comment

The results of the previous experiments were replicated. The performance was not contingent upon the visual field to which stimuli were sent, but upon the hand used to give the response. The hand effect was, however, limited to colours and letters and did not affect either objects or geometrical shapes.

Experiment 5. Colour-form association and colour sorting

In the following experiment, we extended the study of the hand effect to colour tasks not involving matching to sample. The non-verbal tests used, i.e. the colour sorting test and the colour-form association test, have been widely employed and reported in the literature to investigate colour disorders consequent on brain damage. There is substantial evidence that both tests are sensitive measures of colour agnosia (Lewandowsky, 1908; Sittig, 1921) and are impaired following left brain damage (De Renzi and Spinnler, 1967; De Renzi *et al.*, 1972*a*, *b*; Basso *et al.*, 1976).

In the colour-sorting task, 35 small colour patches were scattered on the table in front of the patient, whose task was to sort them according to hue. There were five patches of different shades for each of the following seven colours: blue, green, red, yellow, brown, grey and violet. A score of 1 was given for each card added to the first card selected to designate a colour category. For example, if the patient grouped together all five shades of a colour, he received a score of 4, if he grouped four of them, a score of 3, etc. The maximum score was 28. The task was carried out first with the right hand, then with the left hand. The patient's performance on this test was compared with that on a matching test in which 24 pairs of different coloured cards were scattered on the table and the patient had to pair the cards of the same colour. The maximum score was 24.

On the matching task, Antonio performed flawlessly (24 out of 24) with the right hand and made three errors with the left hand (black was paired with grey, pink with grey, and red with orange). He ran into greater difficulties on the sorting task and the hand difference was much more marked: right hand 15 out of 24, left hand 2 out of 24 ($\chi^2 = 15.39$, $P < 0.001$). When requested to sort with the right hand, he was slow and uncertain and took 8 min 34 s to group together all the green and yellow cards, four blue, four violet and two grey cards. Although defective, this right-hand performance was definitely superior to the left-hand performance: after 4 min he managed to sort out only two green and two blue cards and had grouped the rest haphazardly. The correct rate was significantly higher with the right hand ($\chi^2 = 15.39$, $P < 0.001$)

In the colour form association task, Antonio was requested to colour drawings of objects, animals and fruits having a characteristic colour. Ten coloured pencils and 40 outline drawings were presented and the patient was requested to colour them in first with his right hand and then, after a delay, with his left hand.

The right hand performance was poor (11 out of 40), but significantly less impaired than the left hand performance (3 out of 40) ($\chi^2 = 5.54$, $P < 0.02$).

Comment

Antonio's right hand performance was poor on both the colour-sorting and the colour–form association task, indicating that his ability to consider a hue as representative of a colour category and to imagine the characteristic colour of an object was impaired, probably as a consequence of left brain damage. However, not even these impoverished skills were available to the hand controlled by the right hemisphere, with which the patient performed at chance level. When it was possible for him to sort colours by perceptual identity basis, his performance was much more successful.

Experiment 6. Letter name identity

The final experiment probed the patient's ability to match lower-case letters with upper-case letters. Its aim was to assess whether the presence of a stimulus that could not be matched according to perceptual identity would result in left hand errors.

In half of the trials a lower-case (target) letter was presented together with eight capital letters, and in the other half an upper-case (target) letter was presented together with eight lower-case letters, in a total of 48 trials. The patient's task was to point to the letter that matched the target. Letters with similar shapes in both forms (such as C and c) were not used.

Antonio scored 44 out of 48 with the right hand and 31 out of 48 with the left hand ($\chi^2 = 10.30$, $P < 0.001$).

Discussion

Antonio showed the classical signs of hemispheric disconnection: tactile agnosia, ideomotor dyspraxia and agraphia of the left hand and constructional apraxia of the right hand. This pattern of impairment is typical of patients with total section of the commissures, and it was probably contingent upon the left hemisphere infarct that severed callosal fibres. What makes this case surprising and *prima facie* radically different from other callosotomy patients is that the patient's left-hand impairment was apparent even under conditions in which the information was received by both sides of the brain and hence did not require interhemispheric transmission. The left-hand inferiority emerged when the stimulus was no longer present (memory condition), when it was identified by its name (verbo-visual matching) and when the test involved stimuli (the same capital and lower-case letter) that were not physically identical. Moreover, it was confined to colours and letters and was absent for objects, geometrical shapes and unfamiliar faces. It must be stressed, however, that Antonio's left-hand performance was always well above chance level. Thus we are faced with a partial rather than a total inability to perform the tasks.

The issue to be addressed is why the information that reached the right visual cortex could not assist the ipsilateral motor centre in programming left hand's movements towards the target. The right brain cannot be blamed for this failure, because the patient's performance under the perceptual condition and in tasks involving objects, geometrical shapes and unfamiliar faces provided evidence that the right motor centre did receive sufficient visual and verbal information to steer left-hand movements. Therefore, we must turn to the left hemisphere to solve the enigma of the left-hand impairment.

Despite its lesions, the left hemisphere still had the necessary competence to carry out the tasks in which the left hand failed, as shown by the patient's nearly perfect right-hand performance in most of the tasks. Therefore, the contribution of the left brain to left-hand errors must be perceived as reflecting a deficit of assistance rather than a deficit of function, and must be sought in the after-effects of either or both of the lesions, as revealed by MRI. The relevance of splenial damage can be readily dismissed, given that the left-hand impairment was present when the stimuli were displayed in free vision and could, therefore, be seen by both hemispheres. Moreover, Experiments 3 and 4 showed that the output of the right visual cortex could be transferred to the left visual cortex with no apparent loss of information.

Hence, it appears that the crucial lesion was that located in the left white matter, close to the trunk of the corpus callosum, which interrupted the pathways linking the left brain with the right motor cortex. In essence, the question is why letters and colours had to be initially processed by the left hemisphere in order to be recognized. With regard to letters, we suggest that the left hemisphere plays a crucial role in the identification of their graphemic value. As long as letters are processed by the right hemisphere, they are shapes without a linguistic status and are not recognized as the same entity when presented in different forms (D and d). To become graphemes and subsequently undergo grapheme-to-phoneme transcoding, they must be transferred to the left hemisphere. This assumption is in keeping with the role assigned to the left hemisphere by previous studies carried out in patients with focal brain lesion (Dejerine, 1892; Geschwind, 1962; Hécaen and Kremin, 1977; Sevush and Heilman, 1984) and in patients undergoing complete callosotomy, most of whom have been found to lack grapheme-phoneme correspondence rules, when words are projected to the isolated right hemisphere (Baynes, 1990; Baynes *et al.*, 1992). If the right brain is unable to specify the graphemic value of a letter, it will fail to recognize not only that two different forms of the same letter have identical meaning (name identity task), but also which letter corresponds to a given letter name (verbo-visual matching task). In a similar vein, in the delayed matching-to-sample task letters will be encoded as meaningless shapes, giving rise to traces that, without the reinforcement of their graphic identity, will be weak and difficult to retrieve.

Less is known about the contribution of the left brain to colour identification. *Prima facie*, the presence of a hand effect in the delayed but not in the perceptual condition would suggest that the right brain is equipped with a reduced short-term memory for colours, which hampers the retention of this kind of information during a delay. Davidoff and Ostergaard (1984) reported a patient with a large infarct of the left temporo-occipital region, who committed more than 50% of errors in matching-to-sample colours (but not meaningless shapes) that had been presented 4 s before. However, the idea that discrete short-term mechanisms are dedicated to different categories of stimuli is not entirely convincing and does not account for the whole spectrum of conditions in which Antonio manifested a hand effect for colours.

One may wonder whether the left hand inferiority in the verbo-visual matching test had a verbal origin, namely, that it was dependent upon the fact that colour names, unlike object names, were poorly comprehended by the right hemisphere. The only data we have on this subject come from the administration to two callosotomy patients of the token test, which involves both shape names and colour names (Zaidel, 1976, 1977). When the tokens were shown to one hemisphere, both patients achieved lower scores with the right than with the left brain, but there was no evidence that colour names were more difficult to understand than shape names, as was the case for Antonio.

Therefore, we propose that the left-hand errors, committed in both the verbo-visual and the memory matching test, stem from the same difficulty, i.e. the limited competence of the right hemisphere in colour categorization. In nature, colours do not exist in isolation, but are surface properties of objects. Identifying a colour patch requires an internal colour space (Davidoff, 1991), which stores the mental representations of regions of colours. These representations provide the standard for categorizing the colour of a sample as red, blue, etc. and are activated when a colour must be retrieved from memory. We suggest that this ability is a predominant function of the left hemisphere and that, without it, the encoding of colours by the right hemisphere is weak and at risk of dwindling altogether. Likewise, the ability to categorize a colour is a prerequisite for retrieving the colour that must be matched with a name, and accounts for the left-hand errors made in the verbo-visual matching test. The advantage of this interpretation is that it also holds for the left-hand impairment shown by the patient in colouring drawings and sorting colours according to hue, tasks that involve neither short-term memory nor verbal comprehension, but require the ability to categorize and evoke colours. Both were found to be impaired following left brain damage (De Renzi and Spinnler, 1967; De Renzi *et al.*, 1972*a, b*; Basso *et al.*, 1976), and were in fact performed poorly by Antonio when he used his right hand, suggesting that the failure was in part due to colour agnosia, consequent on left-hemisphere damage. However, the score fell to almost zero when he used his left hand, showing that of its own the right brain was all but virtually incapable of carrying out the task.

In conclusion, we propose that colours, as well as letters, need to be processed by the left hemisphere, whenever their recognition requires the identification of their categorical value. The absence of a left-hand effect in the recognition of objects and geometrical shapes can be accounted for by assuming that their semantic store is represented bilaterally, as shown by the ability of callosotomy patients to use their left hand to point to objects that are semantically related to those presented to the left visual field. As to the lack of hand asymmetry with unfamiliar faces, by definition these are not represented in the long-term store and thus undergo merely perceptual encoding, for which the right hemisphere is equally, if not better equipped than the left hemisphere.

The left-hand effect also emerged in writing and imitating gestures. The right-hand writing errors were linguistic, while those of the left hand were characterized by the dogged perseveration of the same word and poorly formed letters. It is apparent that, without the assistance of the left hemisphere, the right motor centre was incapable of controlling the left-hand writing performance. Interestingly, left-limb apraxia was present when the patient attempted to imitate movements seen by both hemispheres. This is at variance with what is observed in complete commissurotomy patients, in whom left-limb apraxia occurs only when the hemisphere receiving the message cannot communicate with that guiding the gesture, i.e. on verbal command or on the imitation of hand or finger positions projected to the left hemisphere (Zaidel and Sperry, 1977; Volpe *et al*., 1982). These findings led Nass and Gazzaniga (1987) to challenge Liepmann's (1905) classical notion that the motor engrams of the left premotor cortex exert control over those stored in the right premotor cortex. Antonio's left limb apraxia belies this claim. Since his right brain could see the gestures made by the examiner, its failure must be contingent upon the faulty transmission of the motor programmes elaborated by the left hemisphere.

This finding underlines the difference between the disconnection syndromes observed in patients with spontaneous pathology and in epileptics submitted to callosotomy. For instance, essentially negative findings were reported in the latter when the callosal section was incomplete (Gordon *et al.*, 1971). They were able to transfer visual and tactile information from one hemisphere to the other and to carry out matching-to-sample tasks, in the absence of the stimulus (Bogen, 1987; Gordon, 1990). On the contrary, left hand tactile anomia, apraxia for verbal commands and agraphia were manifest when the incomplete callosal interruption resulted from vascular or neoplastic lesions (Sweet, 1941; Geschwind and Kaplan, 1962; Schott *et al.*, 1969; Poncet *et al.*, 1978; Beukelman *et al.*, 1980; Watson and Heilman, 1983; Graff-Radford *et al.*, 1987). Our patient did not have a complete section of the commissures: rostral and genu fibres were not involved in the lesion, a few fibres of the posterior trunk may have been spared and the splenial fibres were functional, despite their damage. Yet while epileptic patients could exploit the few splenial fibres left intact by commissurotomy to carry out lateralized tasks, Antonio was unable to use the residual splenial connections to transfer the output of the left-hemisphere cognitive processes to the contralateral side. In order to activate the right motor centre, this information had to travel along anterior callosal pathways, which were interrupted by the lesion.

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