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PLASTICITY IN SPEECH ORGANIZATION FOLLOWING COMMISSUROTOMY

by MICHAEL S. GAZZANIGA, BRUCE T. VOLPE, CHARLOTTE S. SMYLIE, DONALD H. WILSON *and* JOSEPH E. LE DOUX

(From the Department of Neurology, Cornell University Medical College, New York, NY 10021 and the Department of Neurosurgery, Dartmouth Medical Center, Hanover, New Hampshire)

INTRODUCTION

WE have been studying the cognitive and conscious mechanisms in the separated hemispheres of Case P.S., who at the age of 15 years underwent complete surgical section of the corpus callosum in an effort to manage his otherwise intractable epileptic seizures of longstanding duration (Wilson, Reeves, Gazzaniga and Culver, 1977). Immediately following the operation, P.S., like other split-brain patients, was unable to verbally describe stimuli presented exclusively to his left visual field as these stimuli were directed to his mute right hemisphere (Gazzaniga and Sperry, 1967). He was observed, however, to be capable of behaving as if he comprehended a wide range of language-related stimuli presented to his right hemisphere, although he was completely incapable of describing verbally the nature of the stimuli; he was able to spell by writing with the left hand (Gazzaniga, LeDoux and Wilson, 1977; Gazzaniga and LeDoux, 1978). Now, starting approximately two years post-operatively, P.S. has begun to speak about stimuli exposed in his left visual field.

The development of left visual field naming in the case of P.S. could be attributable to either reinstatement of visual interhemispheric transfer in the visual modality or to the acquisition of speech by the right hemisphere. This report describes the continuing series of experiments that suggest P.S.'s newly acquired capacity may represent the late development of speech in his right hemisphere following callosotomy.

CASE HISTORY AND METHOD

P.S., a right-handed boy, experienced a series of severe convulsions at about 2 years of age, with a seizure focus identified in the left temporal region by electroencephalography. Following this early activity, he apparently developed normally until the age of 10 years when generalized seizures recurred spontaneously and became intractable. In January, 1976, he was operated on for complete surgical section of the corpus callosum. A complete medical history has been published elsewhere (Wilson *et al.*, 1977).

All tasks involved the lateralized presentation of visual stimuli. The subject was seated 1 m from an opaque screen and instructed to fixate on a dot in the centre of the screen. By means of a standard slide projector fitted with an electronic shutter, stimuli were presented at least 5 degrees to the right or left of fixation for 150 ms. Left visual field exposure lateralizes input to the right hemisphere and right field exposure results in left hemisphere lateralization. The stimuli were positive slides of words, pictures, numbers, letters, or nonsense figures not subject to verbal coding, that were rear-projected on to a screen which the subject faced. Further, these stimuli subtended a horizontal visual angle of 2.4 to 3.2 degrees so that the greatest eccentricity from fixation was 8.2 degrees. Because of the line-drawn nature of the picture, word, letter, and number stimuli, measurements of luminosity varied less than 0.5 per cent on all bilaterally simultaneously projected trials. Prior to each exposure, the subject was asked to fixate a point in the midline on the screen. Eye movements were carefully monitored through the use of a video recorder and camera fitted with a 10:1 zoom lens. Tests are carried out once a month in a specially designed mobile testing laboratory.

OBSERVATIONS

Visual Field Naming

The subject was asked to describe identical sets of single three- or four-letter words or single line-drawn pictorial stimuli lateralized to either right or left visual field. Approximately six months post-operatively, he was completely incapable of verbally identifying the nature of left visual field stimuli, but had no problems with right visual field stimuli. One and one-half years post-operatively the results were the same. However, during the recent testing periods twenty-six to thirty-six months

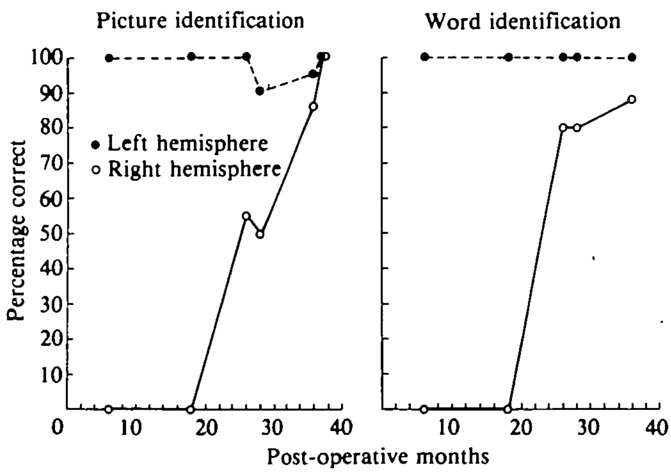

FIG. 1. *Naming of Lateralized Stimuli.* There was a complete inability to name words or pictures in the left visual field during the first eighteen post-operative months. Number of trials ⩾ 25. The developing ability to name left visual field stimuli, beginning some twenty-six months post-operatively, has continued to the present. Number of trials ⩾ 10.

post-operatively (he underwent operation in January, 1976), there has been a marked increase in his capacity to name left visual field stimuli (fig. 1). The predominate error pattern after the first eighteen post-operative months revealed that P.S. almost always insisted he saw nothing or, at best, a 'flash' on the left visual field exposures. When given the opportunity to respond nonverbally, however, he was nearly always correct in pointing to the object which matched the left visual field stimulus (Risse, LeDoux, Springer, Wilson and Gazzaniga, 1978; Gazzaniga *et al.*, 1977).

Same-Different Judgements

The picture and word stimuli used for these trials were the same type as those used for the single field naming. Numbers and single letters were also used. Nonsense figures consisted of amorphous black designs on a white background that were easy to visualize but difficult to name. For these trials P.S. was asked first to state whether two simultaneously presented stimuli were the same or different. When the two stimuli were both presented within either visual field (*see* fig. 2) the same-different

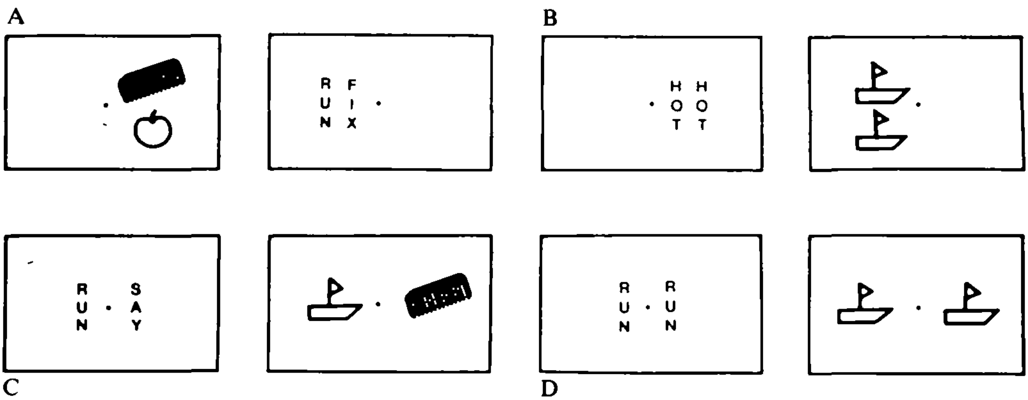

FIG. 2. In A, the word or picture stimuli presented within either right or left field are different. In B, the stimuli are the same. P.S. made accurate judgements in both A and B series of trials. In C and D same-different judgements require interfield comparison and his performance broke down.

judgements were quite accurate. These trials were significantly different from chance ($P < 0.001$), and the decline in accuracy from the initial measurements to the present is more apparent than real. When the judgements required interfield comparisons, however, performance fell to chance ($P = 0.07$), a significant change from the intrafield comparisons (fig. 3).

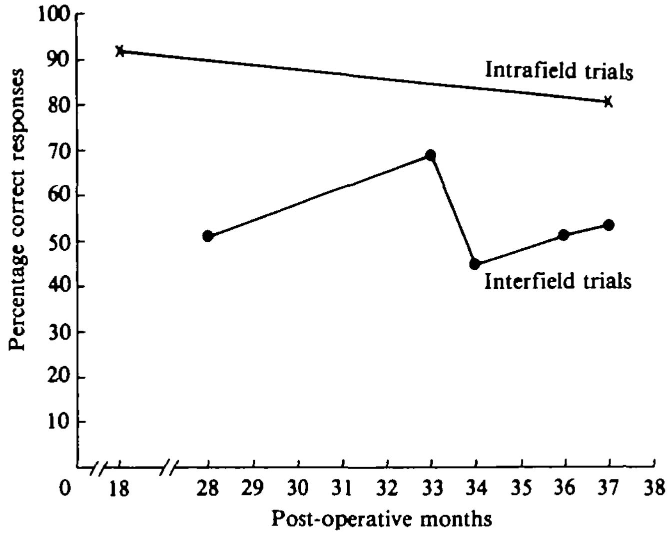

FIG. 3 *Same-Different Judgement.* Intrafield trials (represented by an X) are contrasted with interfield trials (●). Typical examples are shown in fig. 2. Interfield performance is different from chance ($P < 0.001$). Number of trials during each testing session $\geqslant$ 50.

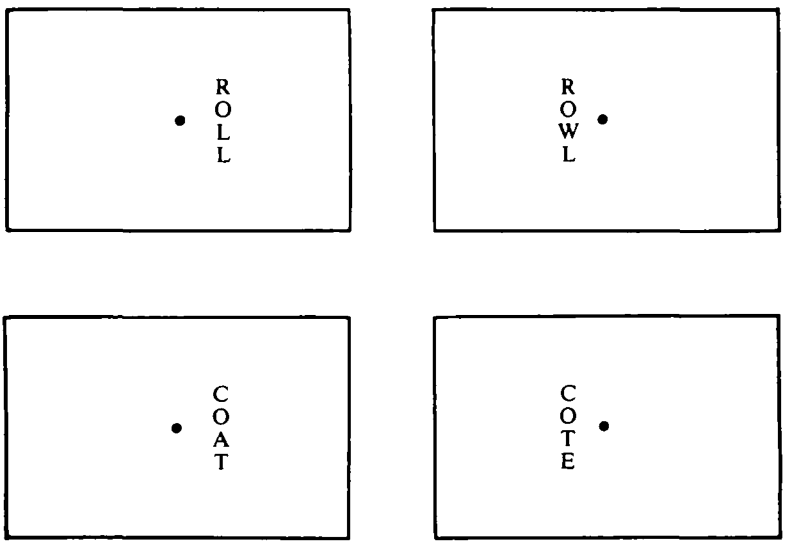

FIG. 4. In these trials P.S. accurately named all stimuli but accurately spelled only the stimuli in the right visual field (left hemisphere). Left visual field stimuli were spelled like the common word of the pair in all instances. *See* Table 1 for results.

TABLE 1. HOMOPHONE TEST

	Left visual field		*Right visual field*	
	Described	*Spelled*	*Described*	*Spelled*
Homophone	7/10	0	7/7	7
Word	13/13	11	14/14	14

Homophone Test

One of a pair of homophones (coat or cote, for example) was presented to one visual field on each trial and P.S. was asked to name what he saw (fig. 4). Subsequent to naming the stimulus, he was asked to spell the word. Following right visual field exposure, the homophones (both members) were correctly named and spelled. Following left visual field exposure, the homophones (both members) were correctly named, but the non-word member of the pair in each instance was spelled incorrectly (*see* Table 1).

Complex Scenes

One of a series of complex pictures was presented to a single visual field on each trial. These scenes portrayed a simple action such as a man holding a gun (*see* fig. 5). Following exposure to either visual field, P.S. produced a single word that accurately characterized that scene. Further, accurate description about the details of the scene occurred only with right visual field/left hemisphere exposure. On left

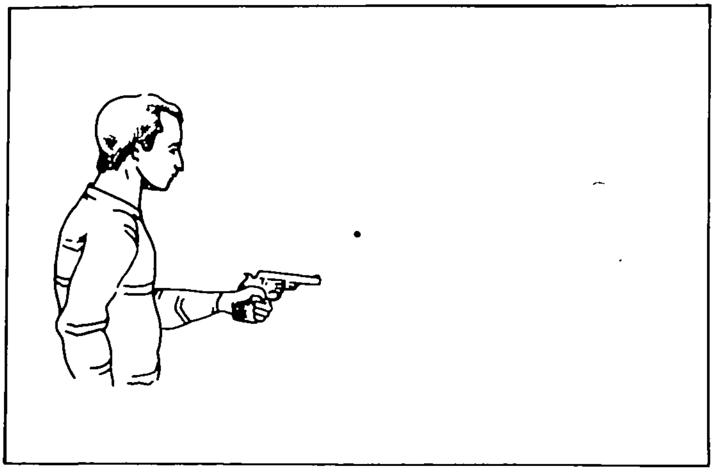

FIG. 5. An example of a complex scene. Pictures like this one were flashed to either the right or the left visual field.

TABLE 2. EXAMPLE OF VERBAL RESPONSE TO COMPLEX PICTURES

Right hemisphere stimulus	*Verbal response*
(A piece of) layer cake	'Cake . . . it was a whole vanilla cake with chocolate icing, silverware is there too'.
Exploding firecracker	'Smoke . . . coming out of a chimney, it's a small house'.
Man, shearing sheep	'Man . . . he is walking through the woods'.
Couple dancing	'Some guys . . . working on building together'.
Man with gun	'Gun . . . hold-up . . . he has a gun and is holding up a bank teller, a counter separates them'.
Left hemisphere stimulus	*Verbal response*
Christmas tree	'A Christmas tree standing alone'.
Fat man, sweating	'Man—big and fat'.
Man with gun	'Guy with a gun'.

visual field exposure, while the word expressed accurately identified the idea represented by the picture, the subsequent explanation, although vivid and detailed, often bore little relation to the content of the picture (*see* Table 2).

Finger Postures

Six line drawings of finger postures were lateralized to each hemisphere (Gazzaniga, 1970). P.S. was required to mimic the postures with each hand. The results in two additional experimental sessions conducted during this twenty-six to thirty-six month post-operative period confirm an earlier report (Gazzaniga *et al.*, 1977) that on right visual field exposure of a finger posture, the right hand assumed the correct posture while the ipsilateral left hand was incorrect on six out of seven trials. This pattern of results was duplicated on left visual field exposure, with the left hand performing the distal co-ordinated act which the right hand could not.

DISCUSSION

Recently, we have described rich language-processing capacities in each hemisphere in the case of P.S. (Gazzaniga *et al.*, 1977; Gazzaniga and LeDoux, 1978). Each hemisphere of this unique young man could process nouns and verbs, as well as rhymes, antonyms, and superordinate concepts when these were presented to either hemisphere by flashing appropriate material in the contralateral visual field. Most striking, however, was the capacity of P.S.'s right hemisphere to produce verbal responses by writing or by the selection and arrangement of letters. This capacity has been contrasted with his left hemisphere's ability to produce normal speech. Now, some two-and-a-half years after complete callosal section, P.S. displays a markedly increased capacity to name verbally left visual field (right hemisphere) stimuli, as well as continued ability to name right visual field (left hemisphere) stimuli.

The mechanism underlying the capacity to name stimuli exposed solely to the left visual field of normal persons who are left hemisphere-dominant for expressive speech typically involves interhemispheric transfer within the visual modality. The left visual field information is projected to the right hemisphere and is then transferred via the commissural system to the left hemisphere where the naming takes place. Surgical section of both the corpus callosum and anterior commissure in man and other primates blocks visual transfer (Gazzaniga, 1965; Black and Myers, 1964). However, when the anterior commissure is spared, visual transfer is typically preserved (Risse *et al.*, 1978; Sullivan and Hamilton, 1973).

Unlike most patients with intact anterior commissures, P.S. was observed to be visually split shortly after section of the callosum, although his anterior commissure was left intact (Risse *et al.*, 1978). Our initial interpretation of the emergence of his capacity to name left visual field stimuli was in terms of the reinstatement of visual transfer. It seemed that his anterior commissure had become functional.

Invoking the visual transfer hypothesis to explain left visual field naming in the case of P.S., however, is not consistent with the above experiments. Callosum-sectioned patients who transfer visual information through the anterior commissure perform like neurologically intact subjects on visual transfer tests requiring inter-field integration. That is, they are capable of stating whether two stimuli, one in each visual field, are the same or different. P.S. was capable of making accurate same-different judgements when the stimuli were both within a single visual field. However, on trials requiring interfield integration where he had to make a judgement about both fields simultaneously, his performance fell to chance. Moreover, inter-field performance was not influenced by the nature of the stimuli involved. He was no better at making interfield judgements involving two pictures, or a word and a picture, than he was when a one-syllable word appeared in each field. These observations show that information channelled to one hemisphere remains inaccessible to the other, and argues against the notion of interhemispheric transfer of visually encoded information.

A further argument against the interhemispheric transfer hypothesis emerged from a test requiring finger movements in response to lateralized visual cues. Each hemisphere has more or less exclusive motor control over the contralateral distal extremities (Gazzaniga, 1970; Gazzaniga and LeDoux, 1978; Brinkman and Kuypers, 1973). Thus, split-brain patients who do not show transfer, when exposed to line drawings of finger postures in one visual field, are unable to mimic the posture with the hand ipsilateral to the exposed hemisphere. Subjects who transfer visual messages between their hemispheres can mimic the postures with either hand following lateralized exposure because the visual cue ultimately reaches both hemispheres. P.S. accurately mimicked postures with the contralateral hand, but performed poorly with the hand ipsilateral to the exposed hemisphere. It appears, then, that visual transfer is not occurring in P.S. through the anterior commissure or any other pathway.

Further exploring the nature of P.S.'s verbal response to left visual field stimuli, several experiments were performed. In the homophone test, when non-words like 'cote' were presented in the left visual field, they were correctly named. Yet, when subsequently asked to spell the stimulus, P.S. spelled the word analogue ('c-o-a-t') of the non-word. If the basis for left field naming was the transfer of the visual stimulus from the right to the left hemisphere, then the hemisphere that said 'cote' should also have spelled 'c-o-t-e'. Both words and non-words were correctly named and spelled following right visual field (left hemisphere) exposure. As in the experiments with single syllable words, inability to perform same or different judgements when the homonym word-pair was simultaneously flashed to both visual fields discredits phonemic transfer to the left hemisphere as the source of left visual field naming.

Over a series of homonym trials the hemisphere that spelled the word (for example, 'c-o-a-t') was not the hemisphere that received the visual input and emitted the output 'cote'. It seems that the right hemisphere when presented with 'cote', emitted the appropriate phoneme. The left hemisphere, which has the more robust and competent speech system, upon receiving the phoneme as an auditory input, assumed control over the situation. Only having access to the auditory properties of the spoken stimulus (kōt, the phonetic description of cote), the left hemisphere produced the spelling of the word counterpart from the flashed non-word.

P.S.'s right hemisphere can now process language in a sophisticated manner. Not only can his right hemisphere emit appropriate writing and spelling, and distinguish nouns, verbs, and superordinate concepts, but it also seems able to vocalize. During each of the many sessions we have observed and video-taped P.S.'s behaviour. The left visual field-right hemisphere trials provoke behaviour that is different from right visual field-left hemisphere speech. In some instances, after left visual field stimulation, an audible response did not occur. However, P.S.'s face, mouth and tongue adopted a posture that appeared appropriate for the verbal expression of the word or picture stimulus. This posturing prior to verbal expression did not occur after right visual field stimulation. Using sensitive equipment we recorded and amplified otherwise inaudible whispers, and actually heard the appropriate word spoken in conjunction with the posturing. More frequently than ever, though, responses to left visual field stimuli are no longer whispers, and, as the results of the present experiments demonstrate, audible and accurate words are produced.

Concerning the mechanism of P.S.'s right hemisphere capabilities, it may be that the language mechanisms of the left hemisphere assume control soon after the right hemisphere programmes the muscles of phonation. For example, when the complex scenes (fig. 5) are projected to the right visual field-left hemisphere, P.S. responds in a rather ordinary fashion. However, on those trials in which the complex scene is projected to the left visual field-right hemisphere, the response pattern is quite different (Table 2). On these left visual field trials he emits a word or two that identifies the dominant activity of the scene but which seems to establish the context for a subsequent, seemingly unrelated, response. These verbal responses bear little relation to the exposed slide, but remain a plausible use of the ejaculated single word response. Furthermore, once he has emitted the initial single word, he tends not to ignore this choice and insists that the subsequent description identified the essence of the exposed slide.

What is of particular interest, of course, is the plain fact that P.S. behaves as if he has absolutely no insight that these story reconstructions of stimuli presented to the right hemisphere are spurious. Through his verbal behaviour, however, he appears very intent on constructing a unity. With an instantaneous response, the left hemisphere moves to construct a theory for a behaviour emitted from the 'self'. This is done by a half-brain that never makes confabulatory responses in test situations which exceed an informational load presented to the left hemisphere. The implications of this for a theory of mind have been expanded elsewhere (Gazzaniga, 1978).

From another aspect, this limited speech capacity of the right hemisphere may reflect an early stage of development for an emerging speech system, even though on physical examination P.S. is clearly an adult. There are only rare clinical reports of language acquisition in late childhood-early adolescence, although there is more evidence regarding the functional recovery of language in groups of childhood aphasics (Hécaen, 1976). Some of the theories have suggested a 'critical period' during which language development depends on necessary neurological events and an unspecified minimal language exposure (Lenneberg, 1967). More molecular, but not completely analogous, non-primate models suggest that sexual hormones may also influence these timing phenomena (Nottebohm, 1977). The emerging speech system in P.S., now that he is beyond any critical period, supports a notion that for a given brain area to become functional, certain cognitive and emotional states must obtain. P.S., unlike all other split-brain patients, was able to respond appropriately to linguistic inputs to the right hemisphere immediately after operation. He was able to respond to verbal questions asked of him by spelling out appropriate answers within the first post-operative year (Gazzaniga *et al.*, 1977), and over two years has been found capable of differently evaluating emotionally rated words (LeDoux, Wilson and Gazzaniga, 1977). In short, although the right hemisphere of P.S. is unique, it represents a developing mental entity that through each of our evaluative measures continues to appear self-aware. It is a mental system of this character that has learned to talk.

The appearance of any linguistic capacity in the right hemisphere of P.S. and other split-brain patients (Gazzaniga, 1970; Zaidel, 1978) is associated with early left hemisphere pathology, and this development does not necessarily reflect normal brain organization. However, acknowledging the early left temporal seizures in this unusual man does not help to explain the progressive development of speech in the right hemisphere, and further experiments will be required to follow and clarify these issues. Yet from another point of view, this study suggests clues underlying the lack of significant recovery in the typical adult patient who is rendered globally aphasic. The loss of language in these patients is so devastating it may be that the remaining cognitive and emotional systems provide little motivation to regain the ability to use language again.

SUMMARY

For three-and-a-half years we have been studying the cognitive and conscious mechanisms in a remarkable 18-year-old man: Case P.S. This unique individual had his corpus callosum divided in order to control intractable epilepsy. Although for some time after the operation he appeared like other split-brain patients, unable to describe verbally stimuli directed to his mute right hemisphere, he behaved as if he was capable of comprehending a wide range of language-related stimuli directed to that hemisphere. Spelling by choosing the appropriate letters with his left hand, he could process nouns, verbs, rhymes, antonyms, and superordinate concepts. When asked about tachistoscopic presentations delivered to his left visual field, he either said he had seen nothing, or only a flash of light. He was also unable to identify verbally tactile 'stereognostic' inputs to his left hand.

In the last year P.S. has begun to speak about stimuli directed to his right hemisphere. This series of experiments suggests that this speech is not inter-hemispheric transfer within the visual modality. Further, plotting the relative increased proficiency of verbal description of inputs directed to the right hemisphere, this speech system seems to be in a process of continuing development.

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