INFORMATION PROCESSING AND HIGHER PSYCHOLOGICAL FUNCTIONS IN THE DISCONNECTED HEMISPHERES OF HUMAN COMMISSUROTOMY PATIENTS

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ABSTRACT

Several patients of P. J. Vogel who had undergone cerebral commissurotomy for the control of intractable epilepsy were tested on a variety of tasks to measure aspects of cerebral organization concerned with lateralization in hemispheric function. From tests involving identification of shapes it was inferred that in the absence of the neocortical commissures, the left hemisphere still has access to certain types of information from the ipsilateral field. The major hemisphere can still make crude differentiations between various left-field stimuli, but is unable to specify exact stimulus properties. Most of the time the major hemisphere, having access to some ipsilateral stimuli, dominated the minor hemisphere in control of the body.

Competition for control of the body between the hemispheres is seen most clearly in tests of minor hemisphere language competency, in which it was determined that though the minor hemisphere does possess some minimal ability to express language, the major hemisphere prevented its expression much of the time. The right hemisphere was superior to the left in tests of perceptual visualization, and the two hemispheres appeared to use different strategies in attempting to solve the problems, namely, analysis for the left hemisphere and synthesis for the right hemisphere.

Analysis of the patients' verbal and performance I.Q.'s, as well as observations made throughout testing, suggest that the corpus callosum plays a critical role in activities that involve functions in which the minor hemisphere normally excels, that the motor expression of these functions may normally come through the major hemisphere by way of the corpus callosum.

Lateral specialization is thought to be an evolutionary adaptation which overcame problems of a functional antagonism between the abilities normally associated with the two hemispheres. The tests of perception suggested that this function lateralized into the mute hemisphere because of an active counteraction by language. This latter idea was confirmed by the finding that left-handers, in whom there is likely to be bilateral language centers, are greatly deficient on tests of perception.

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I. Introduction

The bilateral symmetry of the human body is an evolutionary adaptation which dates from the development of the earliest of the Bilateria, the flatworms. The extension of this symmetry to the morphology of the brain was seen almost from the very beginning in the first fish-like vertebrates. These vertebrates, in whom the bulk of the brain was monomorphic, still had two small identical bulges protruding from either side of the anterior end of the central nervous system. The two protrusions, which constituted the forebrain, conferred a rather small adaptive advantage, namely a primitive and poorly developed sense of smell. Nevertheless, this small advantage was enough to produce the very rapid adaptive radiation which eventually led to the mammalian brain, a brain in which the forebrain has expanded to such a degree that anatomically, physiologically, and psychologically, it dominates the lower brain centers. In primates, and most particularly in man, the bilaterally symmetric forebrain, has attained its largest relative size and has reached its highest level as the integrating organ of the brain.

In considering this double-structured brain, however, philosophers in the past, and scientists in the present, have been puzzled as to how a dual organ can yield a unified conscious function. Descartes could not accept the paradox and pointed to one of the few unitary parts of the brain, the pineal gland, as being the seat of the soul.(1)

More recently, attention has been directed to the corpus callosum, the most massive bridge of fibers in the brain which interconnects the two hemispheres, as the possible mechanism which integrates information from the two sensory half-fields. Since the late 19th century patients with tumors of the corpus callosum have been studied and their psychic functions noted. Liepmann and Mass in 1907 (2) and Hartmann in the same year(3) reported on several patients with tumors of the callosum. The primary symptoms which they noted were drowsiness, inattentiveness, and deteriorated mental processes. In addition, however, they also found a left-hand apraxia in their right-handed patients, the patients generally incapable of utilizing objects placed in their left hands appropriately. Although the investigators interpreted all the symptoms as being part of a commissurotomy syndrome, it is probable that the first set of symptoms reflected damage to other parts of the brain which the tumors had invaded. During the early 1930's Critchley(4), Alpers and Grant(5), and Bell(6) confirmed the earlier observations, also finding general mental inefficiency and deterioration, as well as left-side apraxia. In 1939 Sager and Bazgan(7) observed a woman with a callosal tumor who did not show left-side apraxia. Subsequently, however, the tumor hemorrhaged, destroying whatever remaining callosal fibers there had been, and left-side apraxia developed immediately. The authors concluded that the left hemisphere contains praxic centers, which, when disconnected and isolated from the right hemisphere causes a failure of praxic functions for the left side of the body.

All of these studies suffer from difficulties of interpretation because, in general, the tumors were anterior and extended into frontal association cortex, thus confusing symptoms arising from destruction of the callosum with those arising from destruction of frontal association areas. The true importance of the corpus callosum as an integration system was made available for investigation during the early 1940's. Van Wagenen and Herren(8) performed forebrain commissurotomies on a series of epileptic patients in an effort to confine seizures to a single hemisphere. These physicians had observed several patients who had suffered epileptic seizures which suddenly dissipated or became less frequent and severe. This sudden decrease in epileptic attacks followed the occurrence of brain lesions which destroyed association pathways. It was theorized that the destruction of association pathways prevented the spread of the seizure, and it was then reasoned that commissurotomies might also inhibit seizure spreading. The surgeons noted few, if any, cognitive or emotional changes in the patients following commissurotomies, though seizures were, to a large extent, controlled. A total of 26 patients underwent the surgery. In some, only part of the corpus callosum was sectioned. In others, the entire callosum was divided, and in two, both the corpus callosum and the anterior commissure were entirely separated.

Akelaitis (9, 10, 11, 12, 13, 14, 15), Akelaitis et al.(16), and Smith and Akelaitis(17) applied a large variety of tests to the patients in order to assess the sensory and psychological capacities of these brain-divided people. In general the tests which Akelaitis and his colleagues administered revealed no differences between the commissurotomy patients and normal subjects which could have been a function of section of the callosum. These patients continued to behave as if they had access to information about stimuli on either side of the body. In addition, no differences were seen among patients having partial or complete sections of the callosum or additional sections of the anterior commissure. Neurological science was thus back in the position of Descartes, unable to account for the anatomical-psychological inconsistency. The only explanation for the fact that cutting of the communication cable between the two half-brains results in little, if any, change in function, is that each half-brain is, to a large extent, completely equipped and functionally self-sufficient. If so, we are left with the strong suspicion that evolution may have saddled us with a great deal of unnecessary doubling, not only of structure, but also of function, in the higher brain centers. It has been known, however, since the 19th century (18, 19) that, at least in the human being, the two hemispheres are not identical. Broca found that the main language center was located in the left hemisphere, that the right hemisphere, like the animal brain, was mute. How then, were Akelaitis' subjects able to verbally identify objects presented to the left hand since sensory input from either half of the body projects to the contralateral hemisphere? Should not the patients have been aphasic for stimuli in the left sensory field? A study by Trescher and Ford in 1937(20) indicated that they should have been. Trescher and Ford reported on a woman whose corpus callosum had been sectioned through the posterior half in order to remove a tumor from the third ventricle. These investigators found the woman to be totally aphasic for objects in the left visual or left tactile field. In spite of these very interesting findings the Trescher and Ford and the earlier papers on apraxia were ignored, and Akelaitis' results were accepted as conclusive. Lashley jokingly remarked that the corpus callosum was for the purpose of supporting the rest of the brain, but what Lashley said in jest was not far from the truth as neurologists then knew it.

It was not until 1953 that interest in the corpus callosum was revived with the publication of work by Myers and Sperry on commissurotomized cats(21). Myers and Sperry sectioned the optic chiasm as well as the corpus callosum, thereby limiting the visual input to an eye to the ipsilateral hemisphere. Only very special tests could reveal an effect of callosum sectioning since the animals appeared to be normally alert, well-coordinated, and indistinguishable from normal animals upon cursory examination. However, when a visual pattern discrimination was taught to only one hemisphere, the untrained hemisphere was found to be totally naive with respect to the learning task. It was as if the animal had two brains, each unaware of the associations and memories of the other. Subsequent work by Myers(22, 23, 24) confirmed this first paper. In 1956 findings by Sperry, Stamm, and Miner further confirmed these results (25). Stamm and Sperry(26) subsequently found that somesthetic discriminations, like visual discriminations, were confined to the hemisphere receiving sensory input in the split-brain animal. Later studies in both people and animals have generally upheld these conclusions (27, 28, 29, 30).

It thus appeared that Trescher and Ford were vindicated, and that Akelaitis must have had either atypical case material, inadequate testing procedures, or else the surgery had been incomplete. Subsequent results, as well as studies to be presented in this paper, however, show that the original findings of Akelaitis cannot be disposed of so easily.

Investigations aimed at clarifying the kinds of sensory cues which require the corpus callosum for interhemispheric transfer, have revealed that there are certain classes of sensory input which are available to both hemispheres even in the absence of cerebral commissures. Apparently, simple visual and somesthetic discriminations are available to both hemispheres in the split-brain preparation. Meikle and Sechzer(31) found that brightness discriminations could transfer in the cat. Robinson and Voneida(32) also reported transfer of a brightness discrimination in the absence of the corpus callosum if the anterior and posterior commissures were intact. These results are to be expected in view of the fact that brightness discriminations can be mediated subcortically(33, 34, 35, 36) and would therefore bypass the corpus callosum. In the somesthetic realm, there seem to be ipsilateral pathways for certain types of sensory input. Studies in hemispherectomized cats, monkeys, or people indicate there is at least some small sensitivity to tactile stimuli in the ipsilateral hemisphere(37, 38, 39), and commissurotomized people are able to verbally report painful sensations from the left side of their bodies(28).

In addition to subcortical integration and ipsilateral pathways, recent investigations(40) suggest that symbolic processes in the right hemisphere, as well as compensatory strategies, can account for normal performance by commissurotomized patients.

The picture to date of the split-brain syndrome, then, is that, although certain kinds of sensory input seem to be available to both hemispheres, recognition of complex pattern stimuli seems to be confined to the hemisphere receiving the direct sensory input. It thus appears that, in addition to supporting the brain, the corpus callosum does, in fact, serve to integrate the functions of the two hemispheres.

Yet we have already seen that either half-brain is fully competent to control most ordinary behavior, and that, in reality, the double hemispheres are redundant, a consequence of the bilateral cerebral symmetry established in evolution almost a half billion years ago. Yet in man, as pointed out, the duplication of function is not complete; the left hemisphere is specialized for language. This belated tendency toward deduplication shows up in subhuman primates only with respect to a dominant hemisphere for preferred hand usage (41). In man, recent studies point to an even more specialized lateralization of function than was thought to be the case at the turn of the century. It now appears that the human species, and most probably the genus Homo, underwent an evolutionary change which resulted in a cerebral plan qualitatively different from that of lower forms. While other animals appear to have two cerebral hemispheres which are in all important respects identical, man's two half-brains are clearly differentiated in function. Though Broca(17, 18) located language in the left, so-called dominant, hemisphere, more recent workers have described the special ability of this hemisphere in broader terms, not restricted to language.

Dide(42) has described the higher order specialty as symbolic usage and Denny-Brown and Banker(43) as propositional thinking. Corresponding with the lateral specialization of the left hemisphere, more and more evidence has been accumulating which points to a right hemisphere specialty also. Work by Paterson and Zangwill(44), McFie, Piercy and Zangwill(45), Reitan(46), Hécaen and Ajuriaguerra(47), Ettlinger, Warrington and Zangwill(48), and Warrington, James and Kinsbourne(49) points to perceptual Gestalt integration as a superior function of the right hemisphere. Patients with lesions of the right hemisphere show deficiencies in drawing, in constructing block designs, in map reading, and sometimes in facial recognition, all of which reflect a breakdown in Gestalt synthesis.

The asymmetry of language and perceptual functions has also been confirmed in commissurotomy patients. The unique representation of speech and writing within the dominant, left hemisphere is clearly evident in these patients(50, 51). Such patients are unable, as a rule, to describe in speech and writing any stimulus information projected and confined exclusively to the subordinate, right hemisphere, as by presentation to the left hand, right nostril(52), or through the left field of vision. So consistent has been this evidence for the representation of verbal expression in the major hemisphere that the ability to respond correctly with a verbal description has come to be used and relied upon in many test situations as an indication that a given bit of stimulus information has been received in one or the other hemisphere. Although purely perceptual disabilities had not been demonstrated in commissurotomy patients, Bogen and Gazzaniga(53) found that the right hands of two patients (W. J. and N. G.) were deficient as compared with the left hands in drawing Necker cubes during the postsurgical period when motor control is strictly contralateral. W. J. also showed a relative incapacity at constructing block designs with his right hand. Further tests of this nature could not be carried out since bilateral motor control appeared within 2 or 3 months postsurgically. More recently, an asymmetry between the hemispheres has also been observed for a perceptual task not involving motor ability(54).

In view of the dual, but separate, sensations and perceptions, and the laterally specialized functions in the two hemispheres of commissurotomy patients, several questions are immediately raised with respect to the mechanism of unified behavioral function. How is it that two noncommunicative hemispheres can control a unified motor pattern in response to unilateral sensory inputs? Does each hemisphere have greater access to information in the ipsilateral sensory field than has been thought? If so, how does a hemisphere gain such information? Are there ipsilateral sensory pathways, central pathways through the midbrain, or do the patients use special strategies for cueing information into one or the other hemisphere? Further, if either half-brain can direct total behavior, under what conditions is such control exercised? Do the hemispheres switch control adaptively in response to tasks calling for the specialty of one or the other half-brain? How do these patients perform on tasks requiring the simultaneous usage of the abilities of both hemispheres?

These questions present themselves because we are confronted with the somewhat confusing picture of people whose hemispheres are anatomically and functionally separate, but who, nevertheless, function in everyday life as fully integrated, unified human beings, who are able to carry on all the necessary activities of living, using both hands together for complex tasks, both legs in walking, whose language usage is essentially normal, who seem to show little, if any, deficits in perception. Either our casual observations of these patients have misled us into perceiving essential normality, or the picture of the commissurotomy syndrome to date is not entirely accurate.

The present research was conducted in order to resolve some of these issues. I sought to identify the amount of information which each hemisphere receives from the sensory fields, the possible mechanisms utilized by the patients which enables them to behave in an integrated fashion, the conditions under which such integration fails, the degree of hemispheric specialization in the intact, but separated half-brains, the effect of such specialization in the performance of high level tasks requiring simultaneous and interactive usage of these specialties, and finally, possible clues as to the evolutionary reasons for lateral specialization in the human brain, a specialization which, as pointed out, is qualitatively different from anything seen in lower animals.

II. Method

A. Subjects

The subjects were nine epileptic patients of Drs. P. J. Vogel and J. E. Bogen. Eight of these patients had undergone cerebral commissurotomy for the control of epileptic seizures. The ninth patient, D. M., was unoperated at the time of the study and served as a control subject. The corpus callosum, anterior, habenular, and hippocampal commissures were surgically divided in a single operation. In some cases the massa intermedia was also sectioned. The surgery has been quite successful to date in controlling both the severity and frequency of epileptic attacks, and in some cases has succeeded in eliminating epileptic manifestations altogether.

The degree of presurgical brain damage varied widely in these patients, and psychological measures indicative of brain damage postsurgically also showed considerable variation. A description of each patient follows.

N. G.: N. G. is a housewife in her mid-30's. There was good neurological evidence that she had a small lesion in the posterior temporal lobe of the left hemisphere and a walnut-sized calcification in the central part of the Rolandic fissure of the right hemisphere. Her postsurgical scores on the WAIS (Wechsler Adult Intelligence Scale) were 83 verbal and 71 performance on a second administration.

N. W.: N. W. is a housewife 40 years old. No localizing damage was found neurologically but it is probable that the right hemisphere was damaged following ventricular blockage and subsequent pressure on the brain. Her postsurgical WAIS scores were 97 verbal and 89 performance.

J. M.: J. M. is a 38-year-old woman. In addition to the commissurotomy, she had a right temporal lobectomy. Her postlobectomy, precommissurotomy I. Q. was 102 verbal and 97 performance. Her post-commissurotomy I. Q. is 108 verbal, 76 performance. The drop of 21 I. Q. points in the performance scale following the commissurotomy is highly significant.

L. B.: L. B. is a 17-year-old school boy. L. B. showed no anatomical, physiological, or psychological evidence of brain damage in either hemisphere. His postsurgical WAIS scores are 110 verbal and 100 performance, thus placing his performance score at normal level.

R. Y.: R. Y. is a 46-year-old man. There is some evidence that he has a lesion in the right occipital lobe. His epileptic aura consisted of visual distortion. His postsurgical WAIS scores are 99 verbal and 79 performance.

C. C.: C. C. is an 18-year-old school boy in a home for the mentally retarded. He has a lesion in the medial aspect of the parietal-temporal border of the left hemisphere. His WAIS I. Q. is 72 verbal and 75 performance.

<u>M. K.</u>: M. K. is a 30-year-old woman. She suffers from severe and widespread atrophy of the right hemisphere. Her WAIS I. Q. is 84 verbal and 54 performance.

<u>A. A.</u>: A. A. is a 19-year-old high school student. He has damage to the fronto-parietal area in an area beginning at the Sylvian fissure and extending dorsalward in the left hemisphere. As a consequence of this damage the touch sensitivity of the right hand is markedly reduced. His WAIS I. Q. is 77 verbal and 82 performance.

<u>D. M.</u>: D. M. is a 21-year-old man who suffered from epilepsy. No localizing damage was found. Subsequent to the testing reported here, he underwent a partial commissurotomy involving only the anterior part of the corpus callosum. His presurgical I. Q. was 70 verbal and 87 performance.

In summary, evidence of hemispheric damage has been seen in all of these patients except L. B. and N. W. The performance I. Q., measuring predominantly right hemisphere function(55), falls either below or at the low end of the normal range in seven out of the eight commissurotomy patients. Only L. B. shows a normal performance score. Out of a population of eight patients, we are then left with only one whose right hemisphere can be expected to function as well as that of a normal human being. For this reason, almost all of the extensive testing of higher level psychological functions of the right hemisphere has been confined to L. B. Any deficiencies which might have been seen in these functions in other patients could not have been attributed to innate incapacities of the minor hemisphere. Given the subnormal condition of the minor hemispheres of the other patients, no conclusions with respect to the normal function of the intact right hemisphere of the normal brain would have been possible. Limited testing of the higher psychological processes was done with N. G., and her poor performance compared with that of L. B. was obvious. In essence, commissurotomy patients who are brain damaged must be considered in the same category as other brain damaged patients, and we expect, therefore, certain deficiency syndromes to appear which are unrelated to either the commissurotomy itself or to intrinsic incapacities of the normal specialized hemisphere.

In addition to these patients, 25 Caltech graduate students and postdoctoral fellows in biology, chemistry, experimental and theoretical physics, math and applied math, and in planetary science were tested in order to check an hypothesis concerning the possible adaptive value of lateral specialization. They ranged in age from 21 to 29. Fifteen were right-handed and ten were left-handed or ambidextrous.

B. General Procedure

The first tests were aimed at clarifying the degree of information access possessed by each hemisphere for stimuli in either half of the sensory field. The initial series involved temperature discrimination because Gazzaniga, Bogen and Sperry(27) and

Gazzaniga(28) had reported that temperature sensation was confined to the hemisphere contralateral to the side of stimulus input. This finding is rather surprising in view of the fact that commissurotomy patients can verbally report a painful sensation on the left side of the body(28), and it might be expected that pain and temperature sensibility would be present or not together. Both pain and temperature fibers enter the lateral division of the posterior root, synapse in the gelatinosa, and ascend together in the spinothalamic tract. A careful series of temperature discriminations tests were therefore carried out with N. G. and L. B. The exact description of these tests will be given in the next section.

The second set of tests involved stereognostic discrimination. Discrimination of shape by the ipsilateral hemisphere was reported to be totally lacking(28). This deficiency symptom was supposed to be one of the clearest pieces of evidence for the lack of an ipsilateral somesthetic system as well as for the lack of any midbrain systems sufficient for information transfer between the hemispheres. Again N. G. and L. B. served as subjects.

Linguistic capacities, as pointed out, have so consistently been associated with the left hemisphere that the ability of commissurotomy subjects to verbally describe stimuli has come to be relied upon as showing that a given bit of stimulus information has reached the left hemisphere. In other words, it has been assumed that verbal descriptions of objects presented in the left half sensory field indicated, not that the right hemisphere was speaking, but rather that the patients had somehow signalled the information into the left hemisphere. The validity of this assumption had never been rigorously determined in commissurotomy patients, and certain findings in the temperature and stereognostic discrimination tests suggested the need for a careful assessment of possible linguistic expressive functions mediated by the right hemisphere. Accordingly a battery of tests designed to elicit expressive language from the minor hemisphere, if such was possible, were given to L. B. and to some extent, N. G.

The fourth series of tests were given to R. Y., N. G., A. A., N. W., L. B., and D. M. and were designed to determine the relative abilities of the two hemispheres with respect to spatial-perceptive tasks. As mentioned previously, deficient performance on perceptual tasks has been found to be associated with damage to the right hemisphere. For these tests, R. Y., with right occipital damage, should be considered essentially identical, as a subject. to the unilaterally damaged subjects in these earlier experiments. N. G., also showing evidence of right hemisphere damage, should also be considered to fall into the brain-damaged category. Both these patients had performance I. Q.'s below their verbal I. Q.'s. A. A., while his performance I. Q. was low, at least had a score somewhat above his verbal I. Q. D. M. served as an unoperated control subject. N. W., while likely having right hemisphere damage, had a performance I. Q. within one standard deviation of the norm. Only L. B. has two normal, nonpathological hemispheres whose functions can be validly compared.

Based on the degree of hemispheric specialization found in these tests, one would expect that certain complex functions calling on the abilities of the two hemispheres simultaneously, would be seriously impaired in commissurotomy patients. Therefore, the Wechsler Adult Intelligence Scale, consisting of eleven subtests, was administered to all eight commissurotomy patients. The subtest scores were compared with those made by two groups of epileptics, one brain damaged, the other not. Dr. Charles Matthews of the University of Wisconsin provided the data for the two groups of unoperated epileptics(56).

The results of the studies on lateral specialization led to an hypothesis as to the evolutionary reasons for lateralization of function. The hypothesis predicted that left-handers would show a larger discrepancy between their verbal and perceptual abilities--verbal being superior--than would right-handers. Factor analysis of the WAIS(57) as well as performance on this test by unilaterally brain damaged subjects(55, 58) have shown that the verbal scale measures predominantly left-hemisphere language functions, while the performance scale measures predominantly right-hemisphere perceptual functions. The discrepancies between the verbal and performance I. Q.'s were therefore compared for a group of sinistrals and a group of dextrals.

III. Somesthetic Tests

The degree of ipsilateral somatosensory representation in the cerebral cortex remains somewhat uncertain. Although regions of the head and neck appear to be bilaterally represented through the 5th nerve(59), the primary somesthetic projection of the body below the neck ascends via the contralateral spinothalamic and medial lemniscal tracts. However, there exists physiological, anatomical, and behavioral evidence that an ipsilateral system is also present for regions of the body below the neck.

Ipsilateral evoked responses have been obtained by several investigators in phalangers, rabbits, cats, and monkeys(60, 61, 62, 63, 64). As pointed out previously, studies in the hemispherectomized cat, monkey, or man indicate that there is at least some small sensitivity to tactile stimuli in the ipsilateral hemisphere(37, 38, 39). Some researchers have even reported a complete absence of aphasia or agnosia for somesthetic stimuli whose input was via the left or nondominant side of the body in human patients lacking a corpus callosum(14, 65). Such a finding indicates either an ipsilateral projection or the presence of speech in the minor hemisphere.

Other investigators, in contrast to the above findings, have found severe somesthetic deficits in the recognition of ipsilateral stimuli. Geschwind(29) has found complete tactile aphasia in a patient with a lesion in the midportion of his corpus callosum. Gazzaniga, Bogen and Sperry(27) report that cross-localization of touch, temperature discrimination requiring cross-communication between the hemispheres, and speech recognition of left-side body position were all lacking in a commissurotomized man. Gazzaniga(28) saw these same deficits following commissurotomy in another patient. Absence of interhemispheric transfer of a tactile learning task was found by Russell and Reitan(66) in a patient who had agenesis of the corpus callosum. Recently Lee-Teng and Sperry(30) reported that split-brain monkeys were unable to cross-match somesthetic stimuli according to size.

A. Temperature Tests

1. Introduction

With respect to temperature discrimination, as pointed out(27, 28), commissurotomized patients have been completely deficient in cross-matching or cross-comparison for regions of the body below the neck. This finding is rather surprising in view of the fact that patients can verbally identify a painful sensation on the left side of the body(28). It might be expected that pain and temperature sensibility would be present or not together since both pain and temperature fibers share similar central pathways, one of which is an uncrossed, short-chained pathway which ascends via Lissauer's fasciculus, another being the ipsilateral spinothalamic.

The present study presents the results of a more intensive investigation of the lateralization and cross-integration of temperature discrimination in two commissurotomy patients at 3-1/2 and at 2 years after surgery.

2. Case Material and Procedure

a) Subjects. Two subjects were studied who had previously shown the general symptoms of hemispheric disconnection. Both had undergone cerebral commissurotomy for control of advanced epilepsy. The surgery has been quite successful to date in controlling the seizures, and both people lead essentially normal lives. These are the same two select patients from whom most of the evidence has been obtained to date regarding the sumptoms of forebrain commissurotomy(27, 50, 67, 68).

One of the patients, N. G., is a 35-year-old housewife(69). The full-scale WAIS was administered to her by the author in May, 1967. Her verbal I. Q. was 87 and performance I. Q. was 69, full-scale, 78 on a first administration. The 18-point difference between her verbal and her performance scores suggests minor hemisphere damage. This is also suggested in the particular difficulty she had with the block design subtest both with her right or left hand or with both hands together. Tests administered to her in June, 1967, by Milner(70) showed normal sensitivity for two-point discriminations on both the left and right sides of N. G.'s body.

The second patient, L. B., is a 17-year-old school boy. His I. Q. is in the bright-normal range. He was kept out of school for most of a year and lost one grade because of his surgery, but he is now back in public school in the 9th grade and is doing satisfactorily. He appears bright, has a fine rapport with the investigator, and seems to enjoy the testing situation. L. B. was also tested by Milner in June, 1967, for cutaneous sensitivity and was found to be normal(70).

b) Apparatus. Temperature stimulation was applied with two temperature applicators (Ts) made of brass tubing 1 cm in diameter and 25 cm long, sealed at one end and insulated by foam rubber tubing 3 mm thick except for 5 mm at the sealed end. The applicators were filled with water of the proper temperature and were corked with a rubber stopper holding a thermometer that indicated the temperature of the applicators (see Fig. 1). During inter-trials intervals the applicators were kept in thermos bottles containing water of the desired temperature in order to keep the temperature of the Ts constant.

In some of the tests a finger-tracing read-out was used in which N. G. was required to trace and identify the letters "S" and "O" and select the "S" if the temperatures of the two Ts she had felt were the same and the letter "O" if the temperatures were opposite. The letters were formed of 2 mm soldering wire shaped into "O" and "S". The letters were 2 inches high and 1 inch wide and glued onto a piece of plexiglas 8 x 5 inches. Because these two letters each have identical mirror-images, the plexiglas could be presented to the subject with either letter on the right or left.

Some of the tests were carried out with the subject's hand behind a masonite shield. A space 6 inches high was left at the bottom through

Figure 1. Photograph of Temperature Applicator.

which the subject's hands could be placed. A black fringe hung over the space to prevent S from seeing her hands under the shield.

c) General Procedure. Most of the intensive testing was done with N. G. A limited series of tests were given to L. B., following those with N. G. L. B.'s results were clear-cut and confirmed the findings with N. G.

Three types of tests were administered to N. G. consisting of a temperature comparison on the left side of her body utilizing a verbal read-out, an intrahemispheric and interhemispheric comparison procedure requiring a finger-tracing read-out, and finally intra- and interhemispheric comparisons with a head-movement read-out, i.e. an affirmative up-down headshake indicating that two temperatures were the same, or a negative sideways headshake indicating that they were different. Only the latter procedure was used with L. B.

The sequence of hot-cold presentations was random in all types of tests, and in the cross-comparisons, the side of the body touched first was random. The cold stimulus ranged from 20° to 25°C and the hot stimulus from 35° to 40°C.

3. Observations

In the initial series of tests the Ts were applied to the left side of the body on the foot, calf, back, upper arm, and hand of N. G. and she was asked to state verbally which was warmer. It was assumed that any verbal report would come from the major hemisphere and would indicate temperature discrimination in the ipsilateral hemisphere.

One of the Ts was placed on a particular area of N. G.'s body and allowed to remain there for one second. It was then removed, and the other T was placed on the same area and allowed to remain for one second. N. G. was then asked, "Which was hotter, one or two?", "one" or "two" referring to first and second stimulus. N. G. was lying down, either on her back or prone, with a towel draped at neck level to eliminate visual cues. Twenty trials were given for each area of the body. It had earlier been determined in preliminary trials that N. G. could perform these discriminations accurately when the right side of her body was tested. The results are presented in Table I. A Yate's correction for continuity was done for all Chi Squares.

Area	# Correct of 20	x^2
Foot	15	4.05*
Calf	15	4.05*
Back	14	2.45
Upper Arm	19	14.45**
Hand	15	4.05*

*p < .05

**p < .005

Table I

Number of Correct Trials out of 20 for Verbal Read-out Tests

As can be seen from Table I, N. G. was able to give a correct verbal response better than the 5% chance level for all areas of the body tested except the back which approached the 10% chance level. In these tests it seemed possible that the minor hemisphere might have been able to trigger the simple responses involved here especially after the prompting by the examiner.

Accordingly another testing procedure was tried in which N. G. was instructed that either a hot or cold temperature applicator would be placed on her hand, removed, and then followed by the same applicator or the other one on first the same hand and in later series on the other hand. The solid raised wire letters "O" and "S" were then presented to her left or right hand, and she was instructed to select the "S" if the two temperatures she had felt were the same and the "O" if the two temperatures she had felt were the opposite. Preliminary trials were given with both her hands with the shield removed until it appeared she understood the procedure. During preliminary testing it was established that N. G. could discriminate with both right and left hands the "O" and the "S". It was also established during pretesting that she could not cross-match the "O" or the "S" either from left to right hands or from right to left. This was in line with previous results concerning the transfer on trunk and extremities of shape information between the hemispheres. On each trial a temperature applicator was placed on N. G.'s left or right hand and allowed to remain for one second. It was then removed, and either the same temperature applicator or the other one was applied for one second. N. G. was then given the letters and allowed to select either the "O" or the "S" to indicate her answer. All testing was done with N. G.'s hand behind the shield as described in the apparatus section, so that no visual cues were available either during application of the stimuli or during read-out. Eighty trials were given, forty unilateral comparisons in which the two stimuli were both applied to the same hand, twenty to the right hand and twenty to the left and in which read-out came via the same hand to which the stimuli had been applied, and forty crossed-comparisons in which the two stimuli were applied to different hands. Twenty of these latter trials required a read-out through the right hand and twenty a read-out through the left hand. The placement of the temperature applicators on her right or left hand first for the crossed comparisons was randomized as was the sequence of hot or cold. The results of these comparisons are shown in Table II.

	Hand Controlling Read-out			
	Left Hand		Right Hand	
Type of Trial	# Correct of 20	x^2	# Correct of 20	x^2
Unilateral	9	.05	18	11.25**
Crossed	8	.45	16	6.05*

*$p < .025$

**$p < .005$

Table II

Unilateral and Crossed Comparisons Using Read-out by Manual Stereognosis

Although comparisons, both unilateral and crossed, could be carried out using the right hand for read-out, responses with the left hand remained at chance level for either type of comparison. Whether the minor hemisphere was incapable of performing under these conditions or had failed to grasp the procedure remained unclear.

A final series of tests on N. G.'s temperature discrimination involved a much simpler form of response, namely a nodding or shaking of the head for "yes" or "no" in answer to the question whether the two stimuli were the same or not the same. As above, the two stimuli were applied for both unilateral and crossed comparisons from bilaterally symmetrical areas. Four hundred comparison trials were carried out on ten areas of the body including head, neck, chest, upper arm, hand, belly, thigh, calf and foot. The exact regions tested are shown in Fig. 2. The particular area of the body tested on any given trial was randomized, but the randomization was restricted to the extent that each area of the body received 10 left-side unilateral trials, 10 right-side unilateral trials, and 20 crossed trials. The presentation of the stimuli were randomized as to hot and cold, and on the cross-comparison trials as to which side of the body received the stimulus first. The nature of the trial, whether unilateral or crossed, was randomized throughout the 400 trials. These trials were conducted over a period of five days, 80 trials being given a day during a one-hour period with five-minute breaks being given after every 20 trials. During all trials N. G. was lying on her back on a couch with her eyes covered. The results

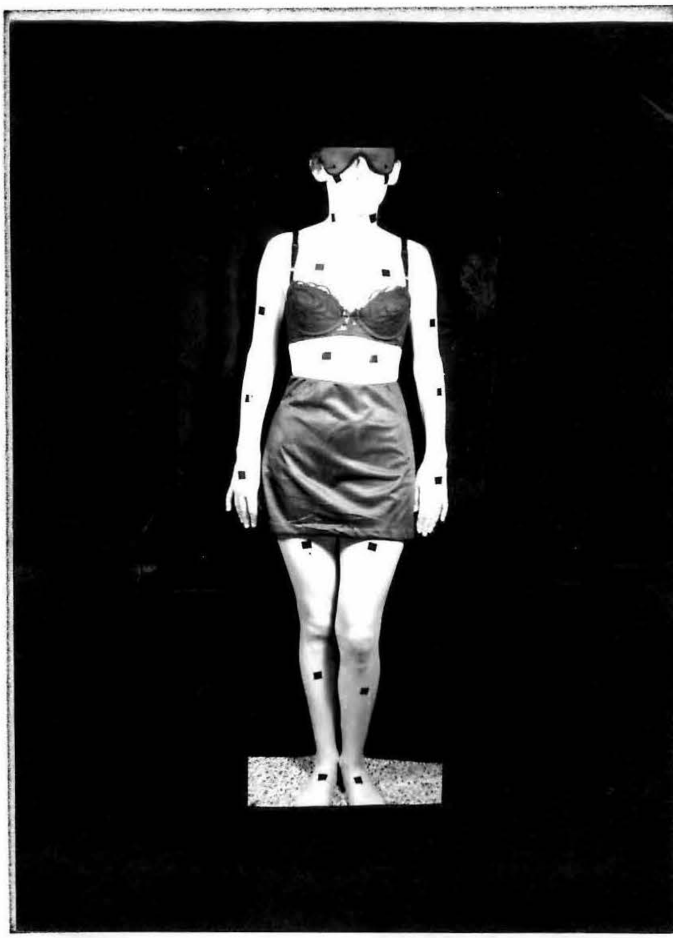


Figure 2. Exact Regions Tested for Temperature Discrimination.

of these comparisons are given in Table III. As can be seen, the unilateral comparisons on the right side of the body resulted in almost perfect scores. Except for the face and calf, no more than one out of ten errors was made. In each of the four general regions of the body as grouped in Table III, discrimination ability was far above chance. Although scores were less accurate on the left side than on the right (difference in left and right scores, excluding head and neck: $x^2 = 17.22$, $p < .005$), three of the four general body regions on the left side also resulted in above chance scores.

	Left Side		Crossed			Right Side	
Area	Correct of 10	x^2	Correct of 20	x^2	x^2	Correct of 10	x^2
Face	10	8.45**	19	14.45**	27.23**	8	11.25**
Neck	7		18	11.25**		10	
Chest	8	8.45**	15	4.05*	21.03**	9	14.45**
Belly	9		20	18.05**		10	
Upper Arm	6		12	.45		10	
Lower Arm	5	.03	17	8.45**	14.01**	9	24.30**
Hand	4		16	6.05*		10	
Thigh	7		13	1.25		10	
Calf	7	4.03*	11	.05	2.81	8	17.63**
Foot	7		13	1.25		9	

*$p < .05$

**$p < .005$

Table III

Results of Comparisons Using Head-movement Read-out

For stimuli presented to the arm region on the left side, however, scores were at chance level. In the crossed comparison tests, scores were above chance for all body areas except for the upper arm and the leg. When the data were pooled from individual areas, three of the four general regions resulted in scores far above chance. Scores obtained from the legs, however, remained at chance.

L. B. was given a total of 80 comparisons of the same nature as the last series of trials described for N. G. above. Only his hands and feet were tested. He was sitting up during all testing with his hands behind the screen and his feet underneath a draped table. L. B. scored 100% correct on all 80 trials: left foot 10, right foot 10, left hand 10, right hand 10, crossed between right and left on feet 20, and crossed between right and left on hands 20.

4. Discussion

The fact that N. G. could accurately describe verbally stimuli presented to the left side of her body can be interpreted either by presuming that temperature information was reaching her ipsilateral dominant hemisphere, or that there is minor hemisphere speech. However, data to be presented make the latter interpretation highly improbable. Except under very specialized circumstances N. G. is totally unable to describe objects by shape when they are placed in her left hand. This inability to give verbal descriptions of such objects is not the result of an inability to identify objects with the left hand, since N. G. can be shown a picture of an object and can select it by touch with her left hand, or she can feel an object with her left hand and can identify the same object visually. In view of this almost total verbal deficiency with respect to shape objects in her left hand, the idea of minor hemisphere speech seems untenable. That the left hemisphere has information available with respect to temperature stimuli coming into the left side of the body seems to be the most reasonable assumption, but whether this information is mediated through an ipsilateral pathway or whether it enters the contralateral hemisphere and is transferred to the ipsilateral hemisphere via the midbrain cannot be determined from this study.

In the cross-comparison tests using a finger-tracing read-out, the inability of the left hand to perform the read-out was at first puzzling. It seemed that perhaps information from the left side was reaching the dominant hemisphere, but that information from the right side was not reaching the minor hemisphere. However, the unilateral comparisons revealed that even when the stimulus input was directly to the minor hemisphere, the left hand was incapable of giving an accurate read-out. Pretesting had shown that the left hand was perfectly capable of discriminating the "S" from the "O", and N. G. could also trace the appropriate letter when she was instructed to do so when the tester said "same" or "opposite." Since the verbal read-out tests had already shown that the left hand was capable of temperature discriminations, and in view of the fact that the minor hemisphere was apparently capable of relating "S" to "same" and "O" to "opposite", the reasons for the deficiency in left-hand finger-tracing read-outs are not obvious. However, the use of alphabetic letters involves aspects of language and symbolic usage, and it was thought, perhaps, that it was this involvement which may have accounted for the minor hemisphere failure.

The final series of tests, therefore, used a head-movement read-out which can be controlled by either hemisphere, and which avoids the problem of language usage. In the cross-comparison tests all areas of the body except for the leg region and upper arm yielded scores well above chance. It is apparent that for most areas of the body stimulus input from both sides of the body gets into the same hemisphere where it is processed and read out. Whether such input gets into both the left and right hemispheres cannot be determined from this test, nor can it be determined which hemisphere controlled the read-out. However, since the scores for unilateral comparisons on the left were far less accurate than those on the right, and since this difference is highly significant ($p < .005$), it seems probable that the read-out for the cross-comparison trials was being controlled by the major hemisphere. It also even seems quite reasonable that the unilateral trials on the left side may have been read out by the major hemisphere. This seems to be particularly likely in view of the findings with the finger-tracing procedure in which the minor hemisphere was not able to read out at all. There is little reason to expect such low accuracy scores on the left side if the read-out had been via the same hemisphere as the stimulus input. High error scores might be expected if ipsilateral pathways are transmitting the information, or if the information is transferred via the midbrain. The known ipsilateral pathway consists of short multisynaptic connections and whether information reaches the ipsilateral hemisphere by way of an ipsilateral pathway or by way of the midbrain, more synapses are involved in reaching the hemisphere on the same side as stimulus input than in reaching the contralateral hemisphere. In terms of information theory, the pathway may simply be more noisy.

In considering the distribution of errors over various areas of the body, it is interesting that when stimuli were confined to the left side, not only the face and neck, but also the chest and belly, show the fewest errors and the distal arm regions, the greatest number of errors. If it is true that the ipsilateral left hemisphere controls the read-out, the results are explainable in terms of Trevarthen's ambient and focal fields(71). Trevarthen has presented evidence that orientational responses are controlled by subcortical regions whose integrational functions are not disrupted by commissurotomy, whereas behavior which is committed to some goal, which is focused on specific qualities of the environment, is controlled by higher neural centers which are lateralized into the two hemispheres and which are interconnected by the cerebral commissures. Those parts of the body which are most concerned with orientational responses would therefore be likely to have sensory projections which are integrated in subcortical areas. The distal arm regions, on the other hand, are most concerned with focal acts, and the sensory projections remain separately integrated in the two hemispheres. In the crossed temperature tests, the left hemisphere, requiring less ipsilateral information than in pure left side tests, manages to accurately control responses reflecting stimulation of the distal arm regions, but fails for the upper arm and legs. Why these specific failures? Strong bilateral projections are likely for the whole body areas of face, neck, chest, and belly, whereas distal arm projections would have a strong contralateral and weak ipsilateral projection. The upper arm and legs, however, present the likelihood of occlusion with bilateral stimulation. These areas most probably have projections similar to the distal arm regions, but also have strong secondary inhibitory ipsilateral projections via connections through the lower centers. The act of walking involves reciprocal inhibition between the legs, as well as between the upper arms as they swing rhythmically. Since acts of locomotion occur within a framework of reafferent effects; perceptions accompanying the action and toward which the brain makes constant predictive adjustments(72), it is likely that, as Trevarthen has pointed out(71), the system of acts and adjustments to sensory reafferences are united in a bisymmetric assemble. We therefore see that in those regions of the body in which reciprocal motor inhibition plays a large role for the dominant activity of those regions, a corresponding reciprocal inhibition for sensory events also. The failure to make cross-comparisons of sensory events in such regions would therefore be due to suppression of ipsilateral information in the hemisphere which controls the read-out.

In any case, these studies with N. G. establish with little doubt that temperature information reaches the ipsilateral hemisphere, definitely from the left side of the body to the left hemisphere, and possibly, although this could not be definitely determined, from the right side of the body to the right hemisphere.

The results with L. B. showed him to be 100% accurate on all trials--cross-comparisons as well as left and right intrahemispheric comparisons for both the foot and hand. These findings with L. B. confirm that temperature information is available to the ipsilateral hemisphere. His high accuracy score may reflect the pure commissurotomy case better than the scores of N. G. L. B. suffered very little trauma from the surgery. He was able to talk almost as soon as he recovered from the surgical anesthesia and even repeated a classical tongue twister within 24 hours after surgery. On the other hand, N. G. was mute for some time following surgery. She displayed labile emotional reactions for up to two weeks following the operation, her mood swinging from her normal happy personality into depression abruptly. X-rays showed calcification in the right hemisphere. As stated previously, her I. Q. difference on the performance and verbal scales, as well as her extreme difficulty with the block-design subtest indicate minor hemisphere damage. The relatively high error scores of N. G. on the left side unilateral, as well as on the cross-comparisons may reflect minor hemisphere damage which is not present in L. B.

The earlier findings of Gazzaniga, Bogen, and Sperry(27) and Gazzaniga(28) that temperature is only represented bilaterally in the head and neck region may result from the fact that when these patients were tested, available ipsilateral pathways had not become functional. Therapists working with neurological patients have found much improvement over time and as a result of training techniques. It is possible that the intensive testing done with N. G. and L. B. since the time of the earlier studies has had a trophic effect on previously non-functional pathways.

B. Stereognostic Tests

1. Introduction

The results to be presented confirm the physiological evidence of an ipsilateral system and indicate that the upper limits of ipsilateral stereognostic abilities are higher than that previously found by Russell and Reitan(66), Gazzaniga, Bogen, and Sperry(27), Geschwind(29), and Lee-Teng and Sperry(30). However, the degree of information processing possessed by this ipsilateral system falls quite a bit below that of the contralateral system, and the high level of functioning reported by Akelaitis(14) seems to be due to clever strategies on the part of the patient which can lead an investigator to misjudge his actual capabilities.

2. Case Material and Procedure

a) Subjects. The same two subjects were tested as in the temperature tests.

b) Apparatus and Procedure. Both N. G. and L. B. were tested with various shape stimuli for intermanual matching. The procedure was to place a test object in the subject's left or right hand and have him or her select a matching object with the other hand. In the case of N. G., the task consisted of matching with one of two objects. In the case of L. B., matching was attempted with as many as five objects.

In the second series of tests, subjects were asked to verbally identify objects held in the left hand. An object was placed in the left hand and the subject was required to either verbally designate its name or write the name of the object with a pencil held in the right hand. Such test objects were selected from groups of two or more objects. These groups were known by the subject or not, depending on the particular test. In the case of written language, E either provided feedback with respect to the correctness of the response or not since it was written out of the subject's sight.

3. Observations

a) Patient N. G.

1) Size - N. G. was tested for her ability to cross-match small plastic barrels which were equated for weight and shape, but which differed in size. The smaller barrel was 2.5 cm in diameter at its largest extension and 1.5 cm in diameter at its ends and was 3.5 cm high. The larger barrel was 3.5 cm in diameter at its largest extension, 2.5 cm in diameter at its ends and was 4.5 cm high. When

one of the barrels was placed in N. G.'s left hand, then taken away, and she then had to select the matching barrel with her right hand, the results were totally random, that is, N. G. could not make the match. However, when a barrel was placed in her right hand and she had to select the matching barrel with her left hand, she got 25 out of 30 correct during the first testing session ($p < .01$) and 13 out of 15 correct during the second testing session ($p < .01$). In summary, N. G. could not do cross-matching of size from her left hand to her right, but performed well above chance when matching was carried out from right hand to left.

2) Shape - Shape cross-matching tests were done with N. G. on three sets of stimuli. The first set consisted of a round and a square wooden rod, each 7 cm long and 2 cm in diameter; the second set, of the letters "S" and "O", formed of soldering wire, each letter 3 cm high and 2 cm wide, and the third set of a bent and a straight wire, each wire approximately 5 cm long. In none of the shape cross-matching tests was N. G. able to perform above a chance level, either for left to right matching or for right to left matching.

3) Verbal Identification - N. G.'s results for the verbal identification test in which she was asked to name an object in her left hand showed that she could perform above chance on this task when only two objects were used from a known set. When the two barrels were placed in succession in her left hand and she was asked, "Which was larger, the first or second?" she got 16 out of 16 trials

correct. When the round and square rods were placed in succession in her left hand, either the round first, or the square, in random order, and she was asked, "Which was square, the first or second?" she got 21 out of 30 trials correct ($p < .05$). When either one or the other rod was placed in her left hand and she was asked, "Which is it, round or square?" she got 25 out of 29 trials correct ($p<.005$). The discrepancy between the left-to-right cross-matching for size as well as all cross-matching tests for shape, and the performance on the verbal tests, led the investigator to do further testing utilizing a written read-out with the right hand. In this case, N. G. was handed either the round or square rod in her left hand and was told to write either the word "round" or "square" with her right hand, hidden from sight. She was unable to give accurate responses on this task, performing at chance level over 30 trials. There are two obvious differences in vocal and written language read-outs which could have accounted for the difference in results. With vocal read-outs, a subvocal movement of the speech organs would provide kinesthetic sensory cues which would project bilaterally into both hemispheres. A subvocal "test" response initiated by the major hemisphere would be perceived by the minor hemisphere, which could then signal the major hemisphere by any small head movement to go ahead and give the vocal response or to change the response, depending upon whether the minor hemisphere perceived the initiated subvocal "test" response to be correct or not. That is, the minor hemisphere could perceive a response initiated by the major hemisphere and could either accept it or reject it. A written read-out by the right hand provides no such bilateral feedback in N. G. Her minor hemisphere would not know what the major hemisphere intended the right hand to write. A second difference in vocal and written read-outs is that, not only are pre-response cues possibly available with vocal read-outs, but also post-response cues. With a vocal read-out the minor hemisphere can hear the answer and know whether it was correct or not. With a right hand written read-out, the minor hemisphere has no way of knowing whether the response which was given was correct or not. That is, the minor hemisphere would not be aware of what the major hemisphere had directed the right hand to write.

Although it was impossible for us to control possible pre-response cues, we could equate postresponse cues for both types of read-out, by telling N. G. after she had written an answer, whether it was correct or not. That is, if her left hand was holding the round rod and her right hand wrote "round", we could say, "Yes, round; that is correct." Under a feedback condition such as this, N. G. performed as well on the written read-out as on the vocal read-out, getting 13 out of 15 correct ($p < .01$). In no case could N. G. give vocal read-outs of objects placed in her left hand which had been selected from an array which was unknown to her.

To summarize the data for N. G.: She could cross-match size only from right hand to left; she could give a perfect vocal read-out for size; she failed all shape cross-matching tests, but was well above chance on vocal read-outs of shape when the set of shapes was known; she failed the written read-out test for shape in the absence of feedback, but was well above chance on the written read-outs if E provided feedback as to the correctness of her responses. She could in no case give a vocal read-out of objects selected from an unknown array.

b) Patient L. B.

L. B. was not tested for size cross-matching because other tests had shown a bilateral representation of proprioceptive cues from the hands.

1) Matching Tests - L. B.'s cross-matching data for the round and square rods were similar to N. G.'s data for size. His left hand to right hand cross-matching scores were random, but on the first testing session with right to left matching he got 0 of 10 trials correct. A score this inaccurate would occur by chance less than one time in a hundred. On the second testing session he got 20 out of 26 correct ($p < .02$). It is important to note that in neither testing session were his scores for right-to-left matching random. He was also tested for cross-matching with three wooden objects, the round and square rod, plus a third round rod in which a slice was cut off longitudinally, thus making the cross section resemble a 3/4 moon. Again with left-to-right matching, his responses were random, but with right-to-left matching he got 11 out of 15 trials correct (chance = 5 trials correct, $p < .001$).

The cross-matching data for N. G. and L. B. are summarized in Table IV.

Patient	Left-to-Right			Right-to-Left		
	Size	2 Shapes	3 Shapes	Size	2 Shapes	3 Shapes
N. G.	Random	Random	No Tests Done	25/30 $p < .01$	Random	No Tests Done
L. B.	No Tests Done	Random	Random	No Tests Done	0/10 $p < .001$ 20/26 $p < .02$	11/15 $p < .001$

Table IV

Summary of Somesthetic Cross-matching Data

2) Verbal Tests - Verbal read-out tests for L. B. showed that he was almost always able to say "round", "square", or "moon" (for the round rod with a side cut off) appropriately when an object was placed in his left hand (17/18, $p < .001$).

However, if unknown objects, such as a plastic cup, plastic spoon, wooden pipe, or pencil were placed in L. B.'s left hand, he was never able to say what they were. The only cases in which he was able to name a familiar object from an unknown array, were those in which objects of high thermal conductivity, compared to the other objects, were presented to him. If a metal spoon was presented among an array of plastic objects, he would sometimes say "spoon", although just as often he would say "fork" or "knife". The previous study, however, has shown that temperature sensitivity projects bilaterally. In any event, with a known array of objects, L. B.'s verbal ability was little different from that of a normal subject. Nevertheless, his written read-out performance was almost identical with that of N. G.'s. When he was required to write "round" or "square" with his right hand hidden from sight and with no feedback from E, his responses were random over 32 trials. When the same tasks were given in the presence of feedback, he got 13 out of 14 trials correct ($p < .005$). Again using the three shapes, without feedback, his responses were random, but in the presence of feedback he got 22 out of 27 trials correct ($p < .001$).

A summary of the verbal read-out data for N. G. and L. B. is given in Table V.

4. Discussion

The present findings fall somewhere between those reported earlier by Gazzaniga, Bogen, and Sperry(27) and Geschwind(29) and those reported by Akelaitis(4). It was found that patients lacking the neocortical commissures can do a certain amount of cross-matching of objects from the right hand to the left but only under certain conditions can they name objects placed in the left hand.

Patient	Vocal Read-out				Written Read-out		
	Size	Shape Comparison	Known Shape Designation	Unknown Shape Designation	No Feedback	Feedback	
N. G.	16/16	21/30	25/29	Random	Random	13/15	
	$p < .0001$	$p < .05$	$p < .005$			$p < .01$	
L. B.	No Test Given	No Test Given	17/18	Random	Random	2 Shapes	3 Shapes
			$p < .001$			13/14	22/27
						$p < .005$	$p < .001$

Table V

Summary of Language Read-out Data for Left Hand Somesthetic Discriminations

It would appear that a weak ipsilateral somesthetic projection system is present which allows the major hemisphere to differentiate objects held in the left hand, but which is not sufficient to allow recognition of precisely what the objects are. In other words, the major hemisphere seems to be aware that two or three objects felt by the left hand are different from one another, but is unaware of just what these objects are. The ability to give a verbal label would then be due to the fact that the major hemisphere is aware that a felt object must be one of a set of two or three objects known by the major hemisphere. If a vocal response is given, the minor hemisphere can hear the response, will know if the response is right or wrong, and can then signal the major hemisphere by some small head movement as to the correctness or incorrectness of the response. In fact, in almost every case where a wrong vocal response was given, both N. G. and L. B. immediately corrected themselves. (Only the initial responses are given in the data tables.) By such a method, the major hemisphere could learn after a few trials just what verbal label to assign to a given object. If an object feels a given way to the major hemisphere, it is given one verbal label; if it feels another way, it is given another verbal label.

If such a mechanism is, in fact, at work, it would explain the written read-out results. In the absence of reinforcement the major hemisphere would have no way to learn the appropriate verbal labels, but if reinforcement is provided, then, as with vocal speech, the major hemisphere can learn the appropriate labels. This mechanism would also explain the patients' failures to name objects selected from an unknown array and can also account for Akelaitis' positive results. Akelaitis presented common objects such as pencils, keys, matches, etc. to his patients, objects which he carried typically on his person, and with which the patients became familiar(9).

The cross-matching data present more difficulties of interpretation. In the cross-matching situation there is no reinforcement. The patient has no way of knowing whether his selection is correct or not, and we cannot assume that a hemisphere perceives an object held in the contralateral hand in the same way as it perceives an object held in the ipsilateral hand. Congruent with the written read-out, no reinforcement data, left-to-right cross-matching was failed by both patients on all tasks. However, the right-to-left data present a different picture. Here N. G. was successful with size, but not with shape, and L. B. was successful with either two or three shapes.

The first question to be asked is: how can the patients be successful on any cross-matching? If at least some information reaches the ipsilateral hemisphere and if the patient is clever, he should be able to make consistent responses, even if they are inaccurate. That is, if each of a set of objects feels different, he should be able to decide that each object represents a particular quality, be that quality round or square, and he should then be able to consistently assign one quality or the other to a given object. On L. B.'s first right-to-left cross-matching test with two shapes, he was incorrect on all ten trials, suggesting that he did use the strategy of being consistent. He was just unlucky enough to assign the wrong qualities to the objects. N. G., on the other hand, failed all shape cross-matching tests, but N. G., having a performance I. Q. of only 69, may not have been clever enough to develop a "consistency" strategy, based on a low level of information input. Her positive results for size discrimination may be due to a higher level of information input for size than for shape.

The second question, of course, is: why were the patients successful on right-to-left matching, but not left-to-right? We can assume that there is an ipsilateral projection from the left hand to the major hemisphere, based on our language read-out data, but we do not know if there is an ipsilateral projection from the right hand to the minor hemisphere. We can therefore start from the premise that the major hemisphere, at least, has access to somesthetic information from both left and right hands. That it is the major hemisphere which performs the matching task is suggested by the previous temperature study in which it was found that N. G.'s minor hemisphere was deficient at comparison tasks.

Based, then, on the idea that only the major hemisphere performs the matching task, the results become more explainable. In left-to-right matching the stimulus object is placed in the left hand. The major hemisphere is unaware of precisely what the object is, there is no second object with which to compare it, and the major hemisphere will never, in any case, ever learn what the object is. The object is then taken away, and the right hand must make a selection. The major hemisphere is now completely aware of the choice objects, but the stimulus object is no longer present. Could the presence of complete, full-blown contralateral information in the major hemisphere block the memory of what was, at best, a vague impression? In right-to-left matching, on the other hand, the stimulus object is placed in the right hand and the major hemisphere is fully aware of what that stimulus is, be it round, square, or partially round, and presumably the major hemisphere would immediately assign a verbal label to the object. When the object is taken away and the left hand is left to make a choice, the major hemisphere is aware of differences in the choice objects and must then direct the left hand to choose one of the objects which the patient decides corresponds with the stimulus. As pointed out previously, with a somewhat low level of ipsilateral stimulus input, the decision may be wrong, but it can at least be consistent since, in this situation, the left hand always has at least two objects to compare. In essence, with left-to-right matching the major hemisphere must identify a single, isolated ipsilateral stimulus, remember it, and then make a choice from a fully recognized set of choice objects, while in right-to-left matching, the major hemisphere must only be able to discriminate the ipsilateral choice objects and choose one which corresponds with a fully known stimulus object.

It would appear from our findings that an ipsilateral somesthetic system is available, at least from left hand to left hemisphere, which can mediate a low level of stereognostic information that is sufficient to discriminate a set of objects, but which is insufficient to identify their precise qualities. This system allows the patient to verbally identify objects selected from a known set, but does not provide enough stimulus information to allow verbal identification of objects from an unknown set. Knowledge of results permits the major hemisphere to assign appropriate verbal labels to objects felt by the left hand. A "consistency" strategy can permit nonrandom responses in right-to-left cross-matching.

IV. Tests of Special Abilities: Language and Perception

The asymmetry of the two hemispheres of the human brain is a well established tenet of neurology. However, the specific nature of major and minor hemispheric abilities is not at all clear. Although the differentiation has mainly been described in terms of language for the left half-brain and constructional praxis for the right half-brain, these categories leave much to be desired. Both descriptions are in terms of output functions of two "black boxes." The real aim is to provide an explanation eventually in anatomical and physiological terms, at present, at least in psychological terms, of the mechanisms underlying such output.

By an intensive consideration of the nature of the outputs, it should be possible to at least offer a suggestion as to the underlying psychological mechanisms. Several studies, conducted over a period of 25 years, reveal a certain consistency which gives us clues as to the central factors responsible for the differing outputs.

A summary review of these studies will be given and their significance subsequently discussed. Paterson and Zangwill(44) reported on two patients whose right hemispheres had been damaged, the first by a penetrating brain wound, the second from a pony kick. The first patient had great difficulty telling time, and could only do so by noting the individual positions of the clock hands separately and calculating time. He was normal on verbal intelligence, but was quite deficient on high-grade visual-spatial tasks. He could draw two-dimensional objects, but not complex designs. There was a confusion of perspective, depth, and planes, as well as a disproportion in relative size. He always drew piecemeal--i.e., item by item, and appeared to lack any grasp of the object as a whole. He was quite poor on block design tests. The second patient, like the first, could reproduce two-dimensional shapes, but not complex objects. He was preoccupied with minute details, ignoring the overall configuration. He was deficient on block design tests. He could identify rooms he had seen previously only by recognition of individual objects. In 1950 McFie, Piercy and Zangwill(45) examined eight patients with right hemisphere lesions. Although there was no overall intellectual impairment, the patients suffered from severe visual-spatial deficits on visual-spatial tasks such as map drawing and block design. Hécaen et al.(73), in examining patients in whom the right parietal cortex had been removed for control of epilepsy, found much difficulty with perspective drawing, dressing apraxia, and two patients with prosopagnosia (facial agnosia), thus confirming earlier studies.

Many workers at this time were beginning to attribute the deficits resulting from right hemisphere damage to unilateral spatial neglect of the left sensory half-field. It was suggested that such neglect only occurred with right hemisphere lesions, but not left. However, Battersby et al. examined 122 patients for spatial neglect (74) and the side of lesion noted. No significant difference was seen in the incidence of spatial neglect between patients with left and right hemisphere lesions. It thus appears that the "minor hemisphere syndrome," whatever may characterize it, is not simply due to unilateral neglect. Ettlinger, Warrington and Zangwill(48) confirmed the Battersby study in ten patients with right hemisphere damage, finding a deficit in appreciating Gestalts, which could not be attributed either to unilateral inattention or to a sensory impairment.

By 1959 researchers were becoming convinced that there was some essential difference between the hemispheres in the methods which were used to process information. It looked as if the minor hemisphere was a Gestalt specialist, not particularly interested in the analytic details of the world of sensation, but overwhelmingly concerned with general configuration, while, in contrast, the left hemisphere was an expert in symbol translation and analysis, but lacked configurational understanding. Reitan and Tarshes(75), proceeding on this idea of hemispheric differentiation, predicted that patients with right hemisphere lesions would perform equally on two tests involving identical configurational aspects, but one of which also involved symbolic understanding. Left hemisphere damaged patients, on the other hand, should be superior to right damaged patients on the one test, but inferior on the test requiring symbolic understanding. These predictions were fully confirmed.

It has been suggested(43) that the right hemisphere was not really specialized for Gestalt perceptive tasks any more than the left, but that such deficits were obscured in left hemisphere lesion cases by the more dramatic deficits in language and symbol usage. If this were true, we would expect the cerebral organization of perception to be the same in both hemispheres. However, Piercy, Hécaen, and Ajuriaguerra(76), in examining the lesion sites of 67 cases of unilateral brain damage with constructional apraxia, found that apraxia resulted from more restricted sites in the right lesioned group. In other words, whatever cerebral mechanism is responsible for constructional praxis, is more focally organized in the right hemisphere than in the left. Since focal organization is considered to be indicative of more highly evolved functions, it would seem unlikely that Denny-Brown's and Banker's suggestion is correct.

Not only does the right hemisphere seem to be more focally organized for constructional tasks, but the quality of constructional apraxia seems to differ for right and left damaged groups. McFie and Zangwill(77) compared a group of eight left hemisphere damaged patients with right damaged patients on a variety of tasks. In drawing, the left lesioned group, showing the reverse of right lesioned patients, produced figures with appropriate relationships and overall configuration, but which were oversimplified and lacking in detail. On the block design test, while the right damaged group appeared to be totally confused as to how to proceed, the left lesioned group proceeded systematically and produced accurate designs except for the last block. Also, the left lesioned group, unlike patients with right hemisphere damage, had no dressing apraxia.

By the early 1960's, it appeared, then, that constructional apraxias in the presence of right hemisphere lesions might be a secondary effect following from spatial agnosia, while constructional apraxias in the presence of left hemisphere lesions might be primary. If so, then right damaged apraxics and non-apraxics would perform more poorly on a purely perceptual task than would left damaged apraxics. In order to test this possibility Piercy and Smyth(78) divided left and right damaged groups into those with apraxia and those without apraxia and compared the groups on the Raven Matrices test, apparently proceeding on the assumption that the Matrices test measures perceptual ability. The face validity of the Matrices would certainly lead one to such a conclusion. In any case, Piercy and Smyth failed to confirm their hypothesis. Although the right apraxics were poorer than left apraxics, apraxics in general were poorer than non-apraxics. The authors therefore concluded that there is no qualitative difference in the origin of constructional apraxias for the two groups. This conclusion is predicated on the assumption that the Raven test really measures a visuo-spatial factor. In fact, factor analyses of the test(79, 80) have shown it to be mainly a measure of general intelligence (g-factor loading = .82) and that it measures a spatial factor (k-factor) in children, but not adults. In view of these factor analytic results, we would not expect perceptual agnosia to be measured by the test, and the authors' conclusion is not warranted. The fact that apraxics were poorer than non-apraxics probably reflects the greater amount of brain damage associated with apraxia which is likely to show up on a test of high g saturation. In fact, Arrigoni and DeRenzi(58) found that left lesioned patients were poorer than right lesioned patients on the Raven test, so that it is likely that any association between Raven scores and side of lesion is due to selection factors operating in the constitution of the two groups measured, such that, for one reason or another, one group suffers more widespread brain damage than the other. In many studies patients with aphasia are not studied due to the difficulty of communication. This type of selection naturally favors the left lesioned group's having less brain damage than a right lesioned group. In the Arrigoni and DeRenzi study, however, aphasics were included. In a subsequent study by DeRenzi and Spinnler(81) no differences were found between right and left damaged groups on the Progressive Matrices. However, a real perceptual difference between the groups did show up, not involving any motor skill. The right damaged group was poorer than the left lesioned group in recognizing incomplete figures and in detecting a figure embedded in other figures.

It thus appears that over and above any differences in constructional praxis, the right hemisphere is necessary for purely perceptual tasks of a complex character. That the two hemispheres actually use different modes of approach in processing information is strongly suggested in a study by Warrington, James and Kinsbourne(49). These authors found that although patients with unilateral lesions on either side were equally deficient at drawing, the nature of their errors were different. Patients with left hemisphere lesions tended to oversimplify and omit details, while patients with right hemisphere lesions tended to build up their drawings from parts and to include an overabundance of details.

In considering these studies as a whole, they all seem to point in one direction, namely that the right hemisphere is not merely skilled in controlling constructional tasks, but that it is more highly developed than the left for the type of Gestalt synthesis typically required in perception. It can appreciate spatial configurations, and ignore unimportant details. It shows a deficiency, however, in analysis and fails to pay attention to specific focal qualities of stimuli, and it shows a relative inability to deal with symbols. The left hemisphere, on the other hand, is an expert analyst. It is able to attend to detailed features of stimuli and can then assign some symbol to represent a given feature. Like a computer, it can analyze and describe the results of its analysis, but, also like a computer, it fails to appreciate the Gestalt. In summary, the two human hemispheres appear to be two specialists--one designed for synthesis, the other for analysis.

The studies to be discussed in this section deal with the special abilities of the two hemispheres--how they differ with respect to symbolic usage and how they differ with respect to perception. It was hoped that a more detailed assessment of the special abilities of the two hemispheres would provide clues as to the adaptive advantage conferred in evolution by the lateral specialization of function in the human brain. An hypothesis was derived and was subjected to test. The last part of this section discusses the confirmatory study.

A. Language Tests

1. Introduction

Previous studies of the language abilities of two commissurotomy patients, N. G. and L. B. (50, 82, 51), have shown that the minor hemispheres of these patients were able to comprehend spoken language at a fairly high level and could comprehend written nouns. They were unable, however, to carry out written verbal commands such as "smile" when the word was tachistoscopically flashed in the left half-field. The authors concluded that the reading ability of the minor hemisphere was confined to nouns since the patients would smile if a picture of a smiling face were flashed to the minor hemisphere instead of the word, and since the patients were unable to correctly select a smiling face when the word was presented in the left field. In other words, the inability to carry out a verb command appeared to be due, not to a lack of executive control by the minor hemisphere, but rather to an inability to comprehend the meaning of the verb. It was therefore concluded that the minor hemisphere, although understanding spoken language, was illiterate except for nouns. These results are somewhat peculiar since apparently both the mechanisms for reading and for a fairly high level of association, as seen in the spoken comprehension tests, are present in the minor hemisphere. The apparent inability of the right hemisphere to read verbs was left unexplained by the authors. However, it should be borne in mind that the testing procedures for determining if comprehension was present or not, were quite different for nouns and verbs. The noun test required that subjects select, by tactile palpation with the left hand, the named object from an array. For the verb test, the subject had to either perform some commanded act or had to point to a picture, presented in free vision, describing the verb. It seems quite possible that the latter procedures would allow a much greater possibility of major hemisphere interference than the procedure for nouns. For this reason, in the comprehension tests to be described, the read-out task for the subjects was kept identical for the various parts of speech.

Tests of language expression in these same two patients had yielded essentially negative results. Neither N. G. nor L. B. was able to describe either by vocal speech or by writing objects presented in the left sensory field. L. B. showed some evidence of expressive ability when cardboard letters 4" high were presented out of sight to the left hand, and he was directed to arrange the letters to spell a simple word like "dog". However, such spelling ability did not require that the minor hemisphere think of a word to be spelled. Subsequent tests, in which he was simply directed to "spell a word," but was not told what to spell, again yielded positive results. This latter test seems to show true expressive ability. The size of the letters was such that large muscle movements of the upper arm may have been brought into play in tracing the letters, and it is quite possible that the kinesthetic stimulation from this movement would have been bilaterally projected. In fact, the results to be described strongly indicate that L. B. does, in fact, possess bilateral kinesthetic feedback. It is therefore possible that in the above-described letter arrangement test, it was the major, and not the minor, hemisphere which did the arranging. In summary, there is no solid evidence that the minor hemisphere of commissurotomy patients possesses any expressive language ability at all. These findings, however, contrast with reports of left hemispherectomy patients who do, apparently, possess expressive language ability(83).

The studies to be presented are further investigations of minor hemisphere language capacity in commissurotomy patients. It was hoped that some of the paradoxes formerly observed could be resolved.

2. Procedure

Tests of language comprehension and expression within the right, minor hemisphere were carried out with N. G. and L. B. The comprehension tests involved measurement of the comprehension of spoken language as well as comprehension of words formed of plastic letters and read tactually with the left hand hidden from sight by a screen. Comprehension of nouns, verbs, and adjectives was tested.

The spoken language tests were carried out by having the subject retrieve, by touch alone with the left hand, either a series of objects designated by E or a series of objects which "went with" a verb or adjective spoken by E. The reading tests were similar except that the stimulus words were formed of plastic letters 1-1/2" high and were felt by the subject's left hand.

Three separate subtests were utilized with L. B. and two with N. G. in attempting to elicit expressive language from the minor hemisphere. First, two or three plastic letters, 1-1/2" high, were presented to the left hand which was hidden from the subject's view by a screen. He was told that if the letters were properly arranged they would spell a word, and that it was his task to put the letters in such an arrangement.

In the second type of test, the subjects were presented with plastic letters which were already formed into words. Their task was to feel the word and then either to say what it was or to write the word with a pencil held in the left hand, the hand screened from view. On some trials, the subject was asked only to write the word and then say what it was. On other trials he was asked to name the word first and then write it.

In the third test, administered only to L. B., instead of word stimuli, a variety of objects such as a plastic spoon, plastic key, smoking pipe, plastic cup, etc. were presented to the left hand, and L. B. was asked to write the names of the test objects.

3. Observations

a) Comprehension Tests. Both N. G. and L. B. were almost 100% accurate in retrieving objects named by E. L. B. also showed a high degree of accuracy in retrieving an object which went with a named verb or adjective. Twenty-five verb-adjective trials were given to N. G. including such words as "cool, hit, chew, sharp," etc. The correct objects for these words, selected from an array of ten objects, were a toy fan, a toy hammer, a rubber bone, and a plastic knife respectively. N. G. got 20 of the 25 trials correct. However, a reversal of this procedure with N. G. in which she was handed a specific object which she was directed to hold up upon hearing an appropriate word spoken by _E_ gave somewhat odd results. _E_ read a list of eight words at the rate of 1/sec. Only 11 of 25 trials were correct, but the distribution of errors was uneven. Ten of the 25 trials had to do with oral activities involving object-word pairs like "smoke-pipe, eat-spoon, suck-rubber nipple," etc. and 15 trials had to do with non-oral activities involving object-word pairs like "roll-ball, sit-toy chair, hit-hammer," etc. Table VI shows the distribution of errors plotted against oral vs. non-oral object-word pairs.

	Correct	Incorrect	Total
Oral	7	3	10
Non-oral	4	11	15
Total	11	14	25

Table VI

Distribution of Errors for Oral and Non-oral Object-word Pairs

When difference in error distribution was compared by the x^2 technique, a x^2 of 4.57 with a $p < .05$ was found. N. G. therefore found associations with oral activities to be easier than those with non-oral activities. The possible significance of this finding will be discussed subsequently.

In tests of tactual reading with the left hand, N. G. was totally deficient. L. B. was tested with nouns, verbs, and adjectives using four different read-outs. With nouns he had to either point to the object described, a picture of the object, or select it by touch alone. Although he was significantly better than chance on all three read-outs, he was much superior in selecting objects by touch, making only two errors in 25 trials. With verbs, he had to perform the action of a command verb, point to a picture representing an action verb, or select an object by touch which went with a verb. On no occasion could he perform the command. He was correct on 50% of the trials in pointing to the correct representation of an action verb out of nine possible pictures. He was able to select the appropriate object by touch from an array of ten objects on 21 out of 25 trials. On the adjective test, L. B. either had to select a plastic face, by touch alone (see Fig. 3), bearing the expression described by an adjective (sad, glad, mad, bad) or an object which went with an adjective (for example: hot-candle). He was 100% accurate on the face selection trials if the right hand was kept occupied building a puzzle in free vision, though on no occasion could he verbalize his choice. He performed at a high level of accuracy (19 out of 25 trials) on the adjective-object association test. In summary, N. G. was unable to tactually read with the left hand, but L. B. could read nouns, verbs, and adjectives, the accuracy of his performance being dependent on the mode of read-out.

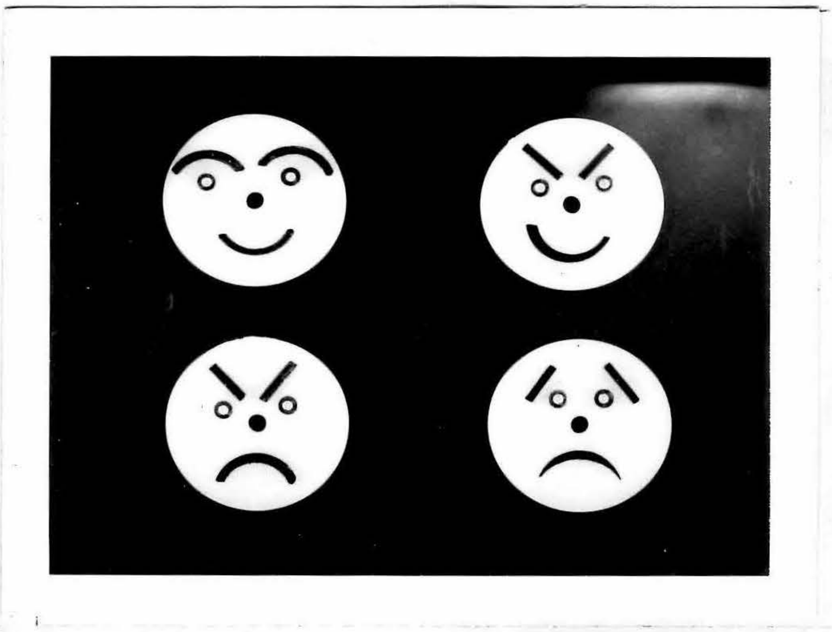


Figure 3. Plastic Faces Presented for Tactual Discrimination.

b) Expression Tests

1) Letter Arrangement - N. G. was completely unable to properly arrange the plastic letters. L. B. was extremely slow on this task and disliked it intensely, constantly complaining that he could not feel the letters, and that he didn't know what he was doing (recall that it was his major hemisphere which was speaking). Nevertheless, six trials were administered, and L. B. was accurate in all six trials, three of which involved two letters and three of which involved three letters $[(.50^3)\ (.17^3) = .0006]$. The probability that he should properly arrange all six sets of letters by chance is thus approximately six in 10,000. We can therefore assume that it was not chance which was responsible for his accurate performance, but rather that his minor hemisphere knew what it was doing. The results are shown in Table VII.

Letters Given	Word Spelled
I,F	If
A,C,N	Can
B,O,Y	Boy
E,P,T	Pet
B,Y	By
O,S	So

Table VII

Results of Letter Arrangement Tests

2) <u>Printing to Word-Stimulus</u> - On the printing test, when previously formed words were presented to the left hand, and the S was required to write it, N. G. was able to do this on only one occasion out of ten trials. Results for L. B. are presented in Table VIII.

Word Presented	S Said	Word Written	S Said
If	don't know	If	--------
So	don't know	So	--------
By	don't know	By	--------
Can	To	Man	--------
Hat	----------	Hat	Hat
Boy	don't know	Bot	--------
Pet	don't know	Pet	Pet
Soon	----------	Soon	Soon
Fat	----------	Fat	Got
Day	----------	Day	O-A-A

Table VIII

Written and Spoken Read-outs of Words Presented
Tactually to the Left Hand

L. B. was correct on all except two trials, and on these trials was incorrect in his printing by only one letter. He was never able to verbalize the word he had felt unless he had written it first. On three out of the five trials in which he was asked to verbalize after having written the word, he was correct, and on the other two trials named a word or letters which were similar in letter form to those he had printed. Note that on the word "pet" he was asked to verbalize the word twice, but could do so only after correctly printing it.

3) <u>Printing to Object-Name Test</u> - In view of the nature of the two printing errors out of the ten trials, it appeared that L. B. may not have been expressing language at all, but may have been only copying sensory outlines, a task quite similar to drawing. In the third expressive language test, he was therefore given objects in his left hand and was told to write their names. He was given only six trials since at the end of the sixth trial, he stated that he hated the task and would not do any more. Table IX shows his results.

Object Presented	S Wrote
Cup	C C
Spoon	S
Pipe	PIE NCIL
Key	Key
Cup	drew picture of cup, then wrote CUP
Doll Shoe	drew picture of shoe

Table IX

Results of Object-Name Test

The fourth trial with the key was invalid because he was able to say "key" before writing the word. In other words, he had somehow been able to tell the major hemisphere what the left hand was holding. The fifth trial with the cup is also invalid because after drawing the picture of the cup, he said "cup", presumably having discriminated his drawing with the major hemisphere via an ipsilateral kinesthetic pathway. He was therefore able to write only the initial letter of the object name on two trials and the first two letters on one trial. Figure 4 shows his printing of "PI." This particular example is rather interesting because he wrote the "PI" with much difficulty and great pressure on the pencil. He then stopped for several seconds, gripped the pencil in a much more relaxed manner, made three horizontal dashes, changing the "I" to an "E," and then wrote "pencil." After completing the word, he stopped again and then scratched out the last four letters. He was then asked to draw the object, and his drawing is at the bottom of Fig. 4. The significance of this series of events will be discussed subsequently.

To summarize, N. G. showed no ability to express language with the minor hemisphere through any means. L. B. was able to express language through letter arrangement with the left hand, through printing with the left hand of words felt with the left hand, and showed a very primitive ability to at least initiate object names. All verbalizations given by L. B. on these tests must be attributed to the major hemisphere.

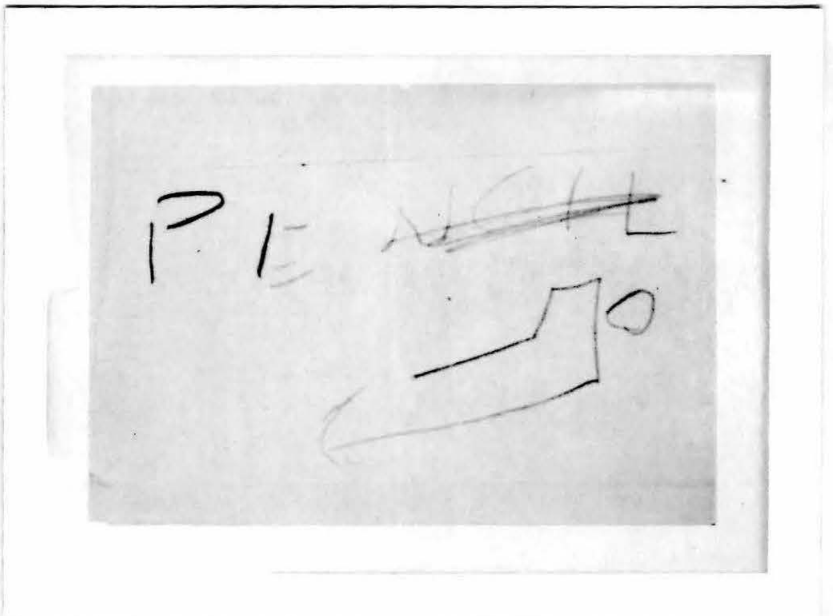


Figure 4. L. B.'s Attempt at Writing the Object-name when Handed a Tobacco Pipe.

4. Discussion

Confirming results of previous studies, N. G. showed a high level of oral comprehension with the minor hemisphere. However, she was unable to read any parts of speech tactually with the left hand.

In contrast, L. B. could not only read nouns, as formerly shown, but also adjectives and verbs.

N. G.'s oral comprehension seemed to be selective, i.e. she showed better comprehension of object-word pairs which related to activities involving the mouth than to other object-word pairs. Although these results are not easily explained, two possibilities present themselves. In the first place, oral activities such as chewing, sucking, or eating are some of the earliest motor activities of a human infant and, at first, are all mediated by subcortical reflexes. During the first year of life they are the dominant mode of interaction between the child and his environment, and, as such, have strong emotional overtones. It is possible that in the adult much stronger emotion is still associated with these activities than with other activities not related to maturational stages. If so, then oral related stimuli might well produce a higher level of attention than neutral stimuli. The minor hemisphere might then be more attentive and alert when such stimuli are presented. It is a common observation, when testing commissurotomy patients, that the minor hemisphere tends to be inattentive and any procedure which serves to keep the right hemisphere activated results in a better level of functioning. It is therefore not unreasonable that oral-related stimuli, having high emotional loading, would alert the minor hemisphere so that it demonstrates a better capacity than otherwise.

A second possibility is that the ability with oral object-word stimuli is actually cued by the major hemisphere. When each word is read off by E, the left hemisphere might initiate the action with the mouth, thus chewing when the word "chew" is read. Although N. G. showed no evidence of bilateral feedback from each side of the body, activities such as chewing are midline motor acts and would be expected to have bilateral projections. As the left hand holds a spoon, for example, the minor hemisphere might associate the spoon with the kinesthetic chewing cues, rather than with the word "chew." Such associations between somesthetic and kinesthetic cues would then be limited to midline, and, in this instance, therefore, to oral kinesthesis. The advantage of this explanation is that it accounts for why N. G. showed no selective ability when she was first given a word and then had to select an object, but did show selective ability when she was first handed an object and then a list of words was read. However, the disadvantages of this explanation are that it fails to account for N. G.'s accuracy for all stimuli in the former procedure and why E did not observe any mouth movements in the latter procedure. It appears to the author that the "alerting" explanation is probably closer to the truth since in the first procedure the overall, non-selective ability could be the result of a general minor hemisphere attentiveness maintained by the left hand's activity in searching for the appropriate object. Since no such activity was present in the latter procedure, the patient's ability would reflect the "alerting-capacity" of a given stimulus.

L. B.'s ability to read tactually depended on the mode of read-out. Using nouns as the control words, since L. B. had already shown noun-reading ability, the critical importance of read-out mode was easily observed. When required to point to the object spelled or to a picture of it, L. B. showed many inaccuracies, but when required to select the object by touch alone with the left hand he got 92% of the trials correct when the expected chance probability was only 10%. It appears that in the former two procedures, the major hemisphere, seeing the array of stimuli, was offered the possibility of interfering with the minor hemisphere's selection. That is, in these procedures, the major hemisphere could guess at what the appropriate object was and could make a selection on the basis of its guess, thereby preventing the minor hemisphere from selecting what it knew to be correct. In the latter procedure, such interference was held to a minimum since the left hemisphere could not know what the left hand was feeling. It seems that this explanation can account for the previous failure to observe verb reading ability in the minor hemisphere. The tests for verb reading confirms this explanation since L. B. was only correct on 50% of the picture-pointing trials with a chance probability of 11%, but was correct on 84% of the tactual selection trials with the chance probability being 10%. Again he showed total failure on the action-command trials. It thus appears that the more opportunity for major hemisphere interference, the greater the chance to observe minor hemisphere failure, and the more such interference was prohibited, the greater the chance of seeing minor hemisphere success. Adjective reading ability was similar to that of nouns and verbs.

In summary, the minor hemisphere is capable of reading nouns, verbs, and adjectives if the mode of read-out optimizes inhibition of major hemisphere interference.

In the expressive language tests, it seems apparent that the minor hemisphere has the capacity to express at least simple language through control of the left hand. Interestingly, the ability to express language, like the ability to comprehend language, by the minor hemisphere, is apparently closely related to the possibility of major hemisphere interference. In the letter arrangement test, in which such a possibility was held to a minimum, L. B. was at his best, while attempts to evoke vocal speech were met with total failure. Minor hemisphere speech would require the wresting of control of the vocal cords from the major hemisphere, and in such a contest between the two half-brains, the minor hemisphere was the loser. Logically, intermediate results were seen in the left hand writing tests--the minor hemisphere exercising motor control part of the time and the major hemisphere exercising control part of the time. In L. B.'s attempt to write "pipe," the competition for control between the two sides of the brain was made manifest.

However, the fact that drawing pictures of objects held in the left hand was easier than writing object names and the fact that writing a word to a word-stimulus was easier than writing to an object-stimulus, shows that, in addition to problems of efferent interference, there also seems to be an intrinsic language ineptitude in the right hemisphere. It is possible that this intrinsic difficulty reflects the fact that up until the time of surgery, the right hemisphere was totally unpracticed at organizing concepts in terms of language, and that all language learning has occurred only in the testing situation following surgery. Such learning would have occurred in a matter of several dozen hours at most. It is therefore reasonable that the earlier failures to find expressive language were due both to the procedures used to elicit and observe language, as well as to the fact that little learning had had an opportunity to occur.

The fact remains, however, that in the normal, unsplit brain the minor hemisphere is most probably linguistically incompetent, and that the process of acquiring expressive ability is apparently quite difficult. It appears that the right hemisphere tends to organize its concepts in ways quite dissimilar to those utilized by the left hemisphere. When a stimulus is presented to the minor hemisphere, the stimulus seems to be visualized and recognized for what it is, as evidenced by the ease with which such a stimulus can be graphically rendered in a drawing, but the attaching of a verbal label seems to be an abnormal and very difficult task. The observation of such an accomplishment is made doubly difficult by the major hemisphere's constant attempts to control the motor apparatus.

The foregoing observations lead one to postulate that the lateral specialization of language functions into a single hemisphere was an evolutionary adaptation that overcame the difficulty which bilateral language control would entail: namely, an antagonistic competition between the two half-brains for control of the mechanisms for language production, an antagonism which the corpus callosum would have to overcome. Whereas most of the motor systems of the body are bilaterally symmetric and their control can be assigned predominantly to the contralateral hemisphere, the control of the motor apparatus for speech cannot be divided. This explanation for the evolution of unilateral organization of linguistic mechanisms, however, does not seem to be the whole story.

B. Perception Tests

1. Introduction

The nature of right hemisphere specialization has been mainly described as constructional praxis, that is, a superior ability at constructing things, at drawing, or at any task requiring the skilled use of the hands in arranging objects in space. The distinction between the perceptual and constructional aspects of such tasks has remained unclear. However, a careful analysis of the neurological literature leads one to the conclusion that constructional apraxia following right hemisphere lesions is a secondary effect deriving from certain perceptual deficits. For this reason a test was devised which measured only perceptual understanding and which did not require any constructional skills. Furthermore, a test was needed which did not depend on unilateral control of the arm and hand for the measurement of a single hemisphere's function, because bilateral motor control develops in commissurotomy patients within a few months following surgery.

2. Procedure and Apparatus

A set of 13 cards, measuring 13 x 10", were prepared. On each card were drawn three two-dimensional representations of three-dimensional geometrical shapes. Each of the three drawings on a card represented a slightly different shape. The original three-dimensional object could be visualized if the representations were mentally folded. Corresponding with the drawings on the cards, 13 sets of wooden blocks were constructed with three blocks in each set. The appendix shows the cards. It should be noted that the 13 sets were presented in the approximate order of difficulty. One of the three blocks within a set was handed to either the right or left hand of the subject, while at the same time, the matching card was presented for his free visual inspection. His task was to feel the block and select the appropriate drawing out of the set of three on the card. Although both hemispheres could thus inspect the card, only one hemisphere knew which block was being felt, and only one hemisphere, therefore, could perform the visualization necessary for a correct selection. One block out of each set was given to the patient for a given series of trials. A series of trials consisted of 13 block and card presentations, that is, presentation of the entire set of cards. A series of trials was given first to one hand, then the other, repeated until each hand had received 12 series of trials. The selection of which block out of a set to present during a given series of trials was determined randomly except that the randomization was constrained to the extent that each block appeared four times for each hand during the 12 series of trials. At no time did the subject see the wooden blocks, nor was he told whether his choice of a drawing was correct or not. In this way, no learning occurred over the series of trials. Prior to the administration of this test, a much simplified test was given to each patient who was to be tested. The simplified test consisted of five plastic geometric shapes--a cone, pyramid, cube, solid rectangle, and cylinder--and the corresponding drawings which represented them. Subjects were tested on this preliminary test to see if they could grasp the concept of matching. If they failed on this test, they were presented with the shapes and drawings in free vision. If they still failed to match shapes to drawings, the drawings were cut out by E and were folded to show the exact correspondence with the plastic shapes. The subjects were then asked to fold the drawings. If the subjects were then successful at free vision matching, they were again tested on cross-modal matching. If they still failed the cross-modal test, testing was terminated, and they were not given the more complex test. If they were successful, the more complex test was given.

3. Observations

Of the six subjects given the preliminary test (A. A., L. B., N. G., M. K., N. W., R. Y.), two failed completely to even grasp the concept of matching a two-dimensional drawing to a three-dimensional object. Both of these subjects (M. K. and R. Y.) had evidence of right hemisphere damage. Of the four who passed the preliminary test, one, N. G., required 15 minutes of careful instruction. It should be noted that a normal 7-year-old child passed the test easily and understood the instructions immediately.

When the final test was administered, N. G. was at chance level with both hands. The results of the other three patients were all in the same direction: their left hands were superior to their right. However, A. A. suffers a sensory deficit in his right hand, so that his results do not necessarily imply visuo-spatial superiority of the minor hemisphere. N. W., although having right hemisphere damage, was still above chance on the first six of the 13 items with her left hand, but not her right. L. B., having no known brain damage, was above chance with both hands, but was vastly superior with his left. Scores were corrected for chance guessing by the formula # right - 1/2 # wrong. When this was done, N. W.'s non-chance right hand score was 1% correct and her non-chance left hand score was 7% correct. However, when only the first six cards were considered, her right hand score was 0% and her left hand score was 21% correct. This latter score yields a $x^2 = 5.64$ with $p < .02$, showing that the left hand was significantly better than chance. L. B.'s corrected scores were: right hand = 20%, left = 52% over the full series of 13 cards. These scores differ significantly from each other with a $p < .0001$. It thus appears that in both N. W. and L. B., the left hand and right hemisphere were superior to the right hand and left hemisphere.

Not only was this quantitative difference seen, but there is evidence that the two hemispheres used different strategies to solve the problems. Each card was assigned a rank score in terms of the number of times a subject was correct, a rank of one being assigned to the easiest card and a rank of 13 to the most difficult. When this was done, the rank order correlation between L. B.'s and N. W.'s left hand scores was .75, but between L. B.'s two hands was only .60. Furthermore, the rank correlation between L. B.'s right hand scores and an unoperated epileptic control (D. M.) was .83. In other words, the orders of difficulty for L. B.'s two hands were more dissimilar than L. B.'s and N. W.'s left hands and L. B.'s right hand and an unoperated subject. These correlations suggest that the problems were solved in different ways by L. B.'s two hands. When the items were checked to see which ones showed the largest rank discrepancy, certain consistencies appeared. The item showing the largest rank discrepancy in favor of the right hand (item 7) contains figures which yield themselves to a fairly simple analytic description, but results in not easily discriminable visualizations. The item showing the largest rank discrepancy in favor of the left hand (item 2) contains figures which would be rather difficult to differentially describe, but which yield themselves to easily discriminable visualizations.

Certain other interesting observations of L. B.'s performance were noted. Although, unfortunately, no record was kept of L. B.'s response times, he seemed to give very rapid responses when the blocks were being felt by the left hand, on the order of two or three seconds. When blocks were handed to the right hand, however, he generally responded only after a delay of 15 or so seconds. Also, when blocks were being felt by the right hand, he had a very strong tendency (not easily inhibited by E) to talk out loud to himself describing the block properties, saying such things as, "Two rough sides, opposite to each other." Even when we finally managed to inhibit the talking, he still tended to move his lips in subvocal speech.

After completion of this study, L. B. was given a standardized test of three-dimensional visualization (Space Relations Test, Form A, of Differential Aptitude Test Battery, 84) in order to assess his percentile rank within a normal population since his left hand performance on the cross-modal test seemed adequate. Surprisingly, L.B. got a score of zero, scoring lower than 99% of the population of his age and education. Subsequent standardization of the cross-modal test on a group of college sophomores at the University of Southern California(85) showed, however, that L. B. was at the 31st percentile, scoring better than 31% of college sophomores with his left hand. The only basic difference in the cross-modal test and the Spatial Relations Test, Form A, is that the latter is a purely visual, paper and pencil test, requiring the subject to inspect a drawing of an opened-up shape and then to designate which of five three-dimensional drawings of closed shapes matches the stimulus figure. For L. B., another difference is that the stimulus figure is presented only to his right hemisphere in the cross-modal test and to both hemispheres, in free vision, in the Spatial Relations Test. The significance of the discrepancy between L. B.'s two scores will be discussed subsequently.

4. Discussion

Of the six patients tested on the preliminary test, two failed completely in spite of verbal I. Q.'s of 84 and 99 and in spite of the ease with which a normal 7-year-old passed the test. It seems that the left hemispheres of these patients, although functioning within the normal range, as measured by verbal I. Q.'s, was incapable of the visualization necessary for even understanding the test principle. This finding is congruent with previous studies of unilaterally brain damaged subjects with injury confined to the right hemisphere who showed severe deficits on perceptual tests(44, 45, 47, 48, 49, 73). In addition to these two failures on the preliminary test, N. G. failed the more complex test completely, again fitting the "right-hemisphere syndrome."

The three other subjects all showed superior left hand performance, A. A., possibly because of a right-hand sensory deficit. However, N. W.'s and L. B.'s results are clear-cut: not only was the left hemisphere deficient in the task, but the right hemisphere was competent. On a purely perceptual task, involving no motor praxis, we thus see a clear differentiation of the abilities of the two hemispheres. Not only was there this quantitative difference in the performance of the two hemispheres, however, the rank order correlations also indicate a qualitative difference. The two hemispheres appear to take a different approach in solving the problems, as shown by the fact that easy and difficult items were not the same for the two half-brains. The nature of this difference in approach was indicated by the two items showing the largest rank discrepancy between the two hands. It appears that the language-dominant left hemisphere attempted to solve the block problems by means of analysis, by observing the detailed block properties and correlating these with the properties seen on the card. In other words, the left hemisphere seemed to require a self-description of the blocks in terms of language. The mute, right hemisphere, on the other hand, appeared to use an immediate synthetic approach, almost instantaneously synthesizing the block Gestalt, visualizing it, and matching the visualizations of the felt block and the seen card. The quantitative superiority of the minor hemisphere is interpreted to be a result of the qualitative superiority of method for this task. The piecemeal drawings of right-damaged patients and the over-simplified, but good-Gestalt, drawings of left-damaged patients (44, 77) is easily understood if the left and right hemispheres are, respectively, analytic and synthetic in processing information.

The essential antagonism between these two modes of approach is clearly apparent if one considers the sequential ordering of stimulus-detail observations which is necessary in order to analyze stimulus properties, but the necessary overlooking of detail and the extraction of a single, basic Gestalt which is required for immediate synthesis. It appears that the two hemispheres have in-built strategies which are incompatible with each other. The presence of language in the left hemisphere seems to give that hemisphere such a strong propensity to observe the world of stimulus events in such a way that those events can be described, that no other means of sensory processing is possible. For example, human faces, which are extremely refractory to accurate description as a consequence of the difficulty of analysis, are recognized by the right hemisphere(47, 73). In some cases of right hemisphere lesions, but not in cases of left hemisphere lesions, the patient suffers from facial agnosia.

If the above description of hemispheric specialization is accurate, we can easily understand why perception is primarily a function of the non-language hemisphere. As suggested previously, language control apparently lateralized into a single hemisphere only partially as an evolutionary adaptation to avoid competitive antagonism between the two sides of the brain for motor control.

If it is true that language creates an analytic propensity, and if it is also true that the analytic approach actively interferes with Gestalt perception, then only a mute hemisphere would be capable of good Gestalt appreciation. If language were to have been organized bilaterally, spatial perception would have suffered as a consequence. This theory of the evolution of the lateral specialization of function, of course, rests on the assumption of a basic incompatibility of language functions on the one hand and perceptual functions on the other. It leads to the prediction that people who have poorly differentiated hemispheres, who have bilateral language centers, will show an abnormally large discrepancy between their verbal and perceptual I. Q.'s, having greatly depressed perceptual scores. The next study describes an investigation aimed at testing this prediction.

The discrepancy between L. B.'s score on the cross-modal test, presented only to a single hemisphere, and his score on the Spatial Relations Tests, administered in free vision to both hemispheres, was, at first, quite surprising. However, upon further consideration of these results, it seemed that in the latter test the minor hemisphere might be prevented from demonstrating its ability due to major hemisphere dominance. In other words, it appeared that the major hemisphere might suppress minor hemisphere expression. This result suggests a critical role for the neocommissures in activities that involve functions in which the minor hemisphere normally excels. The last study of this thesis presents results which confirm this idea.

C. Verbal and Perceptual I. Q.'s in Sinistrals and Dextrals

1. Introduction

Left-handed and right-handed people, in contrast to the widespread idea that they are mirror images of each other, in fact possess brains with very different anatomical plans. Left-handers are more frequently made aphasic by unilateral lesions on either side of the brain, but the aphasia is transitory and there is generally at least some partial recovery. If the left-handed patient then suffers a second lesion in the previously undamaged hemisphere, he again becomes aphasic(86). These results contrast very strongly with findings from right-handed subjects who show a permanent aphasia following only lesions of the language centers of the left hemisphere, and they indicate that both hemispheres of sinistrals, but not of dextrals, participate in language functions. In other words, the two hemispheres of left-handed people are less well differentiated with respect to language functions than are the hemispheres of right-handed people, and, to some extent, language is bilaterally organized in sinistrals.

This being so, it would follow that if language and perception are really incompatible functions, left-handed people, as a group, would be poorer on tests of perceptual function than right-handed people, and it would further follow that their language functions should be significantly superior to their perceptual functions. The relative pattern of their verbal and perceptual I. Q.'s should look similar to that which is seen in patients with minor hemisphere damage.

2. Procedure

The Wechsler Adult Intelligence Scale (WAIS)(87) is an instrument which is particularly suited for testing these possibilities. The WAIS yields three I. Q. scores: a verbal I. Q. (V.I.Q.), a performance I. Q. (P.I.Q.), and a full-scale I. Q. (F.I.Q.). The mean for each of these scores is 100 with a standard deviation of 15. A given individual's scores reflect where he falls on a normal distribution of scores made by persons of his age. The mean of the differences, between V.I.Q.'s and P.I.Q.'s for single individuals, is zero (0) with a standard deviation of 9.6 for the full range of I. Q. scores from -3.5 standard deviations to +3.5 standard deviations. In other words, the scatter of scores with V.I.Q. plotted on one coordinate and P.I.Q. plotted on the other coordinate is homocedastic and linear.

The WAIS has been factor analyzed, and of the six subtests which yield the V.I.Q., five are found to measure a single factor, called verbal. Only the Digit Span test appeared to measure something other than verbal ability. Of the five performance subtests which yield the P.I.Q., all except Digit Symbol measure the same factor, named perceptual. Both Digit Symbol and Digit Span measured a third factor which the authors termed "distractibility"(57). Studies of unilaterally brain-damaged patients show that left-lesioned patients are better on the performance than on the verbal scale and that right-lesioned patients are better on the verbal than performance(55, 58).

These studies show that the two primary factors, verbal and perceptual, which are measured by the WAIS verbal and performance scales, measure, respectively, left and right hemisphere functions.

If sinistrals are actually depressed in their perceptual scores, the WAIS should, therefore, provide a sensitive measure of the depression. With V.I.Q. serving as the baseline, P.I.Q. should be significantly inferior, and the discrepancy between the two scores should be significantly greater than for dextrals.

Twenty-five Caltech graduate students and postdoctoral fellows were asked to participate in the study, and all agreed. These people were selected according to several criteria: they had to be either left-handed or ambidextrous, in which case they were included in the sinistral group, or they had to be fully right-handed and have right-handed parents. In addition, people were selected from various disciplines representing theoretical and experimental physics, math and applied math, physical chemistry, organic chemistry, planetary science, cell biology, genetics, and psychobiology. A group of ten sinistrals and 15 dextrals were finally selected, and the two groups were balanced as well as possible with respect to discipline. None of the subjects had ever taken the WAIS previously, and none had ever shown any evidence of neurological injury.

The administration time ranged from 45 minutes for some subjects to 1-1/2 hours for others.

3. Results

Table X presents the results for the individual subjects. It is obvious from even cursory inspection of Table X that the discrepancies for sinistrals are generally larger than for dextrals. The mean discrepancy for the left-handed group is 25.6 I. Q. points and for the right-handed group is 8.3 I. Q. points. Although both of these differences are significantly different from zero ($p < .001$ for

Subjects	Left-handed			Right-handed		
	V.I.Q.	P.I.Q.	Difference	V.I.Q.	P.I.Q.	Difference
1	150	116	34	151	150	1
2	134	114	20	135	130	5
3	147	119	28	139	139	0
4	134	114	20	138	116	22
5	144	118	26	148	114	34
6	146	127	19	142	127	15
7	140	108	32	136	145	-9
8	145	119	26	133	115	18
9	140	125	15	135	119	16
10	142	106	36	132	133	-1
11	-	-	-	147	128	19
12	-	-	-	130	133	-3
13	-	-	-	144	138	6
14	-	-	-	130	124	6
15	-	-	-	130	135	-5

Table X

I. Q. Scores and Discrepancies for Individual Subjects

sinistrals, $p < .01$ for dextrals, using one-tailed _t_ test for correlated scores), the discrepancy for left-handers is significantly larger than for right-handers ($p < .0002$, one-tailed _t_ test). The mean V.I.Q.'s of the groups do not differ significantly (Left = 142.2, Right = 138.0, $p > .10$). The mean P.I.Q.'s for sinistrals and dextrals are 116.6 and 129.7 respectively, a difference of 13.1 I. Q. points.

The chance probability of finding a difference this large is less than two in a 1000 (one-tailed t test).

4. Discussion

The results strongly support the original hypothesis: namely, that the presence of language functions in a hemisphere interferes with perception. Although the groups tested are not representative of the normal population in the sense of having exceptionally high I. Q.'s, the dextrals and sinistrals do come from the same population, and there is no reason to suppose that there is any selective bias operating which would result in left-handers with low P.I.Q.'s being admitted to Caltech in preference to right-handers with low P.I.Q.'s. Furthermore, there could have been no bias operating in the selection of the two groups tested since the subjects were only selected according to the criteria previously mentioned, and all subjects who were asked to participate did so.

The difference in the P.I.Q.'s is particularly striking in view of the fact that V.I.Q.'s do not differ. In other words, although the academic intelligence of the two groups is the same, they still show a large difference in perceptual functions. The fact that dextrals, as well as sinistrals, have higher V.I.Q.'s than P.I.Q.'s probably reflects the criteria which are used in selecting people for admission to Caltech. These criteria are correlated predominantly with V.I.Q. The difference in P.I.Q.'s of the two groups, as well as the difference in size of V.I.Q.-P.I.Q. discrepancies, show that left-handers have abnormally depressed perceptual abilities.

It is concluded that this depression reflects bilaterality of language functions in both hemispheres of left-handers, language functions which serve to produce such a strong analytic propensity that Gestalt synthesis is inhibited. Further, it is suggested that the lateral specialization of function in the human brain is an adaptation which overcame the problem of a basic incompatibility between the type of analytic information processing of stimuli which is necessary for language description and perceptual synthesis which is necessary for Gestalt appreciation.

D. Performance of Commissurotomy Patients on the WAIS

1. Introduction

As discussed previously, each hemisphere of the human brain is specialized for certain functions, the left hemisphere for expressive language and the right hemisphere for certain perceptual abilities. Results of both language and perceptual testing, however, indicated that not only is the left hemisphere dominant for language functions, it might also be dominant in the control of any motor output, suppressing the expression of minor hemisphere abilities. It was suggested that the corpus callosum might be critical for the expression of minor hemisphere specialties. In other words, it might be that in the normal individual, specialized intellectual functions of the right hemisphere gain expression via the left hemisphere by way of the corpus callosum.

The WAIS(87) was used in an attempt to assess this idea. Although both Reitan(55) and Arrigoni and DeRenzi(58) found that left-lesioned patients performed better on the performance than on the verbal scale of this test and that right-lesioned patients performed better on the verbal scale, they found that when the two unilaterally lesioned groups were compared with each other on the two scales, both groups were equally poor on the performance scale, even though the left-lesioned group was even poorer on the verbal scale. These findings suggest that in some way, the left hemisphere plays a role in the expression of both minor and major hemisphere specialties. The nature of this role for the expression of minor hemisphere functions can most logically be described in terms of the control of motor output. If this description is accurate, then it would follow that commissurotomy patients would be poorer on the performance scale than on the verbal scale, and would be particularly poor on those performance subtests which require fine motor control. It would also seem that bilaterally brain-damaged subjects might be poorer on the performance scale for the following reason: if right hemisphere abilities are read out by the left hemisphere, there may very well be no cortical areas which can serve as intercommunication areas between the two halves of the brain. The corpus callosum is a commissure, not a decussation, and, as such, it connects homologous parts of the two hemispheres. Unless, therefore, lesions on two sides of the brain are exactly homologous, functions subserved by interhemispheric mechanisms will show the greatest deficits since an uninjured part of one hemisphere will be connected to an injured part of the other hemisphere and such a connection could serve no useful function. In other words, functions which require interhemispheric communication would suffer deficits caused by lesions in both hemispheres. The area of lesions affecting these functions would be larger than the area of lesions affecting a single hemisphere's function.

We would expect to find, if these suggestions are correct, that epileptics with commissurotomy perform poorest on the performance scale since all higher level intercommunication is absent, that epileptic patients with generalized brain damage perform next poorest, and that epileptics with no identified brain damage perform best.

The data to be presented are consistent with these speculations.

2. Method

a) <u>Subjects</u>

The subjects were three groups of epileptic patients, all suffering from major motor epilepsy. Two of these groups (KE and UE) were administered the WAIS by Dr. Charles G. Matthews of the University of Wisconsin Medical School. Dr. Matthews was kind enough to supply the data for these groups who served as controls in assessing the performance of commissurotomy patients(56). Group KE was composed of 23 patients who suffered from epilepsy of known etiology, i.e. having identified brain damage. Group UE was composed of 29 patients having epilepsy of unknown etiology, i.e. no identified brain damage.

The experimental group (CP) consisted of eight neurosurgical patients who had undergone total forebrain commissurotomy. The patients ranged in age from 16 to 48 at the time the tests were administered and had undergone surgery from one to five years previously. Six of these patients were known to have brain lesions which were the probable cause of their epilepsy. One patient had bilateral damage, two had left hemisphere damage, and three had right hemisphere damage. The remaining two patients were free of any identified cerebral damage. The group is therefore mixed with respect to presence or absence of brain lesions and with respect to lesion site.

b) Procedure and Data Analysis

The WAIS was administered to all patients, and their subtest scores as well as the mean subtest score on the full scale, verbal scale, and performance scale were compared to those of Wechsler's normal standardization population with a mean age of 32.5 and a standard deviation of ten years, and each patient group was compared with the two other patient groups. This particular subgroup of the standardization population corresponds with the age of the patient groups. In all cases, only scaled scores were used in making computations. As the mean subtest scores on the full-scale were found to differ between groups an analysis was also performed on transformed subtest scores. Each subtest score was transformed by the formula: $\overline{x}'_{ij} = (\overline{x}_{ij}) (\sum_{i=1}^{11} \overline{x} \text{ norm} / \sum_{i=1}^{11} \overline{x}_{ij})$ where $\overline{x}_{ij}$ represents the mean subtest score on the ith subtest for group j and $\sum_{i=1}^{11} \overline{x}_{NORM}$ represents the total of 11 subtest scores made by the standardization population. The full scale mean for each group was thus set equal to that of the normal population, while the relative scores on the subtests were preserved. The purpose of this transformation was to filter out the effects of overall differences in general intellectual capacity between groups so that possible specific subtest differences could be assessed without contamination of g-factor differences. In the absence of such a transformation subtest differences could be interpreted as merely reflecting differences in overall capacity. If subtest differences are still present after such a transformation, then the difference can be interpreted quite clearly as a specific difference over and above general intellectual variation. Rank order correlations of subtest scores were computed for the three epileptic groups, comparing their scores with those made by Reitan's brain-damaged patients, and Pearson r correlations were computed for comparisons among the epileptic groups. The purpose of these correlations was to determine the degree of similarity of performance among the various groups.

3. Results

Table XI presents comparisons of the scores made by the three patient groups with the standardization population, as well as intragroup comparisons of the verbal and performance scales. All three patient groups are significantly inferior to the normal population on the test as a whole, as well as on the verbal and performance scales. The lowest mean subtest score for groups KE and CP (the two brain-damaged groups) was on the Digit Symbol subtest. Although the verbal score was higher than the performance score for

	Epilepsy Known Etiology			Epilepsy Unknown Etiology			Commissurotomy Patients			Norm Mean
	Mean	SD	t	Mean	SD	t	Mean	SD	t	
df		22			28			7		
Inf	8.96	.21	-22.16***	8.83	3.25	-1.81	7.88	2.33	-2.59*	9.92
Com	9.17	3.50	- 1.02	9.72	3.36	- .31	9.38	2.88	- .54	9.92
Ari	8.78	3.10	- 2.80*	8.55	2.76	-1.85	6.88	2.03	-2.69*	9.91
Sim	8.57	4.38	- 1.23	10.10	4.41	-1.66	8.25	3.14	-2.74*	10.12
Dsp	8.00	3.24	- 2.30*	8.86	3.18	- .03	7.88	4.40	-1.20	9.81
Voc	7.87	2.96	- 3.39**	8.83	3.02	-2.02	9.00	3.46	- .78	9.96
Dsy	6.70	2.18	- 5.54***	8.41	2.49	-1.75	4.13	2.23	-6.46***	9.22
Pc	8.52	2.45	- 2.33*	9.14	2.05	-1.50	8.88	2.20	-1.07	9.71
BD	8.78	2.52	- 1.57	8.72	2.70	-1.77	6.00	3.51	-2.91*	9.61
PA	7.13	2.28	- 4.87***	7.72	2.67	-3.48**	5.88	1.64	-6.16***	9.45
OA	8.26	2.15	- 3.15**	9.41	2.67	- .52	6.25	1.83	-5.28***	9.67
df		252			318			87		
Tot (Mean)	8.25	2.86	- 8.36***	8.94	3.03	-4.76***	7.31	2.96	-7.87***	9.75
df		137			173			47		
Ver (Mean)	8.56	3.12	- 5.11***	9.15	3.38	-3.04**	8.21	3.07	-3.94**	9.94
df		114			144			39		
Perf (Mean)	7.88	2.28	- 7.87***	8.68	2.53	-4.05***	6.22	2.73	-7.69***	9.53
		Variance			Variance			Variance		
df		251			317			87		
Ver vs. Perf		7.54	1.94		9.17	1.38		8.51	3.16*	

* = p < .05 (two-tailed test)　　** = p < .01　　*** = p < .001

Table XI

Comparison of Patient Groups with Normal Population and Intra-group Comparison of Verbal vs. Performance all three groups, it was only significantly so for group CP.

Table XII presents the inter-group comparisons. On overall test scores, Group UE was superior to both KE and CP, and KE was superior to CP. None of the groups differed from one another on the verbal scale. On the performance scale, UE was superior to KE and CP, and KE was superior to CP. Scores on the Digit Symbol subtest reflected the greatest difference between groups. It was the only subtest in which UE was superior to KE. Group UE was superior to CP on Digit Symbol, Block Design, and Object Assembly, and KE was superior to CP on Information, Digit Symbol, Block Design, and Object Assembly.

	UE vs. KE		UE vs. CP		KE vs. CP	
	Common Variance	t	Common Variance	t	Common Variance	t
df	50		35		29	
InF	5.94	-.19	9.46	.78	1.24	2.37*
Com	11.70	.58	10.68	.27	11.28	-.15
Ari	8.51	1.06	6.92	.94	8.31	.11
Sim	19.34	-.19	17.54	1.00	16.92	1.13
DSp	10.29	1.72	11.95	1.34	12.66	.22
Voc	8.97	1.14	9.72	-.14	9.54	-.89
DSy	5.56	2.61*	5.94	4.41***	4.82	2.85**
PC	4.98	.99	4.32	.32	5.71	-.36
BD	6.87	-.08	8.28	2.37*	7.79	2.43*
PA	6.29	.85	6.25	1.85	4.60	1.43
OA	6.01	1.68	6.36	3.14**	4.31	2.36*
df	570		405		339	
Tot(Mean)	8.74	2.76**	9.11	4.41***	8.32	2.54*
df	310		220		184	
Ver(Mean)	10.49	1.59	10.94	1.74	9.39	.69
df	258		183		148	
Perf(Mean)	6.01	2.67**	6.74	5.35***	6.06	3.69***

* = p < .05(two-tailed test) ** = p < .01 *** = p < .001

Table XII

Comparison of Patient Groups with Each Other

Comparisons of transformed subtest scores with the normal population are presented in Table XIII, and intergroup comparisons of transformed subtest scores are presented in Table XIV. One-tailed $\underline{t}$ tests were used in determining the probability value of $\underline{t}$ since the directions of difference in scores were already established in the analysis of untransformed scores. Of interest here was whether these directional differences were significant after transformation. It should be recognized that the comparisons in Table XIII are essentially equivalent to comparing a given subtest mean with the group's overall test mean since the overall test mean is identical with that of the normal population. A significant difference for a subtest therefore signifies not only a specific variation from the normal population, but also a specific variation from the group's own test mean. All three patient groups had significant specific deficits on the Picture Arrangement subtest and the two brain-damaged groups (KE and CP) were also significantly inferior on the Digit Symbol Test. When the transformed scores of the groups were compared with each other (Table XIV), only the Digit Symbol test showed significant differences between all groups. Group UE was superior to both KE and CP, and KE was superior to CP. UE was also superior to CP on Object Assembly.

	KE			UE			CP		
	Mean	SD	t	Mean	SD	t	Mean	SD	t
df		22			28			7	
Inf	10.59	.24	-13.40	9.63	3.55	.44	10.51	2.97	- .56
Com	10.84	4.13	- 1.07	10.60	3.67	-1.00	12.51	3.84	-1.90
Ari	10.38	5.17	- .44	9.32	4.81	.66	9.18	4.18	.49
Sim	10.13	3.84	- .01	11.02	3.46	-1.41	11.00	5.87	- .43
DSp	9.45	3.67	.47	9.66	3.01	.27	10.51	2.71	- .73
Voc	9.30	3.50	.90	9.63	3.30	.54	12.00	4.62	-1.25
Dsy	7.92	2.58	2.41**	9.17	2.71	.10	5.51	2.98	3.53***
PC	10.07	2.89	- .60	9.97	2.24	- .62	11.84	2.93	-2.05
BD	10.38	2.98	- 1.24	9.51	2.94	.18	8.00	4.68	.98
PA	8.43	2.70	1.82*	8.42	2.91	1.91*	7.84	2.18	2.09*
OA	9.76	2.54	- .17	10.26	2.91	-1.09	8.34	2.45	1.53

* = $p < .05$ (one-tailed test, testing if $(\bar{x}_{NORM} - \bar{x}_{PATIENT\ GROUP}) > 0$)

** = $p < .025$

*** = $p < .01$

Table XIII

Comparison of Transformed Subtest Means with Mean of Normal Population

	UE vs. KE		UE vs. CP		KE vs. CP	
df	Common Variance 50	t	Common Variance 35	t	Common Variance 29	t
Inf.	7.07	-1.30	11.84	- .64	2.19	.13
Com	15.03	- .22	13.67	-1.29	16.52	-1.00
Ari	24.75	- .76	22.03	.07	24.54	.59
Sim	13.19	.88	16.49	.01	19.47	- .48
DSp	11.00	.23	8.72	- .72	11.98	- .75
Voc	11.47	.35	12.98	-1.65	14.43	-1.73
DSy	7.04	1.69*	7.65	3.30***	7.19	2.19**
PC	6.47	- .14	5.71	-1.97	8.42	-1.49
BD	8.75	-1.05	11.30	1.13	12.01	1.68
PA	7.95	- .01	7.75	.52	6.67	.56
OA	7.57	.65	7.96	1.70*	6.34	1.38

* = $p < .05$ (one-tailed test, testing if $(\bar{x}_{UE} - \bar{x}_{KE}) > 0$;

** = $p < .025$ $(\bar{x}_{UE} - \bar{x}_{CP}) > 0$; $(\bar{x}_{KE} - \bar{x}_{CP}) > 0$)

*** = $p < .01$

Table XIV

Comparison of Transformed Subtest Means of Patient Groups with Each Other

The correlation coefficients among the groups are presented in Table XV. All three epileptic groups are significantly correlated with each other and with Reitan's right (RL) and bilaterally (BL) lesioned groups; except for RL and UE. RL and BL are also significantly correlated with each other. Reitan's left lesioned group (LL), however, is not significantly correlated with either the right or bilaterally damaged patients, or with any of the epileptic groups.

	Reitan's Lesion Groups						Epileptic Patients					
	Bilateral		Left		Right		KE		UE		CP	
	Rho	p	Rho	p	Rho	p	r	p	r	p	r	p
KE	.61	<.05	.20	NS	.61	<.05	---	---	.60	.05	.59	.05
UE	.64	<.05	.02	NS	.48	NS	.60	.05	---	----	.59	<.05
CP	.74	<.01	-.10	NS	.72	<.05	.59	.05	.59	<.05	---	----

Table XV

Rank Order Correlations of Subtest Scores Made by Six Patient Groups

4. Discussion

The comparisons of untransformed scores of the patient groups with that of the normal population clearly indicate that epileptics as a group, whether brain damaged or not, suffer from a diminished general intellectual capacity. This inferiority was reflected in both the verbal and performance scales. Although the groups scored lower on the performance scale than on the verbal scale, this difference was not significant except for the commissurotomy patients. It appears that epilepsy interferes with optimal psychological functioning, that even in the absence of gross anatomical injury, the physiological malfunctioning, revealed in major motor seizures, has psychological manifestations as well. The differences in various subtest scores from the norm may be reflecting only differences in general capacity, and it would seem to be invalid to claim specific deficits since all subtests presumably measure g-factor to some extent.

When the patient groups were compared with each other, groups KE and CP were inferior to UE. The anatomical damage present in both of these groups therefore seems to be responsible for an intellectual deficit over and above that produced by epilepsy alone. In spite of this overall inferiority, however, the three groups did not differ on the verbal scale. The verbal scale is apparently an insensitive measure of cerebral injury in an epileptic population . However, all three groups differed from one another on the performance scale, UE being superior to KE and CP, and KE being superior to CP. Not only did the performance scale differentiate brain damaged from non-brain damaged, it also differentiated patients with hemispheric disconnection from others. Although patients in group KE all suffered from identified cerebral injury, while 25% of those in group CP were non-brain damaged, KE was still superior to CP on the performance scale. The absence of the forebrain commissures therefore produces an even more severe deficit on non-verbal items than does brain damage. The fact that Reitan(55) and Arrigoni and DeRenzi(58) found that the verbal scale differentiated between right and left lesioned groups, but that the performance scale did not, is perfectly consistent with these results, suggesting that while the verbal scale measures predominantly left hemisphere functions, the performance scale measures interhemispheric functions. The results of the present study, in which group CP was inferior neither to UE nor KE on the verbal scale, confirms that only a single hemisphere is needed in dealing with verbal scale items. The fact that CP was inferior even to the brain injured group KE on the performance scale lends confirmation to the idea that performance scale items measure interhemispheric interactions, and that therefore a group in whom such interactions are prevented by the absence of all forebrain commissures, is inferior even to a brain damaged population.

Transformation of the subtest scores, as pointed out, filters out the effects of general factor differences among the groups and allows for conclusions to be drawn with respect to specific differences in subtest scores. When this transformation was performed, all three groups were found to be significantly inferior to the normal population (and therefore to their own full-scale mean) on the Picture Arrangement test, and groups KE and CP on the Digit Symbol test as well. Correspondingly, Reitan(55) found that bilaterally brain damaged subjects scored poorest on the Digit Symbol test and next poorest on Picture Arrangement. These two subtests appear to be most sensitive to brain malfunction, and the Picture Arrangement test even discriminates cerebral impairment in the absence of identifiable anatomical damage. The Digit Symbol test, on the other hand, appears to measure only manifest organic injury. However, the two commissurotomy patients who had no recognized structural trauma were 2.00 and .67 standard deviations below their own means on the Digit Symbol test. The mean standard deviation for the group as a whole was -1.08. It would therefore seem that, at least with respect to the Digit Symbol test, the effects of commissurotomy are similar to those of brain injury. This suggests that the inferior performance on Digit Symbol in the presence of cerebral lesions, is due to a disruption of interhemispheric cooperation, a disruption which would be even more complete in patients lacking the neocortical commissures. The Digit Symbol test involves accurate perception of numbers and symbols, praxic constructive ability, and finally, the ability to carry on symbolic translation using the right hand for drawing the symbols. The first ability is most probably a function of both hemispheres, the second of the right hemisphere, while right hand symbolic translation is likely a function of the left hemisphere. If these conjectures are correct, then we would expect group CP to be inferior to KE on Digit Symbol, even though the patients in group KE are all brain damaged.

The intergroup comparisons of transformed scores (Table XIV) show the predicted differences. Groups KE and CP are both inferior to UE, and group CP is inferior to KE on the Digit Symbol test. The poor performance of brain injured patients on the Digit Symbol test therefore seems to reflect, not cerebral injury *per se*, but rather the interference with interhemispheric communication produced by such injury. A brain lesion in either hemisphere might still allow that hemisphere to perform its special functions by using alternative brain areas. However, we would expect a degeneration of commissural fibers to follow such injury, and it might be that in order for a given interhemispheric interaction to occur, the primary connections must still be intact. In other words, there may be no available pathways for interconnecting a secondary, alternative area of one hemisphere to the area in the other hemisphere which is critical for an interhemispheric task. The fact that the three patient groups did not differ from one another on the verbal scale (Table XII), a scale containing items which call, almost entirely, on only left hemisphere abilities, lends support to this idea.

The patterns of responses on the eleven subtests made by the patient groups again suggest that cerebral injury might produce the greatest disruption of behavior by interference with commissural communication. The data presented in Table XV show that all three groups had a pattern of responses highly similar to that shown by Reitan's bilaterally brain damaged group, group CP showing the greatest similarity. However, none of the patient groups had significant correlations with Reitan's left lesioned group, a group which was mainly deficit on verbal items. Groups KE and CP had patterns of response similar to Reitan's right lesioned group, but UE did not. The lack of significant correlation between UE and the right lesioned group seems to be due to a Rho of -.02 on the verbal scale. The groups were correlated .72 on the performance scale. In other words, group UE tended to approach items on the performance scale in the same way as patients with right hemisphere brain damage, but this was not the case for the verbal scale items. It thus appears that groups KE, UE, and CP, in dealing with performance scale items, all utilized cerebral mechanisms similar to those employed by non-epileptic patients with either right or bilateral brain damage, but different mechanisms from those employed by patients with left brain damage. The three epileptic groups were all significantly correlated with each other. These correlations, of course, account for the fact that on ten of the eleven subtests the groups' transformed scores did not differ. These data lead us to the conclusion that disturbance of normal brain processes, either by the presence of epilepsy, by organic cerebral injury, bilaterally or in the right hemisphere, or because of commissurotomy, leads to the use of similar mechanisms in approaching certain psychological problems. The .72 correlation of UE with right brain damaged patients on performance scale items, but the -.02 correlation on verbal scale items, as well as the absence of significant correlation between any of the epileptic groups and left lesioned patients, suggests that tasks which are not handled exclusively by a single hemisphere, are most sensitive to measuring generalized brain malfunctions. In other words, problems requiring interhemispheric cooperation are most susceptible to impairment in the presence of cerebral abnormality. The fact that group CP was inferior to both KE and UE on the performance scale (Table XII) is therefore a logical expectation.

In summary, the data presented in this study show that general deterioration of ability follows from any form of cerebral dysfunction, that this deterioration is revealed in both verbal and non-verbal items, but shows up most strongly in the latter for patients having epilepsy, bilateral or right hemisphere damage, or forebrain commissurotomy. However, the discrepancy between verbal and performance scores was only significant for commissurotomy patients in whom the mean performance score was .63 standard deviations below the verbal score. Further, although KE, UE, and CP did not differ significantly from one another on the verbal scale, brain damaged epileptics (KE) were inferior to patients with cryptogenic epilepsy (UE), and epileptic patients with commissurotomy (CP) were inferior to those with brain damage (KE) on the performance scale. These findings strongly suggest that performance scale items measure bilateral cerebral functions to a greater degree than do verbal scale items, and that such bilateral functions are more sensitive to disruption by brain abnormality than are single hemisphere functions. This conclusion is consistent with Reitan's(55) and Arrigoni's and DeRenzi's(58) findings that patients with left hemisphere damage are inferior on verbal scale items to patients with right hemisphere damage, but that the two patient groups are equally inferior on the performance scale.

Elimination of general factor differences by transformation of the scores indicates that scores on the Picture Arrangement test are significantly inferior to the test as a whole and to the normal population for all three epileptic groups, and that scores on the

Digit Symbol test are significantly inferior for brain damaged and commissurotomized epileptics. The Digit Symbol test was also found to differentiate between UE and KE and between KE and CP, CP making the lowest scores. We are thus led to the idea that the Picture Arrangement and Digit Symbol tests call on bilateral functions to a greater degree than other WAIS subtests and that the deficiencies in performance on the Digit Symbol test seen in brain damaged people are most likely due to the disruption of intercerebral mechanisms. This suggestion is consistent with Reitan's findings that the lowest score of the eleven subtests made by both right and bilaterally damaged patients was on the Digit Symbol test and that even left damaged patients received the lowest performance score on Digit Symbol. In fact, Reitan's left lesioned group received lower scores on the verbal scale on only Digit Span, Arithmetic, and Similarities, and Digit Span was the second lowest score for his right lesioned group.

The pattern of relative performance on the eleven subtests was similar for all three groups of epileptics and was similar to Reitan's right and bilaterally damaged groups, though not to his left lesioned group. These pattern similarities of CP with the other groups confirm the preceding speculations that performance scale items are more sensitive than verbal scale items, to generalized cerebral dysfunction because such items measure intercerebral mechanisms.

Finally, it is suggested that the intercerebral mechanism which is disrupted is the motor read-out which appears to be controlled by the left hemisphere. Any factor which hinders communication from the right to left hemisphere results in a failure of the left hemisphere to control adaptive responses.

V. General Discussion

In the introduction to this thesis, several questions were posed: how much information is available to each hemisphere from the sensory half-fields, what mechanisms the patients use in order to behave in an integrated fashion, the conditions under which such integration fails, the degree of hemispheric specialization in each half-brain, the effect of such specialization in the performance of high level tasks requiring interactive usage of these specialties, and reasons for the evolution of lateral specialization in the human brain.

It was found that in the absence of the neocortical commissures, the left hemisphere still has access, not only to information from the right half-field, but also to certain types of information from the ipsilateral field, that the left hemisphere can differentiate left-field stimuli, although it is unable to specify the exact qualities of such stimuli. These studies presented the first indication in the present series of investigations that the left hemisphere was superior to the right in its ability to control the motor mechanisms necessary for the expression of its knowledge. Both access to ipsilateral information from the left field, as well as a complex cueing system can account for the ability of the commissurotomy patient to be functionally unified.

Under conditions of specialized testing, this functional unity failed. Competition between the two sides of the brain for control of the left hand was seen in tests of minor hemisphere language competency. These tests revealed that the minor hemisphere, though possessing some expressive language ability, suffers a severe intrinsic limitation which appears to be even worse than it is due to competition for control of the motor mechanisms for language expression exercised by the major hemisphere. We thus again see left hemisphere dominance for motor expression.

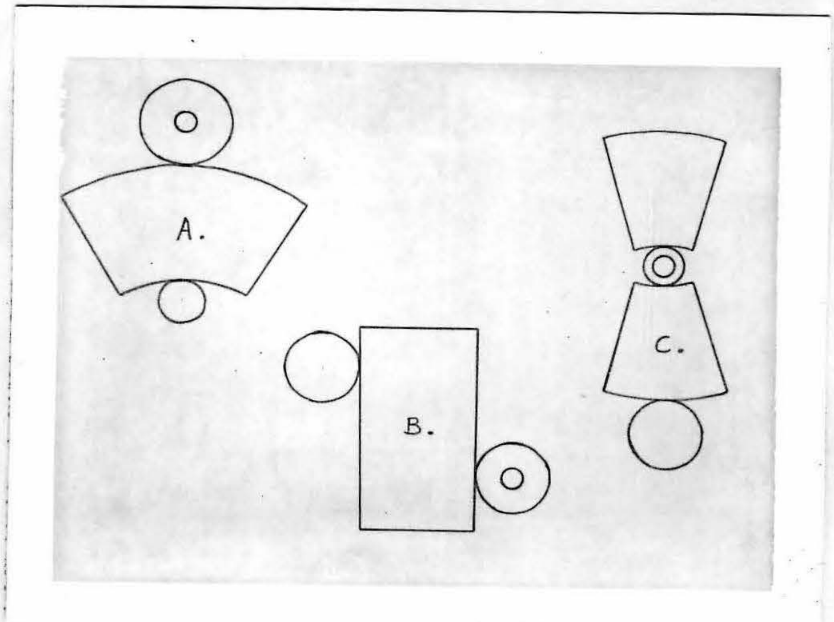
In tests of perception it was found that the minor hemisphere is superior to the major, not only for tasks requiring constructional praxis, but in purely perceptual functions. When perceptual visualization was measured in the unrestricted situation, the minor hemisphere was apparently prevented from expressing its competency, resulting in totally deficient performance.

The above findings support the idea that the corpus callosum plays a critical role in the expression of minor hemisphere specialties, an idea which was confirmed by the results of I. Q. analysis of the patients' scores.

Functional integrity of commissurotomy patients thus seems to be limited to activities not calling on functions in which the minor hemisphere normally excels.

The results of the language and perception studies suggested a rationale for the evolution of lateral specialization: namely, that unilateral speech control was only partially an adaptation which overcame problems of an antagonistic competition between the hemispheres for control of the mechanisms for language production, and that lateralization of function into the two hemispheres was a consequence of a basic incompatibility between the analytic and synthetic strategies of information processing necessary for language description and Gestalt perception, respectively. This latter idea was fully supported by the finding that people who are likely to have bilateral language centers are greatly inferior to others on tests of perceptual function.

APPENDIX



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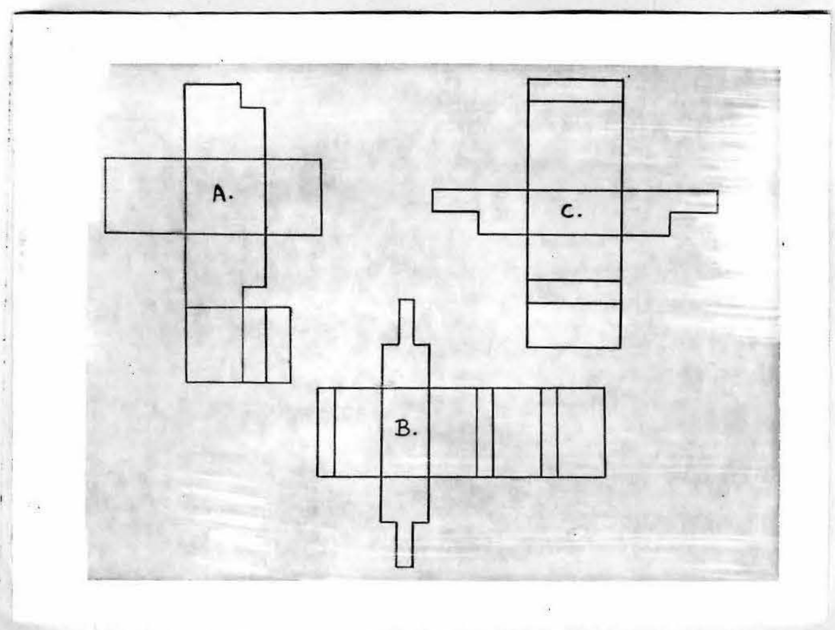

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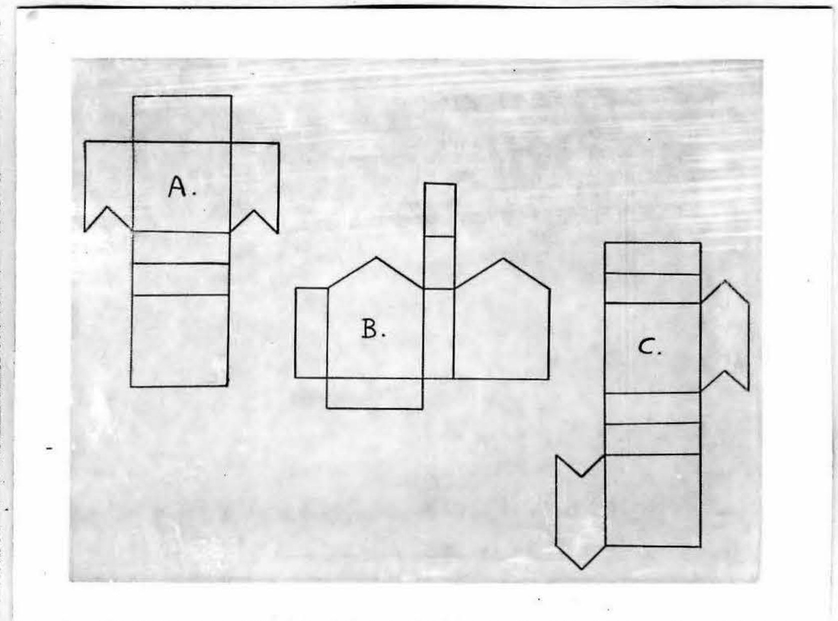

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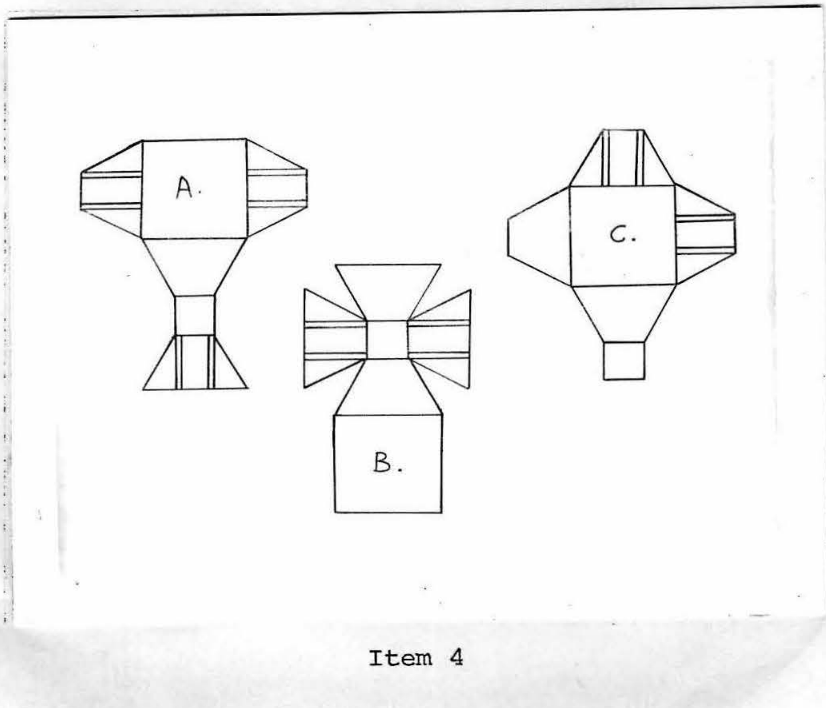

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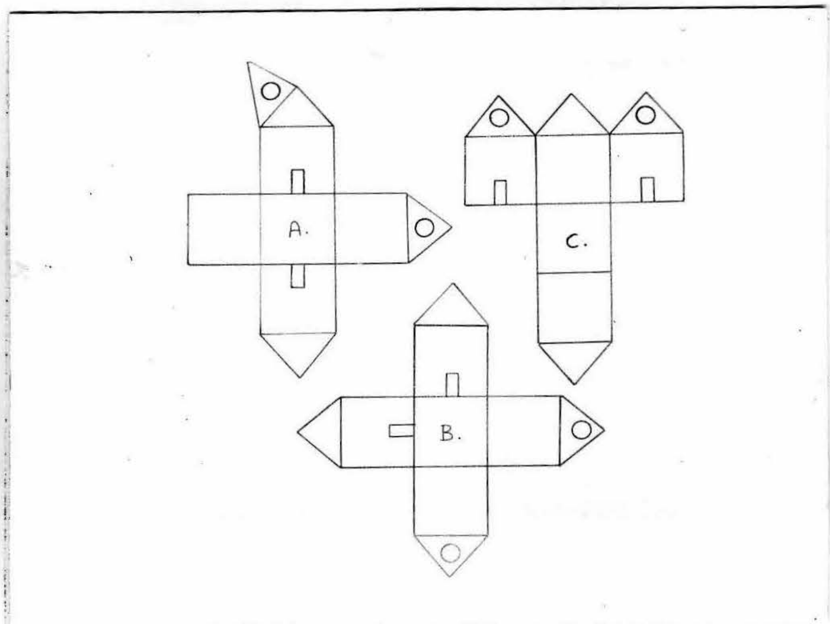

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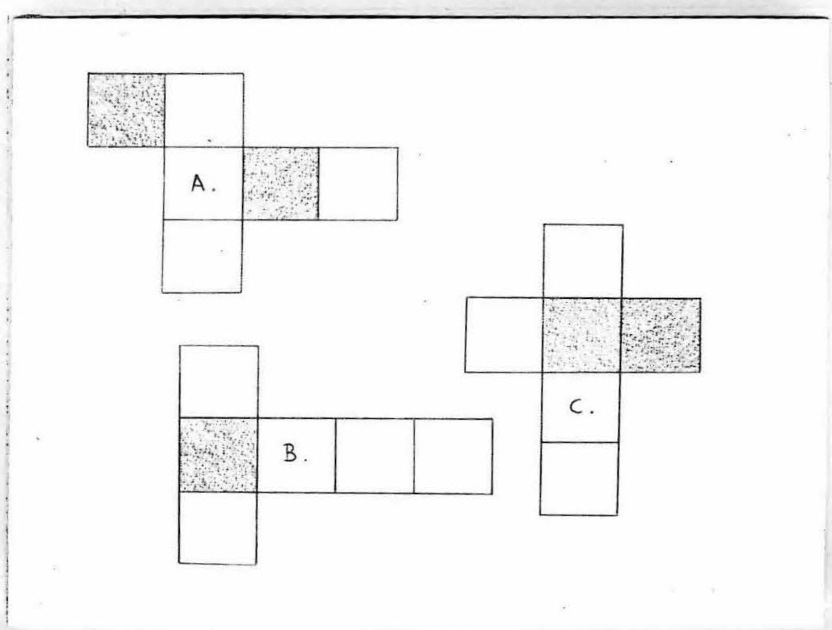

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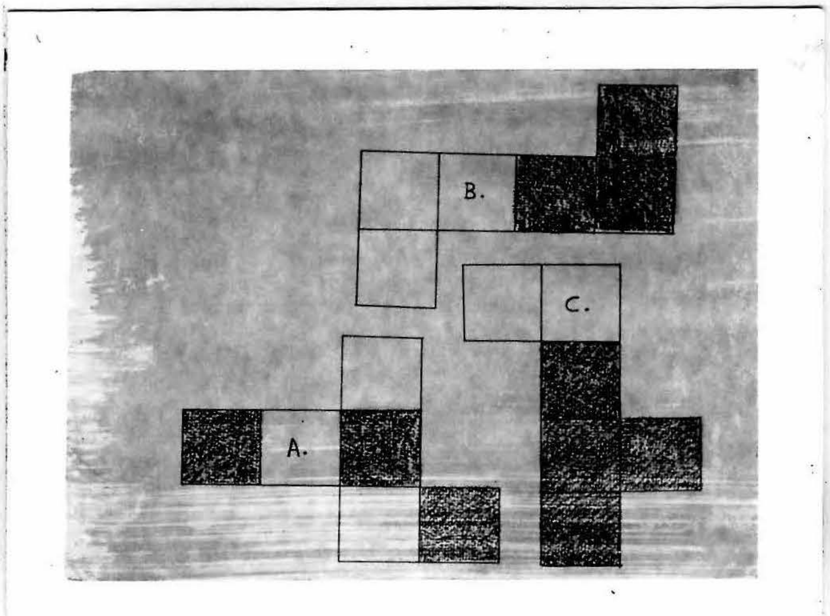

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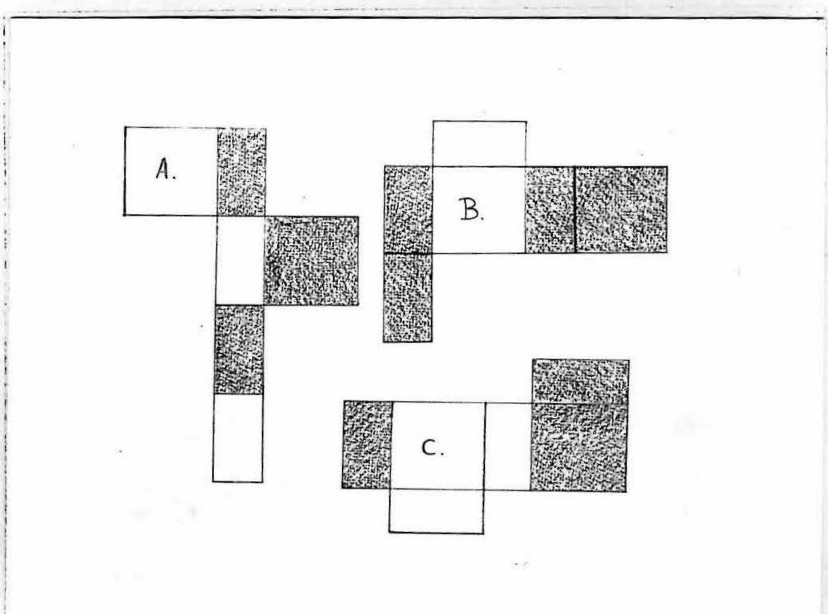

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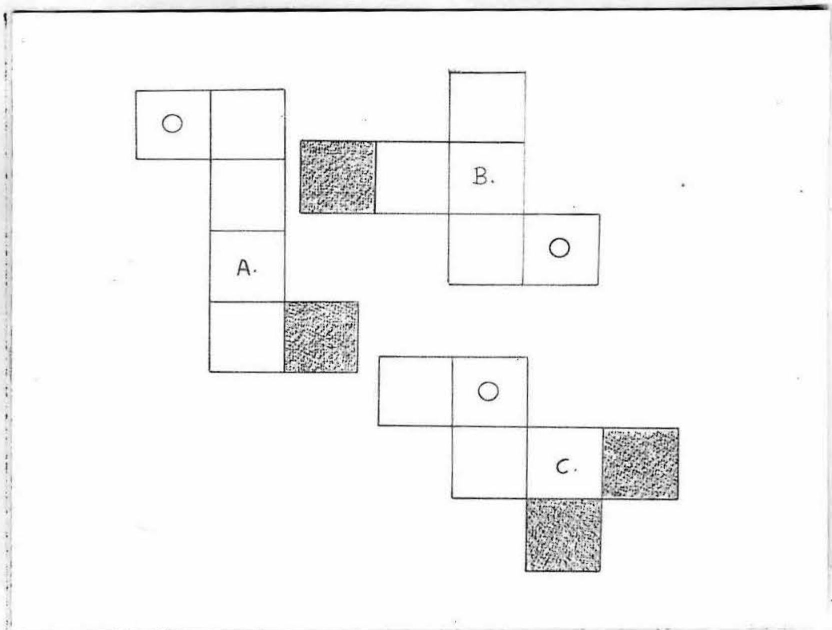

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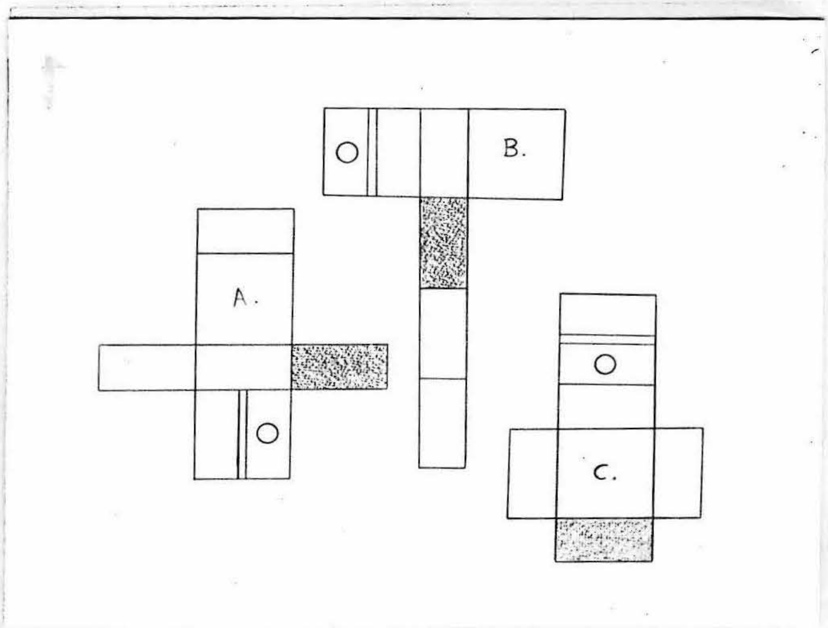

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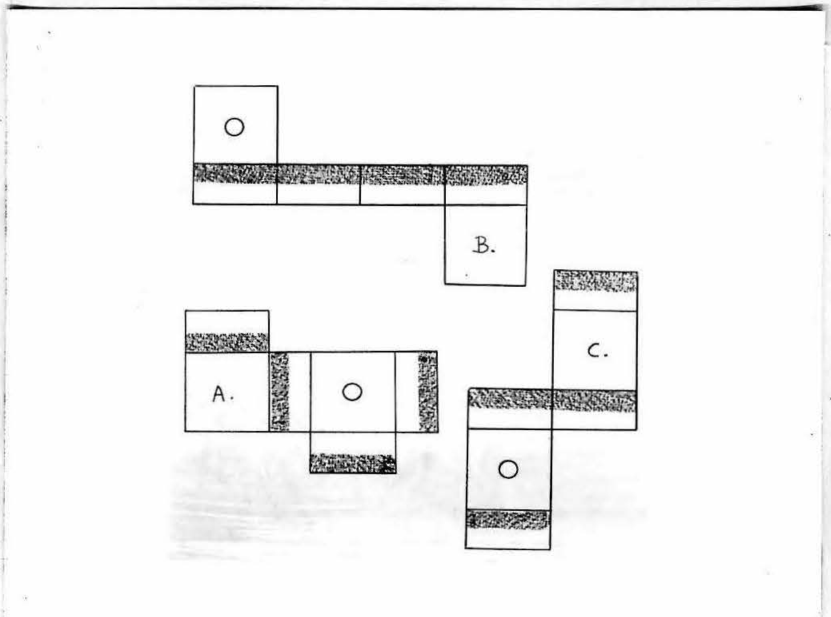

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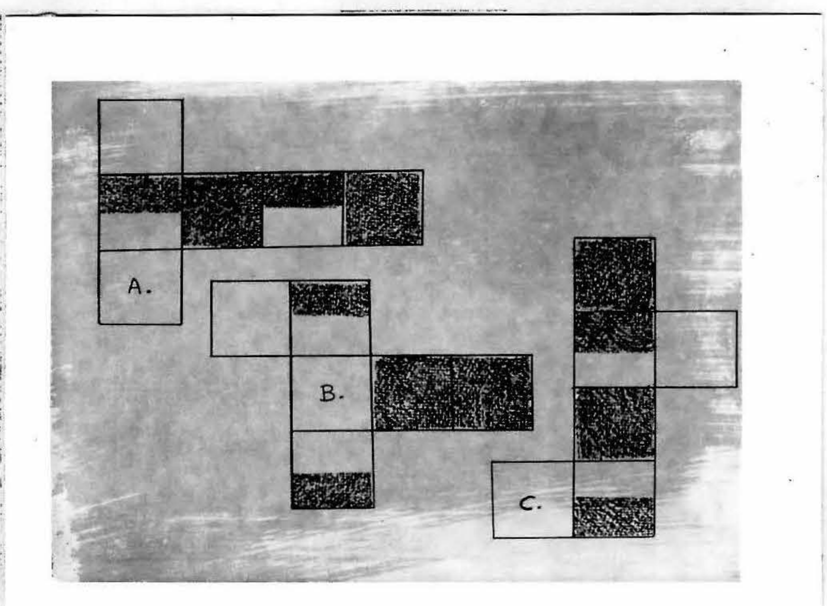

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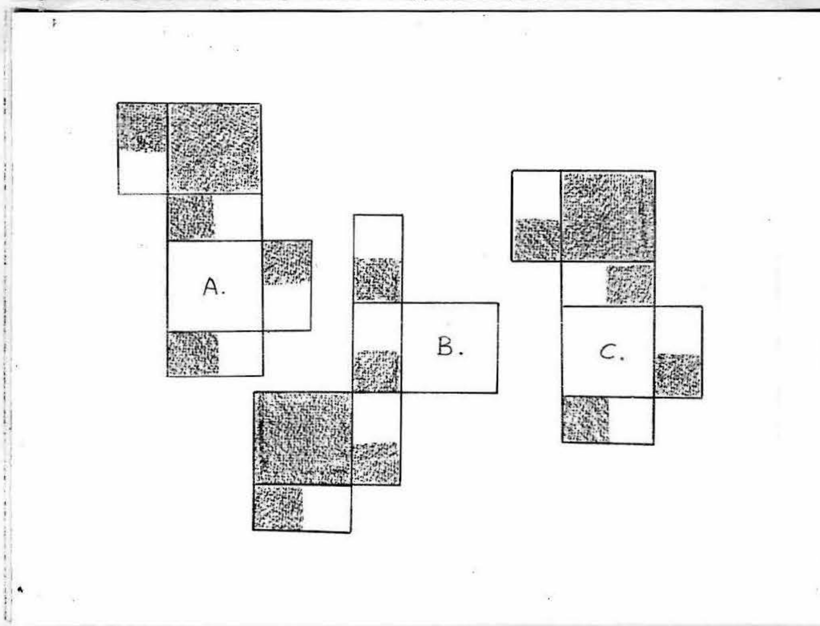

Item 13

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