1973 (173)

THE PSYCHOPHYSIOLOGY OF THINKING

STUDIES OF COVERT PROCESSES

Edited by

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ACADEMIC PRESS New York and London 1973

CHAPTER SIX

Lateral Specialization of Cerebral Function in the Surgically Separated Hemispheres[1]

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The main theme to emerge from the following is that there appear to be two modes of thinking, verbal and nonverbal, represented rather separately in left and right hemispheres, respectively, and that our educational system, as well as science in general, tends to neglect the nonverbal form of intellect. What it comes down to is that modern society discriminates against the right hemisphere.

The evidence for functional asymmetry in the cerebral hemispheres of man goes far back to the early observations of Dax and Broca in the 1800s (Critchley, 1961) regarding lateralization of speech and writing. Thinking has generally been correlated with language capacity, and hence the observed hemispheric lateralization of language could be considered as indicative of a corresponding lateralization in associated thinking processes. It is conceivable *a priori* that thinking must necessarily require the integrated action of both hemispheres, but we know in fact from hemispherectomy and commissurotomy studies that a single hemisphere can think independently in the complete absence of any assistance from the other. This is not to imply that the quality of thinking carried out in

[1] Work of the author and his laboratory is supported by Grant No. MH 03372 from the National Institute of Mental Health and the F. P. Hixon Fund of the California Institute of Technology.

one hemisphere is as good as when the two cooperate, only that the basic cerebral mechanisms requisite for conscious thinking can function effectively through a single hemisphere. We shall come back to this and related questions later.

Most of the evidence for hemispheric specialization in mental capacities comes historically from the differential symptoms produced by asymmetric cerebral damage. This evidence has been subject to the usual uncertainties and difficulties of assessing observations of clinical patient populations. As recently as 1962 (Mountcastle, 1961) the existence of true lateral differences in cerebral organization was still being questioned by the more cautious authorities, and the view that the two hemispheres of man are equal in functional potential at birth (Glees, 1967) continues to have wide acceptance.

The majority of studies in the past decade, however, including those on cerebral commissurectomy where direct comparisons can be made of the positive performance of each hemisphere on the same task in the same person, have come increasingly to reinforce support for a basic inherent specialization in hemispheric organization that, to a large extent, is innately predetermined. The last few years have produced a further burst of studies on normal subjects in which the utilization of a variety of lateralizing techniques including unilateral or competitive sensory input, differential reaction time latency, selective biofeedback techniques, and the like seem to confirm further the existence of qualitative lateral specialization of function in the normal intact hemispheres. Genetic models for the inheritance of cerebral dominance have been proposed, one of the most recent of which (Levy & Nagylaki, in press) postulates two genes, one determining which hemisphere is language dominant and the other determining whether hand control is contralateral or ipsilateral to the language hemisphere.

The following is restricted mainly to a brief review of some of the evidence for hemispheric specialization that has come from studies by a long line of research colleagues and myself on a group of some nine commissurotomy patients. The results, to forecast the outcome, seem to show that the surgically separated left hemisphere has its own mode of thinking that qualitatively is distinctly different from that used by the right hemisphere in the same individual. All are patients of Philip Vogel and Joseph Bogen, neurosurgeons at the White Memorial Medical Center in Los Angeles, and have undergone essentially the same rather special form of brain operation for treatment of intractable epileptic convulsions.

Put crudely, the operation consists of having the brain divided down the middle into right and left halves. More precisely, the surgery involves selective midline division of the main fiber systems that cross-connect the left and right hemispheres (Bogen, Fisher, & Vogel, 1965). The corpus callosum is sectioned in its entirety as is also the anterior commissure. The thin hippocampal commissure closely subjacent to the corpus callosum is not separately visualized, but is presumed to have been divided along with the callosum. The variable massa intermedia, as a potential bridge for seizure transmission, is also sectioned in those patients where it is observed to be present. All these sections are performed in a single operation to effect a rather complete anatomical and functional disconnection of the two cerebral hemispheres.

This kind of surgery is undertaken as a last resort measure for selected severe cases only; it constitutes a last ditch stand against advancing, life-threatening, epileptic convulsions that are not controlled by medication. The outcome with respect to seizure control has been remarkably good to date, but this is another story that we leave to our medical colleagues. Our own work is restricted to follow-up studies on the neurological and psychological effects of this surgical elimination of cross-talk between the hemispheres.

The behavioral symptoms produced by severance of these enormous systems of fiber cross-connections are found first of all to be surprisingly inconspicuous in ordinary behavior (Sperry, Gazzaniga, & Bogen, 1969). The hemispheres continue to function in the separated state at a fairly high level such that a person 2 years recovered and otherwise in good condition could easily go through a routine medical checkup without revealing that anything was particularly wrong—to someone unacquainted with his surgical history. This is what started our studies initially: The remarkable lack of any definite symptoms after section of the corpus callosum, or its congenital absence, was being used back in the 1940's and 1950s to support various far-out theories of how brains can operate at the upper levels without specific fiber connections.

Despite this deceptive normality of the cerebral commissurotomy patient to casual inspection and even in routine neurological tests, we are now able to demonstrate with controlled lateralized testing procedures a whole multitude of distinct neurological symptoms that reflect directly the lack of interhemispheric integration in nearly all mental activity. A long series of studies indicate that the two disconnected hemispheres function independently and in effect have each a separate mind of its own (Gazzaniga, 1965; Gazzaniga *et al.*, 1967; Levy, 1969; Gordon & Sperry, 1969; Levy *et al.*, 1971; Milner, & Taylor, 1971; Nebes, 1971;

Nebes & Sperry, 1971; Sperry, 1968c; Sperry *et al.*, 1969). Each of the separated hemispheres appears to have its own private sensations, perceptions, thoughts, feelings, and memories. Each hemisphere has its own inner visual world, each cut off from the conscious awareness of the other.

I turn now for present purposes to those observations in these same studies that relate to lateral differences in the cognitive properties of the two surgically separated hemispheres. Not being sure where perception stops and thinking begins in the brain, nor where thinking stops and motor expression starts, I will not attempt in the following to draw sharp distinctions along these lines. Very early in the postoperative examination of these subjects it became apparent that the disconnected left hemisphere processing information from the right hand and the right half visual field is the hemisphere that does essentially all the talking, reading, writing, and mathematical calculation in these right-handed subjects (Gazzaniga, Bogen, & Sperry, 1967). The disconnected right hemisphere on the other hand remains essentially mute, alexic, agraphic, and unable to carry out calculations beyond simple additions to sums under 20. In other words, thinking that deals with information processed through the left hand, the left half visual field, the right nostril or with any other information processed entirely within the right hemisphere, remains cut off from the centers for language and calculation located in the left hemisphere. These test results added up to a striking confirmation of hemispheric lateralization with respect to language in general.

With reference to thinking in the disconnected hemispheres, we can infer further that much of the thinking and reasoning that involved linguistic and numeric processes must also have been carried out in the left hemisphere. Those patients least afflicted with extracallosal damage have been able to carry on verbally in their school work and home life at a level where it was questionable in members of the immediate family whether abstract reasoning and symbolic thinking were at all affected beyond a weakening in mnemonic functions.

It was further apparent that the postoperative behavior of these patients was governed almost entirely from the more dominant, leading left hemisphere. Presumably it is the highly developed cognitive and expressive capacities of this dominant hemisphere and its tendency to take command of the motor system that are largely responsible for earlier impressions that no distinct symptoms result from complete section of the corpus callosum. There are reasons to think that the cognitive capacities of a single hemisphere are better inferred from the postoperative behavior of the commissurotomy patient than from that of the patient with a hemispherectomy.

The disconnected minor hemisphere, lacking language like the animal brain and thus unable to communicate what it is thinking or experiencing, is much less accessible to investigation, and accordingly the nature and quality of the inner mental life of the silent right hemisphere have remained relatively obscure. There is reluctance is some quarters to credit the minor hemisphere even with being conscious, the contention being that it is carried along in a reflex, trance-like state, with consciousness centered over in the dominant left hemisphere. The reasoning seems to be that the conscious self by nature has to be single and unified, as if the gates of heaven shall be opened only to one psyche per cranium.

Actually the evidence as we see it favors the view that the minor hemisphere is very conscious indeed, and further that both the separated left and the right hemispheres may be conscious simultaneously in different and even conflicting mental experiences that run along in parallel (Sperry, 1970a). From its nonverbal responses we infer that the minor hemisphere senses, perceives, thinks and feels all at a characteristically human level, and that it learns and remembers and has some reasoning capacity and considerable perceptual insight that is superior to that of the major hemisphere for certain things. Also that it may even do some silent reading of object names and some drawing, not to mention various things that we have not yet tested.

Much has been written and argued about the dependence of thinking upon language mechanisms—upon the implicit use of verbal symbols and the syntactical grammatic structure of language (Furth, 1971). In the performance of the surgically disconnected minor hemisphere we have an exceptional opportunity from which to gain added insight into the level and kind of thinking that can go on in the human brain without benefit of language. Remembering that in the great majority of tests, and in all tests where any linguistic processing is involved, it is the disconnected major left hemisphere that is superior and dominant, we can look now at some of the kinds of exceptional activities in which it is the disconnected minor hemisphere that excels.

It was found very early (Bogen & Gazzaniga, 1965; Bogen, 1969) that the minor hemisphere is superior in the construction of block designs and also in copying and drawing various test figures like a Necker cube, a swastika, Greek cross, etc. The results from these standard tests for visual constructional apraxia left it open as to whether the hemispheric differences involved praxis and motor expression primarily or more central cognitive processing.

Indirect evidence regarding lateralization of more complex central functions was obtained from studies of another patient, an "asymptomatic" case of congenital absence of the corpus callosum (Saul & Sperry, 1968; Sperry, 1968b, Sperry, 1970b). This agenesis patient performed easily most of the tests for hemispheric cross integration that the commissurotomy patients continued to fail even years after surgery. Her performance in more complex mental activities, however, indicated a consistent pattern of impairment. Verbal thinking and reasoning tasks showed normal or slightly above normal performance, like the verbal WAIS score of 112. By contrast, a whole array of nonverbal spatial activities were markedly subnormal, like geometry, geography, and drawing spatial representations.

Amytal tests indicated the presence in this agenesis patient of language in both hemispheres. This of course, precludes the typical division of labor in which the verbal and nonverbal functions are carried out in separate hemispheres. With both the verbal and the nonverbal perceptual functions necessarily forced to develop within the same hemisphere, the latter were apparently handicapped in favor of verbal development. The general observation that intellectual performance appears not to rise above mediocrity in such cases (about 17 asymptomatic cases of agenesis of the corpus callosum are recorded in medical history) suggests that the verbal as well as the nonverbal mode of thinking does not flourish when both are obliged to develop within the same hemisphere.

To better separate praxis from central processing in the commissurotomy subject Levy (1969a) devised a test that required only a very simple motor readout, manual pointing, but a rather complex understanding and manipulation of spatial relationships based on cross-modal spatial transformations. Thirteen sets of wooden blocks small enough to be grasped in the hand were constructed with three similar but different blocks in each set. Each block differed from the other two within a set either in shape or in the relationship of surface textures and markings. One of the three blocks was placed in the subject's left or right hand for identification by touch through the right or left hemisphere, respectively. The working hand and the test items were hidden from view behind a screen. The subject then looked at a card in free view with three patterns of what the blocks would look like if they were constructed of cardboard and unfolded into two dimensions. Both hemispheres saw the two-dimensional patterns but only the hemisphere holding the block knew the answer. The subject was asked to point to the pattern which represented the block which he was holding. The task required that the subject try to mentally fold up the visual pattern or unfold the tactual block, or otherwise reach a correct match between the tactual block and the visual form. The tabulated scores showed the minor hemisphere to be two to three times more proficient in this task than the verbal hemisphere. In addition to the quantitative superiority of the minor hemisphere, Levy also found a qualitative difference. When the left hand was feeling a block, responses tended to be quite rapid, direct, and silent. On the other hand, when the right hand was feeling a block, the subjects often took as much as 45 sec to respond; the responses were hesitant and the subjects tended to verbalize aloud with running comments on their logical approach to the task. It appeared that the two hemispheres were processing the same information in entirely different ways, the left thinking in verbal, symbolic, analytic terms while the right utilized simple visualization. Parts of the test that yielded the best scores for one hemisphere gave the worst scores for the other and conversely. From an analysis of the data, Levy inferred the presence of a mutual antagonism or interference between the two modes of mental processing and suggested that the evolution of cerebral dominance provides for the separation into separate hemispheres of these two different modes of thinking (Levy, 1969b).

The standard Ravens Progressive Matrices Test was modified for presentation to the commissurectomy subjects by Zaidel and myself (Zaidel & Sperry, 1971): In this test the subject examines in free vision a pattern matrix with a missing section and then feels with the left or right hand out of sight behind a screen for the correct missing section among a choice array of several raised Braille-like figures. This test, like the foregoing, involves a cross-modal matching between the visual figure and the tactual perception. The left hand–right hemisphere combination performed about twice as well as did the right hand–left hemisphere. As observed earlier by Levy, the thinking seemed very different depending on whether the subject worked with the left or with the right hand. The performance with the left hand was silent and rapid, while that with the right hand was drawn-out, and accompanied generally by a running, overt vocalization as the subjects talked and reasoned aloud to themselves, with comments like "two lines up, need three dots, spreads to the right," etc.

The special spatial aptitude of the minor hemisphere is not confined to the visual modality. Milner and Taylor (1971) used nondescript shapes made of bent wire to test for perception and memory of shape where both the recognition and the recall were based entirely upon touch with vision excluded. The results again revealed a striking superiority for the disconnected right hemisphere, and showed that in the purely tactual realm, complex patterned stimuli can be discriminated and remembered without verbal coding.

In a test devised by Nebes (1971) for the perception of part–whole relationships, the subject was given a part or segment of a whole circle to identify and then tries to select from a choice array the correct whole circle to match the sample segment. The sample and the choice array were presented in three ways: both through touch, or cross-modally from touch to vision, or from vision to touch. Whereas in control trials the direct matching of whole circles to whole circles, or of arc segments to arcs could be done well by either hemisphere, when it came to matching the parts to the whole, the right hemisphere was much better than the left. In another test used by Nebes (1971) the subject first examined an exploded or fragmented pattern and then felt behind a screen, using either the left or the right hand, for the correct one of three raised patterns which the fragmented pattern would form if put together. Again the right hemisphere–left hand proved much superior, with the scores for the left hemisphere hardly rising above chance. In other words, this task was almost too much for the verbal hemisphere.

In a modification of the Kasan–Haufmann Concept Formation Test used by Kumar (1971) the subjects were required to discover by trial and error, with controlled feedback from the examiner, the correct properties for sorting 16 items into 4 categories. The right hemisphere excelled in acquiring concepts that involved spatial qualities like height, size, shape, and the left excelled when the concepts involved familiar objects with distinctions that were easily verbalized.

Scanning movements of the eyes from the right to the left edge of an object being examined in free vision results in the formation of two complete perceptual images in the divided brain, one in each hemisphere (Sperry, 1970a). The well-known constancy of the visual image in the presence of eye movements must be taken into account. This right–left duplication is something that would logically occur also in the normal brain, not only for vision but for other senses as well. The cortical sensory map for the face is represented bilaterally in both hemispheres. We have often wondered what good may be served by so much redundant right–left doubling in the cerebral operation. If, as we now suspect, each hemisphere processes its sensory imput in distinctly different ways, then such a doubling begins to make sense. In the normal intact brain the right and left contributions to any given perceptual experience become fused, making it difficult or impossible to determine which hemisphere is contributing what.

In another procedure employed more recently in studies headed by Trevarthen and Levy (Levy, Trevarthen, & Sperry, 1972) different conflicting percepts are formed in the left and right sides. A left–right composite visual stimulus such as two separate half faces joined in the midline, is flashed at $\frac{1}{10}$ of a second with the subject's gaze held steady on a central fixation point. Each hemisphere by a process of illusory perceptual completion, gets the impression that it has seen a separate and different whole face. In other words, the two hemispheres are induced to see different things, faces or whatever, at the same point in space at the same time. This is something that the normal brain of course does not do. With the percept of each hemisphere set off in its own inner visual world, each cut off from awareness of the other, the commissurotomy subjects remain blandly unaware that there is anything peculiar about the appearance of these chimeric stimuli, even in the presence of leading questions such as "Did you notice anything strange about the stimulus?" The same principle has been used for presentation of geometric and nondescript figures, words, serial patterns, movement stimuli, colors, and combinations of these.

With this procedure we get two rival competing processes set up in the left and right hemispheres. The question then is which of these will dominate the response under different test conditions, that is, with different categories of test material, with different mental and motor sets, and with different forms of readout and central processing.

In general the results with this type of study conform with the earlier findings in that, if any linguistic processing is involved, the subjects' response is dominated by the left hemisphere. In other words, the right half of the stimulus is responded to rather than the left. However, in the perceptual discrimination of faces, and for any kind of direct visual–visual matching of shape or pattern, the right hemisphere dominates. This is especially true with nondescript shapes that resist verbal description. Even when no competing stimulus is involved the left hemisphere finds these to be exceedingly difficult to discriminate and handle. Special difficulty was also observed in attempts to associate names with faces; whereas the names themselves were easily learned or the faces easily discriminated, the subjects had great difficulty in associating the correct name with the proper face, presumably because the two were processed in separate hemispheres.

Even when words were used as stimuli presented in cursive script the minor hemisphere was found to dominate the verbal hemisphere provided that no interpretation of word meaning was involved and the readout required only a direct visual matching of the word pattern. Dominance promptly shifted to the opposite hemisphere when the task instructions were changed to demand a conceptual transformation involving the meaning of the word.

Although no direct perceptual or psychological conflict seems to be produced by these composite left–right stimuli, the subjects do show signs of secondary confusion as when one hemisphere sees or hears the other giving what the first hemisphere considers to be an erroneous response. This is something that we have to deal with all along in working with these people. When this happens, the correctly informed hemisphere tends to act disgusted with itself—the subject may give a negative shake of the head, or, if it is the verbal hemisphere, he may make remarks like "Now why did I do that? What made me do that?" We purposely do not dwell on these conflicts and pass along to the next trial.

This kind of annoyance, however, in the second hemisphere with what is a correct response for the first hemisphere, along with the occasional double correct responses in which first one and then the second hemisphere gives a different and correct response lends further support to our contention that each hemisphere is indeed having its own separate and different perceptual experience, with both being conscious simultaneously and in parallel.

The chimeric studies also reaffirm our earlier impressions that the left and right hemispheres perceive and apprehend things in ways that are qualitatively different. For example, in dealing with faces, the right hemisphere seems to respond to the whole face directly as a perceptual unit, whereas the left hemisphere seems to focus separately on salient features like the moustache, the eyes, the hair—to which verbal labels are easily attached. The disconnected right hemisphere is found in the tests to date to be the superior and dominant brain for perceptual recognition of faces and of nondescript figures as whole patterns, and for dealing with spatial and part–whole relationships, for noverbal thinking, and for direct perceptual transformation, but not conceptual or symbolic transformation. These latter are done better by the verbal, left brain, which appears to be the superior and dominant brain for verbal communication, linguistic and numeric processing, sequential and analytic thinking, for conceptual symbolic recoding, and for directing motor activity in general.

Another thing to come out of these studies is the demonstration that the minor hemisphere is quite capable of capturing and controlling the motor system under conditions in which it is in equal and free competition with the major hemisphere—where the sensory input is equated and the subject is quite free to use either the left or the right hand. We had not seen this so convincingly before. It suggests that in the normal intact brain the impetus for voluntary, willed movements need not be triggered entirely from the major, dominant leading hemisphere, but may be prompted in some activities directly from the minor hemisphere.

During thinking in the normal brain the two hemispheres cooperate presumably and complement each other, each contributing its respective specialty. A continuum of possibilities is conceivable for such cooperation. At one extreme one could have a distinct alternation of left and right functions performed separately. At the other one can picture a highly unified, bilateral process in which both hemispheres work as one, each contributing fractional elements to a unified whole. I would guess that an intimate interaction along the latter lines, mixing the spatial and the linguistic aspects of the thought sequence, is more typical than is a series of distinct alternations from one hemisphere to the other.

The extent to which thinking is dependent normally on right–left integration should be objectively deducible from the difference in the quality of thinking of these commissurotomy patients before and after their surgery. Unfortunately, precise measurements on logical ability or spatial creativity or the like, are not available and would be difficult to obtain. The majority of the patients already have extensive brain damage in addition to the commissurectomy. We, therefore, would base conclusions on the top performance among the few cases with least impairment. Thought deficits produced by the surgery seem to be sufficiently mild at best (as in L.B. or N.G.) that the patient's family report only an impression that there seems to be some impairment, as in capacity to handle mathematics in school. However, it is not so severe as to be blatantly obvious. Weakening of memory capacity for postsurgical events is the primary consistent complaint. What the foregoing means probably is not so much that few deficits are present, but only that the ordinary social encounter fails to reveal them. One continues to be amazed at what can pass for reasonable mentality under the conditions of ordinary social interaction.

The minor hemisphere of one patient scored better on Levy's spatial transformation test than did 31% of controls from university sophomores. Postoperative scores on the WAIS for these patients gathered by Levy (1969a) show several to be well above normal on the verbal scale. Tasks like comprehension and vocabulary, are relatively unaffected, as compared with performance tasks like digit symbol, block design and picture arrangement which are markedly impaired. The scores for picture completion are exceptional in being high though this last seems at first glance to be a more spatial than verbal task. This test is one, however, in which the minor hemisphere could be used for detecting and fixing on the missing answer, leaving the target of fixation to be named by the major hemisphere. We commonly see this kind of interhemispheric cooperation in the commissurectomy patients and presume that it prevails in the thinking of the intact brain.

It should be remembered that the postulated spatial–verbal antagonism or interference effect in hemispheric processing is not one of total incompatibility. Both functional modes can be carried out within the same hemisphere when conditions require it, as with congenital absence of the corpus callosum (Sperry, 1968b, 1970b), early hemispherectomy, or any extensive lateral brain damage, or in that small percentage of the population in which language develops bilaterally (Milner, Branch & Rasmussen, 1966; Jones, 1966). It is only that forced sharing of the same hemisphere by both modes appears to prevent top level performance for either.

Looking back over the evidence one sees an implication in the findings that strong cerebral dominance and specialization are good, whereas cerebral ambivalence is less so. If it be true that a hemisphere committed to language is thereby handicapped in the spatial, perceptual, nonverbal functions like geometry, drawing, sculptural and mechanical ingenuity, then this should show up statistically in a population of left-handers. This is because cerebral representation of language tends to be more bilateralized in left-handers, as determined from the way in which they recover from cerebral injuries. Silverman, Adevai, and McGough (1966) found left-handers to be inferior to right-handers in basic perceptual tests for "field dependency" and tactual localization. It was suggested that sinistrals have a lesser degree of hemispheric differentiation than do dextrals. Sinistrals have also been reported to do less well than dextrals on tests of spatial orientation and perceptual closure (James *et al.*, 1967). Levy (1969a) compared a group of 10 left-handers with 15 right-handers, selected from graduate science students, and found that the left-handers showed three times a greater discrepancy between the verbal and performance scale on the WAIS. The performance score, reflecting right hemispheric function predominantly, was always lower as predicted. A similar discrepancy has been reported by Lansdell (1969) for persons who have developed right hemisphere speech as a result of early birth injury, etc. Furthermore, Nebes (1971) using his part–whole circle–arc test, found that Caltech left-handers as a group scored very significantly below right-handers, with hardly any overlap.

All of this fits the idea that the verbal and nonverbal perceptual faculties are antagonistic as inferred by Levy and do not do so well when they develop for one reason or another within the same hemisphere. The more common tendency, apparently, when this occurs, is for the nonverbal performance functions to be handicapped in favor of the verbal, though we presume the opposite may also occur. Left-handers who can align themselves with Leonardo da Vinci, Raphael, Michelangelo, and many other giants in history should remember that all of this is very statistical. Individual sinistral brains come in varied degrees and kinds of right–

left asymmetry. A complete mirror switch should leave no effect on cerebral performance—save for those little problems of getting along in a predominantly right-handed world. In any case it may be seen that differential balance and loading between these right and left hemispheric faculties in different individuals could make for quite a spectrum of individual variations in the structure of human intellect—from the mechanical or artistic geniuses on the one hand who can hardly express themselves in writing or speech, to the highly articulate individuals at the other extreme who think almost entirely in verbal terms.

Individual variations of this kind we believe to be hereditary, or at least innate, to a considerable degree, more than is perhaps commonly recognized. Left-handedness, for example, seems to be a familial trait for which genetic models are proposed. Anatomical asymmetries in the brain correlated with cerebral dominance (Geschwind, 1970) have been reported recently (Wada, 1970) to be demonstrable already at birth in the brains of stillborn infants. Dyslexia, a reading and language disability, is agreed to be congenital usually, and often shows a clear family history with a higher incidence among males and sinistrals. I should mention perhaps that one of the commissurotomy patients is a left-hander, and shows a reversal of lateral specialization with speech centered in the right hemisphere, but like left-handers in general no switch has occurred apparently in the specialized spatial perceptual capacities, so that both of these must compete within the right hemisphere.

Through forced training or through spontaneous imitation the genetic left-hander may come to learn to use the naturally subordinate hand for writing, etc., but this is said to invite difficulties, conflict, tensions, stammering, and other impediments to mental proficiency (Trembly, 1970). There is a remarkable account by Jones (1966) of four patients who had been stammerers from early childhood, were shown to have developed bilateral speech by the amytal test, and then all four lost the stammer in their speech as a result of brain operations performed for other reasons that apparently put out of action the speech mechanisms on one side.

The observed dichotomy between verbal and nonverbal mental capacities will suggest to some readers the possibility of looking for correlated male–female differences. We have not pursued this ourselves, as yet, but we note that males are said to be six times more frequently afflicted than females with congenital language disability, that in a world-wide application of the Porteus (1965) maze test in many different cultures girls scored significantly inferior to boys, that Smith (1967) claims females show a selective spatial disability (compensated presumably by extra verbal ability?)

that females lacking one X chromosome are average or above in verbal abilities, but show a profound impairment in nonverbal preceptual performance (Alexander, Ehrhardt, & Money, 1966) and that genetic females masculinized *in utero* by excess male hormone show an exceptionally high incidence of very high IQ (Money, 1970). The common tendency has been to write off observed mental differences between the sexes as a product of social and cultural pressures. More and more the accumulating evidence in psychology (Sperry, 1971) points to more basic biological and evolutionary innate factors. According to Levy, (1971), "It is hard to reject the notion that a spatial-perceptive deficit in women is a sex-linked genetically-determined incapacity, an incapacity which possibly results from hemispheres less well laterally specialized than that of males." The evidence is such, however, that it would seem wise to reserve any conclusions here until more facts become available.

The Discussion of Dr. Sperry's Paper

LED BY DR. PAUL J. WOODS
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Woods: This is certainly exciting and fascinating work. It has been my experience in talking with students, laymen, and professionals outside of the area that when people first hear about Dr. Sperry's work they are immediately interested in the research and impressed with psychology's ability to discover such important aspects of brain functioning. It is a sure-fire way to wake up a disinterested class, and it is excellent ammunition when one has to argue for the value of basic research.

Regarding some of the specific findings, it seems to me astounding that the minor hemisphere is able to process verbal material without possessing verbal ability. As you will recall, a word tachistoscopically flashed to the minor hemisphere could be processed or recognized, as shown by the fact that the left arm could retrieve a related object that was out of sight. The retrieval can apparently be accomplished without the use of language.

One question: What are the implications of the improvement manifested by the young boy? Is it not surprising that he is getting better?

He is certainly not having neural regeneration. Can it be that new functions are being learned by the minor hemisphere, and do your findings have relevance for the theory of equipotentiality?

Open Discussion

Sperry: One possibility to consider is that he is developing speech in the minor hemisphere. A certain fraction of the population does have bilateral speech. We find it in one patient who was accidentally discovered to be totally lacking in a callosum. This was a college sophomore with a C+ record. Another possibility is that the contralateral systems of the brain are being enriched and utilized in a way that they could not be used before. Both hands are represented in both hemispheres, predominantly in the contralateral, of course, but there is a crude representation also in each hemisphere, of the ipsilateral hand. It is possible that vision, also, has its ipsilateral representation. Thus far, we aren't able to select between these alternatives, but suspect some of both.

Dr. Allen Paivio (*University of Western Ontario*): I have a couple of questions that stem from my work and relate to your work with these patients: Is there anything different about your subjects in terms of their introspective awareness of themselves and their environment? Do they feel different after the operation than they did before? The other question is: Can you detect, by common-sense questions, the lack of contact between the systems? For example, consider the illustration that I gave this morning of asking a person to describe his living room. Can your subjects perform such a common-sense task which requires contact between a nonverbal representation and a verbal output of that information?

Sperry: The patients don't report anything to indicate they are aware that they are particularly different than they used to be. Some subjects report things like, "I don't get the message from the left hand" or, "The left hand is numb," during the early months after the surgery. In general, however, the general rule applies that brains seem to be oblivious of what they lack. Take out a whole hemisphere and the other hemisphere doesn't know it. It's like a blind spot in the visual field; you tend not to know it isn't there. In short, we have not seen anything to indicate that there is a difference.

As to the second point, we haven't pushed that thoroughly. I tried this last week, in the smallest boy—asking him to visualize former places where he had lived and been, and so on—and the things that came out were very discouraging, in terms of looking for a separation of the spatial engrams. Since his surgery, they have become pretty intermixed. We are still studying the matter.

Dr. Fred Gault (Western Michigan University): Could you just speak briefly about the effect of these procedures on the epilepsies? Does the individual still have to focus, and if he does, what does this tell us about why it is not expressed as a seizure?

Sperry: The answer in part is that I, by policy, don't know anything about epilepsy. For one patient, the epilepsy was building up, and she came into the hospital in a coma after having had more than 50 seizures the preceding 3 days. She has not had a seizure since recovering from the surgery, and even the EEG, which was abnormal before the surgery is reported by Dr. Bogen to have returned to a normal condition. The very first patient went 7 years without a generalized convulsion, but I'm afraid I would have to refer these and related questions to the medical people.

Dr. T. H. Bhatti (University of Virginia): A study conducted in Italy indicated that injection of sodium amytal in one hemisphere produced emotionally depressive reactions, whereas injection of the second hemisphere of the same individual on another day produced manic, or euphoric, responses. This finding was very consistent over a number of cases, but has not been corroborated by any of the other studies using sodium amytal injection. Have you had occasion to observe any difference between hemispheres in emotional responses?

Sperry: No, but we have not done enough work with emotion to exclude the possibility.

Dr. Allen Rechtschaffen (University of Chicago): I had a thought with respect to dreams. During the REM period of sleep, most of the areas of the brain tested show an increase in unit-firing. In the cat, at least, there is one area which shows a decrease in unit-firing, and that is the callosum. Now the thought occurred to me that perhaps dreams may be the way they are because, during the REM period, it may be that you would one time dream with one-half your brain, the other time with the other half of your brain, and one-half doesn't know what the other half is doing. I was thinking of the two examples I cited yesterday, where in one dream a person has a visual image of talking to an old lady, and then suddenly the phrase comes into mind, "I have got to surround the weekend." Maybe the talking part, with the visual image, is a right-sided dream, and then suddenly, an engram in the left brain takes over, and you get this discontinuity, and she starts to dream with the left side of the brain.

The other example: The subject was thinking about his girl friend's problems, and suddenly he sees the tears falling down her eyes in four straight vertical lines; that could be a shift over from a left- to a right-sided dream. This could possibly account for the very prevalent appearance of strangers in dreams; about 40% of the characters in dreams are strangers, people we don't recognize. They are not unusual in any other way; they are just people we have never seen before. Perhaps these are people we *have* seen before, but if we are having the dream in the right hemisphere, we don't recognize them with a verbal label. In the waking life of your subjects, do they show any discontinuities in spontaneous mentation that resembles our normal dreams?

Sperry: A good analysis of their speech, alone, as well as of their modes of thinking, is certainly called for, but it is a very difficult thing to do. You would expect their thinking and their speech, maybe, to be lacking in certain properties that normally are contributed by the other hemisphere. Even the simple things are hard enough, but we just haven't gotten to an analysis of this kind.

Rechtschaffen: We would not expect their dreams to be different from anyone else's dreams; but you might expect, if my idea has any merit at all, that in waking life, they have sudden dramatic shifts in the stream of consciousness, depending on which kinds of engrams were prepotent in this spontaneous consciousness. And you wouldn't necessarily find evidence of such shifts from conversations with them, because while you are conversing with them, the left hemisphere would necessarily be predominating.

Sperry: That's the trouble. The left hemisphere predominates nearly all, if not all, of the time under ordinary conditions, and if you don't get this kind of information though their conversation, how can you get it? It wouldn't be easy.

Dr. Larry Thompson (Duke University): Have you looked at slow potential changes over the left and right brains of these patients?

Sperry: Not ourselves, and I know of nothing striking to come out of such recording.

Dr. Ralph Hefferline (Columbia University): Does your statement that each hemisphere has motor control, and can initiate action, imply anything about the moment-to-moment muscular status of the body in terms of postural readiness, and so on? Wouldn't there be a tendency toward rather intense conflicts and spastic conditions?

Sperry: There is a whole series of unifying factors that tend to keep motor behavior together, like the double representation of the motor system for the axial body, face, neck, and so on. Whichever hemisphere is running the show, it thus runs it in a unified way.

Audience: Is there a shift back and forth with one side or the other being dominant at any given instant, or does each hemisphere always have partial control?

Sperry: Under testing conditions, you can force the minor hemisphere to retrieve items and do other things; but, under ordinary conditions, the major hemisphere seems to dominate most of the time. It appears that, for the first several months after surgery, the subjects are really alert and conscious only in the major hemisphere, and not in the minor. The minor seems to be more severely depressed, as if it is more subject to cerebral (surgical) shock.

Bhatti: In reference to the coordination of movements, particularly on the two sides, it may be relevant to note that in an encephalic child that is born without any of the forebrain structures, if you hold the child so that his toes touch the table, he will make walking attempts; and if you put him in the water, he will make swimming movements. These apparently are coordinated at the midbrain, or brain stem, level. The basic pattern of these movements is present, and can be initiated by either one, or both, of the hemispheres.

Dr. Peter MacNeilage (University of Texas at Austin): Three brief questions: First, have any of your patients been typists, and if so, have they had problems with typing? How does the right hemisphere perform on visually presented spatial prepositions, like "up," "down," "left," "right," "back," and so on? And third, can the right hemisphere assimilate visual–verbal information? Like, what is the perceptual span, and does a following masking visual stimulus have as much effect as in normal subjects?

Sperry: Our subjects have not been typists. But, some cases of Akelaitis with extensive section of the callosum, apparently, continued typing; and one of them continued to play the piano with both hands, as does one of these present cases at a very simple level.

With regard to spatial prepositions: When we flashed words like "up," "down," and so on, to the minor hemisphere, the responses were pretty nil except in the youngest subject who by now has reached the point where he often can report things flashed for the left-half field. How he does it, we don't yet know. There is a big difference here as to whether such surgery was performed at the age of ten or so, before losing the plasticity of development. The congenital case showed the extreme of this kind of compensation. With her, we can go through all of the tests and discover practically no symptoms at all. It is only in complex mental functions that symptoms show up.

The third question, about how good and how fast is the perceptual capacity of the right hemisphere to assimilate letter information: quicker than the left, I suppose. There is no problem as far as receiving detailed perceptual information. You mean refined details, don't you?

MacNeilage: Yes. I mean how many letters can the subjects perceive in, say, a 12-msec flash; or how much are they affected by a following visual masking stimulus?

Sperry: We haven't measured this, but they perceive four- and five-letter words, flashed at a tenth of a second, or less. There are difficulties with peripheral vision as well as timing.

Audience: In the new learning of new words, are there any differences in the fact that pitch is taken in one hemisphere, and rythm by another?

Sperry: No such differences have been noted after surgery. Rythm is in both.

Audience: Has anyone had occasion to learn a new language since their operation?

Sperry: We have not taken on the problem of new language learning. Some subjects have been bilingual, but we haven't noticed any differences between the original and the second language. Both seem to be lateralized similarly.

Audience: If the left hemisphere is active, can the right hemisphere be independently active? For instance, can you have someone reading with one side, and simultaneously do arithmetic with the other? If so, what is the mechanism?

Sperry: When one hemisphere takes command of the motor system of the brain stem and cord, it tends to prevent the other hemisphere from getting into that system. Now, if there is a common motor set throughout the whole body so that one hemisphere doesn't conflict with, or mutually exclude, the other, two behaviors may be carried out by right and left hemispheres without conflict—in this case, you can get the two hemispheres working in parallel.

Audience: Can one hemisphere read and speak what was read, while the other performs a tactual task?

Sperry: We sometimes deliberately put the right hand to a task, like doing a tic-tac-toe, or sketching, or rolling balls, just to get it out of the picture so that we can get at the minor hemisphere; some such routine tasks can apparently be performed without disrupting the activity of the minor hemisphere expressed through the left hand.

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