SOME EFFECTS OF CEREBRAL COMMISSUROTOMY ON MONKEY AND MAN

Thesis by

Michael Saunders Gazzaniga

In Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

1965

(Submitted October 16, 1964)

ACKNOWLEDGEMENTS

I would like to express my gratitude for the generous advice and criticism given to me by Professor Roger W. Sperry during the course of my graduate studies. Additional thanks go to Professor Ray D. Owen for his assistance in my minor field, to Drs. Joseph Bogen and P.J. Vogel for allowing me to study their patients and to the many people at Caltech who have made these years extremely pleasant and rewarding. All of the above, along with the generous financial support from U.S. Public Health Service grants No. M3372 and 2G86 and the Frank P. Hixon Fund, are acknowledged with deep appreciation.

ABSTRACT

The following studies were aimed at further clarification of certain of the functional effects produced by brain bisection in primates. They involved also the application and implications of brain bisection for problems of normal cerebral organization. In particular, extensive functional testing was carried out on two human patients in whom brain bisection had been performed for the treatment of severe epileptic seizures. In addition, these human studies were combined with experiments on certain related functions in monkeys.

In the human experiments a variety of tests were administered which involved interhemispheric integration of sensory-sensory and sensory-motor information. The psychological capacities of each separated hemisphere were also examined. Results on somesthesis indicated predominately contralateral projection. Ipsilateral responses for some stimuli were apparent in one case suggesting direct afferent pathways may participate in a doubling of somesthetic representation of some body areas. Bilateral cortical projection for all types of somesthesis was indicated in results from the face and head. Visual testing revealed a complete gnostic separation of the left and right visual fields along with a complete lack of subcallosal interhemispheric interaction for any sort of visual stimuli. Motor control

of both arms and both legs from one disconnected hemisphere varied but in general was possible in most testing situations. There was no interhemispheric transfer of learning and memory.

Differences in intrinsic performance capacities of each separated hemisphere with regard to visual-constructional tasks and to speech and language functions were also observed. The left hemisphere appeared capable of verbal communication by both written and spoken means while the right, although unable to express itself in language of any form, could respond to certain verbal cues. Also, only the right hemisphere was capable of performing visual-constructional tasks.

Related studies on monkeys concerning the neural mechanisms responsible for memory and visual-motor coordination, have revealed that pre-operatively learned visual discriminations are retained by only one hemisphere following brain bisection. In addition, control of the ipsilateral arm in split-brain monkeys was found to be impaired in visual learning situations but not in the habitual movements of everyday activity such as reaching for food.

TABLE OF CONTENTS

Section I

PSYCHOLOGICAL AND NEUROLOGICAL EFFECTS OF CEREBRAL BISECTION IN MAN

General Introduction

Past reports concerning the effects of lesions in the human corpus callosum have been inconsistent. Observations pointing to the presence of a distinct functional syndrome of the corpus callosum in patients with vascular or neoplastic lesions or with surgical section (1-5) have been largely outweighed by more extensive studies in which complete absence of any apraxia, agnosia, agraphia and other mental syndromes was repeatedly observed following surgical section (6-14). In numerous animal studies of the past decade, it has been possible to show that the corpus callosum in cats, monkeys and chimpanzees plays a definite important role in the cross-integration of a variety of sensory, motor and associational functions involving interaction between the two hemispheres. In reviews of this material (15, 16) the corpus callosum is found to be particularly critical in the carry-over of mnemonic information from one hemisphere to the other.

The first section of this thesis reports the results of extensive neurological and psychological testing of two human cases with midline section of the corpus callosum and anterior commissure. The multiplicity of functions that must be represented in the human corpus callosum, as well as the difficulty of designing tests by which to detect the majority of them, means it probably will be a long time before all the functions of the human callosum will be fully catalogued and localized in any detail.

Case Histories

Case I:

The patient, a 48 year old male war veteran, had been having grand mal convulsions for ten years subsequent to war injuries received in 1944. His first black-out spells occurred shortly after a parachute jump over Germany during a bombing raid. Incomplete opening of the parachute resulted in several fractures of the left leg and unconsciousness of unknown duration. During subsequent internment in a German camp, he was rendered unconscious by a rifle blow to the left parietal region and during this time he suffered from malnutrition, losing nearly 80 lbs. He developed dystrophic skin changes in both hands along with widespread moderate muscle atrophy.

The seizures were refractory to medical management with a frequency of at best about one per week and at worst about seven to ten per day culminating in status epilepticus every two to three months. The onset of seizures was often clearly related to emotional upset and an hysterical element has sometimes been inferred from the bizarre pattern. Electroencephalograms have often shown a left temporal-parietal focus as well as consistent bitemporal abnormality.

He was right handed, had an I.Q. of 113 and in both pre- and post-operative testing, the patient revealed a high intellectual level plus a good sense of humor and a keen interest in his surroundings. He was relatively well read, his favorite author being Victor Hugo, and he kept apace of current events, showing special interest in the moon shot.

With regard to somesthesis, it was shown in pre-operative testing that the patient when blindfolded could describe or name correctly various objects such as coins and kitchen utensils held in either hand and with either hand could write the name of the object held in the opposite hand. Occasional errors were recorded in the discrimination between similar sized coins with the left hand, e.g., between a dime and a penny.

Visual testing before the operation showed that the patient had uncorrected acuity of 20/70 +1 O.D. and 20/50 O.S.* Extensive tests including perimetry showed no abnormality except some jerkiness of motion. Tachistoscopic presentation of letters, numbers, geometric figures and sentences showed that all stimuli were easily recognized and interpreted correctly in either half field and/or correctly recorded by manual response with either hand. His reading in general was normal.

Motor responsed of all kinds to verbal commands were carried out accurately and with no gross impairments observ-

---

* The optometric tests were performed by Dr. G. Kambara

ed in either hand. He could, for example, write to dictation moderately well with the left hand as well as the right.

At the time of the operation in February of 1961, extra-callosal damage which included atrophy of the right frontal lobe was judged by the surgeons to be present. The corpus callosum anterior commissure and hippocampal commissure were sectioned. There also may have been damage to the right fornix. Immediately after surgery, generalized weakness, akinesis and mutism were evident, but had largely disappeared when post-operative testing was started one month after surgery. Anti-convulsive medication was reinstated shortly after surgery. There have since been sevral brief attacks with loss of consciousness, but as yet no major convulsions. Occasional brief episodes of clonic-like tremors confined to the distal portions of the right arm or leg have also been noted. The operation appears to have left no gross changes in temperament or intellect and the patient has repeatedly remarked that he feels better, generally, than he has in years.

Case II:

The patient, a 30 year old housewife, has two children and a concerned and intelligent husband. Her convulsions were first observed in 1951 when she was 18 years old, shortly after her marriage. Her grandmother is recorded to have had severe epileptic seizures and her daughter is now being treated for seizures. For 7 or so years after their first observance the convulsions occurred usually at a frequency of one per month, and were correlated with the onset of the patient's menstrual period. They occurred usually in the evening and they were severe in nature, causing the patient to be bedridden for two to three days afterwards. In the early 60's the complexion of her convulsions changed. She would have intermittent convulsions for an entire week at a time and would have to be admitted to the hospital for extensive medication. This sort of seizure pattern persisted until immediately prior to the operation.

She scored with an I.Q. of 74 and always displayed a good friendly nature along with a definite slapstick sort of humor. She had a very low motivational level and failing to complete a simple task, she would usually give up. The 74 registered I.Q., however, was not felt to be a good evaluation of her general intelligence. Subsequent administration of various aspects of the test revealed that she was capable of quite higher scores in certain parts, if the instructions were made absolutely clear to the patient before she started a particular task. However, there is no question that the patient was a relatively dull and submissive sort with little regard for the subtle aspects of human activities.

Pre-operative testing with regard to somesthesis showed that the patient had a mild hypoesthesia on the left side. She was completely able, however, to identify objects held in each hand and to cross-localize points of stimulation over the entire body. Pain and temperature discriminations were also carried out equally well on both sides of the body. Visual testing revealed a normal perimetry. There were no motor problems and all actions to verbal commands were easily carried out by both arms and both legs.

At the time of the operation, the entire corpus callosum and anterior commissure were sectioned along with the massa intermedia. The right fornix was also cut. There was no atrophy apparent at the time of the operation; areas of calcification, however, were seen in x-rays in the right hemisphere. The patient's post-operative recovery was good. Within a week, she was up, walking around the hospital and eating without any help. However, for up to two weeks after the operation, the patient displayed labile affect. At one moment, for example, she would be explaining some previous experience and would talk in a normal manner. Suddenly she would be on the verge of tears, while, however, keeping the main train of thought of the conversation. Then just as abruptly she would resume talking in a normal fashion.

During this period she was prone to much confabulation.

When asked, for example, who Dr. Vogel was, whe replied, "A brain doctor." When asked if he had been to see her, she replied, "Yes, in fact he took me to the store." When she was challenged on this, she kept maintaining that she had been taken to the market by Dr. Vogel. She then said to her mother, who was also present, that she had been drinking too much. She seemed to have a good memory and easily picked me out from a group of people when we entered the room after the operation. She also appeared to have good post-operative memory for much of her past, and was able to hum several of her old favorite songs, such as "Sleepy Lagoon."

Experiment 1 *

Observations on Somesthesis

Introduction

There remains considerable uncertainty regarding the nature of somatosensory representation in the cerebral cortex of primates and other mammals, particularly with respect to the presence and significance of ipsilateral components. There is a basic agreement to the extent that cerebral projection of the various somatic afferent systems is mostly contralateral for all regions of the body excepting the neck and head which are bilaterally represented through the ascending pathways of nerve V. (17, 18).

Evidence regarding the presence and extent of ipsilateral representation for the trunk and limbs, however, is less consistent. Survival of at least crude sensitivity to stimuli after hemispherectomy on the affected side in the cat and monkey suggests the presence of significant ipsilateral representation (19, 20). Survival of somatosensory functions is apt to be particularly good following hemispherectomies for infantile hemiplegia, suggesting that potential ipsilateral pathways may tend to lie dormant or underdeveloped in the normal brain (21, 22). Studies of man with cortical bullet wounds have suggested a much

---

* This work was reported in part in Reference 57.

more difuse and bilateral representation for the left hand than for the right (23). The presence of some ipsilateral projection is supported also from both anatomical and electrophysiological studies, particularly with reference to the spinothalamic system now believed to contain some touch and pressure components (17). Evoked cortical potentials are mainly contralateral (20) but recently have been found to be ipsilateral as well (24-30). Two separate potentials appearing in sequence in the ipsilateral cortex of the cat were observed by Patton et al. in response to peripheral stimulation (30). The later of the two survived the combined transection of the rostral portion of the corpus callosum, anterior and posterior commissures, and massa intermedia, plus ablation of the surrounding cortex to eliminate intracortical relays. In evoked potential studies in normal human subjects, some authors have found (31) three main types of waveforms, while others have found five (32). Among these, the two earlier responses are solely contralateral, but the later ones are bilateral. The extent to which the ipsilateral components are transmitted through the callosum remains unclear.

The present experiments provide further evidence bearing on these and related questions; a detailed account is given of somatosensory tests that relate to the laterality of cortical representation and the cross-integration of somesthetic information from one to the other side of the body. In general, the results demonstrate the importance of the corpus callosum for such cross-integration and the lack of appreciable ipsilateral effects except from the head and neck.

Observations

Case I

Localization of light touch: With vision eliminated by a blindfold, the subject was required to localize, by pointing with his finger, the spot on the skin at which a brief, light tactile stimulus was applied by the experimenter with a pencil point or a small, wooden, toothpick-size stylus mounted at the end of a meter-long aluminum handle. In most of the tests, the patient was instructed to use either the right hand or the left hand as designated by the experimenter. In other tests, free use of either hand was allowed and in others, verbal reports of the stimulus locus were obtained.

It was consistently evident throughout the tests that the patient was able to find all points of stimulation if both the stimulus and the response were kept to the same side of the body. For example, if the patient was responding with the left hand, all points of stimulation on his left foot, leg, trunk, arm, hand and face were found with reasonable accuracy. He could locate very accurately, with the left thumb, points of stimulation among the left fingers and did so by responding immediately and also with a 5, 10 or 20 second delay imposed.

If free use of the hands was in order, the patient generally used the left hand for any point on the left half of the body and the right hand for any point on the right side, except in the facial region where either hand was used with seemingly equal facility. Correct verbal description of the locus of stimulation was obtained only for points on the right extremities, right-half trunk and the head. All regions of the head and face were correctly cross-localized with either hand and also reported accurately in verbal response tests.

With the left hand, however, the patient was totally inept in attempts to localize points on the right foot, leg, arm, hand and the half of the trunk. In many cases, when the right leg or hand was stimulated, the patient failed to make any response at all with the left hand.

In the early cross-localization testing, there seemed to be gradients as to the degree of error, decreasing somewhat toward more proximal and axial regions. With further testing, however, the erratic ability to locate proximal points on the right side with the left hand and vice versa was shown to be attributable in large part to failure to confine the stimulation completely to one side. In particular, the patient was discovered to be using incidental auditory and other uncontrolled cues present in the examination. When these were better controlled, the responses involving the axial region became grossly inaccurate like those for the extremities.

When the right hand was being used in response to tactile stimulation, the same sort of picture emerged with some interesting variations. Occasionally a stimulus on the left side would elicit an automatic response with the left hand contrary to the prevailing test procedure, while the right side failed to respond and apparently remained naive to the whole event. After such a left-handed response was completed and the patient was asked why he had not responded with the right hand, he often claimed that he had not been touched that time. It was as if a strong shift of attention to one hemisphere had tended to extinguish perceptual awareness in the other.

Light taps were also applied doubly, i.e. at two separated points simultaneously on opposite sides of the body, occasionally at corresponding symmetrical points, but more often at non-symmetrical points. The same laterality effects prevailed as in the foregoing. All manual and verbal responses were correct in all combinations for points on the face and head. Below the neck double manual responses were carried out accurately with each hand responding to the homolateral stimulus. However, when a subsequent verbal description of the two stimulus points was asked for, those on the left side could not be reported. This was true in spite of the fact that the subject had correctly found the point of stimulation with his left hand.

In a second testing situation, the patient was tapped at points on his body one to four times on a randomized schedule. The patient, seated at a table, responded by tapping the corresponding number of times with his fingers on the palm of his hand. These tests revealed the same sort of lateralization picture; the patient was able to give the correct number of taps only when the stimulus and response were kept to the same side of the body or within the cranial areas where cross-localization was possible. However, if the left hand or foot was touched when the hand was being used in response, or vice versa, the score was never above chance.

All tests to both the left and the right side tended to yield a score somewhat below 100 percent. More mistakes occured when the body was tapped three or four times than once or twice. With the possibility in mind that the errors might be attributed largely to an uncontrolled fluctuation of attention between the two hemispheres, corollaries of this test were carried out, with the aim of potentiating the fluctuation of attention away from the working hemisphere. For example, in the course of tests in which the subject was responding with the left hand to taps on the left side, he was asked to give a simultaneous verbal report of the number of times he was tapped along with the customary left hand responses. Under these conditions, both the manual and the verbal responses dropped to chance.

Temperature discrimination: In testing thermal sensibility, it was observed that those areas on the left side of his body which were not cross-localized by the right hand were also incapable of initiating a correct verbal response as to which one of two randomly presented stimuli were hotter or colder. For example, if the subject was touched on the left hand with a warm and a cool stimulus in series, he responded verbally at a chance level as to whether the first or the second stimulus was warmer or cooler. However, if a warm or a cool glass was first presented to him and he was then required to fetch a glass within similar temperature from two others, he was able to perform at a high level. When this comparison was attempted intermanually, the response again fell to chance. Those areas on the head and face which seem to be bilaterally represented as a result of the tactile test were also adept in thermal discrimination involving either verbal or hand responses on either side.

Pain sensibility: When the patient was stimulated by either a scratch or pin prick over various body regions, no greater ability to cross-localize the stimulus was observed. Indeed, the same sort of mapping found for touch and temperature seemed to hold also for nociceptive stimuli. It may be noteworthy that since the operation the patient has described most stimuli presented to the left side of his body as giving him a non-specific shock. The exact nature of the subjective sensation remains unclear.

It is of interest to note that the patient reported having scalded his left hand with hot water on at least two separate occasions while shaving. However, these incidents took place in the early months after surgery and, according to his wife, his hand showed no reflexive action. When a very hot aluminum drinking glass was presented along with a cool one in the present tests, the subject always withdrew his hand reflexively from the hot glass even though half of the time he described it as being the cool glass.

Position sense: The same lateralization scheme emerged in tests of joint and position sense. In these tests the several joints, such as the wrist, elbow, shoulder, knee and ankle were placed in a given position by the experimenter and the subject, wearing a blindfold, was required to state verbally the position of the relevant distal portion of the limb. This presented no problem for the right hand and foot but the subject was totally unable to describe joint position in the left wrist, fingers, and toes. Sense of position at the left shoulder was preserved while that for the left elbow was inconsistent. Position was correctly reported without difficulty for all joints on the right arm and also for the left knee and ankle. When the end of a pencil was held in one hand and positioned by the experimenter at different angles and positions, the subject was unable to reach accurately for the other end of the pencil with the opposite hand.

As noted above, position of the subject's left arm at the shoulder was generally reported correctly, the arm being lifted and held out straight from the body at different angles. However, when the right arm was held out simultaneously with the left, thereby equalizing and obscuring the secondary mechanical tensions across the spinal column, ability to describe the position of the left arm dropped to chance.

<u>Special studies</u>: No intermanual transfer of tactile discriminations was apparent. Tactile memory problems, where the patient learned to choose one of two stimuli for a beverage reward, showed on the average no transfer. (Fig. 1). Test objects placed in one hand could easily be retrieved with the same hand, but not with the opposite hand, from a grab-bag containing 10 objects. Also, simple jigsaw cutouts could be put together correctly with either hand separately but not when cooperation between both hands was required. (Fig. 2).

Contrary to the above, there was complete intermanual transfer of stylus maze problem. (Fig. 3).

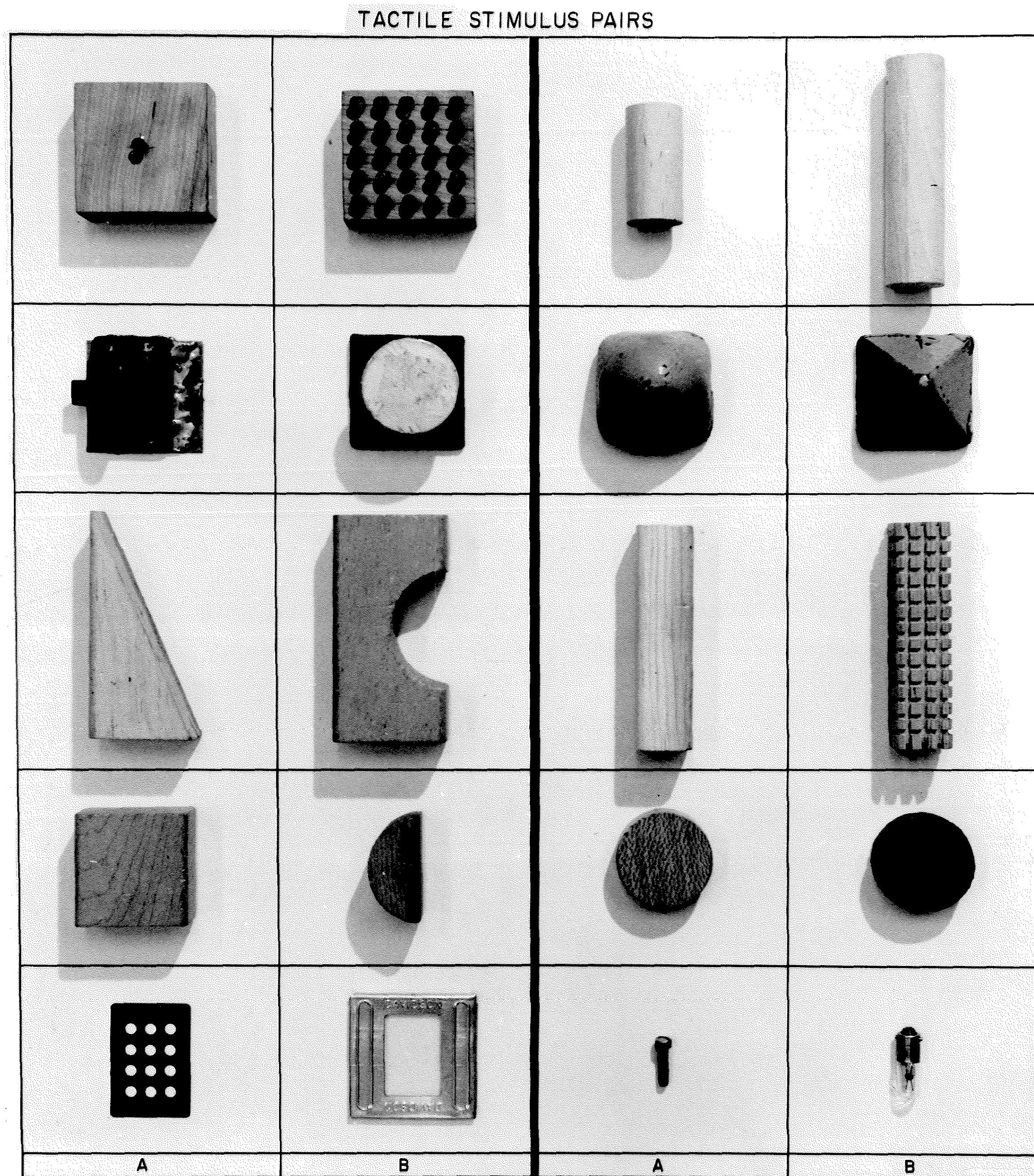


Fig. 1. Examples of tactile stimuli used for tests of intermanual transfer of learning and crossed retrieval.

INTERMANUAL TACTILE COMPARISON

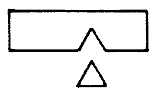
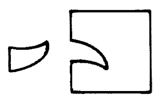
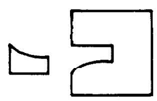
	JIGSAW PATTERN	ONE PATTERN IN EACH HAND		BOTH IN L.H.	BOTH IN R.H.
		L.H.	R.H.		
1		Not Completed		Correct	Correct
2		"		"	"
3		"		"	"

Fig. 2. Shows example puzzles used in tests of intermanual tactile integration.

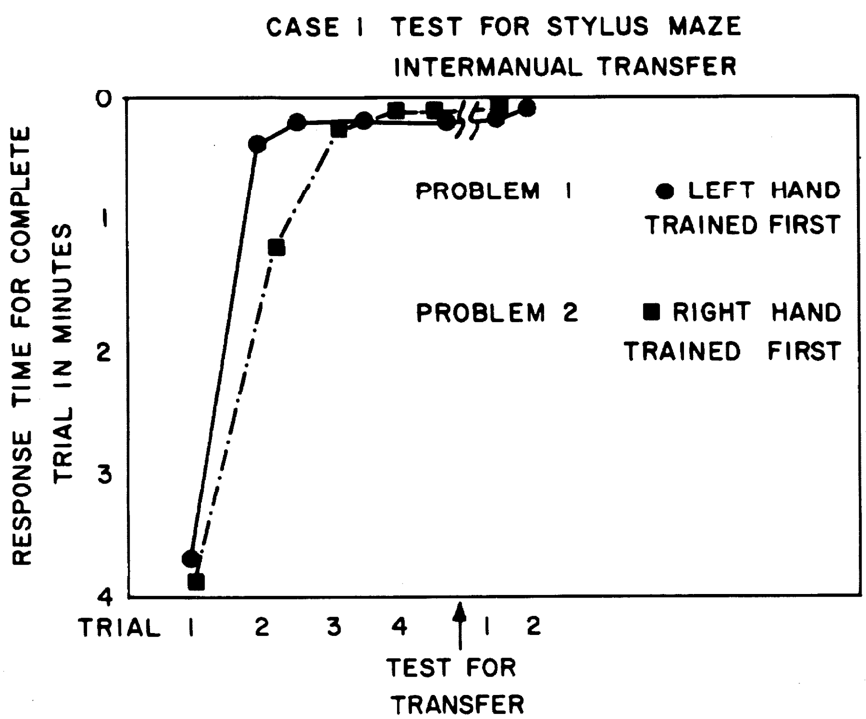


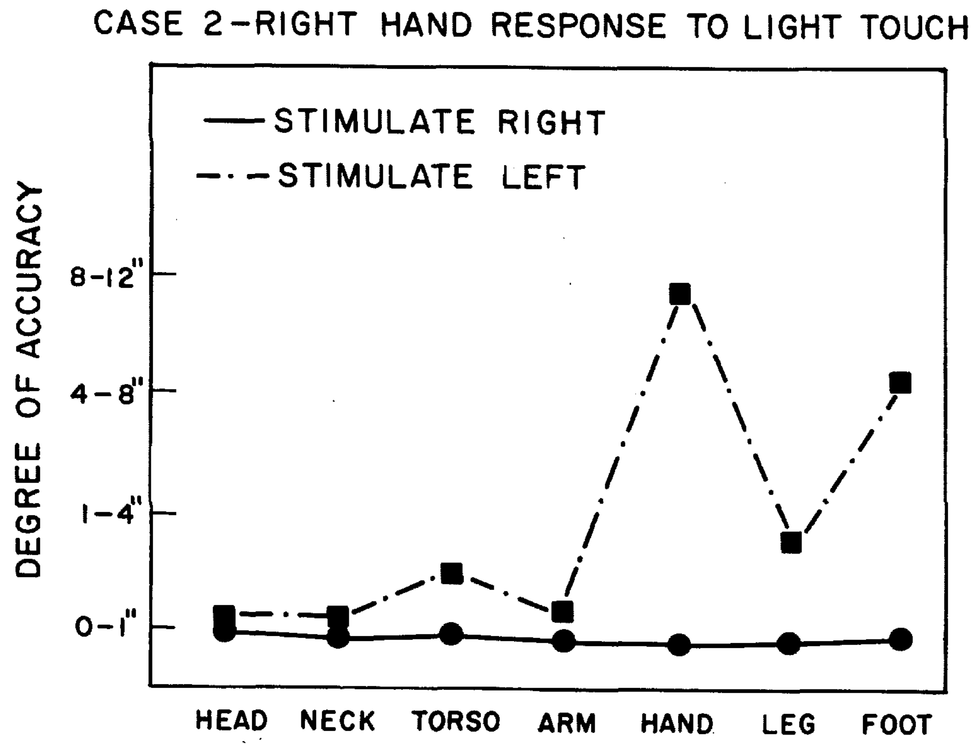
Fig. 3. Results of Case I showing complete intermanual transfer of stylus maze problem

Case II

While results of similar testing on this case were for the most part in accord with the above, certain critical differences were observed. Light touch, for example, was for the most part correctly localized verbally on the left torso and proximal regions of the left limbs in addition to correct localization on the right half of the body. Cross-localization was also possible from either side for these same regions (Fig. 4). In general, however, accuracy broke down for the hand and foot areas; for example, stimulation of the tip of the left index finger would result in the patient responding to the left wrist. Increased accuracy for these hand and foot areas was not induced by painful stimuli. All intra-hemispheric sensory-motor combinations were normally accurate.

In contrast to Case I, a good performance was obtained with the left hand when various areas on the right side were tapped lightly 1-4 times. Right hand responses to left side stimulation were no better than chance in the sixth post-operative month. It is entirely likely that such motor asymmetries may disappear in time.

The remaining tests such as temperature discrimination, position sense and special studies yielded results much in accord with Case I.



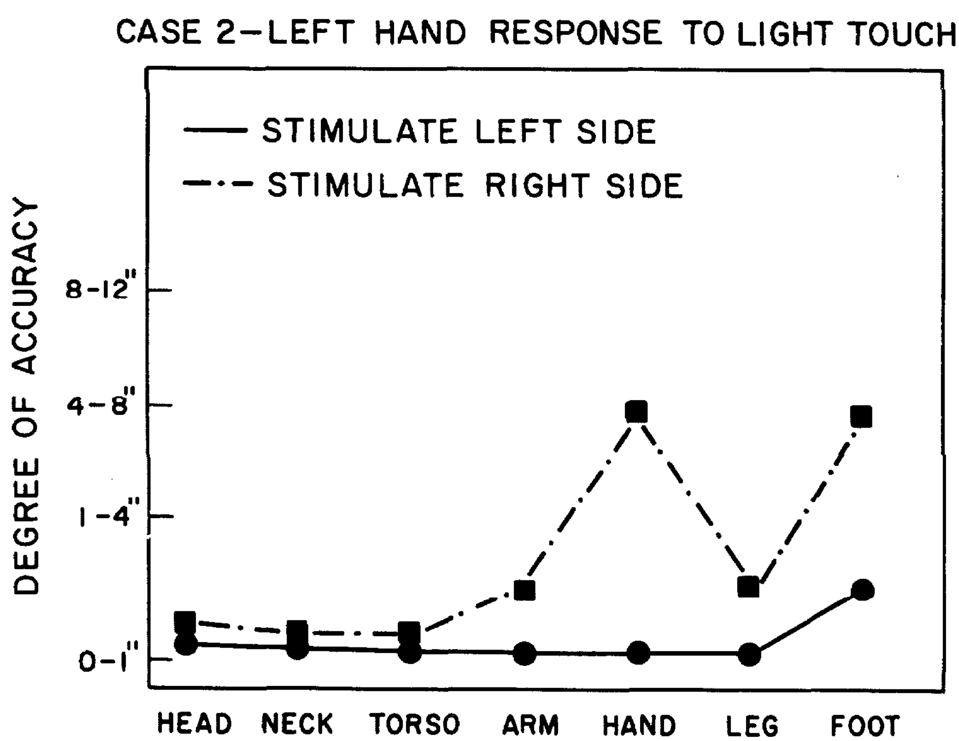


Fig. 4. Each point represents an average of at least 10 test trials during the first 6 post-operative months.

Discussion

The subjects' ability both to verbalize correctly the qualitative nature of somatic stimuli and to localize with accuracy, both verbally and with either hand, cutaneous stimulation on either side of the face and top and back of the head suggests a strong ipsilateral representation of sensation for these cranial areas in both hemispheres which is equal to, or almost as efficient as, the contralateral representation. This is in line with the above cited anatomical and electrophysiological evidence of bilateral projection in the trigeminal system. Cross-localization from the back of the head in the present case suggests that the cortical projection for C_2 is also bilateral following the plan of cranial nerve V rather than that of the lower segments.

Below the neck the results gave a much different picture from the above and were different for each patient. In Case I responses to somatosensory input were made appropriately only when the main cortical motor control came from the hemisphere contralateral to stimulation. Verbal reports of stimulation confined to the left side were grossly inaccurate and often absent, depending on the testing procedure. In Case II, however, crossed responses below the neck went well for the torso and the proximal areas of the limbs. Good verbal localization was also possible for these areas. However, since in both patients there was no ability to verbalize the quality or nature of the stimulus (e.g. hot or cold, sharp or smooth) on the entire left side below the neck, there are perhaps different afferent neural pathways involved for body localization versus qualitative body information. While the tests on verbal and manual localization in Case II suggest direct ipsilateral inputs to each disconnected hemisphere, there was still a greater tendency for inaccuracies when localizing across the midline, suggesting that somatosensory information of this type from each half of the body below the neck is also projected mainly to the contralateral hemisphere. Again the qualitative nature of the sensations involved in both cases appears not accessible in any direct way to the ipsilateral hemisphere.

The different results on the two cases may best be explained in terms of greater extra-callosal brain damage apparent in Case I. Such damage might incapacitate threshold systems conceivably involved in ipsilateral body representation, such as, perhaps, the secondary somatosensory area.

That the subjects were able to report position of the left limbs by using kinesthetic and postural cues arising from mechanical effects across the spinal column, especially during gross or rapid movements of the limbs, has interest for studies dealing with intermanual transfer of learning. Intermanual transfer in Case I of the learning of a stylus maze of the same sort used in earlier studies of callosum-sectioned patients (35) seems attributable in part at least to the nature and size of the maze and the consequent shoulder movement and trunk adjustments involved in its performance. Tactile discriminations limited to palpation of objects with the fingers showed no intermanual transfer. Some of the intermanual transfers reported in monkeys (34) involved the use of proprioceptive cues that might have had secondary mechanical effects at the shoulder.

The neural pathways by which somesthetic information of a qualitative nature from the left side is made available for processing in the major or language hemisphere would appear to involve mainly the corpus callosum rather than direct ipsilateral projection systems according to the present data. In this regard, it would also seem likely that the extra cortical representation for the left hand in the left hemisphere found in other human studies (7) is mediated through the corpus callosum since all areas below the neck in the present case are sharply lateralized.

Experiment 2

Observation on Visual Perception

Introduction

The tests in this section were directed principally at visual functions and were aimed at determining the extent and kinds of interaction, if any, between the perceptual and mnemonic activities of the separated hemispheres, at detecting differences in performance capacity of the right and left visual half systems and at revealing the degree of lateralization in motor responses to right and left visual field stimuli.

Testing Methods

Projection of visual information confined to one or the other hemisphere was effected by presenting stimuli within the right or left visual field while the subject was fixating a central point. All stimuli presented in the left half field thus went to the right hemisphere and vice versa. Inadvertent projection of test information into the wrong hemisphere caused by eye movement away from the fixation point was controlled by tachistoscopic presentation of the stimuli at 1/10 to 1/100 sec. combined with close observations of the subject's gaze. Several variations of the general testing procedure were tried, including the use of goggles equipped with time shutters, ocular electrodes, and different tachistoscopic techniques.

The test conditions most extensively utilized were the following. The subject was seated at a table with his eyes approximately 6 ft. in front of a translucent white viewing screen 4 x 4 ft. with its center at subject's eye-level. A small asterisk figure at the center of the screen was used to facilitate fixation. The stimulus patterns, mounted in pairs or singly on 2 x 2 slides, were rear-projected onto the screen from a distance of 10 ft. by an automatic projector equipped with a tachistoscopic shutter. A second projector, set on top of the first, maintained an even background illumination on the screen before and after each stimulus presentation. All patterned stimuli were black on a white background. They appeared 4 in. high on the screen and were placed no nearer the midline than 5 in. In later tests of the past eight months, the single large screen was replaced by two commercial viewers placed side by side with the screens 4 in. apart as indicated in Figure 5. Each viewer had its own automatic slide projector that could be controlled separately or flashed in synchrony with the other. For some of the tests, a single unit was used with the subject fixating a point at the center of the one screen. Each trial was preceded by explicit verbal instructions and/or overt demonstrations as to the nature of the test performance. One experimenter operated the projectors and watched the subject's gaze while another, sitting beside

Fig. 5. Two automated projector-viewing systems with tachistoscopic shutters were arranged so they could be used separately, in alternation, or in synchrony to present stimulus material in either half visual field from 2 x 2 transparent slides.

the table, recorded the results and checked the subject's general reactions. Because of the language handicap of the right hemisphere, all tests as a rule were run first with the right half field and the right hand. It was easier for the patient to follow instructions for working on the left side after the test procedure had become familiar on the right side.

Observations

Case I

Laterality in visuomotor integration: While the subject was seated before a table fixating on the central marker on a large upright screen, a bright spot of light 1/2 in. in diameter was flashed in a prearranged pseudo-random schedule to different quadrants of the visual field. After each stimulus presentation, the subject responded immediately by pointing quickly to the spot where he had seen the light. When it was desired to test the use of a given hand, the subject's other hand was placed in his lap underneath the table.

Under these conditions, early post-operative testing revealed that when the stimulus fell in the right visual field, it could be localized with only the right hand and/or verbally. Stimuli in the left field could be located only with the left hand and not verbally. When both hands were left free for response above the table, the subject always used the right hand to point to stimuli that fell in the right field and the left hand for those that appeared in the left field. While one hand responded, the other usually remained quite motionless. Tests similar to the foregoing repeated at 24 months after surgery, show the patient now is able to use either hand to locate the visual target in either half field, indicating an increased control of the secondary hand. Responses executed with the primary hand from each hemisphere remain markedly superior to those of the secondary in speed, accuracy and general coordination. Verbal recognition or description are still lacking, however, for the left field stimuli. Reaction time to all stimuli was consistently nearly three times slower than normal.

The results showed, in brief, that when visual stimuli entered one hemisphere, manual responses utilizing the arm governed primarily from the same hemisphere went off appropriately while responses with the other limb were absent in the early months and never became as good as those of the primary arm. Later testing revealed a definite improvement in motor control over the secondary arm. Throughout all these and other tests, it was only those stimuli that fell in the right visual half field that were acknowledged and described verbally.

Retrieval test for pattern discrimination: A series of retrieval tests were designed whereby the subject was obliged to select from a group of five figures on 5 x 3 in. cards placed on a table in front of him, the one that corresponded to the pattern flashed tachistoscopically on the screen. Generally a new set of five cards was placed in front of the subject before each trial. Most sets contained the correct card and one blank card, plus three other incorrect cards. Geometric symbols, numbers, single words and short phrases were used; in some trials a simultaneous verbal description was requested while others involved only the manual response. The stimuli were flashed on the screen in either or both visual half fields on a randomized schedule so that the subject could not anticipate where the next stimulus would appear. The subject then tried to pick out from the series of five cards in front of him the pattern, word or sentence most like the projected figure.

In this situation, the right hand responded correctly with virtually 100% accuracy to all stimuli presented in the right field, regardless of their nature. The retrieval score with the right hand for the same set of stimuli flashed to the left field, however, failed to rise above chance. When stimuli were presented to the left field, the left hand was able to seek out the correct card at a level 2½ times better than chance. The left hand made no response or responded only at a pure guess level when the stimuli were presented to the right visual field. In cases where stimuli were presented in the left field only, the subject, when questioned, would commonly deny having seen anything and often seemed puzzled that he should be asked to pick up a card. When he was asked what figure he had chosen, just after a correct pattern had been retrieved with the left hand following left hand stimulation, the usual reply was, "The blank one."

When stimuli were flashed simultaneously to both fields and each hand responded to its respective stimulus, the _per cent_ of correct retrieval by either the left or right hand did not drop. Nor were there other indications of perceptual distraction, conflict or interference between the hemispheres under these conditions. Verbal recognition remained specific to right field stimuli here as before.

During the first post-operative year, the intermittent apraxia of the left hand often prevented appropriate responses by this hand to stimuli seen in the right visual half-field. During the second year, there was increased ability of the patient to control his left arm so at the present date, 2½ years after the operation, the patient is able to respond with the left hand when discriminating stimuli are projected into the right visual field. There has been only slight, if any, improvement, however, in the ability of the right hand to respond correctly in discriminating stimuli in the left field.

<u>Stimulus preference tests for pattern discrimination</u>: When using the left hand to select one of two test objects or patterns, the subject frequently displayed persistent preferences for one over the other. This applied to tactile as well as to visual discriminations. Such left hand preferences appeared also when no visual field restrictions were imposed and the subject was using the left hand to select objects with both eyes open. Presented with a choice of two objects or cards, the left hand picked one and consistently retrieved it, regardless of right-left position and other variables. This preference could be reversed by deliberately taking the subject's hand and placing it on the other stimulus and then rewarding this choice. As testing of this kind progressed, it became possible after some weeks to reinforce correct responses by reward signals instead of actual rewards, such as tapping a pencil on the table to indicate a correct choice. When an original preference had been reversed, there was a tendency for the subject to revert to the initial preference at the end of a short rest interval of two to six minutes; but a given preference did not carry over with any consistency from one week to the next.

These left hand preferences were sufficiently consistent to make feasible their use in finding out more about the visual discrimination capacity of the relatively inaccessible right hemisphere. Discrimination tests were run with procedures similar to those above but with a second, more portable system in which miniature projector units were positioned 3 ft. in front of the patient's eyes on a 2 x 3 ft. black background supporting board (Fig. 6). These units flashed 3/4 in. geometric figures on a 1 in. ground glass screen at 0.1 sec. A pair of these screens was located in the left visual field and a single one in the right field positioned at points approximately 10 degrees lateral to and on a level with the fixation point. The subject again sat at a table in front of the units where he could easily point to the specific stimulus of his choice. A center hole at the fixation point in the background board allowed the experimenter to observe the patient's eyes and to present stimuli only when the subject's gaze was firmly centered. The visual patterns consisted of a variety of simple geometric figures such as squares, triangles, circles and the like.

In each trial, a pair of different geometric symbols was flashed to the left visual field, side by side (4 in. apart) in a horizontal plane. Simultaneously and at a corresponding point in the right field, either a cross or circle was flashed. The right-left positioning of the two figures in the left field was switched randomly in a standard discrimination procedure. The subject was instructed verbally and by demonstration to have the left hand point

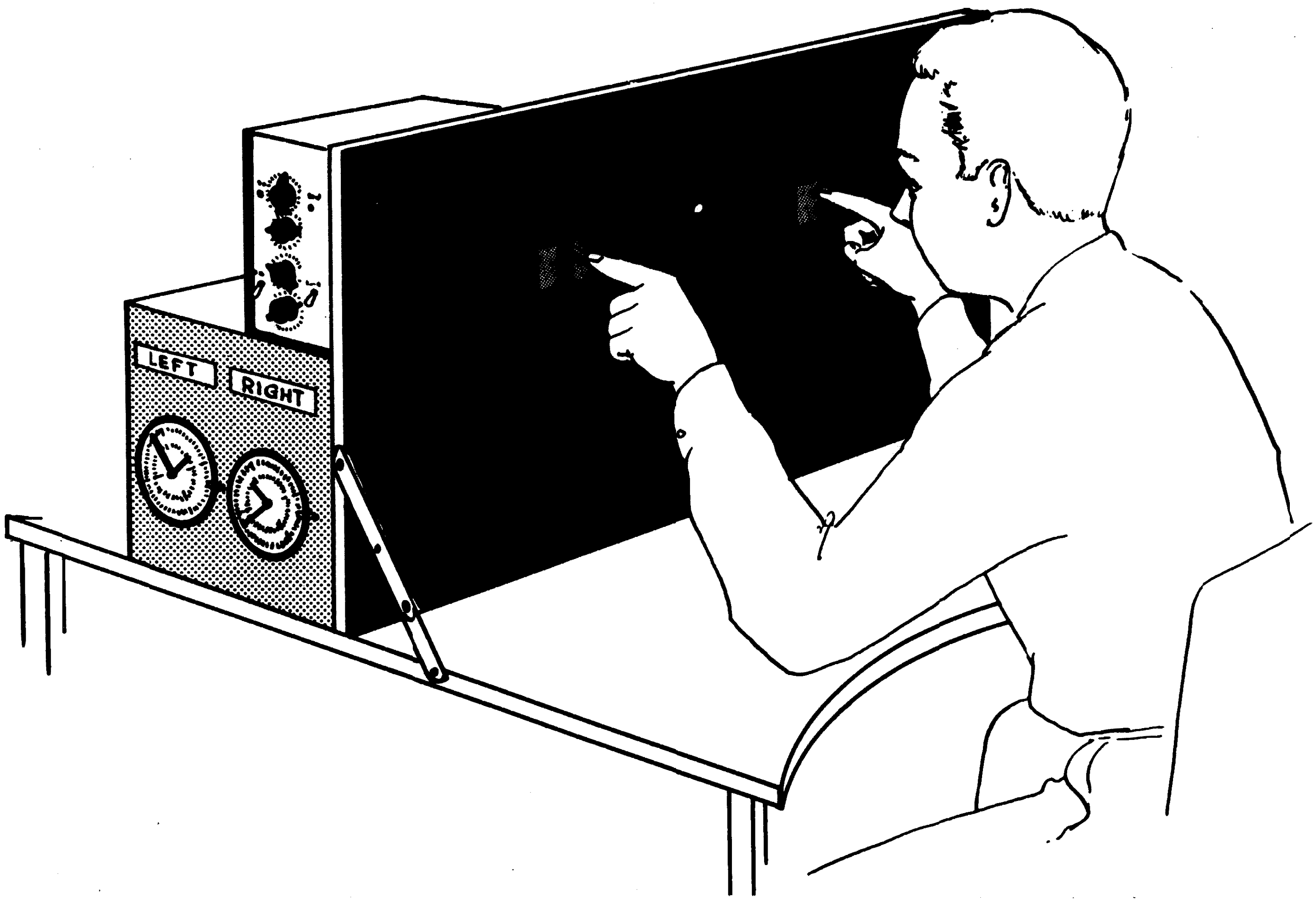


Fig. 6. This apparatus was used for reaction time and was modified for other tests as described in the text. The stimuli were projected on the response panels in either or both visual fields.

to the referred stimulus in the left visual half-field. His left hand responses were made immediately in a proficient, adept and somewhat automatic manner. Following his manual response to the left field, he was also asked which of the two stimuli had appeared in the right field.

The characteristic outcome was as follows: (a) Over a series of trials, the left hand would repeatedly point to one of the two left-field patterns, regardless of its right-left position; (b) the subject was able, on the same trial, to report accurately which of the two stimuli had been flashed simultaneously in the right visual field and (c) when questioned, the subject consistently denied any knowledge of the stimulus flashed to the left field.

Tests for lateral specialization of visual function: The patient had always been right-handed and had never had occasion to write or draw with the left hands, so far as he or his family could recall. Following the commissurotomy, when he copied sample figures that suggested spatial perspective like the Necker cube, his performance with the left hand was consistently better than that with the right (Fig. 7).

In order to get the left hand to perform, the subject was seated at a table and the performance was started with the use of the subject's right hand and verbal instructions. After the test procedure had become familiar, the hands were shifted with the aid of verbal instruction and "do

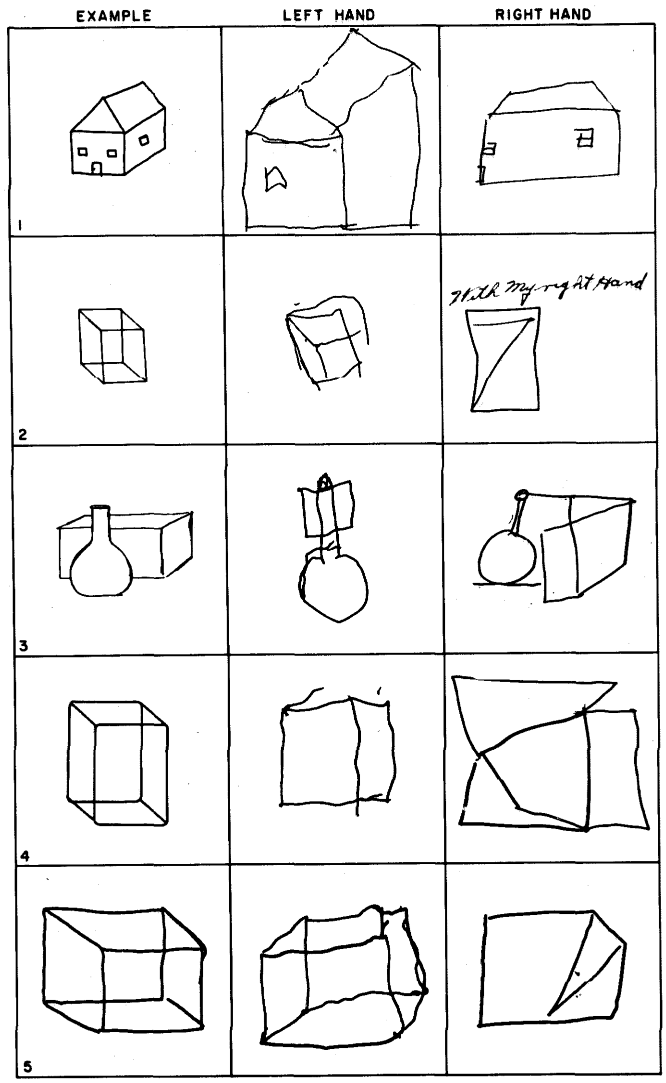


Fig. 7. Samples of the performance of Case I with right and left hand in copying example figures, each trial being limited to three minutes.

this" demonstration. Subsequent changes were then made from one hand to the other and a three minute period was allowed each hand for each drawing. Performance with the left hand was handicapped in that the hand would often tighten and go out of control before the three minute period was up. Most commonly it would slowly swing upward from the paper to a raised position above the left shoulder.

When attempts were made in a recent session to assist the right hand in drawing a Necker cube, by demonstrating the strategy of first drawing two overlapping squares and then connecting the four corners, he was still unable to carry out the task with the right hand. However, immediately after the right hand failure, his left hand drew the complete cube without copying from any example and without using the demonstrated strategy.

The subject was always able to reconstruct standard patterns in a block design test and to assemble complex object puzzles with the left hand. Those patterns that were correctly reconstructed with the right hand were always extremely simple and done so only after much practice. The inability of the right hand puzzled the patient and when it was apparent from his facial expression that he knew the right hand had performed incorrectly, the left hand folded behind him and sometimes restrained by the experimenter, would make spontaneous movements as if to reach out and correct the error. When free use of both hands was permitted, the patient usually was unable to arrange the blocks and/or picture parts correctly, mainly because the right hand would always try to help and would consistently undo the superior accomplishments of the left.

Reading: There was no complaint by the patient of visual impairment during the first several months after surgery even though as evident from the above, he was unable to read or to describe objects, pictures or symbols presented in the left-half visual field. His reading in tachistoscopic tests after the operation, so far as the right-half field was concerned, seemed roughly normal in speed and comprehension. He continued to look at the evening newspaper and to watch television without comment.

Approximately 25 weeks after surgery, however, he began to complain of difficulty in sustained reading. As he described it, printed words tended to fade out until they became indistinguishable and he was obliged to stop and rest for some minutes after which he was able to continue for another short period. When asked to read aloud during a testing session, he did moderately well for about half a page, and then began to slow, to stumble, and had to stop. If the first word on a line was short, he would generally not include it in his verbal recitation. However, his answers to questioning regarding the content of what he had covered indicated good comprehension. With large print and simple material such as found in a book for six year olds he was able to continue a little longer but the same problem persisted.

In March, 1963, the uncorrected acuity was 20/70 + 1 O.D. and 20/50 O.S. Following correction, and if the head was turned to the left, acuity improved to 20/25 O.D. Perimetry with a variety of targets showed a left homonymous hemianopsia. Normal tests, including the Lancaster red-green and orthoptic survey, showed normal stereopis (as also found by Bridgman and Smith, 13).

By about the 7th month, the subject had clearly abandoned efforts to read anything more than the newspaper headlines and the short phrases and words encountered in television. Tests of his reading ability run again at 18 and 30 months indicated little if any change from the condition at 6 months. In addition to this impairment, if short phrases or long compound words were printed out on a piece of paper, such as "ham and eggs", and presented to him briefly, with the last word or word segment being pointed to by the experimenter for a verbal response, the patient would verbalize the last word and claim that was all there was on the paper.

<u>Intermodal transfer</u>: The patient was taught to distinguish with the left hand such objects as wooden ovals, pyramids

or a door latch or electric plug, while wearing a blindfold (Fig. 8F). The patient was consistently unable to give a verbal description of an object that he was manipulating with the left hand. However, as soon as the object and the blindfold were removed, he had no trouble in pointing out, with the left hand, the correct object seen in a chance position among six other objects of similar size. After training and presentation to the left hand, responses carried out with the right hand were no better than chance, and vice versa for objects not audibly named.

Other discriminations of the same sort of objects were made on the basis of unrestricted vision without tactile contact and with the left hand responding by pointing at the chosen object. When the patient was then blindfolded, tactile recognition of the object palpated among a series of others was immediate with either hand.

Case II

As in the first patient, all tests indicated a complete separation of the perceptual, cognitive and mnemonic activity of the left and right hemispheres in all the visual tests. Anything seen, comprehended or remembered as a result of lateralized input restricted to one hemisphere, could not be used to aid in any direct way responses that emanated from the other hemisphere. In even so simple a performance as nodding the head "yes" or "no" to indicate whether red and green colors flashed to left and right fields were the same or not, there was no sign of cross-integration. The same was true in attempts to tell whether broad lines or bars running from left to right field through the fixation point were straight or broken at the middle (Fig. 8A). So far, we have found no evidence that what is perceived in the right half field has any influence on the perception or comprehension of what is seen in the left half field.

The most marked difference between the two cases was seen in the ability of the second case by the sixth post-operative month to use either hand in responding to unilateral cerebral input or to verbal instructions. When a perceptual or cognitive activity was centered or confined to one hemisphere, motor expression was usually better with the favored or primary hand but fair to good response was also possible in many performances with the secondary hand ipsilateral to the working hemisphere. There was no difference between ipsilateral and contralateral combinations in reaction time to a simple flash of light in either half field. This good control and use of the secondary hand in many activities tended to obscure the earlier evidence of hemispheric independence. For example, sketches of the Necker cube that in early months could be performed only with the left hand, indicating specialization of the right hemisphere, could be carried out with either hand by the

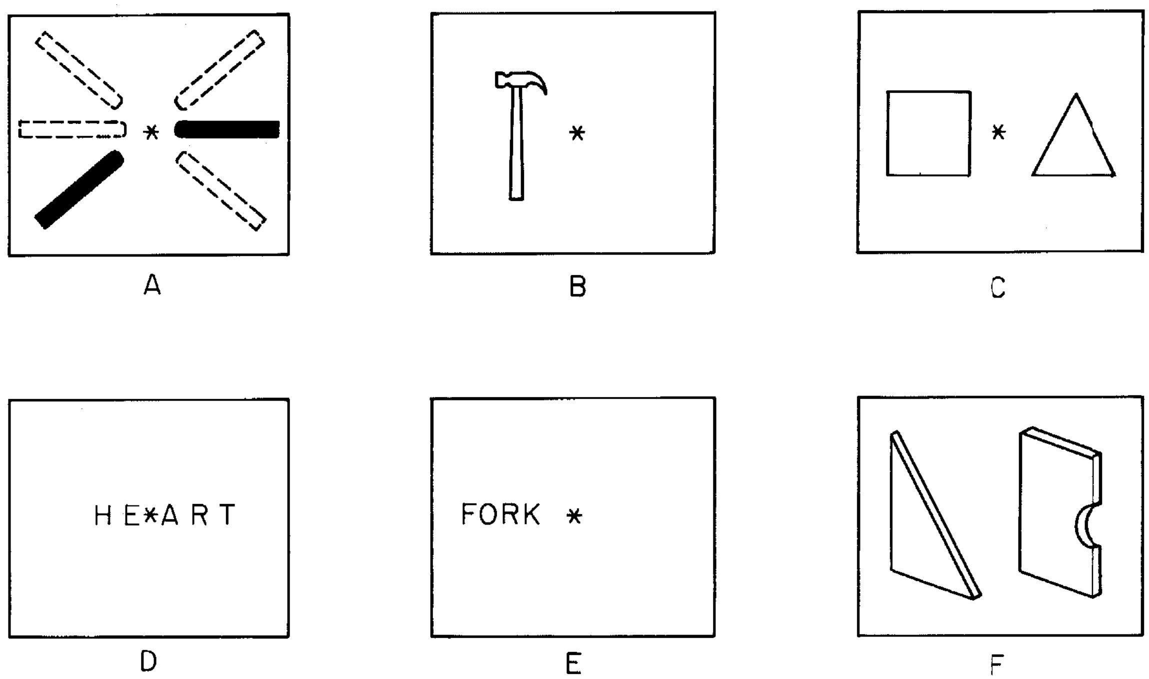


Fig. 8. See legend on page 43.

Fig. 8. Each plate shows representative samples from a series of stimuli used in different visual tests as described. The point of fixation for samples A-E is identified by an asterisk.

A. Split-bar test. Subject compares directional orientation of lines in right and left fields. One of 3 positions on left is paired with one of 3 on right in random order. Subject responds verbally, draws with right, left or both hands, or points to matching samples.

B. Object-retrieval test. Objects pictured in left or right fields are retrieved from among an assortment of other objects using different somatic-visual-cortical field combinations.

C. Double field presentation of geometric figures, objects, scenes, numbers, colors, etc. is combined with verbal plus manual pointing, drawing and writing responses of one or both hands.

D. Triple word test. Commissurotomy patients never identify the whole word, only right and left parts separately and only the right vocally.

E. Name-object retrieval test. Subject's visual and auditory comprehension of verbal material in minor hemisphere is shown by correct non-verbal responses (like pointing at correct one of a number of objects, signaling correct one of several definitions read by experimenter, etc.). Spoken or written answers even by left hand don't rise above pure guess level.

F. Intermodal test. Subject learns to retrieve one of the pictured objects by touch alone and then finds the corresponding object by vision using left or/and right hands. Similar tests were run in a reverse order.

seventh month after the operation.

Even so, when separate and different stimuli were projected to each hemisphere simultaneously, the patient tended to respond in a manner indicating that for each hemisphere, the contralateral hand was definitely favored over the ipsilateral one. For example, when stimulus pairs (Fig. 8C) were presented tachistoscopically and the patient was asked to pick out the "seen" stimulus from a series of sample cards, she characteristically picked only the "triangle" when she was working with the right hand. When responding with the left hand, she regularly ignored the figure in the right field and chose the one that appeared in the left half field, in this case, the square.

The patient could write and execute printed commands only with the right hand during the early months after the operation. Subsequently, the control of the left hand by the left hemisphere improved, until the left hand could also be used for these purposes though generally not so well as the right. Hand use, per se, thus became much less valuable as a criterion of which hemisphere was active than it had been in the first case or during the first several months in the present case and it became necessarry to rely more and more on speech for this purpose.

High to perfect scores were obtained for the discrimination and comprehension of patterned stimuli presented to the right hemisphere (Fig. 8B, E) in a variety of retrieval and matching tests that included words and numbers with non-verbal responses. Her performance in this respect was strikingly superior to that of Case I with known damage in the right hemisphere. Although able to comprehend written material in either field, Case II showed no ability to put together a longer word or a compound word that fell half in one field and half in the other (Fig. 8D). With such a word as "heart" for example, with the fixation point falling between "he" and "art", she would describe only the word "art". Other results involving symbolic capacities of the hemispheres will be reported elsewhere.

Simultaneous discriminatory reaction to double field stimulation: In this test, the subject was seated in front of the apparatus pictured in Figure 6 and with both hands working together, was called upon to react to the green of a red/green discrimination in the right visual field and to make a brightness discrimination in the left field. Both before and after the subject carried out the bimanual task, the right hand was run through on a series of ten trials with single presentation of the right field stimuli. Before each trial, the subject fixated on a center dot. The stimuli were randomly changed within each field from one screen to the other. The results are shown in Table 1. Both cases showed no slowing of their mean reaction time

Table 1

Reaction Times to Visual Stimuli in Milliseconds*

Subject (normal)	Age	R_1. Hand	R_2. Hand-	L. Hand	R_3. Hand	$p(R_2>R_1)$	$p(R_2>R_3)$
GRN	21	438±57	695±97	694±96	391±56	<.005	<.005
TRB	21	465±120	770±140	800±120	496±83	<.005	<.005
HML	28	380±55	470±88	464±95	374±73	<.01	<.01
SRP	50	439±228	574±70	678±88	376±64	<.05	<.005
(operated)							
Case I	49	1150±138	869±92	798±104	848±110	-<.05	>.3
Case II	30	766±156	777±153	869±224	706±280	>.3	>.3

*R. Hand responds to red/green discrimination in right half visual field.
L. Hand responds to brightness discrimination in left half visual field.
Probability calculated by one tailed t test.

for the right hand when the second simultaneous left field discrimination was required. On the other hand, all normal controls showed significant increases in reaction time when the bimanual response was in order. However, it should be pointed out that the reaction time of both operated cases was far slower than that of the normal controls.

Discussion

It is evident in the foregoing that surgical disconnection of the hemispheres, with the resultant separation of the cortical representation for right and left halves of the visual field and for right and left limbs, produced in both cases clear-cut functional disturbances that correlated directly with the anatomical separations effected by the surgery. Performances in which the visual inflow was restricted to one hemisphere and the response involved only the hand for which the primary cortical representation was in the same hemisphere, were little affected, whereas those performances requiring interaction or direct cooperation between the two hemispheres showed marked disruption. Activities that involved speech and writing were well preserved but only insofar as they could be governed from the left hemisphere. It was clear that visual information did not transfer from one hemisphere to the other. Nor was there evidence that the perceptual activities of one hemisphere influenced the other, for both cases failed to achieve even the simplest sort of integration between the two visual half fields.

The impairment of ability to make certain responses with either hand to material seen across the midline of the visual field, especially pronounced in Case I, indicates that in the human brain the corpus callosum in the intact condition plays a major role in the mediation of those responses in which the sensory input is directed to one hemisphere and the primary motor control lies in the other. This conclusion is contrary to a prevailing impression that in man the corpus callosum plays little or no part in such activities (35). The present findings in this regard are also quite different from those obtained in split-brain cats where the visual input into one hemisphere could be used during a learning situation to guide the ipsilateral forepaw as well as the contralateral forepaw (36). Results more in line with the present have been obtained in split-brain monkeys where significant deficits have been observed in activities that pair an eye with the ipsilateral hand (37, 38, 39). These comparative observations, though still meager, suggest that the cortical control in each hemisphere for the ipsilateral upper extremity becomes correspondingly more important in mediating such activity. This appears to be in part a matter of the relative importance of distal versus proximal movement in limb use, the latter being more subject to bilateral control by either hemisphere. At the same time, the severe apraxia seen in Case I and in some of the earlier reports where chronic lateralized cerebral damage was involved (4, 40, 41) may have caused an unnatural dependence on the commissures and lead to some exaggerated conclusions regarding praxic functions of the corpus callosum.

The disconnected right hemisphere displayed subtle perceptual capacities as well as good comprehension for both the testing situation and at times the test stimulus itself. In this regard, results from Case II are especially clear in demonstrating that each of the separated cerebral hemispheres is capable of these higher mental functions. The upper limits of such function in the minor hemisphere, for the most part, remain to be determined.

The exact cause of the first patient's inability to read for a sustained period of time remains uncertain. A new set of eye-movement patterns and attention-forming mechanisms would be called for to compensate for the inability to comprehend the print on the entire left half field. Excess scanning movements of the eyes stimulated by the need of more information from the left field might lead to a distracting fluctuation of attention between the two hemispheres. That a similar reading difficulty has not appeared in Case II suggests that pre-surgical brain damage may be a critical factor in the first case. In general, however, it remains a problem as to what extent the observed differences between the patients should be ascribed to pre-existent brain damage and how much to natural individual differences in brain organization. Cerebral dominance and lateral specialization including language functions along with the unsolved functions of the corpus callosum and other commissures would appear to be subject to a considerable range of individual variation.

One of the interesting questions regarding lateral specialization in the human cerebral cortex concerns the nature of the specialized functions allocated to the so-called minor or nondominant hemisphere. A number of studies based mainly on patients with unilateral cortical damage suggest that the perception of certain kinds of spatial relationships, the recognition of faces and certain non-verbal auditory functions like timbre and tonal memory, are among those that are more highly developed in the minor hemisphere (42, 46). Commissurotomy cases, in which both hemispheres remain essentially intact but separated, offer obvious advantages for the testing of such lateral specialization. To a considerable degree, the properties of each hemisphere are reflected independently in the performance of the appropriate hand, especially in the first patient and during the first months in the second case. The superior performance of the left hand over the right in the block design test, drawing and other simple tasks that incorporated spatial relationships, observed in both patients, offers striking support of the previous inferences that this aspect of visual activity is represented principally in the right hemisphere. Again it would seem that the corpus callosum in the normal brain must play a critical role in serving to integrate this component of visual function with others specific to the left hemisphere.

In regard to the foregoing, it is also of interest to note that while both patients were incapable of reconstructing Necker cubes, block designs and the like with the right hand, they were capable of matching the test stimulus by simply pointing with this hand or indicating the correct design among a sampling of five related patterns. This shows that the primary perceptual capacity of the left dominant hemisphere is capable of discriminating between correct and incorrect reconstructions. Since it is also true that both patients have no motor problems with the right hand, the difficulty in reconstruction in these visual tests must lie somewhere in between these two systems. The further tentative conclusion may thus be drawn from these cases that the lateral specialization lies more in the motor executive or expressive sphere than in the sensory-perceptual components of the performance.

These same problems and the analysis would appear to apply to the speech mechanism as well. Tests now in progress suggest that the disconnected right "non-speech" hemisphere may have a similar capacity to comprehend and to match written or spoken words at a rather high level but yet not be capable of expressing the comprehension through speech.

The total picture of the cerebral disconnection syndrome as exhibited by Case II above, comes considerably closer to that depicted in the Akelaitis-Van Wagenen series (6-14) than does that of our first case. This is attributable in the main to the greater motor control in each hemisphere for the ipsilateral side. Absence and impairments of right-left integration in gnostic functions, however, become strikingly apparent with application of critical tests. All the data are consistent with the earlier conclusion that surgical disconnection of the hemispheres results in a splitting and doubling of most of the gnostic or psychic properties of the brain (15, 16). The normal unity of perceptual awareness in the primate brain may be inferred to be dependent to a large degree on the cerebral commissures, especially the corpus callosum. The functional separation of right and left mental spheres that is produced by cutting the commissures was strikingly evident in a number of the above testing situations, to the point as described where left and right hemispheres were attempting conflicting solutions to the same task.

Experiment 3

Observations on Motor Function

Introduction

There exists in the literature a controversy over the effect that cerebral commissurotomy has on motor response when the sensory input is to one hemisphere and the primary motor control is in the other. At the turn of the century, many neurologists believed in essence that callosal damage resulted in severe apraxia of the limbs ipsilateral to the hemisphere receiving a primary sensory input (2, 3, 4, 40, 41). In general, these observations were made on the left hand in right-handed people with vascular disease and it was concluded that motor function of the right non-dominant hemisphere was impaired because of disconnection from the dominant left hemisphere. In later studies on patients with surgical section of the corpus callosum, no persistent motor dysfunction was apparent after cerebral commissurotomy (6-12). All patients were able to write with both hands after surgery and all were adept at a number of motor integrative tasks such as playing the piano, typewriting and so forth.

Since the inception of split-brain surgery in monkeys and cats, the question of homolateral control of one forelimb from a disconnected hemisphere has been extensively studied. While essentially no deficits have been observed in the cat (36), considerable evidence exists for the presence of ipsilateral eye-hand deficits in split-brain monkeys (37-39). Availability of these two human cases has enabled a reexamination of this topic in man; the results indicate that motor deficits in commissurotomized man are variable depending on the extent of extra-callosal damage as well as other individual variables.

Results

Case I

For the first post-operative year, the patient was almost totally unable to respond with the left hand to verbal commands. During this time, however, good motor function for the left hand was apparent when carrying out "automatic" activities such as the lighting and smoking of a cigarette. The patient would, for example, take a pack of cigarettes out of his left shirt pocket with his right hand, shake the pack so as to loosen a cigarette and then remove it with his left hand and put it into his mouth. He would then light the cigarette with a lighter with his right hand, take a puff and then calmly and smoothly remove the cigarette with his left hand and exhale. At this point, if the patient was requested to take another puff while holding the cigarette in his left hand, the typical picture was one of freezing up of the left hand and tightening of the muscles; as in a stammerer's block, the harder he tried, the worse it became. Moments later, with the experimenter busying himself at other things, the patient in a more relaxed mood would again calmly take a puff from his cigarette with his left hand.

Such simple tasks as pointing with his left hand, in response to verbal commands, to his nose and ears and to the experimenter's body features along with pointing to objects on a table, were done poorly, if at all, during the first year. There was complete incapacity to write and to draw, either spontaneously or from dictation.

None of these apraxic difficulties was apparent when stimulus and response were kept to the same hemisphere. The right hand worked well to verbal commands and the patient often wrote spontaneously. Control of the right hand was normal unless the stimuli were restricted to the right hemisphere; simple light flashes tachistoscopically presented in the left visual field were reacted to readily with the left hand, but not with the right.

Antagonistic movements between the right and left hands were frequently noted. The patient when at home would often pick up the evening paper with the right hand, put it down abruptly with the left, and then have to pick it up again with the right. This activity might continue for 15 to 20 minutes and sometimes was relieved only when his wife came in and removed the paper from his immediate surroundings. She has reported frequently that he would then get up and go around the house and search for the paper, one time climbing into the top shelf of a closet in order to retrieve it. When asked why he was doing this, he would simply smile and say, "I have no idea." Similar contradictory movements were observed occasionally in the course of dressing and undressing and in other daily activities, at times on a scale to be distinctly bothersome. He would frequently emerge from the bathroom with a towel clutched in his left hand. His wife would ask why he had it in his hand and he would reply "I can't let it go." When walking from one room to another, his left hand would frequently hit the door jamb, grab onto it and stop his forward motion. There were even occasional instances of this occurring with the right hand. On almost all occasions the harder he tried to let go of an object, the more intense became his grip. In a more general circumstance, it was as if control of the left arm was strongly centered in the minor hemisphere at such times and hence isolated from the main intent and prevailing control of the dominant hemisphere.

While the independence of the two hands was bothersome to the patient, it did give glimpses into possible effective differences between the separated hemispheres. For example, the wife frequently commented that at times when she was passing by, the patient would grab onto her with his left hand and hold onto her tightly. She would then request that she be released and the patient, while rather aggressively holding and shaking her, would be smiling and saying, "But I want to -- I just can't."

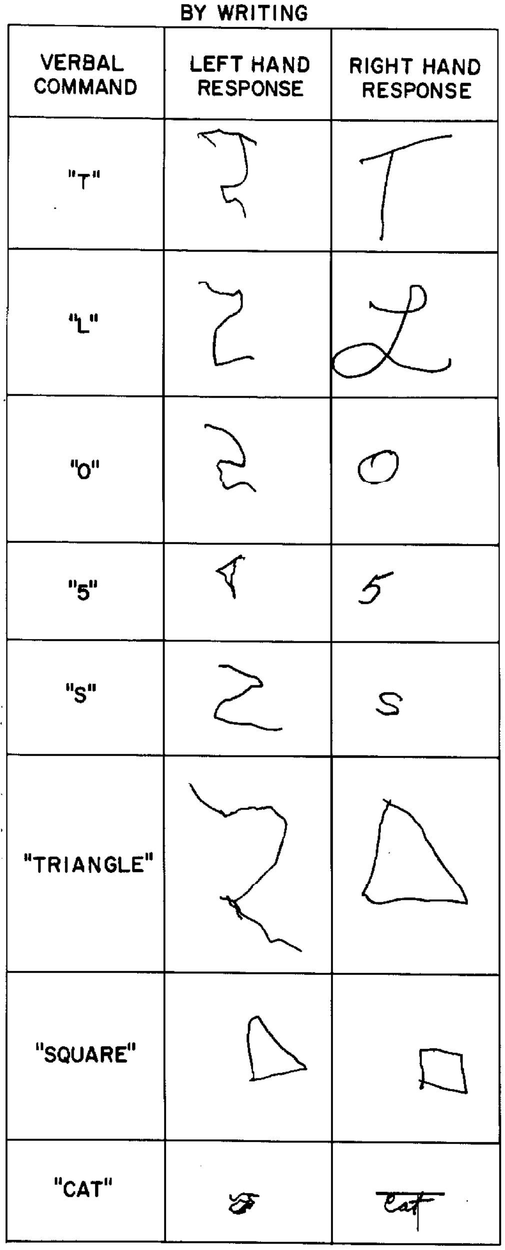
Motor function in post-operative second year: While improvement has been observed in voluntary control of the left arm in the two years since the operation, the overall behavior remains similar to that seen in the first post-operative year (Fig. 9). Improvement in ipsilateral control has occurred mainly for guidance by the left dominant hemisphere of the left hand. The control, however, is seen only when the whole arm can be correctly directed towards a goal by shoulder movements alone. For example, when a large card with seven objects arranged in the manner seen in Figure 9 was placed at shoulder level, the patient responded well with either arm to a verbal command. However, when an identical set of figures was reduced to fit on an 8 x 11 in. card and when only wrist movement was allowed, only performance with the right hand went well.

Severe agraphia with the left hand is still evident two years after the operation. However, earlier studies, indicating that the patient was incapable of pointing to a flash of light across the midline of the visual field, now are contradicted by his increased motor control of ipsilateral arms. Antagonistic movements are also still noted.

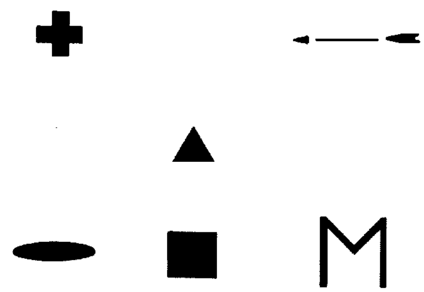
MOTOR RESPONSES TO VERBAL COMMANDS

CASE I:

BY WRITING



BY POINTING



SUBJECT REQUIRED TO POINT TO A REQUESTED FIGURE

a) For wrist movement, actual size of response pattern sheet was 8 1/2 × 11"

b) For shoulder movement, actual size was 22×28"

CASE I: 2 3/4 YEARS POST-OP

RESULTS

Right Shoulder	Right Wrist	Left Shoulder	Left Wrist
21	21	15	3

Scores refer to number of correct responses in 21 trials.
(Chance = 3)

Fig. 9. Shows motor responses of patient in the second post-operative year. The severe agraphia persists as well as the inability to move the left wrist to a verbal command.

Case II

There were considerable differences in the post-operative motor functions of the second patient. For the first two weeks after the operation, the patient reacted well with the right hand to verbal commands. She could point to various objects in the room and to her body features and could write well. The left hand, however, remained totally unresponsive to verbal commands and with it she was not able to localize points of touch on any part of her body. Automatic movements of various kinds were possible. For example, she was walking within a week after surgery and could easily do routine bimanual tasks such as fluffing up a pillow, dressing and so forth. She could also use her left hand to make certain responses to a set of verbal instructions if they were supplemented with a "do this" demonstration. For example, if when asking her to hold up a particular finger, the experimenter held up his appropriate finger, the patient immediately reacted by raising the correct finger of her left hand. She was totally unable, however, to hold up her middle finger or index finger or her little finger to a verbal command.

Gradually the left hand began to respond to verbal commands and to visual stimuli to the left hemisphere. About three months after the operation, most of the motor problems had cleared up except when the left hand was writing to dictation or when the right hand was making a discriminatory response to crossed sensory inputs. At this time, the patient was able to respond with either hand to simple flashes of light seen across the midline of the visual field. However, correct crossed responses in discriminatory situations were not seen through the sixth and seventh post-operative months. There is now evidence to suggest that even this incapacity is clearing up. At six months the patient was able to write to dictation with the left hand (Fig. 10).

Rarely were antagonistic movements seen in this case. Occasionally she reported an inability to get the hands to work together when ironing and the like, but this was infrequent.

Discussion

The two patients are distinctly different and each case tends to represent one side of the controversy that exists concerning motor function following cerebral disconnection. In the early literature along with some more recent reports (2-4, 40, 41), the severe apractic difficulties when stimulus and response were not on the same side occurred in older patients with considerable extra-callosal damage in addition to lesions in the corpus callosum. In short, the apraxia seen in these earlier cases of callosal lesion and in Case I may be exaggerated by an unnatural

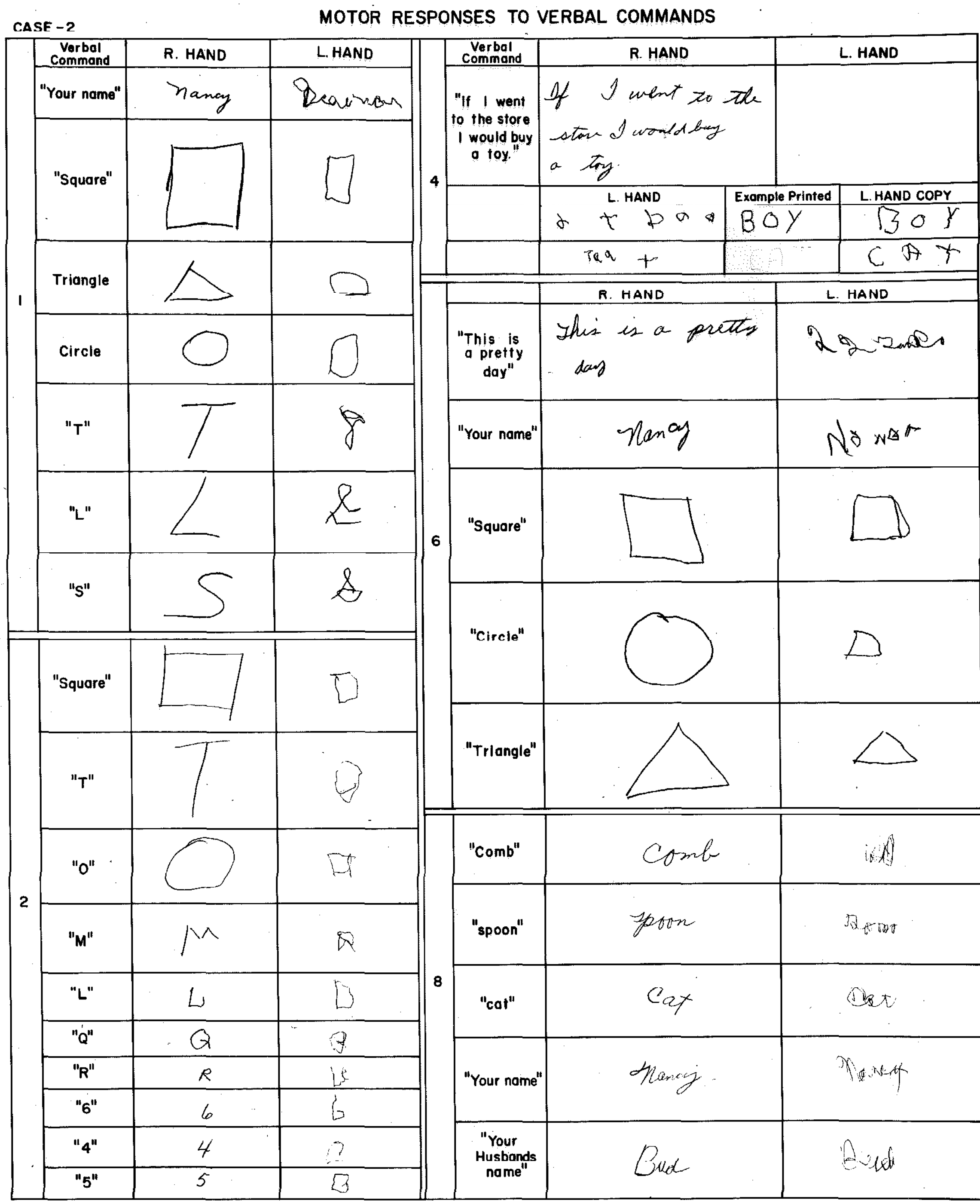


Fig. 10. Numbers in the first and fifth columns refer to the post-operative month the test was given. An increase in the ability to use the left hand is clearly evident.

potentiation of cerebral dominance and lateralization of volitional control as the result of extra-callosal damage.

On the other hand, damage in the right hemisphere which might subtly affect motor control of the left hand may be exaggerated when the left hand is being governed from the disconnected left hemisphere. It has been shown that serial ablations of one disconnected hemisphere in split-brain monkeys leads to little impairment of the ipsilateral hand (47). However, small cortical lesions cause slight impairments in control of the contralateral hand; impairments which become more prominent when the affected hand is being controlled from the ipsilateral hemisphere. In other words, unilateral brain damage in split-brain animals does not affect the hand ipsilateral to it, but rather the opposite ipsilateral eye-hand combination.

Other explanations are available for the difference between these two cases and the divergent reports existing in the literature. It is known that ipsilateral pyramidal tracts exist in varying proportions in man. Some reports suggest there is no ipsilateral fiber system at all, while others maintain that as high as 30% of the pyramidal fibers remain ipsilateral (48). The extent of ipsilateral control, therefore, may reflect variations in the amount of ipsilateral fibers.

It seems likely that movement of the proximal muscle elements is far more subject to bilateral control than the more distal muscular elements. When ipsilateral control returns, if it returns, the last joints to come under control from one disconnected hemisphere are those in the hand and foot. This can clearly be seen in Case I, where, after two years of practice, the patient is still unable to write with the left hand. In Case II, this was the last function to reappear in the first six post-operative months.

The findings on Case II are more in line with those reports claiming that cerebral bisection caused little or no impairment in motor function (6-12). In those cases, good control of both arms was immediately apparent in most situations following surgery. In none of those cases, however, was complete section of the corpus callosum and anterior commissure done at one time. Also to be considered is the possibility that those cases had speech and language capacities in both hemispheres as has been postulated by many people; the lack of any motor dysfunction would then be attributable to the absence of any real ipsilateral sensory-motor situations. In such a case, a verbal command could be acted upon with the left hand because of language and speech abilities of the right hemisphere and vice versa.

Experiment 4

Observations on Speech and Language Function

Introduction

As evident from the foregoing, each hemisphere in man has visual and tactile perceptual capacities as well as learning capabilities. Functions such as primary motor control of the speech musculature are also present in each half brain but the neural organization required for spoken language is usually lateralized to one cerebral hemisphere (49). At the same time, however, the degree of lateralization of the basic symbolic processes and engrams involved in language has been the subject of much disagreement and speculation. The question becomes, is language present in both hemispheres while the capacity to speak is present in one or, is language lateralized to the same degree as the speech mechanism subserving it. Some authors maintain that the engrams involved in language are laid down bilaterally (50) while others restrict them to areas in the left hemisphere(49).

Separation of the hemispheres in these two cases offers a unique means of investigating such questions, and the results of a series of appropriate psychological tests are reported below. In general, indications are that good language function and comprehension can exist in both hemispheres but the ability to communicate by either written or verbal reports is limited to the left hemisphere.

Results

Post-operative verbal capacities of the left hemisphere: In all tests in which verbal or written descriptions were desired of tactile and visual stimuli unilaterally presented to the left hemisphere, both patients showed complete comprehension of the nature of the stimuli and were capable of responding correctly. Visual stimuli presented in the right visual field such as numbers, letters, words and pictorial material plus other stimuli were all instantly perceived and described. Equal verbal facility was shown for tactile stimuli which included handling everyday household items such as spoons, knives, combs, toothbrushes and keys plus a series of objects specifically made for these tests. Temperature and weight discriminations were carried out correctly when presented to the right side as well as descriptions of the position of the extremities. In general the language capacity of the left hemisphere appeared to be normal.

Post-operative verbal capacities of the right hemisphere: Results in this category were different for the two patients; Case II appeared to possess good language capacity in the right hemisphere while Case I appeared to have little or none. In both cases, there were never any written or spoken verbal responses to sensory experiences of the right hemisphere. The language capacity of Case II was revealed to a large extent by the matching of pictures to word cards. Results of verbal reactions to visual, tactile and auditory stimulation appear below and only the results on Case II are discussed in detail since identical testing of Case I yielded little evidence for the existence of language abilities of any sort in the right hemisphere.

<u>Visual tests</u>: When photographic reproductions of objects, scenes, words and so forth were tachistoscopically projected at 1/10 sec. into the left visual field using the apparatus shown in Figure 5, the patient characteristically claimed she saw nothing. Yet upon being asked to best describe the stimulus by selecting an appropriate word printed on one of a series of as many as ten cards placed in front of her, her left hand would immediately point to the word card best matching the visual stimulus. For example, if a picture of a pie (Fig. 11) was flashed into the left visual field, the patient would say that she saw nothing and then proceed to pick up the card with "pie" written on it. Descriptive scenes and scenes depicting an action (i.e. boxing) were also correctly named under such conditions.

She was also able to read in the left visual field (Fig. 8E). Simple words flashed at 1/10 sec. yielded no vocal verbal responses but again the patient was consistent-

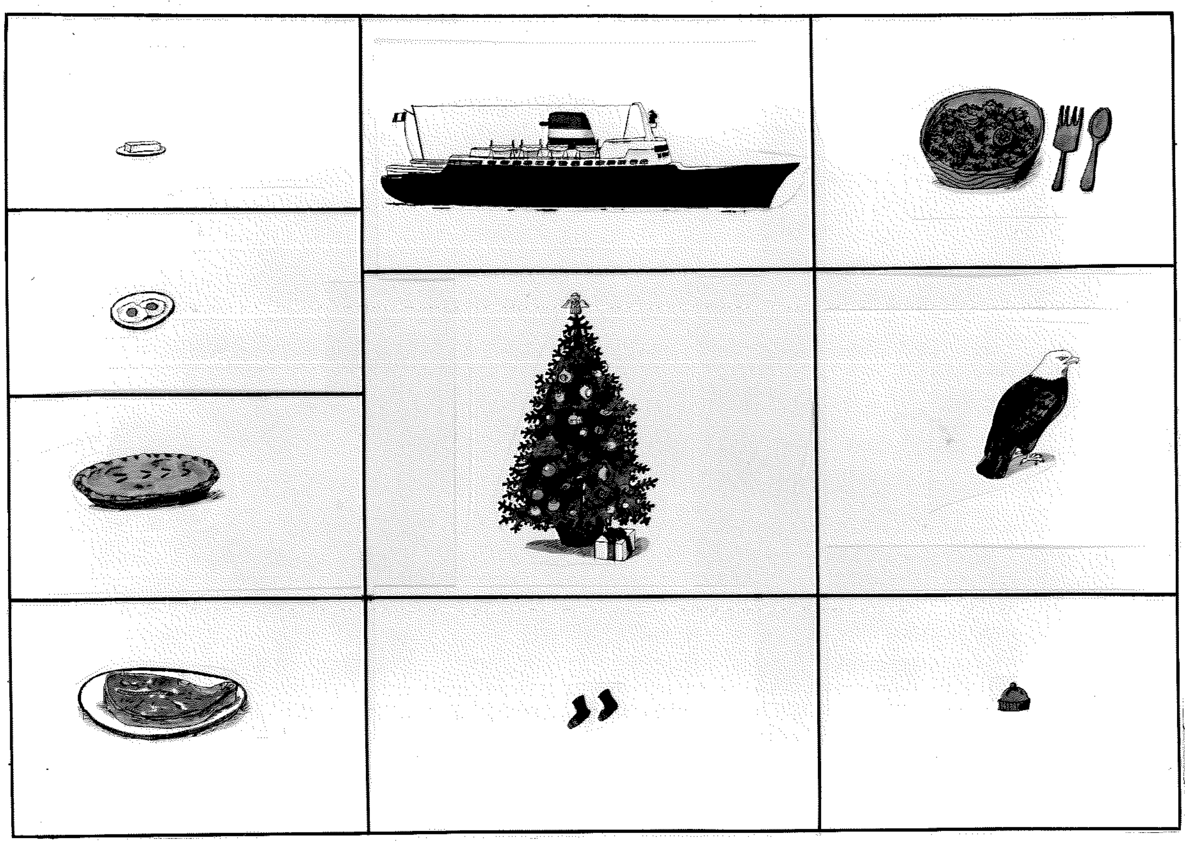


Fig. 11. Representative examples of visual stimuli tachistoscopically presented in either visual field in tests of language capacity of each disconnected cerebral hemisphere.

ly able to retrieve the object best matching the word stimulus. Similarly, she was able to indicate which one of several spoken definitions best fit a word stimulus falling into the left visual field; if the word "milk" was flashed into the left visual field, she would exclaim she saw nothing and then would be able to repeat the correct definition after a series of five had been read to her.

She always appeared unable to act upon a visual word command directed into the right hemisphere. For example, she would not smile at the command to do so when the appropriate word stimulus was presented in the left visual field but had no problem when the same stimulus was presented in the right visual field.

There was also no apparent ability to read across the midline of the visual field. The phrase "Look up", for example, when flashed so that "Look" fell into the left visual field and "up" into the right, never elicited a correct response. Even one word like teapot, sawdust, robin, panties, when presented so the midline of the visual field transected the word in two, yielded answers indicating understanding of only the right field component.

<u>Tactile testing</u>: With both cases, all objects placed into the left hand were described inaccurately (Fig. 12). For example, a pair of scissors when placed in the left hand might be called a hat, a watch or something else irrelevant.

TEST OBJECT	VERBAL RESPONSE TO	
	L. HAND TOUCH*	R. HAND TOUCH
BOOK	"MY HELMET"	"BOOK"
SPOON	"PENCIL"	"SPOON"
TOY PISTOL	"PENCIL"	"PISTOL"
CAN OPENER	"WRIST WATCH"	"CAN OPENER"
PAPER CLIP	"DON'T KNOW"	"PAPER CLIP"
HAMMER	"CLOCK"	"HAMMER"
FORK	"DON'T KNOW"	"FORK"
SCISSORS	"HAT"	"SCISSORS"
CIGARETTE	"CAN OPENER"	"CIGARETTE"
COFFEE CUP	"DON'T KNOW"	"COFFEE CUP"

*ALL OBJECTS HELD IN THE LEFT HAND WERE USED CORRECTLY UPON COMMAND.

Fig. 12. Examples of both patients' inability to verbally describe objects held in the left hand out of vision.

However, no matter what the patients were holding in the left hand and no matter what they proceeded to call it, the left hand would use and manipulate the object properly. In addition, as in the visual tests, only the second patient was able to point to the word on a card best describing the held object. Even if she had misnamed the object verbally while holding it out of vision, she would promptly pick the correct word card with the left hand when allowed to respond.

Both patients were also completely unable to write out, with the left hand, the name of the object in that hand. Similarly, both appeared for the most part unable to draw the form and nature of objects held in the left hand, except for a recent incident when Case II showed signs of being able to draw simple geometric shapes such as squares and triangles.

Auditory testing: In the second patient there were also indications that the right hemisphere had good comprehension of vocal statements. When the patient was blindfolded and requested to retrieve a particular article with the left hand from a series of objects, there was no problem. For example, if six objects were placed in front of the patient, one of which was a toothbrush, the patient could easily retrieve the toothbrush from the six objects. Immediately after the retrieval of the toothbrush, however, if the object was placed into the patient's left hand and she was asked to give a verbal description, she would call it something irrelevant. It appears, therefore, that the higher verbal language capacity for the right hemisphere of the second patient enables her to match the auditory stimulus with the correct tactile stimulus. This behavior was never apparent in the first case.

Discussion

The results show that in both cases visual stimuli falling into the right visual field and objects held in the right hand out of vision could be correctly named and communicated either by speech or by writing. Similar presentation to the left visual field or left hand were neither communicated audibly or in writing. Extensive testing on Case II clearly showed in addition that the right hemisphere possessed good language and symbolic comprehension for auditory, visual and tactile stimuli but that the motor mechanisms to communicate this verbal comprehension were not present.

It appears that the corpus callosum is critically involved in the interhemispheric transfer of qualitative sensory information directly projected to the right cerebral hemisphere. In both these cases, however, although the entire callosum was sectioned, the right hemisphere appeared to have some influence on the main speech mechanisms of the left hemisphere. Indications for this come from the following observations. Neither patient developed symptoms of logorrhea following callosal section. This speech characteristic which usually results from lesions in the right hemisphere would seem likely to appear in these two cases if one assumed that the sole neural pathways for interhemispheric connections for speech coursed through the corpus callosum. Secondly, Case II was able to tell which of a series of spoken definitions best fit a word visually presented in the left visual field, indicating the right hemisphere, when hearing the correct definition, could somehow signal the left "talking" hemisphere as to which one of several spoken definitions was correct. Again the pathways subserving such systems must either be subcortical interhemispheric connections or pathways from the right hemisphere directly affecting a subcortical aspect of the speech mechanism.

The divergent results of the two cases with regard to language capacity of the right hemisphere perhaps underline the well-reported variation in the degree to which human cerebral localization for speech and language can occur. Certainly convincing cases exist which fit and substantiate almost any possible proposal made for the nature of speech and language localization.

Perhaps, however, the lack of the presence of language in the right hemisphere in Case I is the result of the extra-callosal brain damage known to exist. It seems fair to assume in Case I that engrams for specific activities of a sort do exist in the right hemisphere, e.g. being able to manipulate correctly objects held in the left hand. Since it would not seem unlikely that neural mechanisms linking perceptual awareness to word formation would be threshold systems in the right hemisphere, it would be easy to believe that the known damage impaired such systems. Alternatively, one can also not rule out the possibility that the lack of any sort of language capacity for the right hemisphere in this case is evidence for the view that the more intelligent one is, the more lateralized are his language and speech capabilities.

Assuming that speech and language functions of Case II more nearly represent the normal picture, it would be an error to accept the belief held by some that the concepts of a perceptual situation are bilaterally represented, but that verbal engrams are peculiar to the left hemisphere (49). Case II gave every indication of being able to read in the left visual field. She also seemed able to comprehend spoken words. Similarly, presentation of visual and tactile objects to the right hemisphere resulted in her ability to pick the words best describing the particular stimulation. It would seem, therefore, that in fact memories for language can be bilaterally laid down.

The inability of Case II to repeat any of the verbal experiences of the right hemispheres by speaking or in writing is of major interest. Similar peculiarities have been observed in the left dominant hemisphere with regard to visual constructional tasks. Results on these tests clearly showed each patient's ability for such tasks for the right but not the left hemisphere. The same was true for the block design test. The left hemisphere, however, was able to verbally distinguish between correct and incorrect reproductions of such problems. This suggests that the primary perceptual capacities for such tasks were intact but that the ability to perform the necessary motor responses for the test was absent. It seems, therefore, that the property which becomes lateralized for hemisphere specific tasks is the motor expression of that task.

It is of interest to attempt to analyze a standard clinical case of aphasia after accepting the concepts for language and speech proposed from the results on Case II. If this case had, instead of a callosal section, a brain lesion in the left posterior parietal temporal area, of the many possible effects incurred by such a lesion, one could predict that she would have a general inability to speak coherently, comprehend spoken words, read or write. Speech would be impaired because only the left hemisphere is normally capable of such in right handed people and here it has incurred an injury. Comprehension of spoken speech would not seem apparent because of the damage to the left hemisphere and the right hemisphere, while understanding verbal material, could not communicate its understanding presumably because of the complexity of the motor performance involved in speech and writing. Reading ability would be impaired for right field stimuli because of the neurological insult to the left hemisphere; left field stimuli could be comprehended but not expressed because of disconnection from the left hemisphere due to partial degeneration of the corpus callosum, which resulted from our supposed exemplary lesion.

If our patient had, instead, a lesion in the left third frontal convolution, she would again demonstrate the same symptoms of the standard clinical case. Lesions in this area, which generally affect the expressive aspects of speech only, would impair speech since the right hemisphere is considered from our results to be incapable of speech and the left has been injured. Thus the standard behavior pattern of motor speech difficulty would be evident.

In short, the restatement of the proposition that language in the normal adult human brain can be bilaterally represented, conflicts in no major way with normal clinical experience. If the aphasic patient is subject to a lesion that does not cause general intellectual deterioration, the above analysis seems consistent with the general literature and knowledge of speech and language localization.

Section II

BEHAVIORAL STUDIES ON SPLIT-BRAIN MONKEYS

Experiment 1*

Effects of Commissurotomy on a Pre-operatively Learned Visual Discrimination

Introduction

Previous split-brain studies with cats and monkeys indicate that the memory for perceptual and motor learning in which the sensory or motor components have been lateralized to one of the separated hemispheres is generally confined to that one hemisphere (16). On the other hand, when the same kind of learning proceeds in the presence of an intact corpus callosum, the typical result is reported to be a double set of engrams, one in the directly trained hemisphere and a second established in the opposite hemisphere via the callosal fibers (51, 52). From these and related findings it has been inferred that a major function of the corpus callosum in these animals is to keep the two hemispheres equated and up-to-date with respect to the acquisition of the new cortical engrams. It is clear that this is not uniformly true of the human brain where language functions especially are strongly lateralized. The following experiment reveals that in the monkey, also, the

*This work has been reported in part in Reference 55.

presence of an intact corpus callosum during learning does not necessarily result in the laying down of a double set of engrams.

Materials and Methods

Three male (DXZ, SCH, VHT) pigtail monkeys, Macaca nemestrina weighing about 3 kg, and without previous laboratory experience, served as subjects. Training and testing were carried out in an apparatus that permitted the experimenter to control eye and hand use and that produced a minimum restriction of the visual field and arm movement or both. The subject was unrestrained except by the dimensions of the box and voluntarily placed himself in the working position. The visual stimuli, a black cross and a circle on white backgrounds, were back-projected onto two translucent screens. Following a correct response, a reward was discharged into a trough immediately below the screens by means of an automatic feeder.

The training schedule consisted of one session of 80 trials per day five days a week. Pre-operative training involved free use of both eyes with forced alternation of hand shifted every 20 or 40 trials so that at completion of each training session, both hands had been used for an equal number of trials. The stimuli were equated for brightness and were shifted from right to left on a pseudo-random schedule.

The criterion for learning was set at 18 correct trials out of 20. After the problem had been fully learned under binocular conditions, the various eye-hand combinations were tested separately for knowledge of the task. Monkey DXZ was overtrained 300 trials while SCH and VHT received no overtraining. Monkey SCH was temporarily used on another problem that involved presentation of the plus-zero stimuli simultaneously and contradictorily to each eye. None of these variations in pre-operative procedure seemed to have a significant effect on the results.

All three cases then underwent surgery that included complete section of the corpus callosum, anterior commissure and midline section of the optic chiasm in a single operation carried out by exposure and retraction of the right hemisphere. Following surgery (two to four weeks), the animals were tested for retention of the discrimination in the four eye-hand combinations indicated in Fig. 13. All animals are currently being used on further experiments. It will be obvious, however, that the findings and their implications for the present study are such that they would not be significantly changed even if the surgical sections did prove to be incomplete.

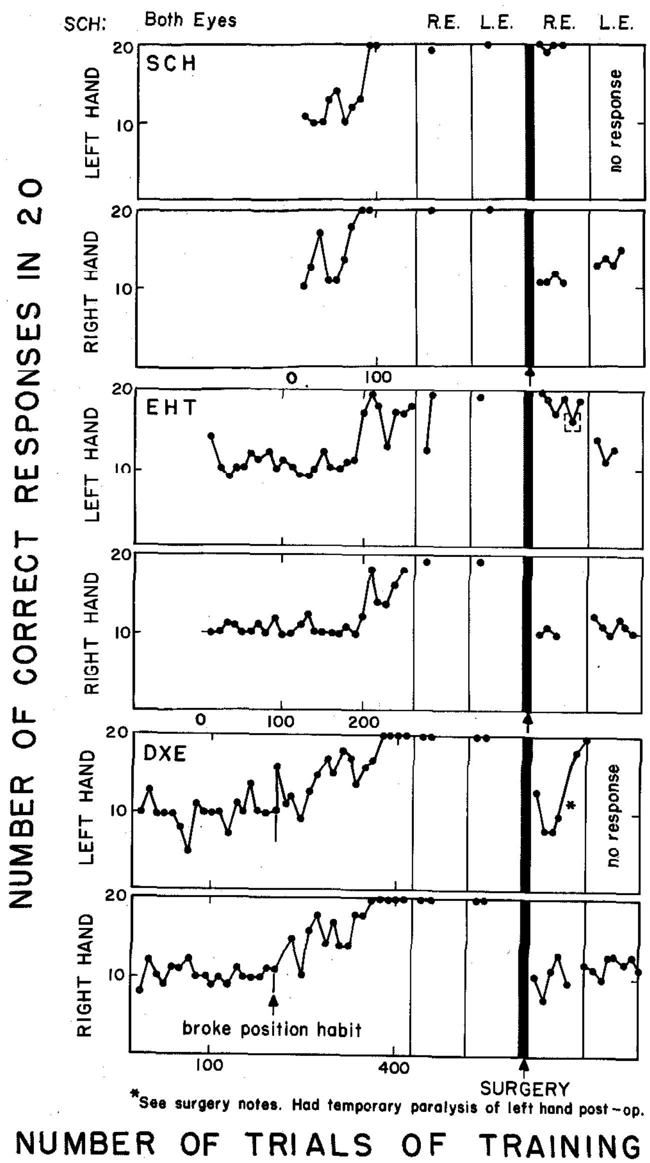


Fig. 13. Performance of SCH, VHT, and DXZ on cross vs circle pattern discrimination both before and after surgery. Number of correct trials in twenty on ordinate; number of trials of training, on abscissa.
*Animal had temporary paralysis of left hand after the operation.

Results

The performance curves for the pre- and post-operative training are shown in Fig. 13. Monkey DXZ had moderate paralysis in the left arm for two to three weeks after surgery which for the most part disappeared coincidentally with his high score for that hand. His initially poor performance is probably attributable to this deficiency, for during that period, he appeared to be incapable of well-monitored hand movements in the testing situation. The other animals had no major motor impairments though they both had transient mild seizures on the left side during the first two weeks after surgery. It is clear that criterion was reached with only one intra-hemispheric eye-hand combination in all three cases. Performance with the other eye-hand combination revealed either mnemonic (L. eye-R. hand) or coordinational (L. eye-L. hand, R. eye-R. hand) deficits, the latter of which will be discussed below.

Additional visual discriminations learned after surgery with the same training procedure also tended to be laid down initially in one or the other hemisphere rather than both. The hemisphere that learned faster in the post-operative task was not necessarily the same one that had learned pre-operatively. For example, SCH learned a second problem first with his right hemisphere and a third faster with the left hemisphere. Animal VHT learned two additional problems more quickly with the left hemisphere. An older animal, PKY, used on another related experiment, also exhibited this same kind of fluctuation in hemispheric performance. Throughout the right-left shifts in the lateralization of learning proficiency, none of the animals showed any change in their natural right hand preference in their everyday activities.

The motor proficiency of right and left hand in the training situation followed a characteristic pattern in all animals according to which eye was exposed. For the most part, intracortical eye-hand combinations (L. eye-R. hand, R. eye-L. hand) in all instances were fast and exact in their movements. Intercortical combinations were comparatively slow and clumsy. Hand movements under these latter conditions typically resulted in the fanning out of the fingers. This deficit was more pronounced when the task involved a pairing of the unpreferred hand and the eye ipsilateral to it. It is of interest that when both eyes were opened, DXZ and VHT had no difficulties in responding at criteria with either hand.

Discussion

The cortical engrams for visual discrimination learning in three normal monkeys were shown by subsequent analysis with split-brain procedures to have been localized predominantly or entirely in one hemisphere. This lateralization of memory occurred consistently in all three cases tested despite the presence throughout learning of the intact corpus callosum and the optic chiasm, and even though bilateral symmetry in engram formation had been further favored by forced alternation in the use of hands, and also by overtraining through 300 trials prior to surgery in the case of DXZ. These findings contrast with earlier reports indicating that the presence of the corpus callosum during unilateral visual training in cats and manual tactile training in monkeys resulted in the establishment of a double system of memory traces, one in each hemisphere (51, 52). The present results suggest that in the normal monkey the memory for visual tasks tends to remain localized in one hemisphere, and when needed by the other, the mnemonic information is tapped via the corpus callosum.

This raises the puzzling question as to why, in the presence of the callosal fibers, the engrams for learning are laid down bilaterally in some cases and unilaterally in others. The present result is directly comparable to the effects of similar commissurotomy on language functions in man, where speech is confined to one hemisphere even though the speech centers of the cortex are richly interconnected by callosal fibers in addition to the fact that either or both hemispheres have the capacity for acquiring language

(21, 22). In the human brain, the cerebral dominance and lateral specialization presumably reflect some sort of asymmetry in anatomical organization. In these monkeys, however, the nonpredictable fluctuation from left to right hemisphere suggests that the lateral dominance is a matter of the transient dynamics of learning rather than a permanent feature of cerebral organization.

Experiment 2*

Cerebral Mechanisms Involved in Ipsilateral Eye-Hand Use in Split-Brain Monkeys

Introduction

Splitting the cerebral commissures and optic chiasm in monkeys isolates a primary visual area from a primary motor area. Such surgical interruptions would, seemingly, create problems in the visual control of ipsilateral eye-hand movements. Recent investigations involving this question reveal inconsistent results. Some studies on split-brain monkeys claim little or no coordinational deficits (53, 54) while others stand in marked contrast and claim there are persistent indications of a visual-motor impairment (37, 38, 55). Split-brain cats reportedly show no deficit in motor control of either upper forelimb when vision is restricted to one eye (36). On the other hand, recent testing of commissurotomized humans has indicated that pronounced deficits exist in ipsilateral sensory-motor combinations (56, 57).

In the present study, split-brain monkeys were trained visual discriminations monocularly accompanied with forced change of the hand used in response. An attempt is made to

---

* This experiment has been reported in Reference 39.

ascertain the nature and quality of ipsilateral hand performance in such testing situations.

Materials and Methods

Five female and five male monkeys (*Macaca nemestrina*) were used throughout all testing and training procedures. The animals were self-trained in an automated apparatus specifically designed and developed for the testing of split-brain monkeys. The apparatus consisted of a triangular shaped box which permitted the experimenter to control eye and hand use and produced a minimum restriction of the visual field or arm movement or both. The unit was clamped onto the back of the monkey's home cage. The visual problems were projected onto two translucent screens by means of a one-plane projector unit. The stimuli consisted of simple geometric symbols or letters and numbers which were equalized for brightness. These patterns were automatically changed according to a predetermined pseudo-random schedule that advanced only if the animal made a correct response. The latter procedure proved to be a simple and efficient way to break position preferences that would characteristically appear during the initial training. Correct responses were rewarded with a food pellet delivered automatically in a trough immediately below the screens. Generally, the automated testing apparatus was on for 12 hours a day and the animals were free to work as often as they wished. Criterion was established at 90% correct over 80 trials. Some animals would work through the four eye-hand combinations within 24 hours of testing, while others took from four to eight days.

For the most part, animals would be exposed to a visual problem monocularly in one of two possible eye-hand combinations. Upon reaching criterion, a change of hands was imposed until criterion was again reached. This was followed by exposing only the untrained eye and then by controlled hand use. In this manner, all intra-hemispheric and inter-hemispheric eye-hand combinations were tested.

All operated animals have been killed and examined except for BRJ, BRN and DPK. All had a complete midline section of the optic chiasm, corpus callosum and anterior commissure except WNL, which had some crossed extrafoveal fibers intact. Functionally the section was considered complete in WNL, however, for the animal never displayed interocular transfer of visual discriminations trained to one eye following section of the corpus callosum.

Results

No major impairments were detected in any of the animals using either ipsilateral or contralateral eye-hand combinations in reaching for food.

Independence of hemispheres: Training one contralateral eye-hand pair in chiasm-callosum sectioned animals to criteria, followed by training the ipsilateral hand to criteria, did not appear to influence the learning rate of the second contralateral eye-hand pair (Table 2A). The same result is also evident if one compares the two ipsilateral eye-hand pairs. In the following analysis of eye-hand learning rates, therefore, the data obtained from the training of each eye will be pooled.

Training contralateral then ipsilateral eye-hand pairs: Forced training of contralateral eye-hand pairs to criteria does not enable the ipsilateral hand, in split-brain monkeys, to perform immediately at criteria. From Table 3 it can be seen that while there is a wide variability in performance of the homolateral hand, there is generally no trend to savings (median savings =-33%). There is complete savings in normal and chiasm-sectioned animals.

The shape of the learning curve for the ipsilateral hand, however, is not necessarily similar to that of the contralateral. From inspection of the learning curves it was clear that individual animals differed widely. For example, GRT was very poor at learning with an ipsilateral eye-hand pair and rarely rose above a chance level; SQY almost always began training at a high level with her ipsilateral hand although she never performed immediately at criteria; FNR demonstrated varied ability ranging from poor to excellent.

Use of the ipsilateral hand appeared not to improve markedly after continued training with several different visual problems, if that hand's performance was compared to the contralateral hand's score on the same task. Evidence for this comes also from an animal who was manually trained on a series of visual discriminations with forced alternation of hand use every 20 trials. The testing box and procedure were similar to the one described above with 80 trials presented per day, five days a week. Four problems were presented to the left eye and three to the right. The percentage savings to the ipsilateral hand were -83, -21, 0, 0, -65, 100, -100, in that order. These results again suggest that a marked increase in proficiency of ipsilateral sensory-motor combinations does not occur.

<u>Training ipsilateral then contralateral eye-hand pairs</u>: Contrary to the foregoing, training ipsilateral eye-hand combinations to criterion first, enables the contralateral eye-hand pair to perform immediately at criterion in all the animals (Table 4).

Table 2

Performance of Split-Brain Animals on Visual Discriminations Trained Sequentially to All Four Eye-Hand Combinations[1]

2A

Animal		First eye		Second eye	
		Contra.	Ipsi.	Contra.	Ipsi.
GRT		120	560	200	840
FNR		160	40	80	720
FKY		160	160	240	1000
	Total	440	Total	520	
		Ipsi.	Contra.	Ipsi.	Contra.
SQY		320	120	200	0
FNR		760	0	560	0
FKY		1440	40	2240	0
	Total	2520	Total	3000	

2B

Animal		First eye		Second eye	
		Contra.	Ipsi.	Ipsi.	Contra.
FNR		1080	520	320	40
SQY		440	360	920	80
FKY		520	1600	1040	0
	Total	2040	Total	2280	
		Ipsi.	Contra.	Contra.	Ipsi.
FNR		680	0	840	0
DPK		1160	0	1080	2240
FKY		1040	0	1080	800
	Total	2880	Total	3000	

[1]Scores refer to number of trials to criteria. Each animal was exposed to the same visual discrimination during training of its four eye-hand combinations.

Table 3

Ipsilateral Eye-Hand Performance Following

Training of Contralateral Hand[1]

Animal	Problem no.	Contra.	Ipsi.	%Savings
FGO (normal)	2	360	0	100
BRJ (chiasm)	1	400	0	100
BRN	1	640	120	81
WNL	2	480	0	100
BRN	3	80	0	100
BRN	4	40	0	100
FKY (split)	1	80	120	-33
GRT	1	40	960	-96
FNR	1	1080	520	52
DPK	1	1080	2240	-50
GRT	2	120	560	-79
GRT	2	200	840	-76
FKY	3	160	160	0
FKY	3	240	1000	-76
FNR	3	840	0	100
FKY	4	520	1000	-50
FKY	5	1080	800	25
FNR	5	80	720	-88
FNR	5	160	40	75
SQY	6	440	360	18
WNL	General experience	240	80	66
			Med.	sav. -33%

[1]Scores refer to trials to criteria. Total visual discrimination experience is also noted.

Table 4

Contralateral Eye-Hand Performance Following

Training of Ipsilateral Hand[1]

Animal	Problem no.	Ipsi.	Contra.	%Savings
DPK (normal)	1	320	0	100
DPK	2	640	0	100
FGO	2	880	0	100
WNL (chiasm)	1	1400	40	97
BRJ	2	280	0	100
FNR (split)	1	320	80	88
SQY	1	600	0	100
DPK	1	1160	0	100
FNR	2	760	0	100
FNR	2	560	0	100
FKY	2	1440	40	97
FKY	2	2240	40	99
SQY	3	1200	0	100
FNR	3	680	0	100
FKY	4	1040	0	100
FKY	5	1040	0	100
SQY	6	920	80	91
SQY	7	320	120	62
SQY	7	200	0	100
WNL	General experience	360	0	100
			Med. sav.	100%

[1]See footnote, Table 3.

Monkey GRT was totally unable to learn a visual problem using an ipsilateral eye-hand combination. Other animals, however, on the average, showed no greater difficulty learning a visual discrimination with an ipsilateral eye-hand combination than with a contralateral (Table 2B).

Discussion

The findings show a marked difference between the ipsilateral and contralateral hand with respect to performing learned visual discriminations. No savings were observed on the average for the ipsilateral hand when it was tested for transfer following training of the contralateral hand after first training the ipsilateral hand. The results from the present study also confirm the absence of interocular transfer on learned visual discriminations even after extensive over-training with both hands through one eye.

The discrepancies that appear to exist in the present literature regarding the existence of an ipsilateral deficit are possibly explained by considering the method of testing for the deficit. Reports that claim no visual-motor deficits result following split-brain surgery in monkeys, chose the animal's ability to retrieve food as the criterion for good ipsilateral eye-hand function. Studies containing the contrary finding, however, observed the deficit when the animals were choosing between two different visual stimuli.

Reconciliation of the question of why split-brain monkeys demonstrate an ipsilateral deficit in a learning situation but not in reaching for food, remains difficult. Related phenomena have been observed in humans and it has been suggested that the presence of two objects in the visual field offers to the observer two possible responses and that these two different motor patterns are competing within the observer for action (2). An incorrect response would thereby suggest that the trigger stimulus to the motor system released the wrong motor pattern. Explanations like this might well apply in the present experiment. However, other interpretations such as viewing the results in terms of hierarchical organization are just as likely at this point and cannot be ruled out.

Absence of the same ipsilateral impairment in the chiasm-sectioned controls suggests callosal involvement in the mediation of visually guided movements when the visual stimulus and motor response are centered in opposite hemispheres. The motor deficit seen in chiasm-callosum sectioned animals is reminiscent of similar difficulties observed in human patients with callosal section (56, 57). In both cases the callosum appears necessary for the successful completion of certain sensory-motor activities.

The question still remains as to whether or not the ipsilateral deficit seen in a learning situation disappears with practice. There are strong indications from the present study that the deficit does remain, but the results are not conclusive.

While it is important to emphasize this demonstrated existence of an ipsilateral eye-hand deficit, split-brain monkeys do have, or can acquire, remarkably good control with ipsilateral eye-hand combinations. It is proposed that the control involves ipsilateral motor centers working in combination with the primary contralateral motor center of the other hemisphere. Once the movement is initiated and grossly directed toward the correct goal by the ipsilateral hemisphere, successful completion is dependent on the necessary motor-proprioceptive feedback systems that go on in the hemisphere which normally controls the responding hand.

That a great deal of the movement would be dependent on the participation of these feedback systems seems true from hemispherectomy data (20, 58). Also, monkeys with bilateral ablation of the motor and premotor areas do not recover control of their extremities while ablation of the motor area alone leaves the animal with considerable mobility (59). Again, as above, the importance of ipsilateral motor centers for initiating movement is indicated.

REFERENCES

1. Alpers, B.J. (1936) *Arch. Neur. and Psychiat.*, *35*, 911.
2. Leipmann, H. (1900) *Monatschr. f. Psychiat.*, *8*, 3.
3. Schlesinger, B. (1962) *Higher Cerebral Functions and their Clinical Disorders*, Grune & Stratton, New York.
4. Sweet, W.H. (1941) *Arch. Neur. and Psychiat.*, *45*, 86.
5. Trechner, J.H., and Ford, F.R. (1937) *Arch. Neur. and Psychiat.*, *37*, 959.
6. Akelaitis, A.J. (1941) *Arch. Neur. and Psychiat.*, *45*, 788.
7. __________ (1941) *Am. J. Psychiat.*, *97*, 1147.
8. __________ (1942) *Arch. Neur. and Psychiat.*, *48*, 914.
9. __________, Risteen, W.A., Herren, R.Y., and Van Wagenen, W.P. (1942) *Arch. Neur. and Psychiat.*, *47*, 971.
10. Akelaitis, A.J. (1943) *J. Neuropath. and Expt. Neur.*, *3*, 226.
11. __________, (1944) *J. of Neurosurg.*, *1*, 94.
12. __________, (1944/45) *Am. J. Psychiat.*, *101*, 594.
13. Bridgman, C.S., and Smith, K.U. (1945) *J. of Comp. Neur.*, *83*, 57.
14. Van Wagenen, W.P., and Herren, R.Y. (1940) *Arch. Neur. and Psychiat.*, *44*, 740.
15. Sperry, R.W. (1961) *Science*, *133*, 1749.
16. ______, (1961) *Fed. Proc.*, *20*, 609.
17. Mountcastle, V.B., and Rose, J.E. (1959) *Handbook of Physiology*, J. Field, Ed. (American Physiological Society, Washington, D.C.), *1*, 307.
18. Torvik, A. (1957) *Am. J. Anat.*, *100*, 1.
19. Bogen, J.E., and Campbell, B. (1962) *Science*, *135*, 309.

20. White, R.J., Schreiner, L.H., Hughes, R.A., MacCarthy, C.S., and Grindley, J.H. (1959) Neurology, 9, 149.

21. French, L.A., and Johnson, D.R. (1955) Neurology, 5, 390.

22. Gardner, W.L., Karnosh, J., McClure, C.C. Jr., and Gardner, A.K. (1955) Brain, 78, 487.

23. Semmes, J., Weinstein, S., Ghent, L., and Teuber, H.L. (1960) Somatosensory Changes after Penetrating Brain Wounds in Man, Harvard Univ. Press, Cambridge, Mass.

24. Adey, W.R., and Kerr, P.B. (1954) J. comp. Neurol., 100, 597.

25. Adey, W.R., Carter, I.D., and Porter, R. (1954) J. Neurophysiol., 17, 164.

26. Amassain, V.E. (1954) J. Neurophysiol., 17, 39.

27. Bremer, F., and Terzulo, C. (1955) J. de Physiol., 47, 105.

28. Brooks, V.B., Rudomin, P., and Slayman, C.L. (1961) J. Neurophysiol., 24, 286.

29. Nakahama, H. (1958) J. Neurophysiol., 21, 611.

30. Patton, H.D., Towe, A.L., and Kennedy, T.T. (1962) J. Neurophysiol., 25, 501.

31. Uttal, W.R., and Cook, L. (1960) IBM Research Reports, Shaker Heights, New York.

32. Goff, W.R., Rosner, B.S., and Allison, T. (1962) Electroenceph. Clin. Neurophysiol., 14, 697.

33. Smith, K.U. (1951) Science, 114, 117.

34. Glickstein, M., and Sperry, R.W. (1960) J. comp. Physiol. and Psychol., 53, 322.

35. Paillard, J. (1960) Handbook of Physiology, J. Field, Ed. (American Physiological Society, Washington, D.C.), 3, 167.

36. Schrier, A.M., and Sperry, R.W. (1959) Science, 129, 1275.

37. Downer, J.L. de C. (1959) Brain, 82, 251.

38. Trevarthen, C.B. (1962) Thesis, California Institute of Technology.

39. Gazzaniga, M.S. (1964) Expt. Neur., 10, 148.

40. Bremer,F., Brihaye, J., and Andre-Galisaux, G. (1956) Schweiz. Arch. Neurol. Psychiat., 78, 31.

41. Geschwind, N., and Kaplan, E. (1962) Neurology, 12, 675.

42. Hecaen, H., Ajuriaguerra, J., and Massonnet, J. (1951) Encephale, 1, 122.

43. McFie, J., and Zangwill, O.L. (1960) Brain, 83, 243.

44. Piercy, M., Hecaen, H., and Ajuriaguerra, J. (1960) Brain, 83, 225.

45. Milner, B. (1962) In: Interhemispheric Relations and Cerebral Dominance, Baltimore, 77.

46. Piercy, M., and Smith, O.O.G. (1963) Brain, 88, 335.

47. Gazzaniga, M. unpublished report.

48. Crosby, E.C., Humphrey, T., and Lauer, E.W. (1962) Correlative Anatomy of the Nervous System, MacMillian Co., New York.

49. Penfield, W., and Roberts, L. (1959) Speech and Brain Mechanisms, Princeton Univ. Press, Princeton, New Jersey.

50. Nielsen, J.M. (1957) A Textbook of Clinical Neurology, Hoeber, New York, 281.

51. Ebner, F.R., and Myers, R.E. (1962) Science, 138, 51.

52. Myers, R.E. (1961) In: Brain Mechanisms and Learning, A. Fessard, Ed., Blackwell, Oxford.

53. Myers, R.E., McCurdy, N., and Sperry, R.W. (1962) Arch. Neurol., 7, 41.

54. Bossom, J., and Hamilton, C.R. (1963) J. comp. Physiol. and Psychol., 56, 769.

55. Gazzaniga, M.S. (1963) Expt. Neurol., 8, 14.

56. Gazzaniga, M.S., Bogen, J.E., and Sperry, R.W. (1962) Proc. Nat. Acad. Sci. U.S., 48, 1765.

57. ______________________________, (1963) Neuropsychologia, 1, 209.

58. Ralston, B.L. (1962) J. Neurosurg., 19, 909.

59. Bucy, P.C. and Fulton, J.F. (1933) Brain, 56, 318.