COGNITIVE TRANSFER
FROM RIGHT TO LEFT HEMISPHERE
AFTER SECTION OF THE FOREBRAIN COMMISSURES

Thesis by

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Abstract

Transfer of cognitive information from right to left hemisphere was examined in patients with complete surgical section of the forebrain commissures.

A simple new technique is described that allows lateralized presentation of visual input for prolonged viewing by a single hemisphere without attachments to the eye. This technique was applied in tests of the ability of two complete commissurotomy patients to name simple visual and tactual stimuli projected to the right hemisphere and to cross-compare bilateral input, in exception to characteristic disconnection effects. Special procedures and control tests were employed to determine the underlying mechanisms of such behaviors, and especially to assess the involvement of the left hemisphere. Three commissurotomy subjects were also tested for their ability to verbally describe pictures and printed nouns, corresponding to items associated with distinctive tastes and smells, presented for prolonged viewing in the left hemifield.

The commissurotomy patients could sometimes name or cross-integrate the simple stimuli. Use of cognitive strategies and access to stimulus information by the left hemisphere was shown under these conditions. The subjects could not orally name more complex pictures and words. They could, however, provide relevant and appropriate verbal reports including evaluations, category and context cues and even distinct perceptual impressions and other specific associations but not the precise identity.

Results demonstrate that certain cognitive aspects of right hemisphere processing can transfer to the left hemisphere through brainstem channels. Verbalizations in response to stimuli presented in the left visual field and other recent exceptions to symptoms of disconnection may result from this subcortical communication. Other possibilities including oral naming by the right hemisphere cannot account for these results. The name or identity of stimuli is not conveyed by these interhemispheric transmissions but rather, less specific information that is more connotative or orientational in nature. Such transmissions are presumed to function also in normal cognitive processing. The findings provide further evidence for relatively high-level cognitive processing by the right hemisphere.

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GENERAL INTRODUCTION

The nature and quality of mental processing within the normal human right hemisphere continues to be one of the outstanding unknowns in the neuropsychological study of higher cognitive function and a subject of considerable controversy. Despite numerous and extensive similarities in structure and metabolism between the two cerebral hemispheres, both at gross and fine levels of analysis, results of neurological and cognitive tests are generally taken to support the contention that only the left hemisphere possesses the capacity for higher levels of reasoning, communication and action which are considered to be the hallmarks of human intelligence (Eccles, 1980; Gazzaniga, 1983). However, the assumption of, and reliance upon, language communication skills in the evaluation of intelligence or cognitive ability (e.g., Turing, 1950), biases such judgements against the linguistically mute right hemisphere. This absence of verbal expression severely impedes efforts to discern the mental aptitudes of the right hemisphere and thus has always tended to depress estimates of its cognitive sophistication.

Studies of the right or left hemisphere must also overcome inherent complications related to the isolation and interpretation of individual hemispheric functions. Presence of the forebrain commissures, with over 200 million interconnecting fibers and interhemispheric transmission times of the order of milliseconds, poses formidable problems for attempts to segregate the contributions of either hemisphere. Nevertheless, investigations of the relative abilities of the typical human left and right hemispheres ideally would satisfy (at least) the following three criteria: (1) the effect (treatment or response) under study would be confinable to a single hemisphere, (2) a well-matched control group or condition would be available for comparing the relative abilities of the hemispheres and (3) the results would be clearly representative of normal cognitive function.

According to these criteria, selected patients with complete surgical section of the forebrain commissures provide one of the best potential sources for information regarding normal hemispheric function. Segregation of the hemispheres is less difficult in the absence of the commissures allowing each side to be tested in relative isolation and permitting controls to ensure that effects are confined to the hemisphere of interest. In commissurotomy patients, both cerebral hemispheres are intact, entirely functional and provide ideal matched controls for intercomparisons of performance. The absence of significant extracommissural brain damage and commissural section well after normal developmental lateralization of function support the likelihood that these patients are representative of the normal brain. Indeed, concerns over the commissurotomy data center upon individual differences in light of the small sample size, and upon possible functional abnormalities due to the very absence of the commissures or to the long term epilepsy which led to the surgery (Whitaker & Ojemann, 1977).

Extensive testing of these commissurotomy patients has demonstrated that the right hemisphere has some aptitude for language comprehension (Gazzaniga & Sperry, 1967; Zaidel, 1978) and can even outperform the left hemisphere on certain perceptual and cognitive tasks (e.g., Levy, 1970; Zaidel & Sperry, 1973; Franco & Sperry, 1977). Yet, surprisingly little can be said regarding the character of right hemisphere cognitive experience (but see Sperry, Zaidel & Zaidel, 1979). As noted above, this lack of knowledge seems to be a direct result of the absence of verbal report by the right hemisphere as opposed to the richly expressive verbal capacity of the left hemisphere. The unusual presence of expressive language abilities in the right hemisphere of two callosotomy patients (Gazzaniga, 1983) is not helpful in this regard because the condition is a result of early left hemisphere pathology and so the representation of language and other cognitive functions in these patients is unlike that expected in the normal brain (Myers, 1984, reprinted in the Appendix).

The transmission of cognitive information from the right to left hemisphere after commissurotomy provides a channel for obtaining information regarding the mental experience of the right hemisphere. This cognitive transfer is the focus of the following experiments.

Chapter 1 describes a simple technique for restricting visual input to a single hemisphere that allows prolonged lateralized viewing with no attachments to the eye. This technique represents an advance over traditional tachistoscopic methods and more recent eye tracking systems (including that of Nettleton et al., 1983) which introduce a number of undesirable limitations and complications upon laterality testing procedures in vision.

The presence of interhemispheric communication after cerebral commissurotomy is tested in Chapter 2. Special tests and control procedures are used to establish that this subcortical transmission of information, and not other possibilities such as right hemisphere naming, accounts for recent occasional exceptions to characteristic symptoms of hemisphere disconnection.

Chapter 3 examines the verbalizations of commissurotomy patients in response to input projected to the right hemisphere and finds evidence for the transfer to the left hemisphere of certain aspects of right hemisphere mental processing. These brainstem communications are shown to allow passage only of circumscribed information not including the name or precise identity of stimuli. Cognitive abilities of the cortically-disconnected right hemisphere such as the comprehension of language and generation of appropriate mental associations in response to pictures and words are demonstrated.

CHAPTER 1

A simple technique for lateralizing visual input that allows prolonged viewing

Abstract. A simplified technique is described for obtaining lateralization of visual input with prolonged viewing. This technique is based on the presence of constant normal lateral limits for horizontal rotation of the eyes with respect to the head. With head movement prevented by use of a standard bite bar, and the eyes rotated to the left and held at their lateral limit, the temporal half of the visual field of the left eye may be used for lateralized input to the right hemisphere or vice versa for input to the left hemisphere. Any form of visual stimuli or visually monitored task can be used if confined within one of the extreme temporal hemifields. In comparison to previous methods, this technique is technically simple, inexpensive, without significant risk or discomfort to the subject, readily applicable to normal and various brain-lesioned subjects and permits prolonged in-depth viewing. An alternative version of this technique uses a stabilized spectacle frame fitted with adjustable central occluders set to allow vision through only one or both of the extreme temporal hemifields.

This chapter presents work conducted in collaboration with Dr. R.W. Sperry that has been published in Behavior Research Methods and Instrumentation (1982, 14, 305-308).

INTRODUCTION

Techniques to selectively lateralize visual input in human subjects must circumvent the natural tendency of eye movements to transfer the intended half-field stimuli across the vertical meridian into the unintended half-field and hemisphere. This has been achieved most commonly in the past by tachistoscopic methods that limit exposure of visual stimuli in the left or right hemifield to 150 msec or less. This restricts tachistoscopic testing to the use of relatively simple visual stimuli and thus excludes the use of many forms of tests for intelligence, memory, perception, emotion and other cognitive functions that require more prolonged examination. The need for a better technique that allows prolonged viewing of more complex visual displays (e.g., sentences instead of single words, complex scenes and objects instead of simple line drawings, etc.) and lateralized viewing of manual performance has long been recognized, particularly for studies with commissurotomy subjects.

Early studies obtained prolonged lateralized exposure of visual stimuli by monitoring eye position with electro-oculograph (EOG) recording while stimuli were presented in the left or right hemifield (Butler & Norrsell, 1968; Trevarthen & Sperry, 1973). The stimulus could be removed or trial excluded whenever adverse eye movements were detected. Inherent inaccuracy due to artifact and drift in the EOG potential has restricted this technique primarily to studies involving peripheral vision.

Special contact lenses which limit vision to a single hemifield or a portion thereof have also been employed to prolong visual lateralization (Dimond, Bures, Farrington & Brouwers, 1975; Zaidel, 1975). The sophisticated lens system developed by Zaidel is a variation of the stabilized image technique in which a half-field occluder, mounted on a collimator on a specially constructed scleral contact lens, is set in the focal plane of a small viewing lens and moves in unity with the eye. This has proved to be an important advance over previous techniques for many kinds of tests but is subject to a number of constraints that severely limit its application.

Another approach to prolonging lateralized visual input involves the use of a double-Purkinje image eye tracker in conjunction with a mechanical occluder or split-screen video display (Zaidel & Frazer, 1977). Presently in the process of development, this technique, if successful, should relieve some of the limitations of the contact lens approach in that there are no attachments to the eye and only a bite bar is fitted to each subject. However, the eye tracker appliance also is expensive and requires exacting technical adjustments that will presumably limit its use to relatively few laboratories.

In this paper we describe a comparatively simple, new technique for obtaining lateralized visual input with prolonged exposure of visual material. Successful in pilot tests and recent studies with commissurotomy patients, the new method offers a number of significant advantages over prior methods and opens new testing possibilities not available with previous techniques. In contrast to previous techniques, the new procedure is inexpensive, involves no significant risk or discomfort for the patient, imposes no stringent limits on the duration or frequency of testing, is widely applicable to normal or brain-damaged subjects, requires no technological expertise either for its construction or its operation and permits prolonged in-depth viewing under relatively natural conditions.

METHOD

The present technique is based upon the normal presence of constant lateral limits for horizontal rotation of the eyes with reference to the head. If head movement is prevented, and the eyes are rotated to the left and held at their lateral limit, the temporal half of the visual field of the left eye can be used for lateralizing input to the right hemisphere or vice versa for the left hemisphere. At these lateral limits of rotation when the head is stabilized, there is no means by which further eye movement can transfer stimuli in the extreme temporal hemifields across the midline into the unintended half-field. The concept was presented earlier in a brief abstract report (Sperry & Myers, 1981).

The technique can be readily adapted to normal and brain-damaged populations and can be coupled with reaction time responses to obtain laterality measures in the presence of the commissures. Any form of visual stimulus or test may be used, provided it is confined to one of the extreme temporal testing fields. Input lateralized to the separate hemipheres in this manner utilizes directly comparable pathways involving the nasal hemiretina and crossed optic pathway to each hemisphere. Since different eyes are used to lateralize input to the different hemispheres, differences between the eyes, such as differences in acuity, may need to be taken into account in making left-right comparisons. For subjects requiring visual correction, a set of corrective lenses may be laterally positioned to cover the testing fields.

No limit is imposed on the duration of lateralized viewing other than the natural development of ocular fatigue from holding the eyes in the extreme sideward position. If fatigue occurs, it is readily relieved by simply relaxing the eyes and directing the gaze forward or to the opposite side. In most cases the eyes need not be held at the lateral limits for an extended period. A series of short views may be allowed and their initiation left to the discretion of the subject. In our experience to date, a single viewing duration of up to approximately 10-15 sec appears to be well tolerated.

Head Fixation

A comfortable means for firmly holding the head of the subject in a fixed position is required during testing. A bite bar is quite adequate for this purpose. If interference with the clarity of oral response becomes a problem, the subject may be allowed to release the bar for reponse after removal of the stimuli. Other means of head fixation may be preferable in studies emphasizing oral performance concurrent with lateralized viewing. When freedom of head movement is important, it may be possible to substitute occluders affixed in spectacle fashion to a stabilized head frame and set to block vision in all but the extreme temporal testing fields.

The bite bar is made from 1/16 in. stainless steel cut into a 1/2-in.-wide U-shaped plate to fit the pattern of the bite. Perforations in the steel plate help to hold in place dental impression compound, which is heated and applied around both arms of the bar and then quickly resoftened in hot water for making the dental impression. Removable bridgework should be taken out prior to fitting and before subsequent testing sessions. Numerous bars can be prepared in advance, ready to be reheated and fitted as needed. The bite bar plate is rigidly bolted to a solid supporting upright bar and firmly fixed to a table at a height comfortable for the subject when seated in testing position. The bite bar is mounted with a slight forward tilt of 4-5 degrees to match the natural tilt of the jaw when the head is held level.

Determination of Testing Fields

The inner boundaries (i.e., the vertical midlines of the visual field at the limits of rotation) of the left and right testing hemifields (see Figure 1) are determined in advance for each subject for use in all subsequent testing. The lateral limits of fixation for most subjects are reported to be in the range of 45-50 degrees from the forward midline (Duke-Elder & Wybar, 1973). Because of individual variation, we determine these limits for each subject by reference to the blind spot of each eye as described below. In the event of a superimposed visual field scotoma, as occurred with one of our subjects, these same measurements can be taken using the abnormal, rather than the normal, blind spot as the reference. In tests in which acuity is not critical and peripheral viewing is acceptable, the two testing fields can be safely demarcated with their inner boundaries at least 50 degrees lateral from the forward midline, eliminating the need for more precise measurements. For expedience in making measurements and locating the testing field boundaries, a large perimetric semicircle is marked on the table top, centered below the middle of the bite bar, with a radius

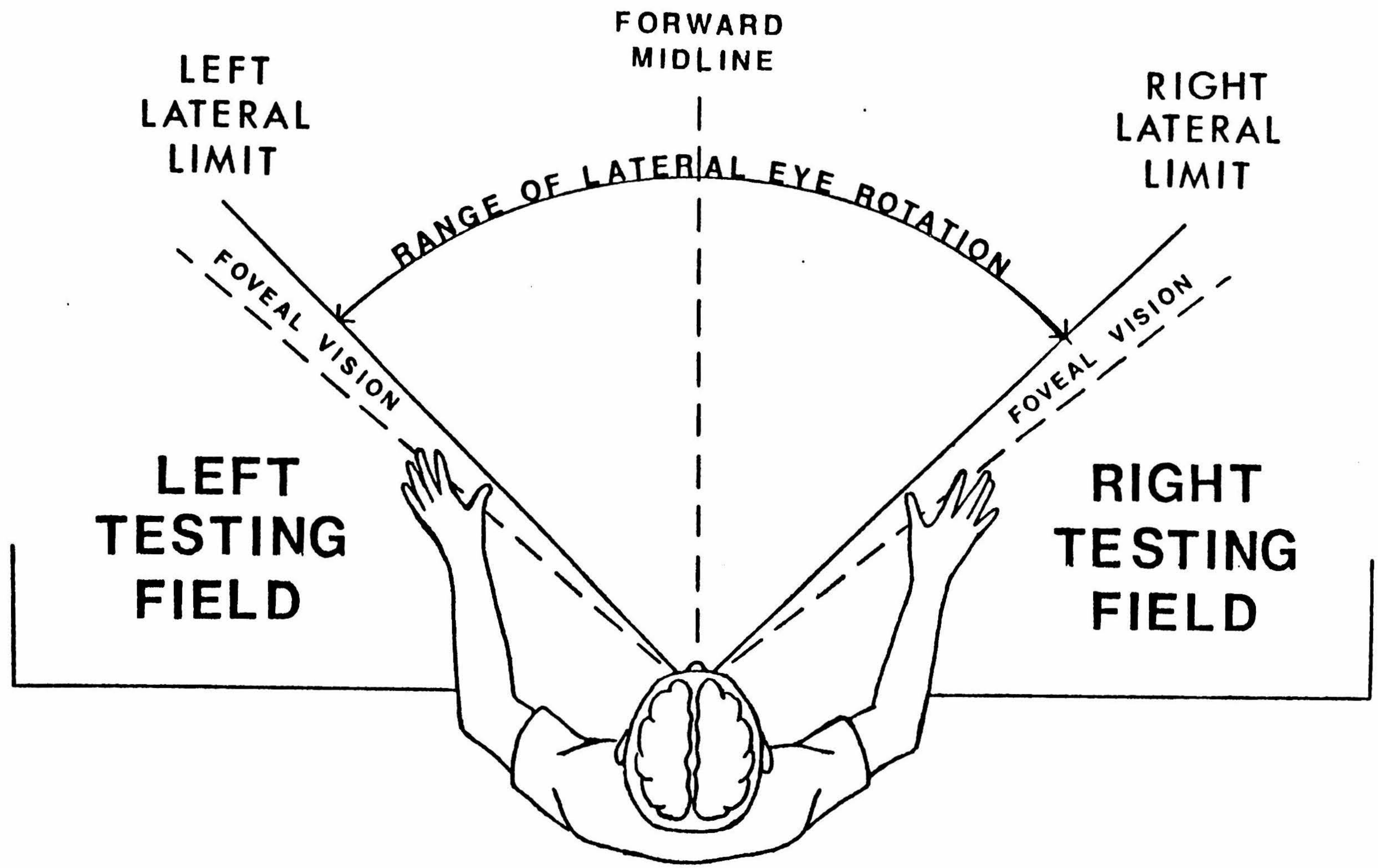

Figure 1. Schematic drawing of testing fields for lateralized visual input as set by lateral limits of eye rotation.

corresponding to the desired viewing distance and with angular displacements from the forward midline marked in the region of the testing fields.

The positions of the vertical midlines of the visual fields at the limits of lateral rotation are determined with the subject seated comfortably at the table and the bite bar in place. One eye is occluded while the subject fixates a small hairline cross presented at eye level, centered directly ahead on a white tangent screen at the desired viewing distance. The angular displacement from the vertical midline to the nasal edge of the blind spot, usually about 13 degrees, is determined by moving a small black target of 1-degree diameter slowly back and forth across the screen along the horizontal meridian, noting on the screen where the subject either verbally or manually indicates its disappearance from view.

The subject is then directed to rotate the exposed eye laterally to its exteme limit while keeping the gaze level, and the screen is relocated to the approximate center of gaze. The location of the nasal edge of the blind spot with the eyes laterally rotated to their extreme limit is determined as before, by having the subject indicate the disappearance and reappearance of the target as it moves across the screen along the horizontal meridian. This is repeated until the subject is unable to cause the target to reappear by further lateral eye rotation. Oblique eye rotations cause the position of the blind spot to shift on the tangent screen and therefore can be ruled out by this procedure. By positioning the tangent screen so that the blind spot is aligned with the previous markings, the vertical midline or nasal boundary of the testing field can be determined and will correspond to the location of the fixation cross. The procedure is then repeated in mirror directions for the opposite eye and testing field. With commissurotomy subjects, the inability to name novel stimuli in the left visual hemifield can be used in determining or verifying the boundary of the left testing field.

Each of the testing fields is congruent with the temporal visual half-field of the corresponding eye at its lateral limit of rotation. For many subjects, the nasal view of the opposite eye is not completely obstructed by the bridge of the nose, so that a small area of the testing field near the midline is open to binocular viewing. Generally no eyepatch is necessary on this opposite eye because the conjugate nature of eye movements ensures that stimuli within a testing field will project to the same hemisphere through either eye.

The method permits rapid alternate testing or comparison of stimuli within the left and right fields, although testing with lateralized input to both hemispheres simultaneously is excluded. The presence of the blind spot within the testing field is not a major concern because it falls well beyond the foveal region and can be compensated by vertical eye movement as well as by normal tendencies to effect perceptual completion.

Stimulus Displays with Combined Manual Tasks and Responses

In tests to date we have used mainly two-dimensional stimuli in the form of cards and test booklets incorporating pictures, words, numbers and so forth, and common three-dimensional objects. Slides and films with moving or animated stimuli can easily be presented through back projection or video monitor displays. Lateralized viewing of live action (e.g., facial expressions, hand movements, etc.) is also possible. It is useful to have a way to keep the stimuli hidden from the subject and to quickly reveal and obscure the stimulus displays, especially in tests involving sequential presentations. Plywood panels can be used for this purpose, with the testing fields occluded by individual screens that can be dropped or raised as desired.

Lateralized visual monitoring of manual responses to choice arrays and tasks that involve manual stereognosis, object manipulation, drawing, writing, tracking and so forth, can all be accommodated within the testing paradigm. In tests with commissurotomy patients, when the left hand is working in the left testing field and the right hand in the right field, visual feedback from responses is available exclusively to the responding hemisphere. For example, visually guided selections from a choice array can be obtained without cuing the nonresponding hemisphere. Among other things, this allows direct controls for successful lateralization of input or for interhemispheric leakage of information by obtaining responses from each hemisphere in sequence. The central area between the lateral testing fields may be utilized to incorporate standard tachistoscopic presentations and test procedures involving both hands and/or free vision.

Alternative Version

An alternative version of the present technique utilizes fixed occluders that move in unity with the head and that exclude all vision except in the extreme temporal hemifields. The central occluders are attached to a firm spectacle frame or headband and are individually set to the lateral limits of eye rotation and adjusted for tilt. While somewhat more involved technically, this approach eliminates the need for head fixation. In addition to increasing the general freedom of movement, this permits unimpeded oral performance and allows the subject to scan stimulus displays through head movement. Tilting of the vertical meridian due to compensatory eye rotations when the head is inclined must be provided for to avoid leakage to the unintended hemifield. Preliminary tests with this version of the technique have been promising.

BEHAVIORAL ASSESSMENT

Basic Deconnection Phenomena

In view of phenomena associated with unilateral neglect and uncertainties regarding the influence of body schema kinetics on the representation of psychological space, it cannot be assumed *a priori* that hemispheric representation for visual space with the eyes rotated laterally to their extreme limit will be identical to that obtained with the eyes directed straight forward. However, tests to date with commissurotomy subjects NG and LB, patients of Drs. P.J. Vogel and J.E. Bogen, indicate a good conformance between the results obtained with the present technique and those obtained with other methods. The same basic functional disconnection symptoms are found in the relation of the left and right visual half-fields to language production and to manual stereognosis. For example, novel objects or pictures of objects are readily named when presented in the right, but not in the left, testing field. Stimuli in the left hemifield that the subject claims verbally not to be able to identify can subsequently be retrieved with left-hand tactual perception from a multiple-choice array hidden from view or presented in the left testing field. Such stimuli, following retrieval with the left hand, still cannot be named or retrieved by the right hand. Conversely, objects or pictures of objects presented in the right testing field cannot be correctly retrieved by the left hand from a hidden array but can subsequently be named. Similar results apply to novel objects identified by unimanual stereognosis. Attempts to point to pictures of such objects in a multiple-choice array succeed only when the array is presented in the corresponding, and not in the opposite, testing field.

The general inability to name or cross-identify stimuli presented in the left visual field or left hand is subject to substantial exceptions in these two subjects, LB and NG, who have been most extensively tested since the surgery 16 and 18 years previously. However, similar exceptions apply to the other testing methods when used in recent sessions with these same subjects. Such exceptions appear to be the result of gradual functional recompensation and reeducation processes through the many years of postoperative testing. Subject LB in particular often succeeds in vocally identifying familiar objects presented in his left visual field or left hand. Also, both subjects can frequently select the match to a stimulus presented visually in one testing field from a visual array presented in the opposite field, although LB (but not NG) fails when nondescript forms are used.

Right Hemisphere Language

Test findings concerning the language abilities of the right hemisphere have in the past most distinguished the different techniques for lateralizing visual input. Results with the present technique replicate the early data obtained tachistoscopically (Gazzaniga & Sperry, 1967; Sperry & Gazzaniga, 1967; Sperry, Gazzaniga & Bogen, 1969) in showing, for example, that the right hemisphere understands, at a moderately high level, words spoken aloud by the examiner and comprehends the meaning of printed object names exposed in the left visual field, as demonstrated by selective manual retrieval or by selection of the corresponding object or picture in a multiple-choice array. Comprehension of object names presented in the left visual hemifield is also apparent in the ability of these subjects to answer yes/no questions regarding characteristics of the object, such as its use, appearance, composition, likely context and so forth, or to select the correct answer when alternatives are listed orally.

The present technique also replicates results obtained with the contact lens method (Zaidel, 1975, 1976, 1978) to the extent that these results have been tested. For example, the subjects can often correctly select from a multiple-choice array of pictures presented in the left testing field the item that matches a printed or spoken name or that fits an oral description, vocal cues and so forth. The right hemisphere fails, however, to derive the sound of a word or picture name presented in the left testing field, nor can it analyze the word or name into component letters, as shown by the inability to make matches based on the sounds of words (rhyming, homonyms) or to select for component letters (e.g., which picture name starts with the letter "b?"). The right hemisphere is also seen with the present technique to be unable to decipher long, nonredundant sequences of spoken words, as when items of the Token test are performed in the left testing field.

Although tests with the scleral contact lens have brought results that in general confirm or extend, rather than revise, the earlier findings obtained by tachistoscopic methods, the two methods have yielded contradictory results in regard to the right hemisphere capacity for processing verbs as opposed to nouns. Zaidel (1976) reported equivalent oral comprehension by the right hemisphere for nouns vs. verbs and action names matched for frequency, whereas the early tachistoscopic findings indicated a selective deficiency in verb processing by the right hemisphere. When we readministered the same set of verbs used in the test by Zaidel to LB and NG with the "lateral limits" technique, but used the infinitive form of the verbs rather than participles, the results showed a marked decline in the performance of the right hemisphere. These preliminary results thus favor the conclusion that the right hemisphere is relatively deficient in the processing of verbs as opposed to nouns.

CHAPTER 2

Interhemispheric communication after section of the forebrain commissures

Abstract. Cognitive information is shown to be transmitted interhemispherically through channels other than the neocortical commissures, presumably through subcortical pathways. What crosses through these subcortical channels does not appear to include the name or identity of stimuli but rather is more contextual or associative in nature. Results obtained with a technique for prolonged visual lateralization indicate that this information, when used in conjunction with cognitive strategies, allows the cortically disconnected left hemisphere under certain conditions to verbally identify stimuli projected to the right hemisphere or to cross-compare bilateral input. The presence of this subcortical communication would thus appear to help explain some of the increasing exceptions to characteristic disconnection symptoms reported among split-brain subjects. In particular, the present results challenge reports which have attributed oral naming of stimuli in the left visual hemifield to the typical disconnected right hemisphere.

This chapter presents work conducted in collaboration with Dr. R.W. Sperry that has been submitted for publication.

INTRODUCTION

Recent studies of patients with complete forebrain commissurotomy suggest that the cerebral hemispheres may have more channels for cross-communication than formerly supposed. Even subtle shades of emotional and semantic information seem to transfer from one hemisphere to the other through midbrain or brainstem channels as shown in tests for self-recognition and social awareness in the right hemisphere (Sperry, Zaidel and Zaidel, 1979). Other recent studies (Johnson, 1984a; Trevarthen and Sperry, 1973) appear to revise the early disconnection findings with reports that human split-brain subjects can occasionally cross-integrate information projected to the separate hemispheres. There are additional reports that these subjects can sometimes name or vocally describe stimuli presented exclusively to the right hemisphere (Butler and Norsell, 1968; Levy, Trevarthen and Sperry, 1972; Trevarthen and Sperry, 1973; Teng and Sperry, 1973; Johnson, 1984b), further suggesting the possiblity of channels by which information may be transmitted across the midline to the speaking hemisphere.

Before it can be concluded that such findings unequivocally establish the cross-communication of cognitive information via subcortical channels, it is necessary to rule out alternative possibilities such as the use of peripheral cross-cuing, emergence of right hemisphere speech, or the use of ipsilateral sensory systems to circumvent the intended lateralization of input. Similar questions are raised by the absence of disconnection symptoms with congenital agenesis of the callosum (Sperry, 1970; Milner and Jeeves, 1979; Chiarello, 1980) and by the apparent presence of bilateral speech in some callosum-sectioned patients (Gazzaniga, Volpe, Smylie, Wilson and LeDoux, 1979; McKeever, Sullivan, Ferguson and Rayport, 1982), although for both of these latter conditions transfer through the intact anterior commissure must be added as a possibility (Myers, 1984).

The presence of some vocal naming ability in the right hemisphere after complete commissurotomy has been strongly supported by recent evidence in which split-brain patient LB was able to name pairs of stimuli flashed one to each visual hemifield but was unable under similar conditions to make a simple cross-comparison of whether the stimuli were the same or different (Johnson, 1980; 1984a). Patients NG and RY, however, could correctly make the cross-comparisons on these same tests but could name only the stimulus in the right visual hemifield. This latter favors subcortical interhemispheric transfer in which, as noted previously (Sperry _et al_., 1979), the general context or "sense" of the stimulus is communicated but apparently not its name or identity.

The present study was undertaken to first reconfirm that patients with complete forebrain commissurotomy can, under adequately controlled conditions, name stimuli presented only to the right hemisphere or cross-compare stimuli projected to the separate hemispheres, and if so to then try to ascertain the means by which such exceptional behaviors are now accomplished. It is critically important that the mechanism of these forms of cross-integration be better understood to enable us to design and properly interpret further commissurotomy studies. A new lateral limits technique for prolonged exposure of lateralized visual input (Myers and Sperry, 1982) was employed, permitting the application of special tests and control procedures designed to better distinguish among the possible mechanisms such as right hemisphere speech, bilateral projection of input, peripheral cross-cuing or subcortical interhemispheric transfer.

MATERIAL AND METHOD

Subjects

Split-brain patients NG and LB were selected for this study because they have been prominent in previous reports of the exceptional left visual field naming and cross-integration phenomena in question. They also are relatively free of extracommissural brain damage and are considered most representative of the symptomology of hemisphere disconnection (Sperry, Gazzaniga and Bogen, 1969). Each had undergone complete surgical division of the forebrain commissures for relief of intractable epilepsy, involving midline section of the entire corpus callosum along with the anterior and hippocampal commissures (and the massa intermedia of the thalamus if encountered). The surgeries were performed by Drs. P. J. Vogel and J. E. Bogen upon NG, a female, in September 1963 at age 30 and upon LB, a male, in April 1965 at age 13. Both subjects are right-handed and right eye dominant and detailed case histories have been published (Bogen and Vogel, 1975; Sperry *et al*., 1969).

Stimuli and Apparatus

Stimuli were selected to include items similar to those found previously to permit crossed responses contrary to the usual disconnection symptoms. Visual stimuli included single digits, uppercase letters and line drawings of common household objects, all 1-4 cm in size and drawn in black ink with lines 1 mm thick on standard white index cards. These stimuli were presented at a viewing distance of 57 cm, approximately 2 degrees eccentric from the midline subtending a visual angle of 1-4 degrees. Tactual stimuli consisted of plastic 5 cm digits and uppercase letters. Tactual tests were conducted with the hands of the subject positioned under and behind a screen to exclude the use of vision.

Prolonged lateralized exposure of visual material was obtained without attachments to the eye by use of the lateral limits technique (Myers and Sperry, 1982). With this method, stimuli can be presented to either visual hemifield at the corresponding lateral limits of horizontal eye rotation where further eye movements cannot be used to transfer the stimuli into the view of the unintended hemisphere. A biteboard, clamped to the edge of a table, is used to hold the head of the subject in a fixed position and the visual midlines at the limits of lateral eye rotation are determined with monocular vision using the blindspot of each eye as a reference. Once these limits have been determined no eyecover is needed and lateralization to the right hemisphere can be achieved by having the subject look to the exteme left while stimuli or response arrays are presented to the left hemifield just beyond the left lateral limit of the center of gaze (and vice versa for input to the left hemisphere). Movable panels, placed in front of the stimuli or response arrays, were used to control the timing of presentation.

Procedure

The subjects were tested individually. During testing, they were seated at a table in a private room with their hands in clear view. Stimuli were presented in random order either to one visual hemifield or to one hand in blocks of 24 trials. Generally only a few seconds were allowed for the inspection of a stimulus and formulation of a response. Guesses were encouraged and immediate vocal corrections were permitted but noted as such. Occasional trials on which there was reason to suspect interhemispheric cross-cuing because of unusual hand, eye or facial movements or extra delay in the response were excluded and repeated later in the same session. All data were analyzed using one-tailed binomial probability distributions.

Naming of left visual field and left hand stimuli. The patients were first tested for their ability to name stimuli projected to the right hemisphere. Single letters, digits or line drawings were used in the visual naming tests and letters or digits in the tactual tests. Prior to a block of trials the subjects were either shown the stimuli and given practice rehearsing the names (informed) or were told only the category of the stimuli to be presented (uninformed). The subjects were then instructed to name each stimulus in the subsequent test presentations. A block of trials consisted generally of eight different stimuli repeated three times each in dispersed random order. However, since NG performed poorly under these conditions (as expected from previous results), additional blocks of trials were administered in her case with the number of alternatives reduced to two (repeated twelve times each) or three (repeated eight times each).

Tests for left hemisphere participation. To assess possible involvement of the left hemisphere when correct verbal responses had been made to stimuli projected to the right hemisphere, selected blocks of trials were repeated under the same conditions but a response other than naming was requested. In one such test the subjects were asked to silently point to the corresponding digits in choice arrays restricted by the lateral limits method to either the left or right visual hemifield. In another control test the subjects were instructed to respond on each trial by generating a novel rhyme to the digit name. In previous tests of these subjects with words and pictures, the right hemisphere has been shown to fail even to recognize rhymes (Levy and Trevarthen, 1977; Zaidel, 1978; Zaidel and Peters, 1981).

Cross-comparison tests. A previous report (Johnson, 1980; 1984a) noted that LB could name stimuli in either visual hemifield with bilateral tachistoscopic presentations but could not make even simple same-or-different judgments across the visual midline. NG, on the other hand, performed in the reverse fashion. Present tests assessed the ability to make such cross-comparison judgments under other conditions in which the stimuli were presented either tactually, to the two hands simultaneously; or visually, to right and left hemifields in alternate succession.

RESULTS

Naming of Left Visual Field and Left Hand Stimuli

Results of tests for the ability to name aloud stimuli projected to the right hemisphere are shown in Table I. The data are presented separately for the two subjects because different test conditions were employed in accordance with their individual abilities.

Subject LB named letters or digits each from a set of eight presented to the left visual hemifield or left hand virtually without error even though he was not preinformed of their identities. When simple line drawings of familiar objects were similarly presented to the left visual hemifield, however, and LB was told beforehand only that the stimuli were pictures of common objects, he failed to name any of the eight drawings presented three times each. Yet, when the test was repeated after LB was told the names and shown the drawings in free vision (where the information reached both hemispheres), he correctly named them all. The near perfect performance for both letters and digits with tactual or visual presentations suggests that the naming ability was unlikely to have been mediated through ipsilateral channels in either modality.

Subject NG failed to name either one of just two different letters or digits randomly presented to her right hemisphere if she was not given advance knowledge of the identities. She could, however, occasionally name one of two line drawings under these conditions apparently on the

Table I.

Naming of stimuli projected to the right hemisphere.

Subject	Condition	Modality of presentation	Stimulus set size	Percentage of stimuli named correctly: Digits	Letters	Line drawings
LB	Uninformed	Visual	8	100**	100**	0
		Tactual	8	100**	96**	
	Informed	Visual	8			100**
NG	Uninformed	Visual	2	17	12	8
		Tactual	2	8	0	
	Informed	Visual	2	100**	96**+	100**
			3	62*	46	42
			8	29*	29*	33*
		Tactual	2	67	100**+	
			3	54*	58*	
			8	33*	8	

*P<0.05

**P<0.001

+Actual responses were reversed (see text).

basis of information which had transferred subcortically. After being shown any two stimuli and rehearsing their names in advance, NG correctly named the two stimuli at a level substantially above chance when they were randomly presented to the right hemisphere. When the size of the stimulus set was increased to three or to eight, the number of correct identifications dropped although remaining above chance. These results suggest that the mental set of the left hemisphere was important and when informed of the stimuli to be presented, correct identifications could then perhaps be prompted by a single transmitted cue. This is further supported by a few occasions on which NG gave long sequences of reversed responses for a given pair of visual or tactual stimuli (e.g., saying "S" when the letter was "N" and vice versa) similar to reversals noted earlier for LB during a tactual cross-matching test (Levy, 1970). The close conformance of the results when either visual or tactual stimuli were used, along with the occurrence of reversals in both modalities again argues against explanations in terms of ipsilateral projection systems.

Tests for Left Hemisphere Participation

The ability of the left hemisphere to respond to stimuli projected to the right hemisphere paralleled the respective oral naming abilities of the subjects for these same stimuli. When preinformed of their identities, NG gave appropriate rhymes for one of two different digits on 18 of

24 trials (75%, $p<.05$) and on 9 of 24 trials (38%) for three different digits. LB, even though not preinformed, responded with appropriate rhymes to 22 of 24 presentations (91%) of one of eight different digits ($p<.001$).

Nonverbal tests involving the manual selection of a match from a choice array confined within the left or right visual hemifield in response to a number projected to the right hemisphere concur with the rhyming results in support of left hemisphere involvement (Table II). The subjects could easily point out the match with the left hand from an array of eight digits presented in the left visual hemifield and could also similarly select the correct match in a right hemifield display using the right hand (presumably guided by the left hemisphere). The less than perfect performance of LB in the right hemifield may be attributable to visual field anomalies (Myers, 1982).

Cross-comparison Tests

Both subjects could sometimes judge whether two stimuli presented visually to opposite hemispheres were the same or different (Fig. 1). NG failed to make correct judgments when the stimuli were presented tactually and LB appeared least able to cross-integrate the line drawings. Nearly 75% of all errors by LB were misjudgments in which two similar stimuli were reported as different.

Since LB proved to be generally able to make these judgments in contradiction to previous tachistoscopic

Table II.

Oral and manual identifications of digits projected to the right hemisphere.

Subject	Stimulus set size	Percentage of correct identifications: Right hemisphere (left hemifield) matching	Naming	Left hemisphere (right hemifield) matching
LB (Uninformed)	8	100**	100**	67**
NG (Informed)	2	96**	83**	88**
	8	96**	42**	42**

**P<0.001

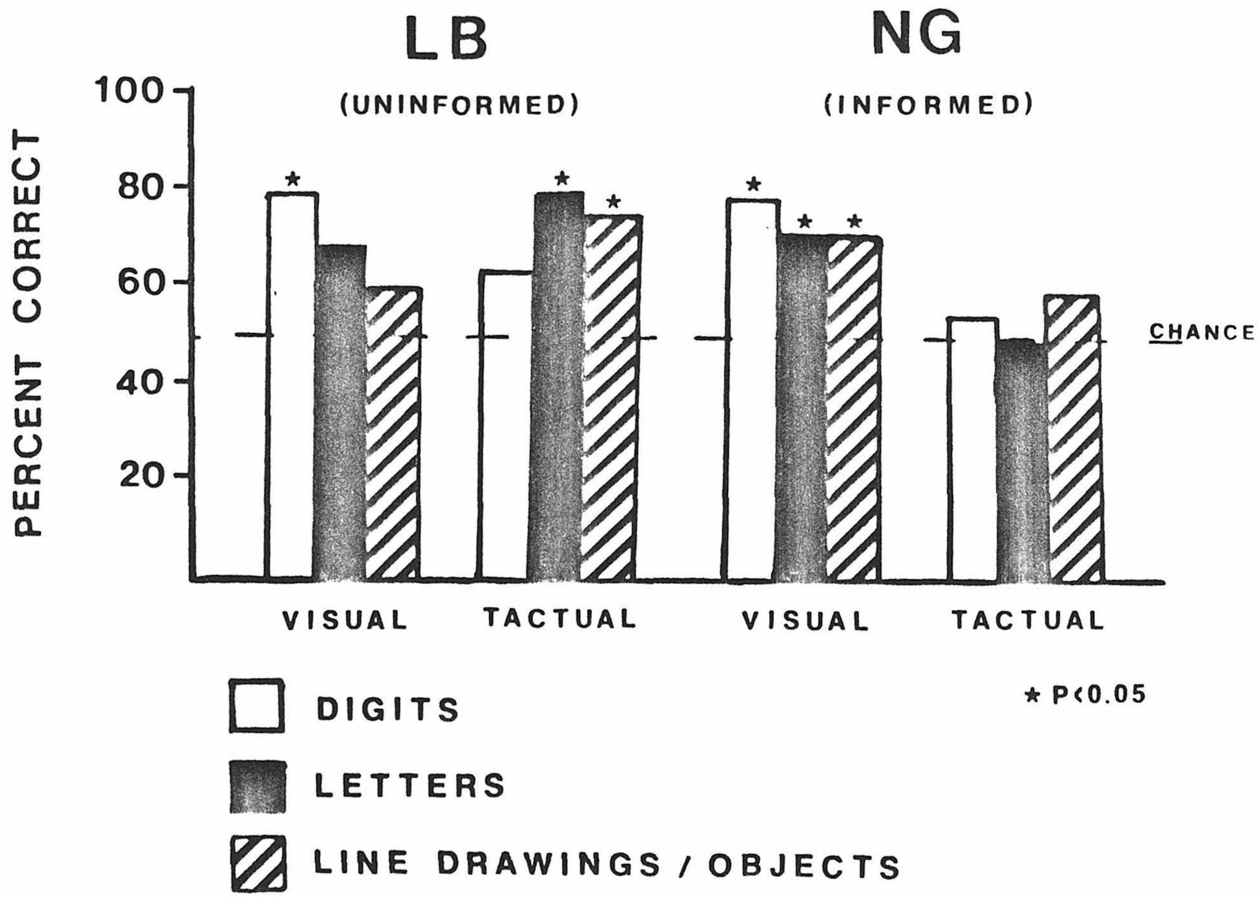

Figure 1. Oral cross-comparison judgements of stimuli presented bilaterally.

findings (Johnson, 1980; 1984a), he was retested with bilateral tachistoscopic presentations of letters (1.5 degrees in size, backprojected for 100 ms, 2 degrees to the right and left of central fixation mark). His responses on this test were similarly accurate (18 of 24 or 75% correct, $p<.05$), in contrast to the earlier reports under these conditions, although all of the errors were incorrect "same" decisions for two stimuli which were actually different. LB commented that the letters in the left visual hemifield were difficult to recognize and that in order to make the same or different judgments he had to first identify both letters.

DISCUSSION

The present results strongly indicate that subcortical channels are able to mediate communication of cognitive information between the cerebral hemispheres. The foregoing tests of patients who had undergone complete section of the forebrain commissures demonstrate that the left hemisphere can still obtain sufficient information about stimuli projected to the right hemisphere to allow correct naming or to allow comparison with stimuli projected directly to the left hemisphere under the experimental conditions described. The use of ipsilateral sensory input, peripheral cross-cuing or right hemisphere speech was not detected in these tests. Hence, we conclude that the exceptional naming and cross-integrational performance observed in this and other recent studies (Johnson, 1984a,b) must be mediated by subcortical communication channels. The extent to which these function also under normal conditions in the intact brain remains conjectural but no reason is seen to rule out normal function.

The exact nature of the information which crosses through subcortical pathways is difficult to determine from the present results. At most, it seems to be sufficient to allow the left hemisphere to recognize but not to generate recall of stimuli presented to the right hemisphere. The subjects' descriptions and behaviors suggest that what transfers is neither precise nor complete nor unprocessed. It appears to consist rather of arousal or orientational cues and partial, contextual or ambient impressions analogous to "mental block" or "tip of the tongue" sensations in which there is available some relevant information which is yet insufficient to trigger precise identification.

The apparently limited amount of information which crossed between the hemispheres in the present tests may, however, reflect in part the use of relatively simple, neutral stimuli. With stimuli which are richer in sensory or semantic associations or which are more emotionally arousing, a greater amount of information seems to transfer (Sperry _et al._, 1979) allowing the left hemisphere in some cases to identify the stimulus without using a rehearsal strategy.

The presence of these additional communication channels contradicts a contention (Gazzaniga and LeDoux, 1978) that the left hemisphere language system only becomes aware of right hemisphere processing through the observation of overt actions. It also supplies an explanation for certain unified responses to differential bilateral input recently described for split-brain patients (MacKay, 1981; Sergent, 1983). The disconnected left hemisphere, in the present tests, appeared to actively search for an appropriate response on the basis mainly of partial, sometimes ambiguous, information transmitted implicitly and subcortically, using cognitive strategies such as the rehearsal of likely alternatives. Peripheral cues or crude ipsilateral sensations would presumably also be used if available.

The differences in the performance of the two subjects examined in this study seem largely to reflect differences in the cognitive strategies they employed. As in earlier tests (Johnson, 1980; 1984b), subject NG was generally able to make only dichotomous distinctions in her responses to stimuli lateralized to the right hemisphere as demonstrated by the failure to name stimuli when the number of alternatives in the stimulus set was increased beyond two or when she was not preinformed of the identities (but see the exception for line drawings above). The occasional sequences of reversed responses when only two stimulus alternatives were presented further demonstrate her reliance upon distinction rather than identification.

In contrast to NG, the strategy of LB permitted him to name alphanumeric stimuli presented to his right hemisphere when told merely that they would be either letters or digits. As noted on previous occasions (Gazzaniga and Hillyard, 1971), LB appeared to mentally rehearse the likely stimulus alternatives until a matching one "sticks out." Such a strategy was evident here when he was unable to name line drawings presented to his right hemisphere unless informed of their identities prior to testing and was further verified in his subjective reports. The same explanation would account also for results in an additional test (not reported) in which LB could name only the common primary colors from a Dvorine color wheel presented in the left visual hemifield while making poor guesses for somewhat less salient colors such as brown or orange.

The possibility that a capacity for oral naming exists within the disconnected right hemisphere, based initially on verbal identifications of left hemifield stimuli (Butler and Norsell, 1968; Levy, Trevarthen and Sperry, 1972; Trevarthen and Sperry, 1973; Teng and Sperry, 1973; Johnson, 1984b), has received recent support from evidence that some split-brain patients are able to name bilaterally presented stimuli but cannot cross-compare them under similar conditions (Johnson, 1978, 1980, 1984a; Gazzaniga et al., 1979; McKeever et al., 1981). However, an inability to cross-compare stimuli is not a sufficient control given the tendency to neglect one hemifield with bilateral tachistoscopic presentations (Teng and Sperry, 1973; Levy, 1983). None of these prior studies entirely ruled out other possibilities such as the kind of interhemispheric transfer demonstrated here. Correlated support for a second, right hemisphere, speech mechanism based on longer oral response times (Johnson, 1984b) could just as well be attributed to delays involved in subcortical transfer, rehearsal strategies and so forth. Additional controls, such as those included here, would seem to be required to ensure that it is not the left rather than the right hemisphere doing the speaking in these situations.

The present rhyming tests and lateralized manual responses, which both strongly implicate the left hemisphere in responses to left hemifield stimuli, counter recent indications of oral naming by the typical disconnected right hemisphere (Johnson, 1980; 1984b). Prolonged viewing of left hemifield stimuli, rather than allowing vocalization by the right hemisphere (Butler and Norsell, 1968), may serve mainly to facilitate the subcortical transfer of information. A few exceptional cases in whom there appears to be definite speech in the right hemisphere after section of the corpus callosum (Gazzaniga et al., 1979; Sidtis, Volpe, Wilson, Rayport and

Gazzaniga, 1981; McKeever et al., 1982) seem best ascribed to the atypical bilateralization of language caused by early left hemisphere pathology (Rasmussen and Milner, 1977; Myers, 1984).

The possible role of subcortical structures in the interhemispheric transfer of cognitive information has only recently been revealed in tests of patients with complete section of the forebrain commissures. The present findings further reinforce the notion (Sperry et al., 1979) that these subcortical transmissions are largely connotative, contextual or orientational in nature and may not resemble typical commissural communications. It seems reasonable to infer that the kind of less structured information involved in these transmissions may normally play a role in cognitive processing, as in memory retrieval and in helping to regulate and direct attention.

CHAPTER 3

Subcortical interhemispheric transmission of connotative information

Abstract. Section of the forebrain commissures allows the segregation and study of interhemispheric transfer through subcortical pathways. Verbalizations of complete commissurotomy patients in response to stimuli projected for prolonged duration to the right hemisphere show that ambient or connotative information, but not the name or precise identity, can pass through these channels to the left hemisphere. The verbal responses included affective and evaluative reactions, category and context cues, and even distinct perceptual impressions and other specific associations. Such brainstem communications are presumed to play a functional role in normal cognitive operations as in memory retrieval and overall mental orientation. Together with occasional facial responses and cuing behaviors, the results further demonstrate the ability of the commissurotomized right hemisphere to comprehend verbal material and to make appropriate mental associations.

INTRODUCTION

Certain aspects of right hemisphere mental processing can be observed to transfer to the left hemisphere through subcortical channels after complete section of the forebrain commissures. While stimuli projected to the disconnected right hemisphere generally were found to be inaccessible to the left (Sperry, Gazzaniga & Bogen, 1969), emotional responses appeared to rapidly spread across the midline, presumably through brainstem connections or through peripheral reactions (Sperry, 1968; Gordon & Sperry, 1969). Later testing of self and social awareness in the minor hemisphere (Sperry, Zaidel & Zaidel, 1979) further suggested that the prevailing mental set or "aura" elicited by key personal or familiar stimuli such as pictures of people, national or religious symbols, well-known scenes and so forth, could cross to the left hemisphere through the brainstem. More recent experiments (Myers & Sperry, 1984; Johnson, 1984b) affirm that even for relatively neutral stimuli such as digits, letters, and drawings of common objects, relevant information may cross through subcortical structures.

The nature, limits and functional role of this subcortical communication have yet to be fully described. Unlike the more specific and structured information which can be passed through the higher neocortical commissures, whatever crosses through these lower channels appears to include the "sense" or connotative aspects of a stimulus but not the name, sensory image or precise identity. This ambient information is often sufficient to provide clues which allow the disconnected left hemisphere to make correct categorical distinctions in response to questions regarding a right hemisphere stimulus (e.g., "is it someone you know personally or from entertainment?"; Sperry et al., 1979). Although direct evidence has not yet been obtained, such subcortical transmissions may play a significant role in normal brain function such as in mnemonic retrieval, orientation of attention and general associative processing.

It has not been possible to dissociate these brainstem cognitive components for separate study except in patients with a complete cortical disconnection of the cerebral hemispheres. In these patients, transfer of information through the brainstem can be evaluated by presenting stimuli exclusively to one hemisphere and then examining responses of the unstimulated hemisphere for knowledge of this input. Other possible channels to the uninformed hemisphere as through peripheral cuing or ipsilateral leakage of the input must obviously be excluded. Thus, for example, in light of recent evidence discounting oral naming by the right hemisphere among these patients (Myers & Sperry, 1984), spoken comments prompted by a left field stimulus can be considered to reflect information which has crossed to the left hemisphere through subcortical channels, especially if the patients are unable to identify the stimulus orally despite being able to provide other relevant and associated verbal responses.

Verbalizations of commissurotomy patient NG in a recent unpublished test suggest that even distinct sensory characteristics may be conveyed through subcortical transmissions. Pictures of an onion and of two lemons were projected solely to the disconnected right hemisphere and NG was asked to point to the one she preferred. After selecting the lemons, she suddenly released the biteboard and exclaimed, "I taste garlic! Did you put garlic on this thing?" Apparently sensations generated by the picture of the onion in the right hemisphere were transferred across the midline allowing the left hemisphere to realize a garlic-like taste sensation but not to be aware of the source. In free vision, NG later identified the onion in the picture as garlic.

The present study was designed to examine more systematically recent observations of this type of subcortical interhemispheric transfer of cognitive information among commissurotomy patients. The ability of the cortically disconnected right hemisphere to transmit information associated with visual stimuli chosen for their correspondent gustatory or olfactory sensations was examined by analysis of the left hemisphere verbalizations in response to stimuli projected to the right hemisphere. The results are taken to reinforce the existence and functional significance of interhemispheric brainstem transmissions of connotative information.

METHOD

Subjects

Three right-handed split-brain patients of Drs. Vogel and Bogen participated in the present study. For alleviation of intractable epilepsy, all had undergone complete surgical division of the forebrain commissures including the corpus callosum, anterior and hippocampal commissures and, when encountered, the massa intermedia of the thalamus. In each case the surgery was completed in a single operation 15 years or more prior to the present tests. Table 1 presents brief descriptions of these subjects. Published case histories (Sperry, Gazzaniga & Bogen, 1969; Bogen & Vogel, 1975) can be consulted for further details.

Apparatus

Input was lateralized to the right hemisphere using a new lateral limits technique which allows prolonged in-depth exposure of visual material to either hemifield with no attachments to the eye. This technique employs a biteboard to restrict movement of the head so that stimuli can be projected to a single hemisphere by presentation beyond the left or right horizontal limit of lateral eye

Table I.

Patient descriptions.

Subject	Sex	Postop IQ	Age at			Hemisphere of Predominant Extracallosal Damage	Surgical Details
			Seizure Onset	Surgery	Testing		
NG	Female	77	18	30	51	Right	Complete forebrain commissurotomy Right hemisphere retraction Divided right fornix and (large) massa intermedia
LB	Male	106	3:6	13	32	Right	Complete forebrain commissurotomy Right hemisphere retraction Damaged right fornix No search for massa intermedia
AA	Male	78	5:6	14	34	Left	Complete forebrain commissurotomy Right hemisphere retraction Difficult operation Some damage to small area of right parietal lobe

rotation (monocular fixation). A more complete description of this technique has been published (Myers & Sperry, 1982).

Procedure

The presence and quality of subcortical interhemispheric communications was investigated by assessing the ability of the cortically disconnected left hemisphere to verbally respond when selected stimuli were projected to the right hemisphere. The stimuli were 16 pictures and 8 names of foods, animals and other items (e.g., feet, soap) from the Peabody Articulation Cards (Smith, Dunn, Horton & Deutsch Smith, 1971) selectively associated with distinctive gustatory and olfactory sensations. The pictures were full color lifelike drawings at least 12 cm in size. Item names were nouns printed in black lowercase letters 2 cm tall and 4-8 cm across on a white background. Some examples appear below. The cards measured 17 x 22.5 cm and were presented 57 cm from the eye where 1 cm subtends 1 degree of visual angle.

Each subject was seated at a table and held in fixed position with a biteboard during the stimulus presentations. The subject was asked to examine each picture or word by rotating the eyes to the leftward limit where the material was presented for inspection in the left visual hemifield near the visual midline (Fig. 1). An occluding panel placed before the stimulus was raised by

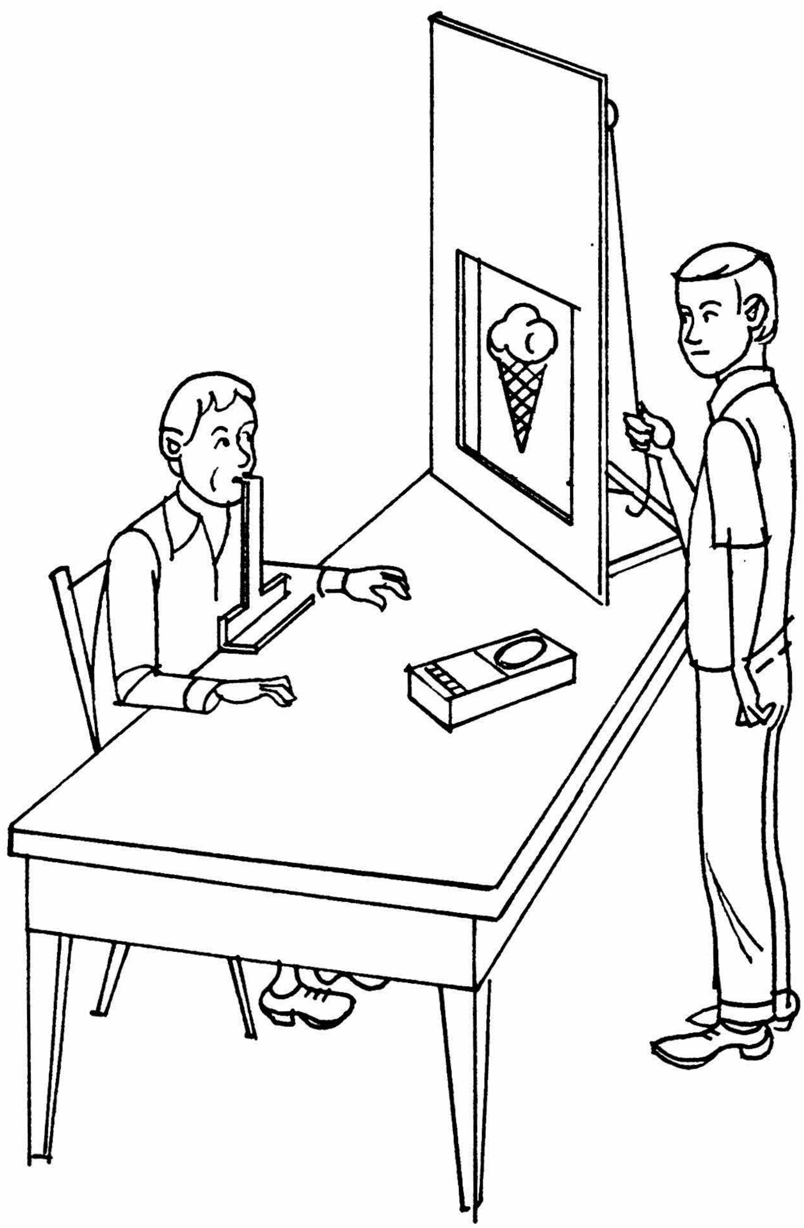

Figure 1. Lateral limits testing set-up for presenting visual material to the right hemisphere.

the examiner to initiate a trial and dropped when the gaze returned forward or if the biteboard was released. On a few occasions, a second viewing was allowed. The examiner stood directly across the table facing the subject in order to observe eye movements and facial expressions and to detect peripheral motor cuing.

After the occluding panel was replaced, the subject was permitted to release the biteboard for response and was asked to verbally describe what had been seen. The subject was encouraged to create a "picture in the mind's eye" and to imagine any associated tastes, smells, textures and so forth. If no information was volunteered, the examiner prompted with appropriate questions in a guessing game format. The ensuing dialogues were designed to obtain as much verbal detail as possible without unnecessarily providing additional information. In a few cases, a stimulus was shown to the subject in free vision after the trial to elicit further comments or to encourage performance on subsequent trials. All sessions were tape recorded using a standard cassette tape recorder with built-in microphone placed on the table directly in front of the subject.

RESULTS

The complete commissurotomy subjects were able to furnish relevant oral descriptions of visual material projected to the right hemisphere. Selected pictures and words presented in the left visual hemifield led to appropriate verbalizations, presumably arising from the left hemisphere, regarding associated tastes and smells, evaluatory comments, the likely context or category of the item and recall of related sensations and personal experiences. Correspondence of these remarks to a given stimulus appeared to be largely connotative rather than direct.

The inability of the patients to name the item in question confirmed that in virtually all cases the left hemisphere was producing the verbal responses even though it lacked direct access to the stimulus. While previous reports have shown that commissurotomy patients can verbally report crude forms and movement in the left field, apparently through use of midbrain visual systems (Trevarthen & Sperry, 1973; Zaidel, 1973), such ipsilateral channels cannot convey pattern information. Thus, the detailed verbal descriptions demonstrate the transfer of selected aspects of the response of the right hemisphere.

Understandably, the verbal hemisphere often seemed reluctant to hazard comments regarding a stimulus it had not seen and could not name. Although verbal comments were sometimes volunteered without prompting during the oral dialogs, more often they were given only in response to questions by the examiner. Occasionally, an incorrect left hemisphere conjecture would dominate a subject's oral responses and answers, especially for the printed words, and the resulting verbalizations would be unrelated to the actual stimulus. For example, when the word "carrot" was presented in the left visual field, subject LB gave a number of inaccurate verbal responses on the basis of a false impression that the word was "coat." Yet when the examiner interposed, "If I said it's something that goes with a rabbit would that make any sense?", LB immediately realized the correct word and began running through the previous answers, changing them to correspond to "carrot." The ability of the right hemisphere to comprehend and maintain its own perception of a stimulus despite dominant and contradictory responses by the left hemisphere is evident in this example.

In addition to information transmitted directly through the brainstem, emotional responses, facial reactions and peripheral cues initiated by the right hemisphere also sometimes helped to inform the left hemisphere. Examples of peripheral cross-cuing were particularly apparent for subject LB. In one case, he was able to identify a picture of an ice cream cone presented to the right hemisphere after observing the fingers of his right hand curl as if grasping the cone (although he contended that the picture was actually a goblet of ice cream). On another occasion, when a picture of a paper bag filled with popcorn was shown in the left visual hemifield, LB was noticed moving his jaw in a peculiar manner. When asked what he was doing, LB's reply shows a failure of the left hemisphere to understand this response by the right hemisphere: "I'm thinking of the back of my teeth. Back here for some reason. You know how your teeth...your back teeth...I'm thinking of those. I don't know why. What I'm doing is running my tongue along my back teeth."

The patients also had access to their own spoken remarks and the directed oral prompts of the examiner as well as to the information obtained through subcortical or peripheral transfer. This oral information was available to both hemispheres and appears to have assisted in the elaboration of associations and concentration of attention upon the stimulus. Once spoken, the subjects could often readily identify (almost always correctly) whether a guess or choice alternative was related to the test item. This information was usually the give-away when a subject came up with the name of the stimulus in question.

Some overall qualitative differences were observed in the respective abilities of the subjects to verbally respond to the left field stimuli. The responses of subject LB were quite specific and he could often home-in upon the identity when pictures were presented. He had difficulty responding to words, either due to dominance by the left hemisphere or to reduced subcortical transfer, although the words were often comprehended by the right hemisphere. NG readily supplied simple evaluative and generalized or categorical verbalizations which were typically less precise than those of LB although she responded equally well to words or pictures. AA gave the fewest and simplest responses, which also were more often incorrect, but he too was able to orally provide some information especially with prompting.

Many of these general observations can be better illustrated by actual examples in the context of the specific stimulus and subsequent dialog. Therefore, a few selected sample transcriptions of test trials for each subject are presented below, each with an accompanying interpretation. Most are complete verbatim accounts although in one case irrelevant dialog was deleted for brevity.

Sample Trials

Stimulus: a picture of a skunk drawn in profile

Ex: What do you get there? Any taste or smell?
LB: Yeah, Skip used to smell like that...sort of icky...(quietly) when they had been in a fight...
Ex: Who is Skip?
LB: Oh, Skip was a dog who has long since passed away...smells icky...(pause) Skunk! That's what it is! We had skunks up where Dad lived. They would come in the back yard, the dog would chase them out and the skunk would let'm have it.
Ex: I'm curious about the sequence...
LB: The nose was the first thing.
Ex: Okay, so you knew it was bad...
LB: Yeah, ick!
Ex: Then you remembered the dog?
LB: Yeah, where have I smelled that bad smell before?

Ex: And then you placed the skunk?
LB: Yeah, I smelled it on the dog. The dog tracked to the skunk.

Interpretation: LB responded to this picture by associating the smell with a memory of his childhood pet, Skip. While his facial reaction to the imagined smell provided cues, the association with the dog indicates that a rather specific impression of the odor had transferred subcortically from the right hemisphere. Although the left hemisphere responded with the dog's name it was not aware initially that the picture was of a skunk. Subsequently, however, the left hemisphere did come to realize the correct referent for the transmitted connotations.

Stimulus: a picture of a package of red chewing gum

LB: Oh! (Starts writing on the table with his right index finger.)
Ex: Okay, stop the cues. What taste comes to mind?
LB: Sweet.
Ex: Can you smell it? Texture?
LB: Cherry! No, not like a cherry...an artificial cherry. Texture is real stringy.
Ex: Okay, do you know what it is?
LB: No...interesting.

Interpretation: The identity of the picture remained confined to the right hemisphere throughout. An attempt to cue the left by spelling the name was quickly squelched. The left hemisphere readily identified taste and texture, presumably from sensations which crossed through the brainstem. Specificity of the transmitted information apparently allowed the rather detailed distinction between real and artificial cherry flavors.

Stimulus: a picture of a skunk drawn in profile

NG: Oh no! I don't want that!
Ex: Why?
NG: I just don't like it.
Ex: It's not good?
NG: No.
Ex: Are you getting a taste or smell?
NG: Smell. It smells terrible!
Ex: No taste though?
NG: No, just a smell. It smells terrible.
Ex: Like what?
NG: (Coughs) Far out! It just smells terrible.

Ex: Far out? (NG laughs) What's far out?
NG: (Laughing) In other words I'm far gone. I don't want that.
Ex: What does it smell like?
NG: Terrible...icky.
Ex: Sour?
NG: Spoiled. (Laughs)
Ex: Something you've smelled before?
NG: I don't know. I'm not sure.

Interpretation: NG strived to characterize the unpleasant perceptions or connotations which transferred from the right hemisphere in response to the picture. The tone of voice and general demeanor which accompanied her sudden "far out" comment along with the laughter it triggered, gave the striking impression that NG (right hemisphere?) had started to say the smell was like a "fart." This exclamation may have been pre-empted by the left hemisphere which was not able to account for either the remark or the laughter.

Stimulus: a picture of a package of red chewing gum

NG: Oh...good.
Ex: It tastes good?
NG: Uh-huh.
Ex: Any texture?
NG: I don't know...it looks like it tastes good.
Ex: What kind of flavor?
NG: Sweet.
Ex: Sweet?
NG: Sweet, sweet, sweet ... something sweet.
Ex: Try to imagine the texture.
NG: Was it licorice? It reminds me of a licorice stick ... like those kind you get for trick or treats. That's what it tastes like.
Ex: Okay, is it liquidy, runny ... was it crunchy?
NG: Soft! Not crunchy or gooey, soft.

Interpretation: A generalized impression or actual sensation of sweetness was communicated from the right to the left hemisphere. The left hemisphere was able to assert that the picture was something good and to generally categorize the taste. After a request to imagine the texture, NG's guess, "Was it licorice?" and subsequent remarks show the kind of narrowing down process made possible by the presence of transmitted connotations.

Stimulus: a picture of an ice cream cone with red ice cream

Ex: Don't be afraid to guess or think out loud. You look like its right on the tip of your tongue.
AA: Sweet.
Ex: Some kind of candy?
AA: I think so.
Ex: You're not sure if its candy?
AA: I'm not sure.
Ex: Is the texture chewy, hard, soft...?
AA: A bit hard.
Ex: Something warm, room temperature, cold?
AA: (Pause) Cold. Maybe cold hard rock candy.
Ex: Any flavor other than sweet?
AA: I don't know.
Ex: You think its hard rock candy?
AA: That's what I'd guess.

Interpretation: AA volunteered only that the taste was sweet but he could correctly identify characteristics of the item when these were listed orally by the examiner. Other than the initial "sweet" response, the other remarks could have been made on the basis of simple transmitted recognition sensations generated by the right hemisphere upon hearing pertinent adjectives.

Stimulus: the printed word "cake"

NG: Oh...sweet.
Ex: Sweet, what else?
NG: Sweet.
Ex: Good?
NG: Yes.
Ex: Do you know what it is?
NG: No. (Laughs) Sweet though, whatever it was.
Ex: What kind of sweet?
NG: Good sweet. Sweet sweet.
Ex: Like...
NG: Like what?
Ex: Like a fruit?
NG: No...something sweet. Like a dessert?
Ex: A dessert?
NG: Yeah...yeah, like a sweet dessert.
Ex: Any other flavor?
NG: I don't know.
[Irrelevant dialog deleted.]
Ex: Think about things you have for dessert.
NG: Okay...ice cream, cake...Ice cream! Ice cream, cake. there you go.
Ex: There I go what?
NG: Thats my dessert. That's what that reminds me of.
Ex: Okay.

NG: Got it?
Ex: Yes, and what was it?
NG: I don't know but that's what it reminds me of.

Interpretation: The right hemisphere clearly understood the meaning of the word. Transmitted information allowed the left hemisphere to orally identify the taste. Prompted to categorize the type of sweet taste, NG's tentative guess, "like a dessert?" became a certainty when it was apparently heard and affirmed by the right hemisphere. As NG listed alternative desserts, the right hemisphere again presumably transmitted a signal when the correct name was spoken. However, the timing of this response confused the left hemisphere causing the mistaken initial emphasis of "ice cream."

Stimulus: the printed word "spinach"

Ex: Do you know what that is?
LB: No.
Ex: Can you picture it in your mind?..not the word but the thing itself.
LB: Green.
Ex: Green? Are you getting a picture of it?
LB: I got green. One thing at a time. I'm working on a shape right now...circular, box-shaped, triangular...
Ex: Any taste?
LB: No.
Ex: Do you know where you might have seen this before?
LB: My dad's house.
Ex: What context...where?
LB: In the kitchen. I'm still working on the taste.
Ex: Well, some tastes are hard to characterize.
LB: Kind of like what's corn taste like? It tastes like corn.
Ex: How about a smell. Any smell?
LB: No.
Ex: Is it a food?
LB: Yeah. That's what I'm working on, a food...things like food categories. What is it in?
Ex: Okay, what category of food is it in?
LB: I don't know. (Laughs) Probably a vegetable.
Ex: Okay, most green foods are, I guess.
LB: (Snaps fingers.) Popeye eats it. It comes in a can.
Ex: Now what happened there?
LB: I got green, I got the class down and I got the "s-p." I knew what the rest of it was.
Ex: So Popeye didn't just pop into your mind.
LB: It did after I got the "s-p" and knew it was spinach.

Interpretation: On this trial, LB's left hemisphere adopted a strategy of mentally rehearsing categories (colors, shapes, etc.) until a matching item was encountered. Even so, this strategy, which has been observed in previous tests (Gazzaniga & Hillyard, 1971; Myers & Sperry, 1984), seemed to require that some information from the right hemisphere be available to the left for recognition of the correct response. LB identified the first two letters of the word, presumably by mentally running through the alphabet. In general, LB seemed to show less connotative transfer for words despite comprehension by the right hemisphere.

Stimulus: the printed word "onion"

AA: I have no idea.
Ex: Okay, does a taste or anything come to mind?
AA: No.
Ex: Do any of these pictures go with the word you saw? (Places five pictures, of lemons, an onion, an ear of corn, an apple and pancakes, on the table before AA)
AA: (Pointing to the onion with the left hand) Garlic.
Ex: Why do you pick that one? Did you remember a taste?
AA: Odor.

Interpretation: It is unclear whether any information was transferred to the left hemisphere in this example. However, comprehension of the word by the right hemisphere of AA was demonstrated by his correct selection of the corresponding picture. The left hemisphere may have received connotative impressions of the odor but showed no awareness of the actual word.

DISCUSSION

The foregoing tests affirm that certain aspects of right hemisphere perceptual and cognitive processing can cross through subcortical channels to the left hemisphere. While the identity typically remained confined to the right hemisphere and the stimulus could not be named, the left hemisphere was able to provide a verbal report (of sensory characteristics, evaluative responses, contextual cues, associated recollections, etc.) demonstrating that connotative information pertaining to the stimulus had transferred. The nature and selectivity of these verbalizations go beyond the kind of description possible by use of ipsilateral visual systems (Trevarthen & Sperry, 1973; Zaidel, 1973) or covert cross-cuing schemes (Gazzaniga & Hillyard, 1971) and yet, in agreement with recent control tests (Myers & Sperry, 1984), strongly implicate the unstimulated left hemisphere rather than the right hemisphere as the source of the speech.

The subcortical transmissions observed in these tests provide a source of information regarding the level and nature of mental processing within the right hemisphere. The right hemisphere apparently could reconstruct a perceptual image from a stimulus and transmit rather specific semantic attributes and connotative information to the left hemisphere not just in response to pictures (Zaidel, 1983) but also for words. These communications demonstrate the ability of the disconnected right hemisphere in all three commissurotomy patients to comprehend simple words and pictures and indirectly reinforce claims that the right hemisphere is capable of making quite complex mental associations (Sperry, 1968; Sugishita, 1978; Cronin-Golomb, 1984). This capacity for comprehension and association was also evident in the initiation by the right hemisphere of appropriate facial expressions, evaluatory exclamations and occasional peripheral cues (and presumably extends also to some of the words spoken in the oral dialogs). Recent opposing findings of limited right hemisphere cognitive skills in callosum-sectioned patients with considerable right hemisphere language abilities (Gazzaniga & Smylie, 1984) may be attributable to limitations of tachistoscopic testing methods or left hemisphere dominance effects through the intact anterior commissure (Myers, 1984).

With tachistoscopic presentations, limited examples of interhemispheric brainstem transfer have been reported among complete commissurotomy patients, the transfer typically consisting of emotional overtones following strongly arousing stimulation (Sperry, 1968) and little cognitive information (Johnson, 1984a,b). The more extensive transmission of connotative and orientational information has principally been observed with methods devised for prolonging the exposure of lateralized visual presentations. Preliminary observations involving unimanual stereognosis now show essentially similar results for stimuli presented to the left hand. Prolonged access to the stimulus may enhance the ability of the right hemisphere to process the material and to transmit connotative sensations, although long term functional compensation in these patients may also be a contributing factor. These transmissions are clearly facilitated also by strong emotional, affective or self-significant reactions which may, as in speech and motor output, serve to overcome dominance by the left hemisphere.

The amount of information which actually transferred through subcortical channels from the right to left hemisphere is difficult to assess in the present tests, especially given the presence of additional information from peripheral cues and from the oral dialogs. At one extreme, the vocalizations of the left hemisphere may have been a simple readout of multiple right hemisphere associative impressions all of which transferred through the brainstem. At the opposite extreme, only a few, simple, generalized keys may have crossed which, perhaps in conjunction with other cues, triggered associations within the left hemisphere. The present findings appear to fall somewhere between these two extremes. The occasional specificity of verbalizations not preceded by external cues in these tests, clearly indicates that the transmitted sensations could carry quite detailed information.

Subcortically transmitted connotative sensations might serve in the normal brain to help establish the proper context or mental set for the reception and interpretation of callosal transmissions and for cognitive processing in general. The importance of cognitive set, expectancy and contextual factors for processes such as memory recall and recognition is well-documented (even a very familiar face can be difficult to recognize in an unexpected context). These lower brainstem communications are thus perhaps analogous to procedural channels used to set the stage for efficient higher level cognition and communication. The transmissions from right to left hemisphere may also be important in the selective orientation toward left hemispace. However, it is not yet known whether these transmissions can pass also from the left to right hemisphere nor whether similar transmissions cross through the forebrain commissures (surprisingly similar results seen after only partial, posterior section of the corpus callosum were reported to disappear after subsequent anterior section; Sidtis, Volpe, Holtzman, Wilson & Gazzaniga, 1981). Brainstem systems largely involved in regulation of arousal and attention would seem to be natural candidates for conveying the type of orienting connotative information described above but may be less well-suited for transmitting more precise information such as the identity of the stimulus.

APPENDIX

Right hemisphere language: Science or fiction?

Right Hemisphere Language: Science or Fiction?

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The recent article on right hemisphere language by Gazzaniga (May 1983) contains a number of inaccuracies, omissions, and misrepresentations that, if taken into consideration, explain why the arguments he advances have not been taken seriously by most neuropsychologists who are directly concerned with these questions. In this and other recent writings (e.g., Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981), Gazzaniga (1983) returns to a view of right hemisphere language that is quite similar to that which had prevailed prior to the 1960s, in which the right hemisphere is claimed to be normally lacking in competence for either the comprehension or expression of language or for higher cognitive functions in general. In his view the typical disconnected right hemisphere (in representative right-handed, split-brain patients) does not possess "language of any kind" (p. 525), has only "rudimentary cognition" (p. 536), and is an "extremely passive" mental system "capable of performing, at best, simple match-to-sample nonverbal perceptual tasks" (p. 534). He sums up his position as follows: "Indeed, it could well be argued that the cognitive skills of a normal disconnected right hemisphere without language are vastly inferior to the cognitive skills of a chimpanzee" (Gazzaniga, 1983, p. 536).

These conclusions are based on the argument that the more recent enhanced views of right hemisphere language and cognition are founded mostly on a few select split-brain patients, which now, in the light of experience with a larger series of patients, are perceived by Gazzaniga to be exceptions to the rule and unrepresentative. The more accurate picture, he tells us, is that reflected in a new "East Coast" series in which he has "seen evidence for right hemisphere language of varying degree in only 3 of 28 patients" (Gazzaniga, 1983, p. 527). Therefore, right hemisphere language is concluded to be a rare occurrence and, when present, to be an abnormal condition attributable to early left hemisphere brain damage.

On the surface, this argument, as presented to readers of the *American Psychologist*, seems to be straightforward and well substantiated. A closer inspection of the underlying facts and evidence, however, as presented below, reveals remarkably little that will stand up under examination.

Even the central contention on which the argument rests, that only 3 of 28 patients show language in the right hemisphere, proves to be spurious. The reader naturally assumes that 28 cases have undergone tests for language in the right hemisphere. However, in many of these cases, right hemisphere testing is not even feasible by Gazzaniga's methods. Up to 7 of the 28 cannot be located in his publications, and all but a few of the others must be disqualified because of neurological or other inadequacies that make them unsuitable for contributing to the issue one way or the other.

When such factors are taken into account and appropriate eliminations made, the corrected ratio of patients with right hemisphere language in the East Coast series appears to be closer to 3 out of 3 than 3 out of 28, and of the 3 with right hemisphere language, 2 have to be excluded as not relevant for understanding language organization in the normal brain because of presumed early damage to the language system of the left hemisphere.

A survey of the publications from Gazzaniga's laboratory reveals a total of only 21 patients mentioned anywhere. This includes the 20 published cases of Donald Wilson (Wilson, Reeves, & Gazzaniga, 1982; Wilson, Reeves, Gazzaniga, & Culver, 1977) plus V.P., a patient of Rayport also known as P.O.V., tested earlier by McKeever and associates, who first suggested that V.P. had right hemisphere speech (McKeever, Larrabee, Sullivan, Johnson, Ferguson, & Rayport, 1981). Although there are other cases in the literature that might be invoked (Amacher, 1976; Gur et al., 1982; Luessenhop, de la Cruz, & Fenichel, 1970; McKeever, Sullivan, Ferguson, & Rayport, 1981), none are suitable for ruling out language or cognition in the right hemisphere.

Of these 21 patients, 5 (T.C., J.Kt., J.C., P.G., and C.E.) have incomplete frontal commissural section sparing the splenium and thus have insufficient functional disconnection to allow testing with behavioral methods for either right hemisphere language or cognition. Another 4 (J.Kn., D.H., D.S., and S.P.) also are reported to have complete visual transfer through the uncut anterior commissure (Risse, LeDoux, Springer, Wilson, & Gazzaniga, 1978), rendering any assessment of their right hemisphere abilities difficult, especially because Gazzaniga regards vision as the only modality that can insure that the right hemisphere is performing a task. There are no published results of any tests of right hemisphere language for these 9 patients in whom the hemispheres remain

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connected in a manner that allows free transfer of vision and other functions. However, other complicating factors and neurological deficiencies among these patients, including prior removal of the right temporal lobe (J.C. and P.G.), atrophy of the right hemisphere with left hemiparesis (D.H.), uncertainties about the extent of surgery (J.Kn. and D.S.), severe retardation (S.P.), and death shortly after surgery (C.E.), could as easily account for this lack of published data.

Of the remaining 12 patients, 8 have neurological or cognitive deficiencies that also could readily account for any failure to see evidence of right hemisphere language. The defects of these patients include extensive damage to the right hemisphere with accompanying left hemiplegia or hemiparesis (T.O., J.H., S.A., and S.Y.); prior removal of the right temporal lobe (S.A.); pathologies of language (T.C., L.L., L.R., and G.H.); and severe mental retardation (L.L. and G.H.). Excepting the 3 patients acknowledged to have right hemisphere language, the cerebral deficits of these remaining 8 cases and presumably of the most recent case, S.W., are sufficiently severe, apparently, to have prevented any meaningful testing of either language or cognition in the right hemisphere. As with the above patients, there are no published data regarding the performance of these 9 patients on tests of right hemisphere language. In fact, 6 (T.C., L.L., S.A., L.R., G.H., and S.Y.) are never mentioned in any of the published experimental reports.

Table 1 presents a complete list of the 21 patients of which, as described above, all but 3 have to be disqualified on the grounds that the inability to demonstrate language in the right hemisphere could obviously be attributed to other known factors. Hence, for Gazzaniga to inform the unsuspecting reader that he has seen evidence for right hemisphere language in only 3 of 28 cases is not just meaningless but clearly misleading.

After eliminating patients in this series that fail to meet the criteria of having a reasonably undamaged right hemisphere that is separately testable and for whom there are published data on right hemisphere language capacity, only 3 remain, P.S., V.P., and J.W., all of whom have language in the right hemisphere.

When it comes to the main question at issue, that of assessing the laterality of language and cognitive function as represented normally, P.S. and V.P. must also be excluded as mentioned above because of early left brain pathology. P.S. is reported to have suffered left brain damage centered in the main language center of the left hemisphere at 20 months of age. It is a standard neurologic doctrine that such pathology under 4 years of age may abnormally force language, including speech, to also develop in the right hemisphere. Case V.P. similarly is presumed by Gazzaniga and others to have early brain damage to the left hemisphere. Bilateral language including speech is not at all uncommon under these conditions (Rasmussen & Milner, 1977). Thus, what Gazzaniga (1983) describes as the "surprising development of right hemisphere speech" (p. 532) in these patients would seem to be the natural expectation of any neurolinguist.

The right hemisphere language profiles of P.S. and V.P., including speech, writing, syntax, phonetics, and verbal praxis, in addition to semantics, represent pathological exceptions within the split-brain population and can hardly be lumped in a continuum with other cases as Gazzaniga does to support general statements about the quality, variability, or frequency of occurrence of language in the right hemisphere. By contrast, the two select cases of Vogel and Bogen, N.G. and L.B., have minimal or no evidence of early left hemisphere lesions. The epilepsy in N.G. was not recognized until her late teens, and a familial predisposition offers a likely explanation.

Among the 20 published Wilson cases and V.P. we thus come down to a single patient (see Table 1) who can possibly furnish evidence representative of the nature and extent of language in the normal disconnected right hemisphere. This patient, J.W., is described as the case most like N.G. and L.B., similarly judged to be the most qualified in the California series.

Interpretation of the results from case J.W. poses some special problems, however, that apply to most of the Wilson patients but are not encountered with L.B. or N.G. Two years after his second surgery, J.W. was described as a "second case like 10 (P.S.) with speech in his right hemisphere" (Wilson, Reeves, & Gazzaniga, 1982, p. 695). Gazzaniga now tells us, however, "J.W. has shown no sign of right hemisphere access to speech in the four years following surgery" (p. 531). Discrepancies of this kind are not confined to J.W. Patient J.Kn. also was described initially as having undergone complete section of the anterior commissure as well as the corpus callosum (Wilson et al., 1977) but subsequently was presumed to have some remaining splenial fibers (Gazzaniga, Risse, Springer, Clark, & Wilson, 1975). In more recent reports (Risse et al., 1978), it has been decided that the anterior commissure may be intact. In one or more additional cases, the surgery is also inferred to be incomplete (Wilson et al., 1982), perhaps owing to Wilson's frontal surgical approach (Greenblatt, Saunders, Culver, & Bogdanowicz, 1980), calling into question the extent of disconnection in Wilson's other patients.

Although differences between patient groups are mentioned, the Wilson series as a whole, including J.W., is presented at the outset by Gazzaniga (1983) as being basically comparable to the California series in having undergone "similar surgery" (p. 525). Many arguments and comparisons are made on this basis. Later the reader is informed that the surgeries in the two series had some critical differences. Commissural disconnection in the Vogel and Bogen series is virtually complete, whereas in the Wilson patients, it is only partial or incomplete in all but 2 cases (T.O. and J.H.), both of whom have extensive damage to the right hemisphere.

In 5 of the Wilson cases, the splenium of the corpus callosum remains uncut, and in the other 14, including the 3 with right hemisphere language, the hemispheres remain functionally interconnected through the uncut anterior commissure. Containing roughly 3,000,000 fibers (Tomasch, 1957), this commissure interconnects, among other things, the cortex of left and right temporal lobes. It is known from animal studies to play a significant role in interhemispheric transfer, especially of visual information (Sullivan & Hamilton, 1973), and patients having an intact anterior commissure but congenitally lacking the corpus callosum exhibit almost none of the basic split-brain disconnection phenomena, showing seemingly normal cross-integration in vision as well as other modalities (Milner & Jeeves, 1979; Sperry, 1968).

Table 1
Characteristics of Gazzaniga's East Coast Patients

Patient	RH language abilities	Visual transfer	IQ	Age at seizure onset	Surgery	Other data
1. TO	Data unavailable	No	74	6 years	Complete forebrain commissurotomy	Early RH lesion; left hemiparesis since birth; grossly abnormal RH; age 9 years at surgery
2. JH	Data unavailable	No	84	14 years	Complete forebrain commissurotomy	Extensive damage to RH; left hemiparesis; RH unresponsive
3. JKn	Data unavailable	Yes	81	4 years	Complete forebrain commissurotomy (intact splenial fibers or anterior commissure?)	Extent of surgery uncertain
4. TC	Data unavailable	Yes (splenium intact)	74	19 years	Frontal commissurotomy (posterior half of the corpus callosum intact)	
5. JKt	Data unavailable	Yes (splenium intact)	112	18 years	Frontal commissurotomy (posterior half of the corpus callosum intact)	
6. JC	Data unavailable	Yes (splenium intact)	84	10 years	Frontal commissurotomy (posterior half of the corpus callosum intact)	Prior right temporal lobectomy
7. PG	Data unavailable	Yes (splenium intact)	"Witless"	Birth	Frontal commissurotomy (posterior half of the corpus callosum intact)	Prior right temporal lobectomy, lost to follow-up
8. CE	Data unavailable	Yes (splenium intact)	Not reported	18 years	Frontal commissurotomy (posterior half of the corpus callosum intact)	Died 12 days after surgery
9. DH	Data unavailable	Yes	82	10 years	Corpus callosotomy (anterior commissure intact)	Atrophy of RH; left hemiparesis; prior partial right temporal lobectomy
10. PS	Comprehension and speech	No	89	18 months	Corpus callosotomy (anterior commissure intact)	Early LH damage to temporal lobe; apraxia of left hand; impaired object recognition with right hand; severe hearing loss in left ear
11. DS	Data unavailable	Yes	83	12 years	Corpus callosotomy (anterior commissure intact; also fibers in bridge of callosum)	Prefrontal LH tumor removed at age 14 years; extent of surgery uncertain
12. SP	Data unavailable	Yes	65–80	7 years	Corpus callosotomy (anterior commissure intact)	Retarded?
13. TC	Data unavailable	Not reported	76	9 years	Corpus callosotomy (anterior commissure intact)	Bilateral damage from brain injury; severe dysphasia

continued

Table 1 (*continued*)

Patient	RH language abilities	Visual transfer	IQ	Age at seizure onset	Surgery	Other data
14. LL	Data unavailable	Not reported	60	15 months	Corpus callosotomy (anterior commissure intact)	Severely retarded; bilateral brain damage; severe dysphasia
15. JW	Comprehension (and speech?)	No	91+	13 years	Corpus callosotomy (anterior commissure intact)	Concussive head trauma at age 13 years
16. SA	Data unavailable	Not reported	80	10 years	Corpus callosotomy (anterior commissure intact)	Perinatal head injury; left hemiparesis since birth; prior right temporal lobectomy
17. LR	Data unavailable	Not reported	84	11 years	Corpus callosotomy (anterior commissure intact)	Left hemisphere dysfunction; speech hesitant
18. GH	Data unavailable	Not reported	<70	10 years	Corpus callosotomy (anterior commissure intact)	Severely retarded; dysphasia
19. SY	Data unavailable	Not reported	71	8 years	Corpus callosotomy (anterior commissure intact)	Perinatal head injury; left hemiparesis since birth; retarded
20. SW	Data unavailable	Not reported	83	6 years	Corpus callosotomy (anterior commissure intact)	
VP (Rayport patient)	Comprehension and speech	No	Not reported	6 years	Corpus callosotomy (anterior commissure intact)	Presumed early LH pathology; IQ 72 (McKeever, unpublished)

Note. RH = right hemisphere; LH = left hemisphere.

In the Wilson series itself, earlier reports by Gazzaniga and his associates admit that the intact anterior commissure allowed "complete visual transfer in four of the five patients tested" and sometimes mediated the transfer of auditory and olfactory information (Risse, LeDoux, Springer, Wilson, & Gazzaniga, 1978, p. 28). Further acknowledgments indicate that it may also be involved in the transfer of emotional tone (Gazzaniga & LeDoux, 1978); linguistic information (Gazzaniga et al., 1982); attentional activation (Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1981); distribution of processing resources (Holtzman & Gazzaniga, 1982); and access to speech by the right hemisphere (Gazzaniga, 1983). One might accordingly be led to question whether these patients qualify for the designation *split brain.*

Gazzaniga tends to downplay the importance of this unsectioned commissure. It is conspicuously absent from his "Guide and Glossary to Split-Brain Research" (Gazzaniga, 1983), and the experimental reports often gloss over or omit mention of the anterior commissure, describing the surgery as complete surgical section of the corpus callosum or complete callosal commissurotomy. Although those familiar with these cases may understand Gazzaniga, for others such references clearly invite misinterpretation.

The presence of remnant commissural interconnections introduces complications associated with cerebral dominance, unity, and suppression of function (Plourde & Sperry, in press; Sperry, 1982) that are also overlooked or ignored in Gazzaniga's arguments both in reference to recovery after stroke and to the intact anterior commissure. Were the Wilson patients otherwise suitable, this latter complication in itself would need to be eliminated before one could confidently assess the higher aptitudes of the right hemisphere. These factors may be involved also in the contradiction between Gazzaniga's findings and those of McKeever (McKeever, Sullivan, Ferguson, & Rayport, 1981) regarding sensory transfer through the anterior commissure.

Overall, the incomplete disconnection and the uncertainties, inconsistencies, and a general lack of precision in the description of the Wilson patients make it difficult to interpret reports on this series, including those on J.W.

In agreement with the longstanding considered judgment of those who have worked with the Vogel and Bogen patients, the two select cases N.G. and L.B. thus appear to remain the most relevant patients in the split-brain population for assessing the functions of the normal right hemisphere. Although Gazzaniga is repeatedly critical of the emphasis placed on these two select cases, his own publications include 11 papers devoted solely to P.S., V.P., and J.W., 6 of which are single case studies based on P.S. alone, who definitely cannot be considered representative.

Gazzaniga's argument rests also on several inaccuracies and misleading impressions regarding the Vogel and Bogen patients, some of which have already been pointed out by Levy (1983) and Zaidel (1983b). Relevant to the present comment are Gazzaniga's statements concerning the frequency of right hemisphere language in this series. Gazzaniga (1983) tells the reader that "all of the evidence for right hemisphere language in the West Coast group is derived solely from cases L.B. and N.G." and "no published data to date" (p. 528) suggest otherwise. This is contrary to several reports that present evidence of right hemisphere language for at least four additional patients in the Vogel and Bogen series (Levy, Nebes, & Sperry, 1971; Levy & Trevarthen, 1977; Zaidel, 1983a). Even Gazzaniga himself earlier recognized right hemisphere language abilities in three of the four patients then available: "In one case there was little or no evidence for language abilities in the right hemisphere whereas in the other three the amount and extent of the capacities varied" (Gazzaniga, 1967, p. 27). Given these reports, plus the fact that other conditions (as in the Wilson series) readily account for the lack of reported right hemisphere language, the assertion that only 2 of 15 patients in the California series show any evidence of right hemisphere language is as misleading as the similar statement about the East Coast patients.

The most recent experiments from Gazzaniga's laboratory with P.S. and V.P. deal with interhemispheric transfer of cognitive information and personal awareness, from which Gazzaniga (1983) concludes that his results "suggest that subcortical structures may play a significant role in relaying information" (p. 533). Although this conclusion is directly applicable to related earlier findings (Sperry, 1982; Sperry, Zaidel, & Zaidel, 1979) that already had demonstrated in N.G. and L.B. subcortical interhemispheric transfer of semantic, emotional, and connotational information and the presence in the right hemisphere of both personal and social awareness, this same conclusion cannot be drawn with the Wilson patients without ruling out the function of the uncut anterior commissure. Retention of this effective interhemispheric communication channel, anatomically classified together with the corpus callosum as a neocortical commissure, undermines much of Gazzaniga's argument about the meaning and importance of these cognitive experiments. Further, the patients P.S. and V.P., as pathological curiosities or "idiosyncratic patients," as Gazzaniga describes them, with their early left hemispheric damage, bilateral speech, bilateral ideomotor praxis, and intact anterior commissure can hardly be used for direct assessments of what is normal in either inter- or intrahemispheric processing of cognition or language.

All things considered, the enhanced view of right hemisphere cognition that gained acceptance in the 1970s and has been further reinforced by hemispherectomy data, cerebral lesion findings, studies of neurologically normal populations, and results from other sources remains the best interpretation of the collective evidence available to date. The criticisms that have been advanced in recent years by Gazzaniga and summarized in the *American Psychologist* are seen, on the other hand, to contain serious flaws and misrepresentations, as here outlined. The point to be made is that the data and arguments presented by Gazzaniga unfortunately cannot be taken at face value and thus far have failed to make a substantive contribution to our understanding of either right hemisphere language or cognition.

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