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Interhemispheric relationships: the neocortical commissures; syndromes of hemisphere disconnection

R. W. SPERRY, M. S. GAZZANIGA* and J. E. BOGEN**

California Institute of Technology, Pasadena, Calif.

Until a few years ago, prevailing views regarding the syndrome of the corpus callosum in man were based very largely on the studies of Akelaitis and his co-workers (Akelaitis et al. 1942; Akelaitis 1944). Using a wide variety of tests Akelaitis examined a series of more than two dozen patients with partial and complete surgical sections of the corpus callosum and anterior commissure and was unable to find any consistent neurological or psychological dysfunctions that could be reliably attributed to the commissural sections. Symptoms such as unilateral astereognosis, alexia, agraphia, ideomotor apraxia (Sweet 1941), as well as apathy, amnesia, personality changes and related effects, that earlier had been ascribed to callosal lesions (Alpers and Grant 1931) seemed accordingly to be more properly explained in terms of the extracallosal cerebral damage that commonly accompanies lesions in the commissures. These Akelaitis reports in combination with confirmatory observations on absence of symptoms after callosum section in animals established the general doctrine of the 1940's and 1950's in which it was believed that behavioral deficits seen in connection with callosal lesions are best ascribed to associated brain damage (Bremer et al. 1956). Meanwhile, the discrepancy between the enormous size and strategic position of the corpus callosum on the one hand and the observed lack of any important functional disturbance following its complete surgical section on the other remained during this period one of the more puzzling enigmas of neurology.

In a subsequent series of so-called 'split-brain' animal studies begun in the 1950's (Myers 1961; Sperry 1961) it became possible through utilization of various experimental devices and controls to eliminate some of the ambiguities in the earlier evidence and to find at last a considerable number of important functions mediated by the neocortical commissures. In brief these 'split-brain' studies, conducted mainly with cats and monkeys, showed that the neocortical commissures are necessary for the interhemispheric transfer of learning and memory and also for the interhemispheric integration of many sensory and motor functions that involved the left and right hands or paws, and the left and right halves of the visual field. By 1960 the broader features of the cerebral deconnection, or 'split-brain' syndrome, were well established with respect to subhuman mammals.

Not long thereafter comparable symptoms were observed in a human patient with cerebral

* Now at University of California, Santa Barbara, Calif.

** Ross-Loos Medical Group, Los Angeles, Calif.

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neoplasm and callosal infarction (Geschwind 1962; Geschwind and Kaplan 1962) and in another patient with surgical section of the forebrain commissures (Bogen and Vogel 1962; Gazzaniga et al. 1962). Bolstered by these confirmatory observations in man, the emerging picture of the connectional role of the neocortical commissures seemed sufficiently validated that it might be used to settle at long last some of the many confusing contradictions in the clinical literature (Geschwind 1965). A return to some of the older views of Dejerine, Liepmann, and others seemed to be indicated at this point along with a corresponding rejection of the Akelaitis reports. It shortly became evident, however, that the long and complex controversy of the corpus callosum was not to be settled quite so quickly and that further significant swings in the pendulum of opinion were yet to come. During the past several years, further observation of additional human patients with surgical section of the forebrain commissures has brought a mass of new evidence and with it a further shift in the theoretical outlook on the callosum (Gazzaniga et al. 1965, 1967; Gazzaniga and Sperry 1967; Gazzaniga 1967; Sperry 1967; Sperry and Gazzaniga 1967).

This more recent evidence comes from the study of a series of patients of Dr. Philip Vogel in whom surgical section of the commissures was carried out to help treat severe convulsive disorders not controlled by medication (Bogen and Vogel 1962; Bogen et al. 1965). All of these patients had undergone, in a single operation, complete transection of the corpus callosum, the anterior commissure and the hippocampal commissure plus, in several individuals, the massa intermedia. The same operation had been carried out previously in many dozens of monkeys the results of which, along with the observations on callosum section in man, indicated that the behavioral outcome should not be seriously incapacitating (Sperry 1961). There was reason, further, to favor the single complete section over partial sections performed seriatim. It was hoped that this surgery might help to confine the epileptic seizures to one side and tend to preserve consciousness during

an attack, that it might enable the patient t
take precautionary or control measures at th
onset of a seizure, and that the severity an
duration of the attacks might be reduced by th
elimination of the commissural contribution t
mutual reinforcement of seizures during th
generalized phase, and especially during *statu*
epilepticus.

When the surgery proved effective in elimi
nating generalized convulsions in the first tw
patients it was subsequently employed in addi
tional cases most of whom are still too recent t
evaluate. Although the therapeutic effect ha
been mixed among the later patients of thi
series, the outlook continues to hold promise fo
selected severe cases.

Included among the earlier patients of th
series were two individuals (N.G. and L.B.) i
whom the postsurgical course was particularl
smooth, postoperative functions relatively un
impaired, and in whom the extracallosal brai
damage seemed to be at a minimum for th
series. These two select patients have bee
tested most thoroughly and are given greate
weight in our present interpretation as outline
below on the supposition that they come close
to a pure hemisphere deconnection syndrom
In both cases, however, there is presumed t
have been some epileptogenic cerebral damag
stemming from birth injuries that may possibl
have resulted in a less than average amount o
lateral specialization in cerebral function. Be
cause of the special weight given their symptom
in the present account, further details of th
case histories of these two select patients ar
here provided as follows:

Case history N. G.: N. G. was born June 29, 193
in the sixth gestation month, was in an incubator fo
some weeks, and on leaving the hospital weighe
five pounds (2300 grams). In spite of this, she wa
considered normal in development until she bega
having convulsions at age eighteen, a year after sh
graduated from high school. Her condition worsene
as described in a previous case report (Bogen et a
1965) and she was admitted for cerebral commissu
otomy. She was always right-handed and righ
footed, as were both of her parents and all fo
grandparents. Evidence for preoperative brain dam
age included: repeatedly abnormal EEGs, sometim
suggestive of a left temporal focus; hypaesthesia t

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pinprick in the left hand shortly after a seizure; and
a one-centimeter mulberry size calcification beneath
the right central cortex seen on skull X-rays. A right
carotid angiogram was negative and a pneumoen-
cephalogram showed minimal ventricular dilation
bilaterally. Preoperative IQ was 73. Operation was
uneventful except for division of a sizeable bridging
vein draining the right parietal area. Recovery from
operation was smooth, with intelligible speech on
the second postoperative day and orientation for per-
son and place on the third day. Since discharge she
has remained convulsion-free and, although needing
help from her husband the first year, has been able
to take on full management of her household.

Case history L. B.: L. B. was delivered on May 15,
1952, by cesarean section (his mother's third such
delivery). He weighed five pounds, was cyanotic and
was in an Isolette for eight days. He was an active
baby, sat alone at five months and stood with sup-
port at seven months, but did not walk unaided until
eighteen months, at which time he weighed fifteen
pounds and was already talking. The patient and
both parents are right-handed; an older half-brother
is left-handed. His first seizures occurred at age
three and despite intensive efforts at control by med-
ication these became progressively more frequent
and severe as he grew older. In the year preceding
operation (i.e. during 1964), he had over fifty gener-
alized convulsions while taking phenobarbital, Mys-
oline and Elipten. Despite an IQ of 115 and home
tutoring, his school grades deteriorated until he was
failing in all subjects. Evidence for preoperative
brain damage was restricted to the convulsions,
which had no localizing feature except an occasional
epigastric aura, and generalized abnormalities on
repeated EEGs. Neurologic exams, skull X-ray, brain
scan and bilateral carotid angiogram were negative,
as had been an air study at age four. Operation was
uneventful; there was relatively little retraction and
no bridging veins were interrupted. He spoke readily
on the first postoperative day, and by the fifth day
was ambulatory and well oriented. In the first three
years after operation, he had three generalized con-
vulsions and eight left-sided jacksonian episodes
without loss of consciousness. He returned to public
school after a year away, one grade below his age
level and has since done passing work in all subjects
except mathematics.

In many respects the difference between our
current interpretation and that as seen three
years ago would seem to reflect the differences
in symptoms obtained with clean surgical sec-
tions per se, and those obtained with commis-
sural lesions accompanied by additional and
especially by progressive extracallosal cerebral
damage. In contrast to the cerebral disconnec-
tion syndrome as recently depicted, these new

eferences p. 289

select cases are able, for example, to write meaningful material and perform written calculations with the subordinate hand. They draw with one hand the shapes of objects presented to the other hand or opposite half visual field. They locate with either hand points of tactile stimulation on the opposite half of the body. They carry out verbal commands with the subordinate hand; and they are not 'word-blind' and 'word-deaf' in the disconnected minor hemisphere. Whereas these and related observations tend to swing the over-all syndrome picture significantly back in the Akelaitis direction, there nevertheless remain certain important contradictions making our current interpretation described below a rather heterogeneous composite of earlier opinion. The general syndrome picture is still developing and it would be premature even now to attempt global value judgments regarding historic developments and contributions on the controversial issues involved.

Disconnection symptoms

The most remarkable effect of sectioning the cerebral commissures continues to be the apparent lack of change with respect to ordinary behavior. The least affected of Vogel's patients, in whom complete section of the entire corpus callosum and anterior commissure was clearly visualized during surgery, exhibit no gross alterations of personality, intellect or overt behavior two years after operation. Individual mannerisms, conversation and bearing, temperament, strength, vigor, and coordination are all largely intact and seem much as before surgery.

Despite this outward appearance of general normality in ordinary behavior, distinct impairments are readily demonstrated with more detailed tests specifically designed to detect loss of interhemispheric integration. In general, the results of such specific tests indicate functional disengagement of the right and left hemispheres with respect to nearly all cognitive and other psychic activities. Learning and memory are found to proceed quite independently in each separated hemisphere. Each hemisphere seems also to have its own conscious sphere for sensation, perception, ideation and other mental activities and the whole inner realm of gnostic experience of the one is cut off from the corresponding experiences of the other hemisphere – with only a few exceptions as outlined below.

For the sake of unity and convenience of description, the various disconnection symptoms that have been demonstrated to date are outlined below with specific reference where possible to a general testing unit that we have used regularly for examining these patients illustrate in Fig. 1. The subject is seated at a table o which is mounted an adjustable shield that pre vents the subject from seeing his hands or th test items on top of the table or the examine and other equipment in the rear. The shiel also serves to hold a white glass viewing scree for the back projection of 2 × 2 slides in a automatic projector equipped with a mechani cal shutter for quick-flash tachistoscopic prese tation.

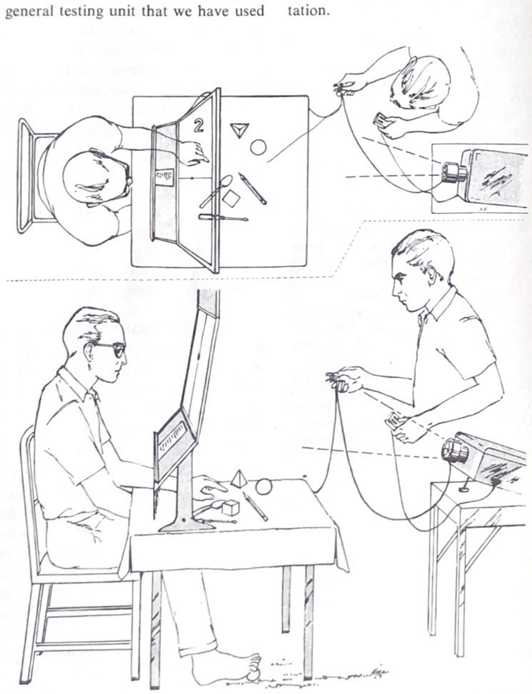

Fig. 1. Top and side views of basic testing unit used extensively to examine commissurotomy patient Visual stimuli are back projected at 1/10 sec or less onto translucent white screen with subject's mono ular gaze centered on designated fixation point. Moveable shield with fringe at bottom and table top wi towel surface serve to exclude visual and minimize auditory cues.

ISUAL SYMPTOMS

isual material can be presented selectively to ne or the other or both hemispheres as deired, by having the patient fix his gaze on a esignated point on the viewing screen. Pictures f objects and other visual stimuli are flashed o the left and right halves of the subject's visual ield using tachistoscopic exposure times of 1/10 ec or less. The brief exposure insures that timuli intended for a given half-field will not e projected into the wrong hemisphere through canning movement of the eyes. Visual material een to the right side of the vertical midline is rojected to the left hemisphere and vice versa.

Under these testing conditions vision in the ommissurotomized patients has been found to e essentially normal in the right half-field. The atient reads and describes pictured material of arious kinds in the right field at a level subtantially the same as before surgery. When timuli fall in the left field, however, in a ranom right–left presentation schedule, the subect's comments indicate he did not see the timulus. If further questioned, he usually inists he saw 'nothing' or at most, a 'flash of ght'. In literally hundreds of such test trials, onducted over the past three years, the comissurotomized patients have remained conistently unable to describe in speech or writing ictures or objects presented visually to the left de of the vertical meridian. This is not true if bjects are merely held in the left field or shown ith longer exposure times, presumably beause very rapid eye movements bring stimuli n the left into the right half field. Failure to nd the foregoing left field defect in the Akeitis studies seems best ascribed to the fact that chistoscopic projection was not used in the sual testing.

Further analysis indicates that the difficulty the left half-field in these patients is not a efect of vision but a defect in verbal commuication resulting from the disconnection of sual function in the right hemisphere from the echanisms for speech in the dominant left misphere. When simple manual or other nonrbal responses are used to demonstrate comehension, it is clear that stimuli presented in the left half-field are seen, and can be recognized, learned and remembered. Pictures of objects, geometric figures, colors, lines, dots, arrows in different directions, and the like, are recognized and correctly identified and described if the subject is allowed to communicate his understanding through nonverbal means. For example, the subject is able to point to particular features of a stimulus, to trace its outlines, to point out a matching or associated object, or to the correct name of the pictured object when shown a list of names. He can also pick out by touch an unseen object matching the one pictured from among a collection of other items. Whereas standard testing for vision in the left half-field may thus give an impression of hemiagnosia or even hemianopsia, tests employing nonverbal readout indicate retention of good visual function in the subordinate half-field.

An outstanding feature of visual perception in these patients is the independence of the two visual half-fields. Things seen in one half-field, that is in one hemisphere, remain dissociated in perception and memory from what is seen in the other half-field. If a word like *catkin* falls half in one field and half in the other, the two parts are perceived only as two separate words; the complete single word is never perceived as such unless the gaze is centered to left or right of the whole word. Things that have been seen previously are recognized and remembered on a subsequent presentation only if they are presented in the same half-field. When a given stimulus is presented in the opposite half-field, the patient responds as if it had not been seen on the previous occasion. Even in very simple tasks involving discrimination of gross color differences and simple directionality the patients showed no cross integration between what is perceived in one half-field and what is perceived in the other.

If a pair of objects or images is presented simultaneously, one to the left and one to the right visual half-field, and the subject is told to retrieve a matching object by touch with the left hand, the left hand picks out only the object pictured in the left half-field. If, before he can look at it, the person is asked what he has chosen with the left hand, he responds with the name of the object seen in the other – the right – half-field (Fig. 2). This occurs even with gross discrepancies between the two objects. The right–left division of the visual field, as indicated in such tests, is abrupt at the midline without noticeable central sparing or overlap. Letters, dots or lines as close as one degree to the central fixation point on the left side are not included in the verbalized responses covering the right half-field and the converse is true of the manual readout for the left half-field.

A large variety of such visual tests point to the conclusion that in the absence of the commissures things seen in the left and right halves of the visual field are processed separately in the right and left hemispheres respectively. The normal interaction between elements within each half-field is preserved, but visual integration across the midline is eliminated. Each of the separated hemispheres has its own visual sensations, percepts, associated concepts and short- and long-term memories; the gnostic visual experiences of the one seem to have no direct contact with those of the other. In many ways it is as if two separate brains were viewing the left and right halves of the visual field, only one of which is able to communicate what it sees through speech or writing.

From the foregoing it seems evident that the commissures in the normal, intact condition subserve a large variety of visual functions, sensory-sensory, sensory-motor, and associational in nature. One of the most critical of these from the clinical standpoint is the integration of the visual functions of the minor hemisphere with the language and related comprehension and volitional mechanisms of the major hemisphere. The visual deficits resulting from cerebral commissurotomy do not cause much difficulty under ordinary conditions apparently because scanning movements of the eyes bring the contents of the left half of the visual world into the right visual field. Vision is further unified by the conjugate control of the eyes from each hemisphere along with other factors that tend to make each hemisphere view and attend to the same material all the time. Except in artificial testing situations, in which much care

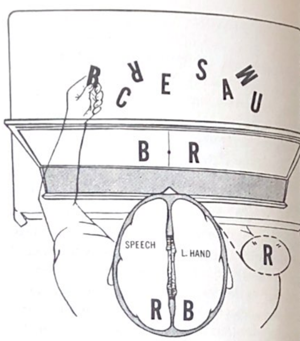

Fig. 2. When 2 letters, numbers, pictures of object or other stimuli are flashed simultaneously to le and right visual fields, subject denies seeing any b the *right* field stimulus. If seen stimulus is bein retrieved by touch with left hand, however, subje consistently selects the letter or other item th matches the *left* field stimulus. When asked to co firm verbally what item was selected by left han subject names incorrectly the *right* field stimulus

is taken to obtain a discretely lateralized visu input, there is generally a large common de nominator of similar activity in each hem sphere.

SOMESTHETIC SYMPTOMS

Very similar symptoms are seen when the rig and left hands are tested for stereognosis. I this case a variety of test objects are plac directly into each hand for recognition – th hands and test objects being screened from th patient's sight behind and under the shield (Fi 1). Objects placed in the right hand are handle named, and described in normal fashion. I contrast, attempts to name or describe objec held out of sight in the left hand consistent fail. Generally the patient can tell when som thing is placed in the left hand, presumably b cause of the presence of a weak ipsilater cerebral projection in the somesthetic pathwa However, with objects in both hands, the p

ient usually denies even the presence of the eft hand stimulus while describing that in the ight hand. The major system appears to occlude the competing ipsilateral activity within he same hemisphere.

When an object is placed in the left hand lone, the subject tries to guess what it is, calling ames for whatever comes to mind and using whatever clues are available. Auditory cues in articular must be carefully guarded against. Sounds of the moving fingers or finger nails, or novement of a ring against the surface of the est object or brushing of the object over a table urface may be sufficient to give the answer to he dominant hemisphere, especially where a mall number of known objects is involved. When all such indirect sensory avenues to the lominant hemisphere were controlled, the present patients were unable to name or describe objects or any other complex stimulus patterns resented to the left hand. Why this symptom was not seen in the Akelaitis studies is not clear. nsufficient control of indirect cues might be he explanation.

It could be shown in respect to the left hand, s for the visual field, that the minor hemiphere can nevertheless perceive, recognize, earn and remember these same test items which he patient says he cannot feel. The patient can often demonstrate, by appropriate manipulaion the use of a given test item such as a penil, a toy pistol, a cigarette, a fork, etc., even hough the attempt to name these same objects n speech or writing remains purely fortuitous. Also a given test item, after being felt with the eft hand, can then be retrieved by blind palpaon when placed in random position out of ight among a collection of other items. This is ossible with delays imposed of several minutes r longer, i.e. the minor speechless hemisphere earns to recognize an object and retains the oncept over a delay period well beyond the aximum level for delayed response in subuman primates.

The most conspicuous symptom in the somesthetic sphere is this apparent astereognosis in the eft hand that proves to be more exactly a unilateral *anomia*. This may be attributed to the reak in communication between the left hemisphere centers for speech and writing and those for the left hand in the right hemisphere. Other deficits, not involving speech, are also demonstrable. If the fingers of the left hand are touched lightly on the tip, middle or basal segment or at in-between points, the patient, with vision excluded, can easily locate the stimulated point with the tip of the thumb of the same hand. The normal person can also indicate with the opposite right thumb the corresponding mirror point in the opposite hand. Nearly all such cross-localization between the hands breaks down in the commissurotomized patient who is usually unable to cross-locate without vision even the correct finger, much less points within a finger. Similarly a posture imposed on thumb and fingers of one hand by the examiner cannot be copied in the opposite hand.

The lack of cross-integration for topognosis within the hand does not apply uniformly to the entire cutaneous half-field of the body. In the head and neck regions little or no breakdown of cross-integration is apparent owing presumably to strong bilateral representation of the head and neck in each hemisphere. Stimuli on the left as well as on the right side of the face are located, discriminated, and described verbally in speech or in writing. There is no unusual difficulty in naming objects placed in the mouth.

Over most of the torso and limbs, excluding the hands and feet, the situation tends to be intermediate. While verbal report is fairly good for localization on the left side, it is poor for even simple determinations of modality and position sense. More complex and refined discriminations, like the interpretation of skin writing or perception of shapes, which in the normal person exhibit cross-communication from left to right side, fail in the commissurotomized patient.

Cross-integration of stimuli from the hands themselves is severely impaired but not entirely eliminated – suggesting the presence of at least a weak system of basic sensory input from each hand to the ipsilateral hemisphere. Onset and presence or absence of tactile stimulation of the left hand can be reported verbally as can also a distinction between stimuli applied to the wrist or palm, thumb or palm, and thumb or little finger. Sharp points that yield mild pain on pressure can also be detected by the major hemisphere. More refined discriminations fail, however, as between the fingers or between curved and straight lines drawn on the palm or even between crosswise and lengthwise movements of a stylus on the palm. Considerable individual variation is to be expected in the proficiency of these weak ipsilateral systems.

INTERMODAL ASSOCIATIONS BETWEEN TACTUAL, VISUAL AND AUDITORY SPHERES

If a picture of an object like an apple, a pencil, or an ashtray is flashed to the left half of the visual field, the commissurotomized subject can retrieve by touch the corresponding item from among an array of test objects out of sight. Unlike a normal person, however, the commissurotomized subject is able to do this only with the left hand when the visual cue is flashed to the right hemisphere, and it can be done only by the right hand when the visual input is in the right half-field (see Fig. 3). Conversely, if the object is first presented tactually to the left hand, the visual picture of the object is then identifiable only when it is seen in the left half visual field and vice versa. In the normal person, of course, visual identification under these conditions goes readily in either field.

The foregoing is consistent with the conclusion, supported by a wide variety of tests, that manual stereognosis for the left hand and visual perception of things in the left half of the visual field are both processed in the right hemisphere only. All such tests must be conducted with careful exclusion of secondary stimuli that are not confined to the intended manual and visual sensory fields. Objects that give off distinctive auditory cues like the jingle of a key case, the click or ring of a metal object, the rustle of a ball of tissue paper, etc., can subsequently be found and retrieved by blind palpation. This can be done by either hand indicating bilateral recognition and retention of the auditory percept by both hemispheres.

In summary, tasks that are dependent upon intermodal associations are possible only when the sensory and related information is all pro ected into the same hemisphere. The cros integrations between oppositely lateralized vis al and somesthetic inputs that are easily carrie out with the commissures intact are no longe possible.

SPEECH AND WRITING

Under ordinary conditions these patients gi the impression of being able to converse a write at a normal level. As already explaine however, the right-handed commissurotomiz patient is generally unable to express in spee or writing things seen in the left half of t visual field or felt with the left hand. By co trast, verbal expression is essentially normal a rule for things perceived through the rig half visual field and the right hand.

These and related observations support t conclusion that speech and writing in these p tients are organized almost exclusively in t major left hemisphere, and that section of t commissures thus leaves the minor hemisphe

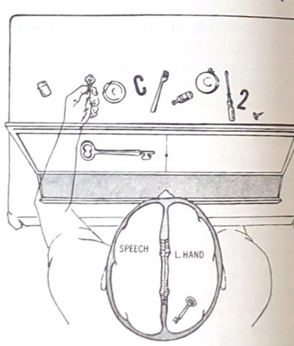

Fig. 3. Visuotactile associations succeed but only visual and tactual stimuli both project to same hem sphere. Subject here denies seeing anything but flash of light on left. However, if left hand is allow to 'make a guess', correct object is selected or ev an object 'used with' the projected stimulus if subj is so instructed.

peechless and agraphic. This conclusion may e extended to intermodal performances and the general rule that speech and writing are ossible for the conscious experience of the ajor hemisphere only. Speech in the minor emisphere seems to be almost totally lacking tests applied to date. However, the ability of e minor hemisphere to sing or to utter simple, amiliar, or exclamatory words (Smith 1966), r to manage a little childlike writing in some ases cannot be excluded and remains to be xplored.

ALCULATION

y one year after surgery these patients were arrying out mathematical transactions verbally nd in writing, in testing sessions, in marketing, nd in school work with a proficiency approxi ating the preoperative level. Difficulties in alculation are the rule in the first months after rgery. These difficulties may depend in part n diaschistic after effects as well as other ctors including impairments in short-term emory and incomplete scanning of the visual elds all of which subside in time. More exact g measures of the upper level of attainment ave yet to be made.

Tests for mathematical performance in the inor hemisphere with nonverbal readout and ith the sensory input restricted to the left sual field or the left hand, indicate, by con ast, that the capacity for calculation on the inor side is almost negligible. By manipulating arbles or dowel sticks, watching spots of light ashed to the left field and pointing with the ft hand, these patients may succeed in match g numbers or in adding one to numbers below n but they fail when required to add or sub act two or higher numbers and they fail also the simplest tasks in multiplication and divi on.

We have inferred accordingly that calcula on, along with speech and writing, plus the sual functions associated with the right half eld, and the stereognostic functions of the ght hand and all the associative and integra ve activities dependent upon the foregoing are organized predominantly in the major hemisphere. Further it would seem to be these activities of the major hemisphere that set nearly all the upper limits of behavior after commissurotomy and that are mainly responsible for the impression of near normalcy in ordinary behavior.

LANGUAGE COMPREHENSION IN THE MINOR HEMISPHERE

Symptoms seen in the first patient in this series were in conformity with the view that the minor hemisphere disconnected from the language centers of the major hemisphere is rendered 'word-blind', 'word-deaf', and tactually alexic (Geschwind 1965). This is not true of our later cases, however, in whom comprehension of both spoken and written words has been shown, although this comprehension is not demonstrable by verbal response.

Auditory comprehension of language was indicated by the ability of the subjects to retrieve with the left hand a particular object named aloud by the examiner and located out of sight among a collection of test objects. In such tests words like the following appear to be understood in the minor hemisphere: pyramid, cylinder, tack, coin, pliers, fork, flashlight, bulb, screwdriver, round, square, scissors, etc. This performance was frequently successful when the test object was not directly named but only indirectly described with definitions like: 'used to light fires with' for a *match*; 'a measuring instrument' for *ruler*, or 'liquid container' for a *glass*. Because tactual recognition with the left hand was shown to be a function of the minor hemisphere, it would appear that the names and descriptions of the test objects, and to some extent the verbal instructions, must have been heard and understood by this same hemisphere. Conversely, if an object were presented to the left visual field or the left hand, the subject could subsequently signal the name of the object when it was read aloud among a series of other names. The minor hemisphere in such tests seemed to have at least a moderate vocabulary. In these tests, however, the major hemisphere also hears and comprehends the auditory material, and might therefore be suspected of aiding the minor hemisphere with feedback effects, subcortical sets, or other facilitative mechanisms.

Comprehension of *written* words in the minor hemisphere was demonstrated by similar procedures. After a printed word had been flashed to the left half visual field, the commissurotomized subjects were able to retrieve the corresponding item from among an array of objects by blind palpation with the left hand (Fig. 4). Conversely after a given test object had first been recognized with the left hand, the patient could look at a list of printed names or a series of names flashed successively to the left half-field and signal by pointing to the correct name of the test object. Control by the major hemisphere in these latter tests could be excluded because incorrect verbal descriptions given immediately after a correct response by the left hand showed that it was only the minor hemisphere that knew the answer.

The discrepancy between these findings and the accounts of 'word-blindness', and 'word-deafness' in the separated minor hemisphere remains to be accounted for. In part the discrepancy may stem from a failure in earlier studies to use nonverbal readout in testing for comprehension. Perhaps our subjects with early brain injury have a greater than normal bilateralization of the ability to comprehend words. Or it may be also that the disconnected minor hemisphere is capable of functioning at a higher level with the opposite hemisphere intact than where it must function in the presence of lesions on the opposite side. However, after surgical removal of the dominant hemisphere in an adult, language comprehension has been found to be far less impaired than expression (Smith 1966). It is further possible that in the presence of an aphasiogenic lesion in the left hemisphere, language comprehension by the minor hemisphere may be better in the absence of commissural influences. Only further observations can determine to what extent the picture described above represents a typical condition.

Tests involving comprehension and response to printed commands, in which the subject is instructed to mimic or carry out simple ac[ts] indicate a much lower level of performance [in] the minor hemisphere. When verbs such [as] *smile, nod, frown, blow, point, wave, knoc[k]* etc. were flashed to the left half-field, the p[a]tients were unable either to comprehend or [to] act, but did so readily from the right half-fie[ld]. Lack of comprehension for the left half-fie[ld] would seem to be the limiting factor in view [of] the subjects' inability even to point correctly [to] matching pen and ink sketches depicting the test words. The patients were, however, able [to] carry out the actions correctly when the senso[ry] input consisted of these same sketches, inste[ad] of the words, flashed to the left field. T[he] difference between names of objects and ver[bs] remains to be explained. There is also a proble[m] with regard to the role played by postoperati[ve] learning in the establishment of word compr[e]hension in the minor hemisphere. At prese[nt] the evidence favors the conclusion that t[he] minor hemisphere possesses fair auditory com[]prehension but only an elemental reading v[o]cabulary consisting mainly of object-nouns.

No deficits in language comprehension we[re] demonstrated in the performance of the maj[or] hemisphere. These patients could read in t[he]

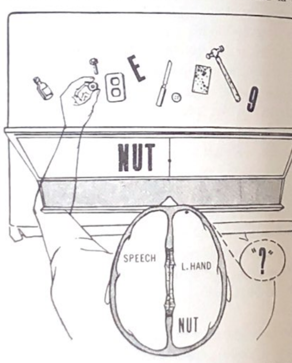

Fig. 4. Names of objects flashed to left half field c[an] be read and understood but not spoken. Subject c[an] retrieve the named object by touch with the l[eft] hand, but cannot afterwards name the item nor [re]trieve it with the right hand.

[ri]ght half-field and were able to converse, carry [o]ut verbal commands, and write on a level not [n]oticeably different from before surgery. How[ev]er, tests for exact measurement of more sub[tl]e pre- and postoperative differences have yet [to] be carried out. The specific tests applied thus [fa]r have been aimed mainly at the minor side [an]d have not taxed the capacities of the major [h]emisphere.

[M]OTOR FUNCTION

[T]he nature and degree of praxic impairment [w]as subject to large individual differences es[pe]cially in the early weeks after surgery. At [fi]rst the patients showed some left-sided apraxia [to] verbal commands. For example, commands [su]ch as 'raise your left arm', 'move your left [fo]ot' and 'make a fist with the left hand' could [no]t be carried out. In one patient (L.B.) control [fo]r this type of movement was present already [on] the first postoperative day; in the majority it [ha]d returned by the end of the second week. In [th]e other patients, the left-sided apraxia was [m]ore enduring and in one person (W.J.) the [im]pairment is still present four and one-half [ye]ars following surgery. During the initial [pe]riod when the left-side apraxia to a verbal [co]mmand was still present, the patients could [us]ually carry out the required act if it was [de]monstrated by the examiner. To what extent [th]is early deficit on the left side was caused [so]lely by division of the commissures, or was [de]pendent also on extracallosal damage is not [se]ttled.

In all cases there was gradual recovery of the [lo]st motor control, but the recovery process [va]ried considerably in its speed and in final [ex]tent in different individuals. In the two cases [te]sted most intensively, the same type of dys[pr]axia was evident in the left hand when the [in]formation projected to the left hemisphere [w]as nonverbal, as in drawing with the left hand [th]e shapes of objects presented to the right hand [or] to the right half visual field. The fact that [d]yspraxia for verbal command is restricted to [th]e left hand need not necessarily reflect uni[di]rectionality associated with cerebral dominance, in the commissural participation in praxis. It is the right hand which appears dyspraxic when certain constructional tasks are presented by nonverbal means, or when the right hand is responding to sensory input restricted to the right hemisphere. That is, praxic difficulties following division of the commissures may appear in either hand in those activities for which the ipsilateral hemisphere is specialized. Interpretation of the early post-surgical apraxia is further complicated by diaschistic, inflammatory, and other pathological factors. Hence, the gradual improvement in motor control may be attributed to a variety of factors, including subsidence of edema, recovery from diaschisis, and improvement of language comprehension in the minor hemisphere, as well as increased use of ipsilateral pathways. Accordingly, the following description is focussed on the more stable, long-term effects as observed mainly in the two select cases (N.G. and L.B.).

No basic motor impairment was evident in tasks where the motor control involved the main or contralateral system (i.e. the major hemisphere–right hand and minor hemisphere–left hand combinations). However, there was some tendency after surgery to use the left hand less than usual, under ordinary conditions. Special effort and stimulation was often necessary to bring the left hand into action. In general, motor symptoms were particularly evident in those activities in which a hemisphere was required to direct movement of the ipsilateral extremities. Good ipsilateral control was first attained for responses carried out by the axial and more proximal limb musculature. Thus responses that involved pointing to an object were performed well in the second month. After several months, most of the patients could form a variety of hand and finger postures, with either hand to verbal instructions. This included for example 'stick out your left middle finger', 'make a circle with your thumb and little finger', etc. Even writing with the left hand was possible when free shoulder movement was allowed, although the penmanship was crude compared to that of the right hand. Eventually the writing with the left hand could be performed by L.B. with finger and wrist movement alone with the forearm fixed.

Crossed motor control is measured by flashing to right and left visual field outlined sketches of the hands and fingers in different postures (Fig. 5). The subject then mimics these with the hand on the same or opposite side. The responses break down in the commissurotomy patient when the hand response is on the side opposite the visual input. Again, simple postures, such as the closed fist or the open hand or the extended thumb can be achieved under these conditions by some patients, but more differentiated poses that are readily copied on the same side fail when the contralateral hand is employed. The deficit was especially marked when the nondominant right hemisphere attempted to control the right hand. Using this combination, the patients were usually unable even to make a fist or to merely spread out the fingers and hand as a whole. Whether the occasional success of the left hemisphere–left hand combination reflects ipsilateral corticospinal control of the forearm musculature remains unclear. It may be that these simpler movements follow in part as a natural conse-

quence of movement patterns initiated at t
shoulder level.

What ipsilateral manual control was prese
seemed to be easily overpowered at any tir
by the contralateral system whenever the o
posite hemisphere decided at the same mome
to make a different movement in the sar
hand. In other words, the right hemisphere c
direct the right hand toward a particular obj
only if the left hemisphere does not at the sar
time have contradictory information as to wh
it thinks the right hand ought to be doing. F
example, a triangle flashed to the right hem
sphere can be drawn by the right hand provid
some other figure is not also flashed to the l
hemisphere at the same time. In the latter ca
the right hand seems to be obliged to draw t
figure seen by the left hemisphere. Again, a
tivity in the contralateral system suppresses
cancels that in the weaker ipsilateral system.

Other problems in motor control arise wh
both hands are working together on the sar
or separate tasks. Inability to do two differe
things concurrently as in writing with the rig
and sorting cards with the left hand was stat
to be the most consistent symptom in the earl

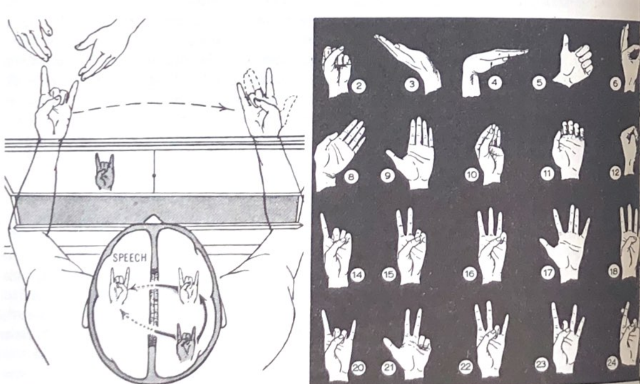

Fig. 5. One of a series of sample hand poses as shown above on right is projected in outline to right
left visual field and subject attempts to copy the posture with the homolateral and/or contralateral ha
The specific pose to be copied may also be impressed on one hand by examiner.

Akelaitis series (Akelaitis 1944). The present
patients were fairly good at coordinate use of
he two hands, as for example in catching
hrown objects, or in judging two objects, and
ne of Akelaitis' cases could play the piano and
ype by touch after complete section of the
allosum. In these latter activities both hands
vere presumably governed through the major
emisphere.

The capacity of either hemisphere, and par-
icularly the left hemisphere, to control the ipsi-
ateral as well as the contralateral arm accounts
or many of the discrepancies between the pres-
nt picture of the cerebral deconnection syn-
rome and that described a few years ago
Geschwind and Kaplan 1962; Gazzaniga et al.
962) – like the ability to write and to carry
ut verbal commands with the subordinate
and, and to draw with one hand the shapes of
bjects presented to the other hand or to the
pposite half visual field. Ipsilateral motor con-
rol and other less robust cerebral functions like
anguage comprehension in the minor hemi-
phere appear to be more easily disrupted by
xtracallosal damage, leaving in control only
he sturdier crossed systems.

It would seem reasonable to conclude from
ome of the foregoing that the initiation of
oluntary responses was not restricted to the
najor hemisphere. However, the presence of
peech, writing, calculation, the bulk of lan-
uage comprehension, and the ideation de-
endent on all these, along with the motor and
ensory representation of the dominant hand
vould strongly favor the left as the leading
emisphere. Except in those special testing situ-
tions in which considerable care was taken to
voke leading activity in the minor hemisphere,
ne had the impression that the separated major
emisphere was in command most of the time.
lthough good ipsilateral motor control of the
ft extremities was evident after commissuroto-
ny, it did not fully return to the preoperative
roficiency. It would thus appear that the cal-
osum normally plays an important role in the
ontrol of hand movements that are directed
om the homolateral hemisphere. The exact
ature of the information transmitted across the
allosum in such motor activity, as well as in its

various sensory and associational functions, remains to be determined.

MASKING OF DISCONNECTION SYMPTOMS IN ORDINARY BEHAVIOR

Whereas specific behavioral tests indicate, as described, a high order of mental activity in each of the disconnected hemispheres, and an almost complete functional separation of gnostic processes, remarkably little evidence of this splitting and doubling of the mental controls is apparent in general behavior. The great majority of the symptoms described above are readily concealed or compensated for, when the special restrictions of the testing procedures are lacking. The visual symptoms, for example, including the presence of two separate inner visual worlds is not apparent ordinarily to either the patient or an observer. These people do not complain spontaneously about a perceptual division or incompleteness in their visual experience, nor in all probability does the right hemisphere either experience a divided visual field. One can compare the visual experience of each hemisphere to that of the hemianopic patient who, following accidental destruction of one visual cortex or even hemispherectomy, may not recognize the loss of one half of visual space until this is pointed out in formal tests. The visual defects are only conspicuous when the visual material is flashed at 1/10 sec or less to prevent scanning by rapid eye movements.

Similarly the cross-integrative impairments in manual stereognosis are not apparent unless vision is excluded and auditory cues carefully controlled. Objects to be verbally identified must be kept away from the right hand and from the head and face. In many tests the major hemisphere must be prevented from talking and thus giving away the answer to the minor hemisphere through auditory channels. Similarly the minor hemisphere must be prevented so far as possible from giving nonverbal signals of various kinds to the major hemisphere. There are many indirect ways in which an informed hemisphere can cue in the uninformed hemisphere and hence conceal the commissural defect in unrestricted behavior.

minor hemisphere still leaves much to be answered (Mountcastle 1962; Zangwill 1964; Ettlinger 1965). There was no question but that in most of the postoperative tests administered, the right hemisphere has been decidedly less proficient than the left. The extent to which the comprehension of language in the disconnected minor hemisphere is a result of postoperative learning also remains a question.

The above description is to be applied with caution in other respects as well. It applies to a complete surgical division of the commissures in the presence of relatively little additional cerebral damage. Complications introduced in different types of clinical cases by partial, sequential, or progressive lesions of the commissures and also by different patterns of associated cerebral damage, when added to individual differences in asymmetry of both structure and function, along with other variables introduced by training, by age, native intelligence, and related factors add up to a variety of possible manifestations of symptoms in the clinic that become truly formidable in their complexity and diagnostic complications. In any practical application of the foregoing, allowances should be made accordingly and also for the great plasticity of the neocortical systems in general.

Addendum

Since the above was written, the testing program has been continued with studies still in progress on the same patients and also on 4 additional new patients of Dr. Vogel, all with the same surgery. The more recent findings confirm in the main the general syndrome as described above and extend its manifestations into olfactory and auditory modalities. The capacity for calculation in the minor hemisphere now appears to have been underestimated in the above, and some of the more elemental (midbrain) attributes of vision as well as of somesthesis have since been found to transfer across the midline. Otherwise the more recent developments are largely in the nature of individualized qualifications and natural extensions of the basic syndrome as described. Some

of these later details are included in subsequ
publications (Sperry 1967a,b, 1968a,b; Gord
and Sperry 1968; Milner et al. 1968).
These more extended observations reveal
impressive array and range of individual var
tions for so small a patient series. Since th
variations occur in both directions, i.e. tow
greater and also toward lesser severity in diff
ent instances, the above account continues
stand as a reasonable average for the syndro
At the same time the degree of individual var
tion as such would seem to reflect a high
gree of functional plasticity in the commissu
and related systems involved, particularly dur
developmental stages. Recent application of
above battery of tests to a patient with t
agenesis of the corpus callosum disclo
almost none of the callosal symptoms produ
by surgery in the adult (Saul and Sperry 196
This patient, a college girl with a verbal IQ
111 and with an average scholastic reco
performed all the cross-integrative tasks
scribed above at an essentially normal lev
In other kinds of performances, however,
congenital absence of the corpus callosum
this 'asymptomatic' patient appears to remai
definite handicap. She is subnormal in bl
design tests, in drawing, in spatial puzzles, a
in a variety of perceptuomotor tasks. She is p
in arithmetic, especially geometry. Although
scores above normal in verbal reasoning, sh
very low in non-verbal reasoning. In general
kinds of callosal functions that are not comp
sated, appear to be those associated with
lateral specialization of mental function. Se
tive impairment is found in those activities
which the specialized non-verbal and spa
faculties of the minor hemisphere would n
mally reinforce, complement and enhance
verbal and volitional performances of the ma
hemisphere. With verbal functions clearly
vored in at least one (maybe both) hemisphe
the non-verbal, minor hemisphere faculties m
remain either underdeveloped for having
share a verbally-committed hemisphere, or
adequately integrated with the verbal he
sphere – or both.
Studies in progress along with many i
dental observations indicate that the above fu

onal syndrome that we see in this agenesis
atient is present also in more exaggerated form
1 the commissurotomy patients. Marked im-
airments are evident in the same kinds of per-
eptuomotor, non-verbal and spatially-oriented
asks. The syndrome of hemisphere deconnec-
on – the very existence of which in any form,
as long in doubt – thus continues to grow the
ore we study it. Recent findings (Levy-Agresti
nd Sperry 1968) suggest the presence of basic
rganizational differences in the surgically dis-
onnected hemisphere of a nature that would
ad to active interference effects within the
ame hemisphere. A distinct strategic advantage
an now be seen to having the verbal and non-
erbal functions develop separately within dif-
erent hemispheres.

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ology.

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