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MENTAL UNITY FOLLOWING SURGICAL DISCONNECTION OF THE CEREBRAL HEMISPHERES*

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I. Introduction

THE material covered comes from a series of studies with which my colleagues and I have been involved for some years and that share in common the surgical elimination of the main channels for direct cross-communication between right and left hemispheres of the brain. Surgical disconnection of the mammalian hemispheres is permanent and irreversible; cats, monkeys, and people lack the brainpower of the salamander when it comes to regeneration of central fiber tracts. The first figure will help to visualize the general anatomical effect of disconnection shown schematically with reference to the monkey brain. Typically, the midline surgery includes division of all the forebrain commissures plus the optic chiasm, plus various lower cross-connections depending on the experimental design. The bisection shown in Fig. 1 is carried down through the roof of the midbrain and through the cerebellum. Figure 2, also schematic, shows the same in cross section. This is presented to illustrate that each of the disconnected hemispheres retains intact the full complement of all its various cerebral centers and cortical areas and all their intrahemispheric interconnections as well as all the lower level associations. Hence, the great majority of the main cerebral functions tend to be preserved within each hemisphere.

By way of comparison with the schematic drawings, Fig. 3 shows some photographs of monkey brain cross sections following commissurotomy. The surgery leaves little or no damage except in the very midline. The small scar that splits the midbrain tectum in

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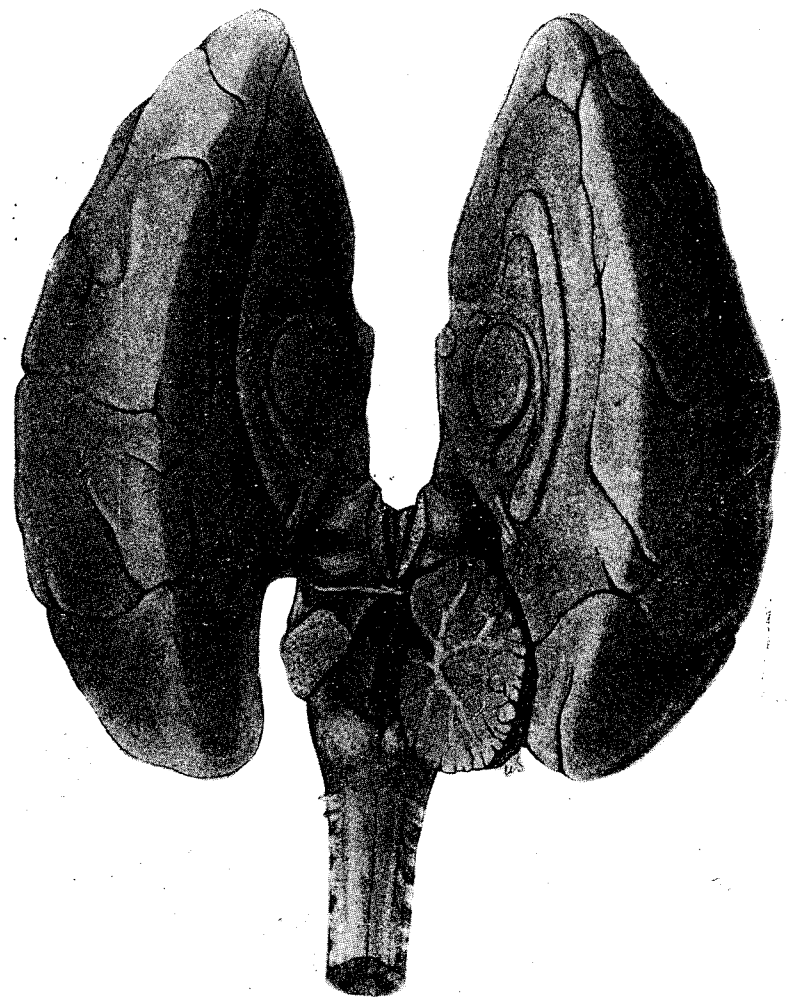

FIG. 1. Bisected monkey brain divided through midbrain roof and cerebellum, schematic.

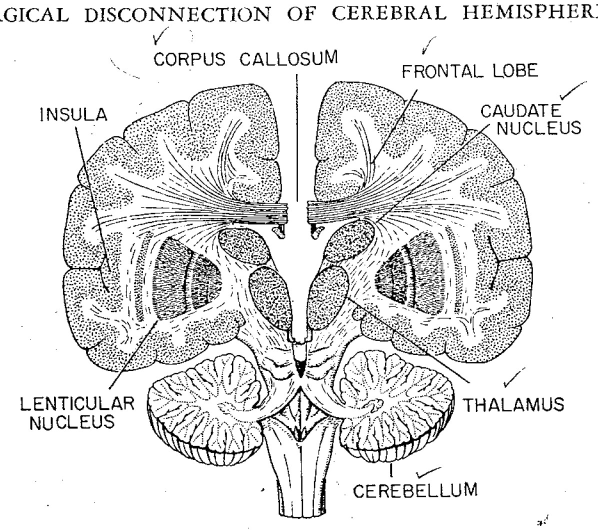

FIG. 2. Cross section of bisected primate brain, schematic.

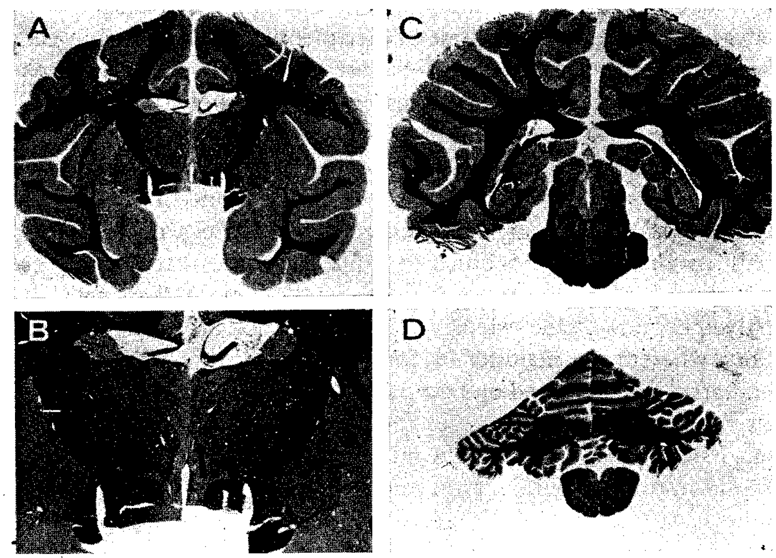

FIG. 3. Photographs of cross sections of surgically divided brain of rhesus monkey (see text).

section C is hardly visible at this magnification. Section B, detail from A, shows the midline scar passing through the massa intermedia, and in section D the bisection scar is shown passing through the cerebellum. It is only when cerebellar division is added to the higher level sections that definite behavioral symptoms become conspicuous. A clean bisection carried down through the midbrain roof leaving the tegmentum, pons, and cerebellum intact produces hardly any lasting behavioral impairments that are noticeable in ordinary laboratory behavior.

With the application of more specific tests for right-left cross integration, however, it has been possible over the past ten years, starting with the experiments of Myers, to demonstrate a large variety of functional deficits (see reviews of Myers, 1961; Sperry, 1961, 1964a). To forecast a little here, the results indicate very generally that the two disconnected hemispheres tend to function independently to a large degree in most of the higher so-called gnostic or mental activities. In other words, each hemisphere seems to have its own sensations, its own perceptions, its own memories, and its own cognitive, volitional, and learning and related experiences. After the surgery, these higher mental activities within each hemisphere seem to be out of contact with and cut off from, the corresponding mental experiences of the other hemisphere.

In short, the split-brain animal (or person, as we shall see later) behaves in many ways as if it had two separate brains—each with a mind of its own. It should be noted in this connection that when one divides a brain in half anatomically one does not divide in half its functional properties in quite the same way. In a sense many of the brain's functions are doubled more than they are halved because of the extensive bilateral redundancy in brain functions wherein the majority of functions get double representation and are fully organized on both right and left sides. Released from its reciprocal cross controls each hemisphere is then free to carry out its respective functions. A number of experimental advantages found in this split brain, twin mind, one body condition has given a new lift to our brain lesion methods for the unraveling of cerebral organization (Sperry, 1961).

The experimental surgery involved is not overly difficult if one is willing to use a stereomicroscope and appropriate instruments,

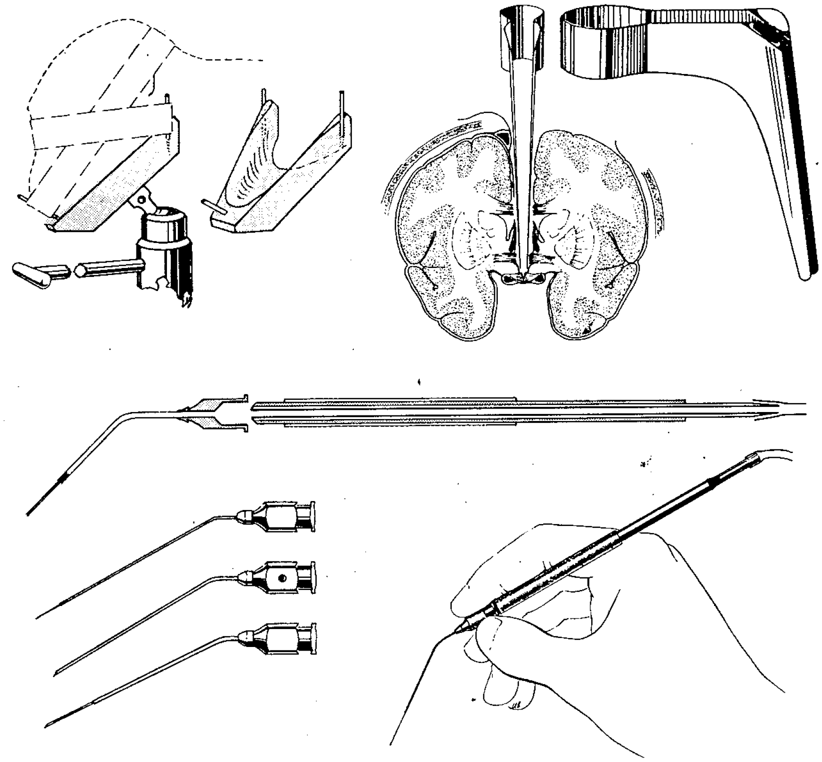

FIG. 4. Instruments used with stereomicroscope for sectioning cerebral commissures include mandible mold head holder, stainless steel cerebral speculum, and aspirating needle with interchangeable tips.

a few of which are sketched in Fig. 4. Most of the cutting is done with an aspirating needle that has interchangable tips made of fine gauge hypodermic needles. These are worked deep down between the double blades of a specially tailored cerebral retractor. As indicated, it is routine to cut even the optic chiasm at the base of the brain by tunneling down from above. Figure 5 illustrates some of the various approaches that have been followed with the cerebral speculum or retractor to make selective lesions that leave intact for study different combinations of cerebral cross connections. The *massa intermedia* is sectioned differently by pulling a fine thread through it from below upward. A 6–0 surgical suture is untwisted into its component strands and one of these is looped under the

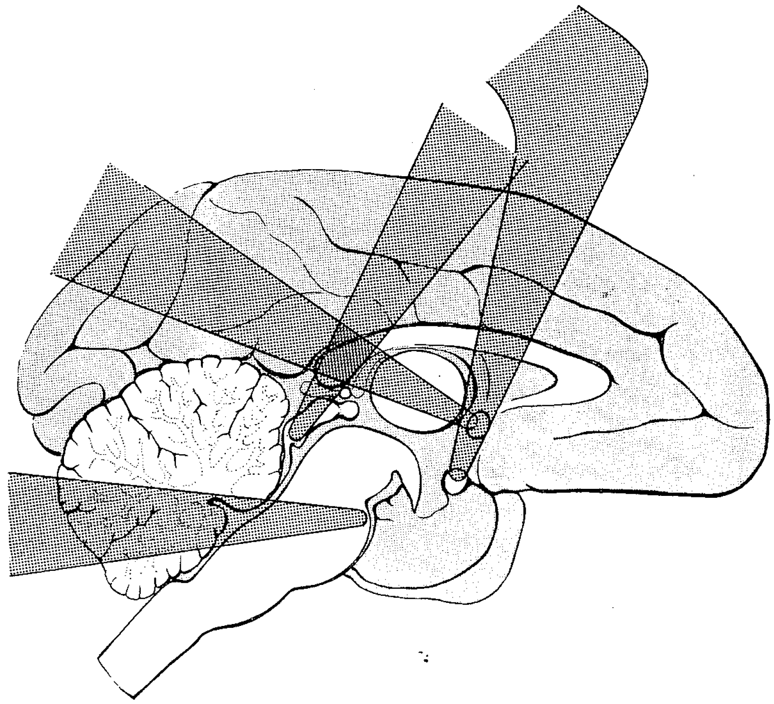

FIG. 5. Variety of surgical approaches utilized with cerebral speculum (see Fig. 4) to achieve different combinations of selective lesions in the commissures.

massa intermedia from in back with a fine wire shaped to follow the 3rd ventricle.

In order to demonstrate the disconnection symptoms produced by commissurotomy it is necessary to have behavioral and physiological methods for testing the lateralized function of each of the two hemispheres separately. It is mainly for the limb extremities and for the right and left visual fields in subhuman mammals that one can obtain lateralization of cerebral function with behavioral testing methods. Figure 6 shows top and side views of an apparatus that we routinely use for the behavioral testing and training of split-brain monkeys. This unit allows the experimenter separate control over the use of right and left eyes and of the hands for any and all eye-hand combinations. It is sketched here in combination with automated testing equipment and with a closed circuit TV monitor but may be used also in the standard "Klüver" or "Wisconsin" manual testing apparatus. Polarizing or color light filters may also be incorporated (see Trevarthen, 1962).

II. Cerebral Commissurotomy in Man

I am going to bypass further comment on the animal studies at this time in order to turn now to some work with human patients from which new and more detailed insight has come in the past five years regarding the behavioral effects of brain bisection. These are all patients of Drs. Philip J. Vogel and Joseph E. Bogen of Los Angeles, patients in whom an extensive midline section of the cerebral commissures was carried out in an effort to contain severe epileptic seizures that were not controlled by medication. The corpus callosum is presumed to be completely divided in its entirety in all these patients as is also the smaller anterior and hippocampal commissures plus, in some cases, the massa intermedia —all in a single operation.

The first patient (W. J.) in whom this surgery was tried (Bogen and Vogel, 1962) had been getting steadily worse over a 12-year period until his seizures had built up to where, in his best condition, he was still having one to three major convulsions per week with episodes of *status epilepticus* occurring every 3 to 4 months. These latter are seizures that fail to stop spontaneously and may easily be fatal. Since this man left the hospital after his surgery, about five and a half years ago, he has not had, according to last reports, a single generalized convulsion. He also describes an improvement in well-being generally, freed from the seizures and requiring less medication. A second similar case (Bogen *et al.*, 1965) was then tried and has also been seizure-free for almost four years since the surgery. Dr. Bogen reports that even the EEG patterns have returned to normal in this second case.

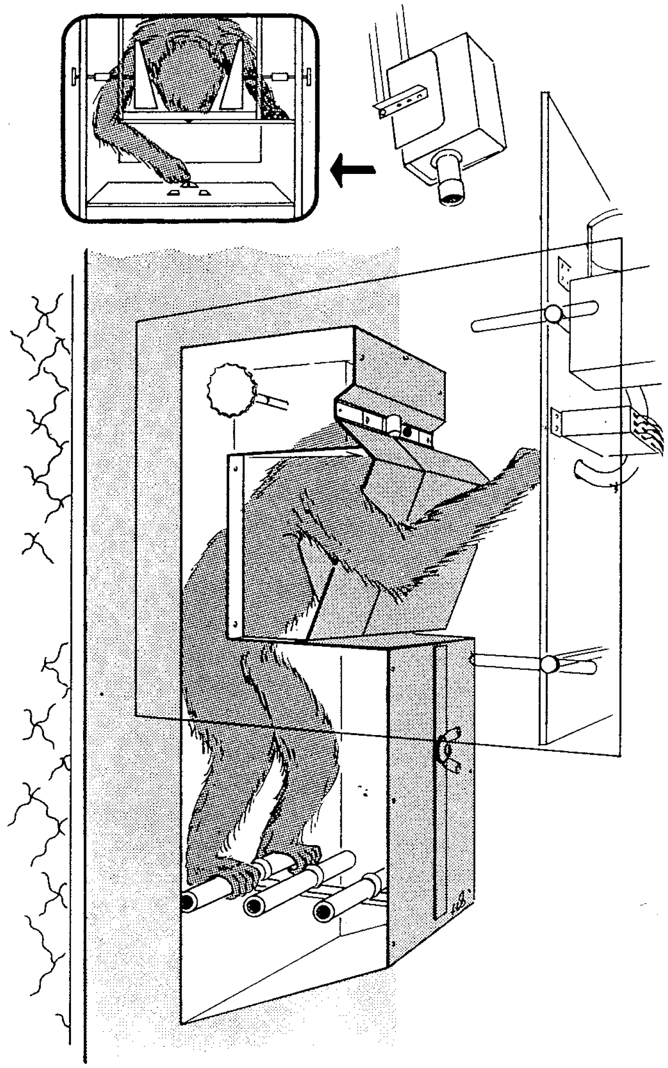

FIG. 6. Basic training unit developed by writer for controlling lateralization of eye and hand use in split-brain monkeys.

The excellent outcome in these initial, apparently hopeless cases has led to application of the surgery to some nine more individuals to date, in most too recently to warrant extensive evaluation. Although the therapeutic effect has not held up 100 per cent throughout the series, it remains predominantly good and the general outlook continues to hold promise for selected severe cases. This therapeutic success, however, and all other medical aspects are matters for our medical colleagues; our own work is confined entirely to examination of the functional, i.e., the behavioral, neurological, and psychological, effects of this surgical elimination of cross talk between the hemispheres.

Whether any of the split-brain symptoms demonstrated in the earlier animal experiments would show up in these people remained a very open question, particularly in view of the historic Akelaitis studies on callosum-sectioned patients which set the widely accepted doctrine of the 1940's and 1950's that no important behavioral symptoms are to be seen in man following surgical section of even the entire corpus callosum provided that other brain damage is absent (Akelaitis, 1944; Akelaitis *et al.*, 1942). In view of the intervening animal experiments, however, it came as no great surprise that we could demonstrate in this first patient the same basic disconnection syndrome that had emerged from the animal studies (Gazzaniga *et al.*, 1962, 1963). In fact, the symptoms were not only present, but grossly exaggerated. For example, this man after surgery was unable, with either hand, to locate points of cutaneous stimulation across the midline of the body or to trace with either hand simple visual forms seen across the midline of the visual field, nor could he use the left hand (now cut off from the language centers) for writing or to carry out simple verbal commands. Similar somatic symptoms were also seen shortly before by Geschwind and co-workers in a patient from Boston with a tumor that had involved the frontal and mid sections of the callosum (Kaplan *et al.*, 1961; Geschwind and Kaplan, 1962).

At this point it began to look as though a consistent cerebral disconnection syndrome was at last discernible and applicable to man and other mammals alike (Geschwind, 1965). How the human symptoms could have been missed in the earlier Akelaitis work was difficult to imagine. Incomplete surgery, inadequate testing procedures, and atypical case material were variously advanced in efforts to explain the apparent lack of behavioral symptoms in the earlier studies. As it now turns out, however, the curious story of the corpus callosum with all its to and fro contradictions was not to be so simply and quickly settled.

Today, after examining several more of these commissurotomy patients we find that the balance of the overall evidence has undergone another significant shift back in the older, Akelaitis, direction. A number of the salient features of the cerebral disconnection syndrome described three years ago seem now to be directly contradicted in the postoperative performance of some of these later patients. Unlike that first case, these later patients *are* able to localize cutaneous stimuli and to trace visual shapes across the vertical midline. They *are* able to carry out verbal commands and even to do some writing with the left hand, and they can draw correctly with one hand the shapes of geometric blocks held out of sight in the other hand—this, of course, is not easy to reconcile with the older story stemming from the animal work that the one hand knoweth not what the other is doing. And further, with proper testing, one can show that these people are not "word blind" nor "word deaf" nor tactually alexic in the subordinate hemisphere as was thought to be the case only three years ago.

Our current views are based very largely on two select patients chosen for special study on the basis of their smooth and rapid recovery from the surgery, the relative lack of signs of associated brain damage, and the absence of other medical complications. These two patients thus appear to represent relatively clean surgical lesions of the commissures. One of these in particular (L. B.), a boy of thirteen, was talking fluently on the morning following the surgery and was able to recite the tongue-twister, "Peter Piper picked a peck of pickled peppers . . . etc." He also had recovered already his former personality and sense of humor and was passing off facetious quips to the doctors and nurses on the ward about having such a "splitting headache" that morning. (Both he and his family had been pretty well filled in on what was involved in the surgery.) The other patient (N. G.), a housewife and mother, 35 years of age, was talking on the second day and joking mildly over the phone on day three. Like W. J., the initial case, this woman has remained seizure-free since recovery from the surgery, nearly four years ago. The boy has had 3 or 4 seizures in two and a half years since recovery, but all these incidents were on occasions when he failed to take his medicine. He has been able to return to public school after having lost one year, and is reported to be doing passable work even though he had long been only a D student before surgery.

The surgery in all these patients was carried out at the White Memorial Medical Center in Los Angeles by Dr. Philip Vogel assisted by Dr. Joseph Bogen both of the California College of Medicine. Dr. Bogen, various research fellows, and graduate students are collaborating in our behavioral testing program; among these Michael Gazzaniga in particular worked closely with us and administered in much of our testing during the first several years. The patients themselves have been highly cooperative, and the program is supported by grants from the National Institute of Mental Health. Most of the symptoms outlined below have already been described in our earlier papers (see Gazzaniga *et al.*, 1962, 1964, 1965, 1966; Sperry and Gazzaniga, 1967; Sperry, 1964a–c, 1967; Sperry *et al.*, 1967).

We are ready now for a closer look at the syndrome of hemisphere deconnection as we see it today in man. The large majority of the symptoms can be illustrated for the sake of convenience with reference to the simple testing set-up shown in Fig. 7, which we have been using regularly for examining these people. It permits lateralized testing of sensory and motor functions of the hands and feet with visual and other cues excluded. It provides also for lateralized presentation of visual stimuli to right or left hemisphere selectively. In testing vision one eye is covered and the subject is instructed to hold his gaze on a designated fixation point whereupon the visual stimuli on 2 × 2 slides are projected to the right, the left, or both visual fields at 0.1 second or less; too fast, that is, for eye movements to get the material into the wrong half field. I have added a further control against eye movements recently by flashing simultaneously a tiny number or letter within the fixation spot, so small that it requires foveal vision. The subject is then required to report both the central and the main lateral stimulus. Figure 8 is a reminder that the right half visual field for *both* eyes is projected into the left hemisphere and similarly everything exposed to the left of the fixation point is projected into the right hemisphere from *both* eyes. The optic chiasm, re-

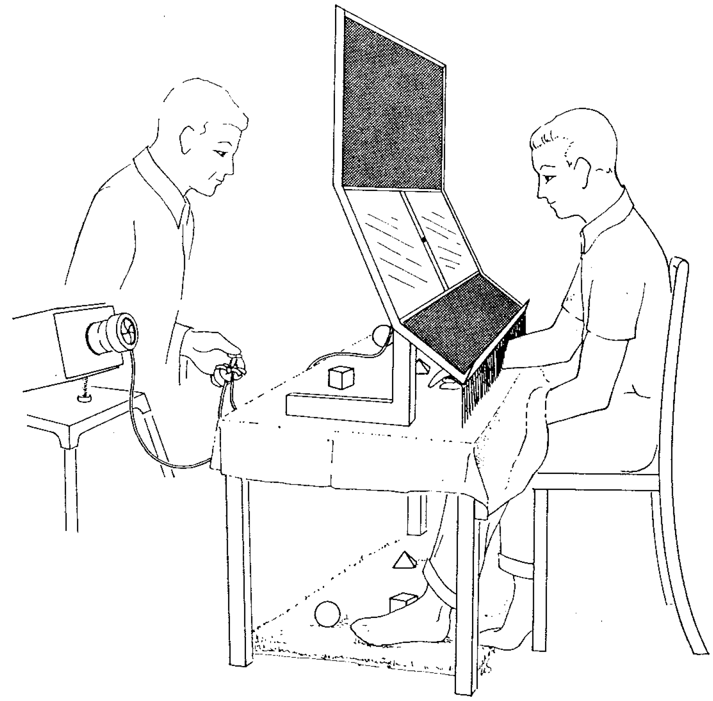

FIG. 7. General testing apparatus used for study of human commissurotomy symptoms.

member, remains intact, so we do not get separated lateralized input from right and left eyes as in the split-brain animal studies.

III. VISION

If pictures of objects, letters, numbers, or other visual material are flashed into both right and left halves of the visual field in this apparatus and the subject is asked to describe what he sees, he reports readily everything that falls in the right half visual

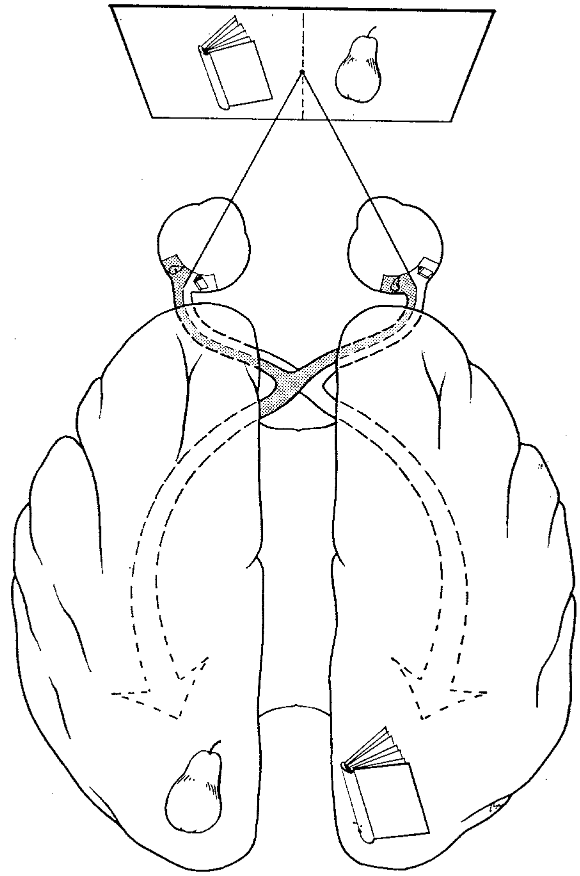

FIG. 8. Visual material exposed tachistoscopically, projects separately from left and right visual half fields into right and left hemispheres, respectively.

field, but he misses everything that falls in the left half field. When a picture is presented to the left field only, in a randomized right-left schedule, the subject consistently insists that he saw nothing on that trial, or that all he saw was just a flash of light. Now, one might easily get the impression after several hundred such reactions that these subjects are simply blind or agnostic for the left half field of vision.

With further testing, however, it can be shown that these people do indeed see and identify the left field stimuli but, like a deaf mute, they are unable to talk about what they see. Worse yet, they also are unable to write about it. Good perception, recognition, comprehension, and memory for the left field stimuli can all be demonstrated if the tests are so designed that the subject's minor hemisphere can express itself by other than verbal or linguistic means. For example, by simple manual pointing or other simple signals, the subject is able to select correctly from among an array of stimuli a particular picture or object that matches the left field stimulus which he has just verbally informed us that he did not see. (And, of course, everything indicates that the hemisphere talking to us did not see the stimulus.) This manual designation of the same or a matching stimulus works, however, only if the answer is viewed through the same, i.e., the left half field of vision. With selective lateralized presentation one finds that visual recognition of previously seen stimuli does not work across the vertical midline as it does, of course, with a normal individual. In other words, the right hemisphere fails to recognize things seen only moments before by the left hemisphere and vice versa.

When we put it all together, the evidence supports the interpretation that these people have, in effect, not one inner visual world any longer like the rest of us, but rather two separate and independent inner visual worlds—one for the right and one for the left half field of vision, each in their separate hemispheres. And further, the visual experiences and memories of the right hemisphere, unlike those for the left, can no longer be communicated in language because this hemisphere is cut off from the speech and writing centers which are located only in the opposite left hemisphere. Thus we have one so-called dominant or major hemisphere that can talk to us or write and one subordinate or minor hemisphere that cannot express itself in language. (As we will see later, the absence of the capacity for linguistic expression in the minor hemisphere does not mean that the minor hemisphere does not understand and passively comprehend a certain amount of language including simple spoken instructions.)

I would speculate that neither of the two inner visual spheres in either hemisphere notices itself to be particularly incomplete. We never hear complaints from the talking hemisphere at least that it cannot see in the left half visual field. I think of each of these inner visual domains as being comparable to the visual world experienced by the hemianopic patient who, following destruction by accident of the visual cortex of one hemisphere, fails to notice the loss of the whole half field of vision until this is pointed out in specific tests. Similarly with respect to the commissurotomy patient, one can imagine that neither visual realm much misses the loss of the other except perhaps in some of our artificial testing situations with carefully lateralized input. In trying to interpret these visual and other tests we find it generally less confusing if we do not try to think about the behavior of the commissurotomy patient as that of a single individual any longer, but try instead to think in terms of the mental properties and performance capacities of the major and the minor hemispheres separately.

Two different competing stimuli may be projected simultaneously to right and left fields. For example, say we flash a square into the left field and a triangle into the right, and the subject is drawing what he sees with the left hand out of sight behind a screen. In this case the minor hemisphere then proceeds to draw a square with the left hand, whereupon, if the subject is asked what he is drawing, he replies that it is a triangle. We see in passing many such indications of this double parallel mental performance wherein each hemisphere appears to be quite unaware and out of touch with the perceptual and other mental and recall experiences of its opposite partner.

IV. Stereognosis

In this same testing unit we can present objects directly to the right and left hands for tactual or stereognostic perception and identification. The subject's hands, remember, are hidden from his own view under and behind a slanted shield. Tests involving the sensory surfaces of the right and left hands give results much the same as those for visual perception, i.e., the subjects respond normally to objects presented to the right hand, but they are at a loss to name or describe the same objects placed in the left hand.

Remember that the main cortical representation for the right hand is in the left or major hemisphere and that for the left hand is in the minor right hemisphere.

Here again, when the results are checked out the difficulty in tactual perception in the left hand proves to be primarily a problem of verbal expression, not one of perceptual impairment or agnosia. By using nonverbal readout one can again show that despite his statements to the contrary, the subject does indeed perceive, recognize, and remember the test items inspected with the left hand. For example, when blindfolded the subject can manipulate different items correctly and may demonstrate how they are used. Also a given stimulus object taken from the left hand can be retrieved by blind touch, and with a time delay imposed, from among a large array of other objects. However, in such retrieval tests these subjects are obliged to use the same hand by which the object was initially identified. Unlike the normal person, they are unable to recognize and retrieve with one hand objects previously identified with the other. Further indications of a loss in right-left cross integration are found in tests involving skin writing on the hands and feet, the discrimination of different hand postures and other somesthetic discriminations.

Again, we appear to be dealing with two distinct realms of inner experience—one serving the left hand, left foot, and left half of the body about which the patients are unable to talk or write, and the other serving the right side of the body for which verbal communication is normal. There are certain qualifications in the case of somethesis, however, regarding the degree to which the two are distinct and separate because the sensory pathways seem not to be so fully lateralized as are those for vision. In particular the sensory input from the head and neck is strongly bilateralized so that cross integration is no problem for the face region. Also from the torso and even the extremities some of the simpler aspects of body sensation appear to register bilaterally. Unlike the case for vision, we *do* hear complaints (that come from the major hemiphere, of course), that the left hand is numb, that it has no feeling, that it does not work properly. Whereupon after a number of correct trials in succession that show the subject that he can, in fact, work with the left hand, he may say something like, "Well, I must have done it 'unconsciously.' "

V. Auditory and Intermodal Associations

We have tested auditory functions only incidentally as yet because of the difficulty of lateralizing auditory input which is mixed right and left and permits either of the separated hemispheres to listen through either ear. Comprehension in the major hemisphere can be determined by direct questioning, and we have not noticed anything subnormal on this side so far. It might be mentioned in this connection, however, that in general our tests to date have not included anything that would really tax or give any precise measure of the upper levels of performance in the dominant hemisphere. It is to be expected that more refined tests for auditory, spatial, and many other functions will eventually show that the performance of the major hemisphere after its surgical disconnection is not equal to that with the commissures intact.

When testing for auditory comprehension in the minor hemisphere we have resorted to various intermodal or other mental associations that tie the auditory function to other functions that already have been shown in a given individual to be confined to the minor hemisphere as, for example, stereognosis in the left hand or visual perception in the left half field, etc. Such perceptual associations between the different sensory modalities for vision, hearing, and touch all seem to proceed well in all directions and in all combinations within both hemispheres. The intersensory intermodal transfer of perception and of perceptual learning and memory involved in some of these latter tasks has special theoretical interest because this seems to be essentially a human capacity, something that monkeys cannot manage, or do so only at a very low level with great difficulty (Ettlinger, 1967). It also indicates the presence in this largely unknown mute, noncommunicative minor hemisphere of the cerebral capacity for things like insight, mental association, and ideation.

These intermodal recognitions can be achieved successfully only within each hemisphere. Right-left crossed associations between sight in one hemisphere and touch in the other, for example, that are easily performed by the normal person, consistently fail in these commissurotomy patients. For example, if the subject tries to search out with the wrong hand an object that he saw pictured in the left visual field, the right hand, in this case, or rather its hemisphere, perceives and could call off correctly each item that the hand comes to if this were allowed. However, the hemisphere of the right hand does not know what it is looking for in this situation, and the hemisphere that knows what it is looking for does not get the requisite feedback from the right hand. Hence the two processes never get together and the performance fails (see Fig. 9). This also applies to the reverse situation; i.e., if the subject is holding an object out of sight in the left hand, he is able to recognize the same or a matching object or picture of it presented visually. But, unlike the normal person he has to see this object through the left half field of vision and is quite unable to recognize the held item if it is presented in the right half visual field.

Other reactions from the minor hemisphere suggest the presence of ideas and some capacity for mental associations. In the same visuotactile tests, instead of selecting objects that match exactly the pictured stimuli, the minor hemisphere seems able to select related items or items that "go with" the particular stimulus, if the subject is so instructed. For example, if we flash a picture of a cigarette and there is no cigarette among the test items, the subject may come up with an ashtray or a box of matches selected from among nine other items that have no direct association with cigarettes. Or if the picture of a dollar sign is flashed to the subject's left field, the subject may feel around and choose a metal coin after rejecting other items without monetary associations.

Figure 10 shows a tentative schematic summary of some of the basic points covered above and of some yet to come. Note that the right half visual field integrates with stereognosis in the right hand and right leg and that these integrate with speech, writing, and calculation, all within the major hemisphere. In nonverbal tests for calculation in these subjects the minor hemisphere was found unable to do so simple a task as subtract two from numbers under ten. The major hemisphere on the other hand has carried on with math courses in school and in making change in the mar-

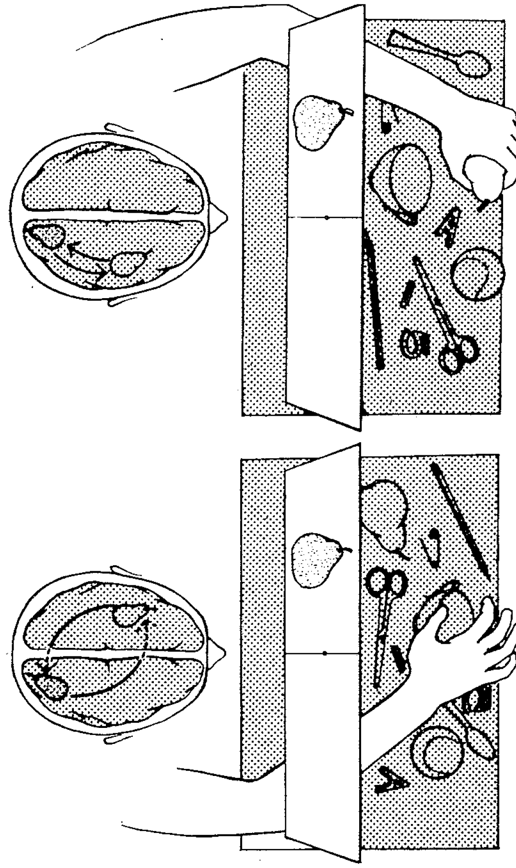

FIG. 9. Associations between vision and touch fail when the two stimuli project to opposite hemispheres.

ket at a level approximating that which prevailed prior to the surgery. Absence of calculation in the minor hemisphere is now being questioned, however, in some current work still in progress by Biersner and myself in which we are using different nonverbal testing procedures. Moderately good addition, subtraction, and multiplication for at least small numbers under 20 has been demonstrated using left-hand stereognosis and left-hand signals for

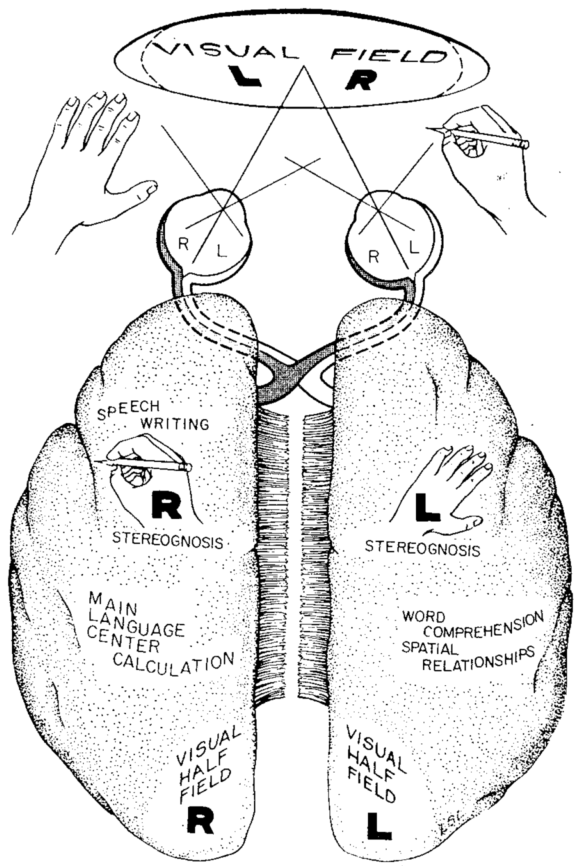

FIG. 10. Basic cerebral functions separately represented in major and minor hemispheres as indicated by behavioral tests after commissurotomy.

readout. No speech is indicated for the minor hemisphere in Fig. 10, but we cannot exclude, on the basis of tests to date, the possibility that the minor hemisphere is capable of a little singing, swearing, and the triggering of at least simple familiar words as suggested in some aphasic patients after destruction of the language centers of the major hemisphere (Smith, 1966). In tests where a choice of only two or three simple words is involved and these have been spoken and prompted by the examiner, there are strong indications in some of our current studies that the minor hemisphere can then trigger speech for the correct word.

VI. Unifying Factors in Ordinary Behavior

Note in passing that nearly all the cross-integrational deficits detected with the above procedures are easily hidden or compensated under conditions of ordinary behavior. The visual material has to be flashed in a fraction of a second to one half field to prevent compensation by eye movements. Defects in stereognosis are not apparent unless vision is excluded and associated auditory cues are controlled. The right hand must be kept away from the left and the test objects must be prevented from touching the face or the head area. During testing the major hemisphere must be prevented from talking to the minor hemisphere and giving away the answers through auditory channels, and the minor hemisphere must be prevented so far as possible from giving nonverbal signals of various sorts to the major hemisphere. There are a great diversity of response signals implicit as well as overt by which an informed hemisphere can cue in the uninformed hemisphere. Normal behavior under ordinary conditions is favored also by many other unifying factors. Some of these are very obvious, like the fact that these two separate mental spheres have only one body and therefore they always get dragged to the same places, meet the same people, see and do the same things all the time and hence are bound to have a great overlap of common, almost identical experience. Just the unity of the eyeball and its optics and—even after chiasm section in the monkey—the conjugate movements of the eyes, means that both hemispheres automatically center on, focus on, and hence probably attend to, the same items in the visual field all the time.

In split-brain studies by Mark and Sperry (see Sperry, 1964a) on crossed localization of a target perceived proprioceptively, it was found that crossed manual localization was still possible in monkeys even after deep surgical bisections extended down through the midbrain roof and cerebellum including the front tip of the tegmentum. It was inferred that a triangulation on the target perceived through either arm was registered bilaterally in the adjustments of the trunk, head, neck, and associated cerebral centers. Once a fix on the target was obtained through information from one arm it was easy to shift to the opposite hand. Direct postural aiming at the target was not necessary; the frame of reference was apparently sufficient. Further investigation of similar mechanisms operating in eye-hand coordination has been carried out by Gazzaniga (1966). With selective cerebral lesions he obtained evidence that a target fix obtained visually through one hemisphere, is automatically registered also in the other hemisphere. Midbrain (centrencephalic) or other centers apparently bilateralize the cortical adjustments for axial structures, including the eyes and shoulder girdle. To get different activities going and different experiences and different memory chains built up in the separated hemispheres of the bisected mammalian brain, as we do in the animal studies, requires a considerable amount of experimental planning and effort.

Our testing efforts with the human patients have been aimed primarily at the detection of basic deficits in cross-integration and to a lesser extent at determining the mental faculties present in the uncommunicative minor hemisphere. The upper limits of performance with unrestricted behavior in tests for reasoning, calculation, memory, abstract thinking, comprehension, etc., have yet to be investigated methodically. One notices indications in the group as a whole of a number of mild-to-severe impairments in general mental faculty present during the first year after surgery. Among these are such things as weakened memory capacity, impaired orientation in time and space, reduction in attention span and mental grasp both spatial and temporal, early mental fatigue, lowered ability to plan and coordinate, trouble with rapid distinction between right and left, lowered capacity for creative drawing, tendency to talk more incessantly than before surgery, lessened inhibition of abrupt emotional outbreaks combined with a prevailing increase in general apathy. Any capacity for which the minor hemisphere is normally superior may be expected to show impairment. These vary in degree from one case to another and tend to disappear with time. It is uncertain to what extent they result from section of the commissures or may be caused by extracommissural factors, such as damage to the fornices, or by more generalized effects resulting from traction during surgery, impairment of circulation, and combined pressure and inflammation effects that peak about the fifth day after surgery. From our experience with monkeys, we judge these latter to be especially critical in this operation in which no extra space is provided for the widespread edema that commonly follows callosal section. At present one can only emphasize that satisfactory evidence on these and related matters has yet to be obtained.

In motor control we have another important unifying factor in that each hemisphere can direct the movement of both sides of the body including even movements of the ipsilateral hand and fingers to some extent. Figure 11 shows a sample series of hand, thumb, and finger postures that we use in a test which I improvised for determining the upper limits of ipsilateral motor control. A sample finger pattern is flashed on one or the other half field and the subject is instructed to mimic with the hand on the same or the opposite side. With the hand on the same side there is no problem, but when the subject is obliged to use the hand on the opposite side, the performance does not go so easily and may not be possible at all. The closed fist and the open hand can usually be copied under these conditions when the ipsilateral control system is involved, but not most of the more difficult finger combinations. Control of the left hand through the major hemisphere in this test seems to be somewhat better than control of the right hand through the minor hemisphere. In another part of the test involving sensory as well as motor control with vision excluded the subject holds both hands out of sight with palm up and fingers extended. He then points with his thumb to spots stimulated by the examiner on different segments of the fingers and upper palm of the same hand. The normal person can generally point to corresponding symmetrical spots on the opposite hand using the opposite thumb, but not the commissurotomy subjects. Inability to perform this latter test was still present at five, four, and two years after surgery in the first three patients.

Preservation of the more delicate ipsilateral control systems in some patients and not in others would appear to account for many

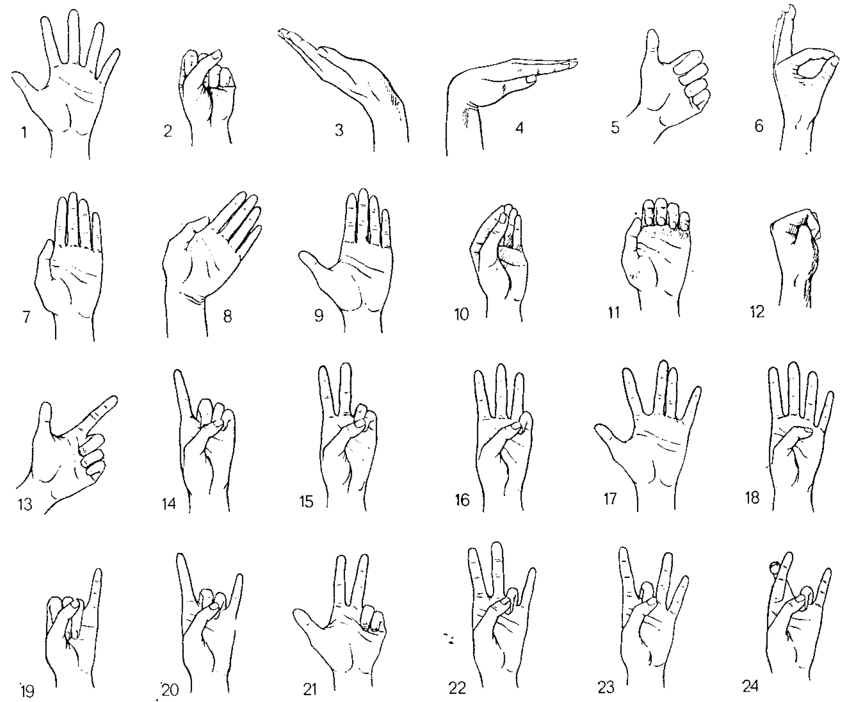

FIG. 11. Sample sketches of hand and finger postures presented tachistoscopically to right or left visual fields for readout with same and/or opposite hands.

of the discrepancies found in the literature including a number of those between our present picture and the story that prevailed three years ago. It is evident that our present findings on dyspraxia come much closer to the earlier Akelaitis observations than to those of Liepmann or to others expounded in recent years (see Geschwind, 1965; Gazzaniga *et al.*, 1962).

VII. Language Comprehension in the Minor Hemisphere

According to one doctrine of long standing in the writings on aphasia, the minor hemisphere, cut off by callosal or other lesions from the main language centers on the opposite side, is supposed to be left "word blind" and "word deaf" (reviewed in Geschwind, 1965). This view seemed to be supported in the first patient that we examined but is directly contradicted in the later more select cases examined since. In these latter patients the minor hemisphere seems to exhibit definite comprehension of words written as well as spoken. It is critical to remember, however, that this, like other kinds of comprehension in the minor hemisphere cannot be expressed either in speech or writing. For example, the subjects readily find a correct item from among 10 or more other objects after it has been named or described aloud by the examiner in a situation where the subject is obliged to use blind tactile identification through the left hand, which you recall, is shown to be confined to the minor hemisphere. Even moderately advanced definitions of objects like "kitchen utensil," "container for liquids," "used for slicing," "inserted in slot machines," seemed to be understood by the minor hemisphere under these conditions. Or conversely, if an object is placed in the subject's left hand, i.e., to his minor hemisphere, and the examiner then either calls a list of ten names out loud or shows to the subject a printed list of names, the subject can then signal or point out accurately the correct answer, which is known, remember, only to the minor hemisphere. Or, in a more critical test of this same question, if we flash the printed name of a test object into the left half visual field, i.e., into the minor hemisphere, the subject is then able to search out the corresponding item from among an array of test objects using blind palpation with the left hand. If names of parts of the head and face are flashed to the left field of vision the subject can point to the proper facial feature but cannot call the name until the identifying movement is carried out. In other words, the minor hemisphere apparently reads and understands the meaning of these word symbols.

In the visuotactile task the subject consistently fails if he is obliged to use the right hand instead of the left, and further, if the subject is asked at the completion of a correct response with the left hand what the item is that the left hand has chosen and may still be holding, the patient, or rather the major hemisphere within, can only guess at random. Since the major vocal hemisphere thus does not know and cannot tell us the answer, we infer that it has not been giving assistance to the minor hemisphere in these verbal comprehension tests. The upper limits of language comprehension in the minor hemisphere have not been determined as yet. There are indications that the reading vocabulary may be rather restricted and perhaps even childlike, and auditory comprehension considerably more advanced. The explanation of the difference between these findings and the previous accounts of word-blindness and word-deafness is not yet clear. Failure to use nonverbal readout in earlier tests would seem to account for at least some of the discrepancies.

VIII. Two Streams of Conscious Awareness

As we look back here, it seems evident that we have been dealing all along in these testing conditions with what appears to be a striking unawareness on the part of each hemisphere for the mental processes going on or that have just been going on in the other hemisphere. We have inferred from such observations that go way back into the animal experiments that in the split-brain syndrome we deal with two separate spheres of conscious awareness, i.e., two separate conscious entities or minds running in parallel in the same cranium, each with its own sensations, perceptions, cognitive processes, learning experiences, memories and so on (Sperry, 1964c).

However, the nature and quality of the conscious gnostic experience of the mute inarticulate minor hemisphere can only be inferred indirectly, and hence to a large extent it must remain an unknown. Some have suggested that perhaps the minor hemisphere behaves mainly as an automaton, a true or unified consciousness being preserved only on the dominant side (Eccles, 1965). With this question in mind, let us review briefly here in closing some of the things that the minor hemisphere seems to be capable of doing. We have seen that it can perform intermodal associations at a level characteristically human, displaying at least some insight, reasoning, and ideation. Also it can read object nouns, at least, and can also go from spoken words to named objects found tactually and vice versa, and it can follow simple spoken instructions. In work in progress headed by Parker we find that the minor hemisphere can also sort objects into groups by touch on the basis of shape, size, and texture. Further, it can concentrate on a task of its own and can follow through to a correct answer, even while the major hemisphere meantime is making distracting comments and giving erroneous advice. This is seen in a task like spelling a word such as *coat* when large block letters for this word are presented to the left hand to be identified and put in position by blind touch. While the letter "A," for example is being explored and put in place, the major hemisphere is apt to observe aloud that this is an "M" and so on, the running verbal commentary from the major hemisphere showing throughout only fortuitous correlation with the actual letters being handled by the left hand.

The minor hemisphere also seems to be superior to the major under some conditions and in some tasks like drawing spatial relationships and performing block design tests. Recall further in this connection that the disconnected minor hemisphere regularly learns and remembers rapidly, at a level that is characteristically human. The divided hemispheres have also been shown to be capable of seeing different things at the same point in space at the same time. This latter was demonstrated in some of the earlier monkey work by Trevarthen (1962) with the use of polarizing light filters. Unlike the normal person these commissurotomy patients can carry out a double voluntary reaction time task as fast as they carry out a single reaction (Gazzaniga and Sperry, 1966). In this situation each hemisphere has to make a separate and different discrimination in order to push the correct one of a right and left pair of panels. The double task goes as fast as the single without evidence of the interference and consequent delays found in normal subjects when the second task is added to the first.

The minor hemisphere also seems to demonstrate appropriate emotional reactions, as for example, when a pin-up shot of a nude is interjected by surprise into a series of neutral or nonemotional stimuli being flashed to right and left visual fields at random. The subject under these conditions will characteristically say that he or she saw nothing, just a white light, as regularly happens for stimuli projected into the left field. However, one may then notice an inner grin beginning to spread over the subject's features which then lingers and carries over through the next couple of trials or so. It may also cause blushing and giggling and affect the tone of voice coming from the major side. If one then asks the subject what he is grinning about, the reply suggests that the talking hemisphere has no idea what it was that had turned him on. He may say something like, "That's some machine you have there!" or "Wowee—that light!" Apparently the emotional tone alone gets across to the speaking hemisphere as if the cognitive aspect could not be articulated through the brain stem. The minor hemisphere also commonly triggers emotional reactions of displeasure. This is evidenced in frowning, wincing, negative head shaking, and the like, in test situations where the minor hemisphere hears the major making stupid verbal mistakes—in other words, where the correct answer is known only to the minor hemisphere. The minor hemisphere seems in such situations to be definitely annoyed by the erroneous vocal response of its better half.

Taken together, these and related results seem at this time to favor the presence in the minor hemisphere of these patients of a second, separate, conscious system that is definitely human in nature and which may be likened perhaps to that of the aphasic patient who knows and understands what he sees, hears, and feels, and perhaps even a little of what he would like to say, but who is unable to express himself in speech or writing. It should be emphasized, however, that there still remain many uncertainties about this interpretation that can be resolved only with further evidence.

Since the foregoing picture is based almost entirely on two select patients, the extent to which it can be considered to be representative of commissurotomy symptoms in the average right-handed individual can only be guessed at present. The fact that brain injury stemmed from birth in both these cases suggests the possibility of greater-than-normal bilateralization of cerebral function and the presence of other functional shifts in interhemispheric integration. We have emphasized that there are good reasons to predict a great deal of individual diversity in the integrative role of the forebrain commissures, particularly in man (Sperry, 1967). This is to be expected in association with variations in handedness, patterns of cerebral damage, early training, age, developmental distribution of ipsilateral fiber systems, and related factors.

Studies in progress headed respectively by Basch, R. Biersner, M. Biersner, Nebes, and Saul extended currently to eight similarly operated commissurotomy patients already show, in fact, that the basic syndrome in these people who all have very similar surgical sections, is subject to a considerable range of individual variation. A given behavioral symptom may be manifested quite differently in different patients, indicating preservation of significantly more cross integration than described above in some cases and less in others. In the same patient the deficits may be less pronounced in one sphere and greater in another. Not unexpectedly these high level neocortical fiber systems appear to show striking educative plasticity in response to different functional demands.

Thus the corpus callosum would seem to provide an example of a long corticocortical fiber system, the functional role of which may be demonstrably altered by training. Consider, for example, the fibers of the corpus callosum that are utilized in order to route speech through the minor hemisphere following destruction of the motor centers for articulation on the dominant side. This and similar functional shifts effected by training in the fiber systems within the callosum furnish what is perhaps one of the more promising models yet discernible in the mammalian brain for exploring questions concerning the nature and location of the new connections formed in learning.

Our current studies reveal further that the basic disconnection deficits produced by commissurotomy may be partially compensated by reeducation, particularly in the young patient. By and large, the syndrome described above represents, very roughly, the picture seen following recovery from diaschisis but prior to any substantial reeducative changes. One patient (L. B.) is now, approximately two and a half years after surgery, performing various cross-integrational tasks at levels well above what he was able to do during the first year after surgery. The performance of these intermanual and right-left visual integration tasks is observed to improve significantly from one testing session to the next, from week to week. The general overall picture is thus being pushed even farther back in the direction of the Akelaitis description of the 1940's. It may be pertinent in this regard that in the Akelaitis patients the corpus callosum had been sectioned in at least two successive operations with ample time between for considerable functional readjustment to take place. That such readjustment might have contributed to the final level of performance left by complete section remains a real possibility in view of our current findings on reeducation. Just how far the new cross-integration will go in the present patients and how to interpret it remain problems for the future. More evidence will be needed before we can expect to define a standard or "type" syndrome or to understand satisfactorily the numerous variations in commissurotomy symptoms presented in different patients.

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