

The behavioral consequences of sectioning the cerebral commissures raise fascinating questions about the physical basis of conscious behavior

The idea of consciousness stands out alone as man's most important, most puzzling, and most abused problem. Most other human ideas pale in complexity next to this one and to the long series of associated questions surrounding the nature of brain and mind. Indeed, upon studying the problem and reading the literature, one cannot help but conclude that the only subjects of greater mystery are the articles written about or around the problem of consciousness.

It is difficult if not impossible with our present knowledge to define explicitly what is meant by conscious experience. What I mean by the term can be illustrated by considering what you the reader presently feels. It is the dimension which makes you more like a dog than a computer. Since this is hardly a sophisticated or formal notion, we talk about the *functions* of consciousness in order to make the subject of consciousness scientifically manageable. Thus eating, drinking, reading, loving are all analyzed in their separate parts. By studying these aspects of conscious activity we hope to gain some understanding of the whole idea of consciousness. In real terms, of course, how such processes relate to brain mechanisms remains unknown. Yet it is these kinds of questions that arise when

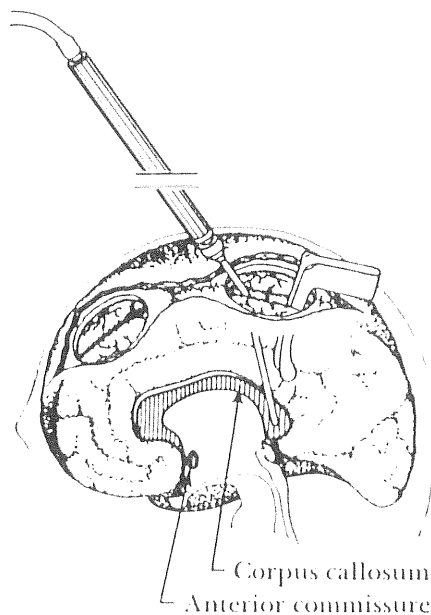


Figure 1. Both a frontal and a posterior opening are made in the split-brain operation. The corpus callosum and anterior commissure are sectioned in one operation.

considering the problems of the bisected brain in both animal and man.

Over the past ten years we have collected evidence that, following midline section of the cerebrum, common normal conscious unity is disrupted, leaving the split-brain patient with two minds (at least)—mind left and mind right (5, 25). They coexist as two completely conscious entities, in the same manner as conjoined twins are two completely separate persons. This view has been contested by a variety of people (2, 19). In what follows we will first review the basic findings of the split-brain phenomenon and then report on several recent advances that give further support to our view that two minds can exist in one head.

In many ways, the split-brain phe-

nomenon is as startling and basically mysterious today as when R. E. Myers and R. W. Sperry first discovered it in animals in the early fifties. As experimental animal evidence for the double-brain phenomenon developed and expanded to include the monkey and the chimpanzee, the question became: Could a human being be considered to have double consciousness as a result of midline section of the cerebral commissures? Could a pass of the surgeon's knife produce two separate and distinct coexisting mental entities both within one head—each operating outside the realm of awareness of the other?

In recent experiments on both animals and man, additional supportive evidence has accumulated for the double mind view. Studies examining the neural substrates involved in setting response probabilities, as well as preliminary work examining cortical-hypothalamic interactions, all argue for the double mind view. In addition, our ongoing work on teaching left brain-damaged patients an artificial language gives support to the earlier view of the natural mental capabilities of the right-half brain.

General review

Clearly, in man the issue of "double mind" is more dramatic than in the animals. In most of the following we will be talking about double mind as it exists in split-brain patients. All of a group of several patients operated on by Dr. P. J. Vogel and Dr. J. E. Bogen, at the California College of Medicine (1), were epileptics, and the aim of the surgery was to prevent the interhemispheric spread of seizures. To this end, the great cerebral commissure, the corpus callosum, which

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spans the midline of the brain and interconnects the two half brains, was sectioned in one operation (Fig. 1). In addition, a second, smaller commissure, the anterior commissure, was also cut.

Therapeutically the operation has been largely successful. Behaviorally, the patients for the most part appear entirely normal, and the untrained observer would be unable to ascertain that brain surgery had ever been performed. It is only under special testing conditions that the peculiar phenomena reveal themselves (5). The left hemisphere, because of its intact language and speech system, can fully communicate its thoughts and ideas; it seems to be normal and conscious. It is the right hemisphere's status that is both crucial and difficult to ascertain. It does not have a speech system and thus cannot tell about its experiences through speech. We have circumvented this problem by using nonverbal response procedures (Fig. 2). As a result we have been able to define many right-hemisphere functions that can go on independently and largely outside the awareness of the left hemisphere. It can read, learn, remember, emote, and act all by itself. It can do almost anything the

left can do, with admitted limitations in the degree of its competence.

Since this original series of studies delimiting the syndrome of cerebral commissurotomy, there have been continuing efforts to extend and further define the behavioral consequences of the surgery. Some of the work emphasizes the role of brainstem processes and the amount of information that can be exchanged at these levels (27). Other studies caution against this view and point out how many of these assertions have other explanations (8, 9). Still others have analyzed the way such separated hemispheres approach and solve perceptual tasks of all kinds (26). These latter studies claim, for example, that the right hemisphere remembers faces in terms of a "gestalt"—of the actual pictorial and configuratory cues—while the left hemisphere is more analytical and tends to remember by analyzing specific features of a face. The idea here is that mind left is poet-like and mind right is the painter in us.

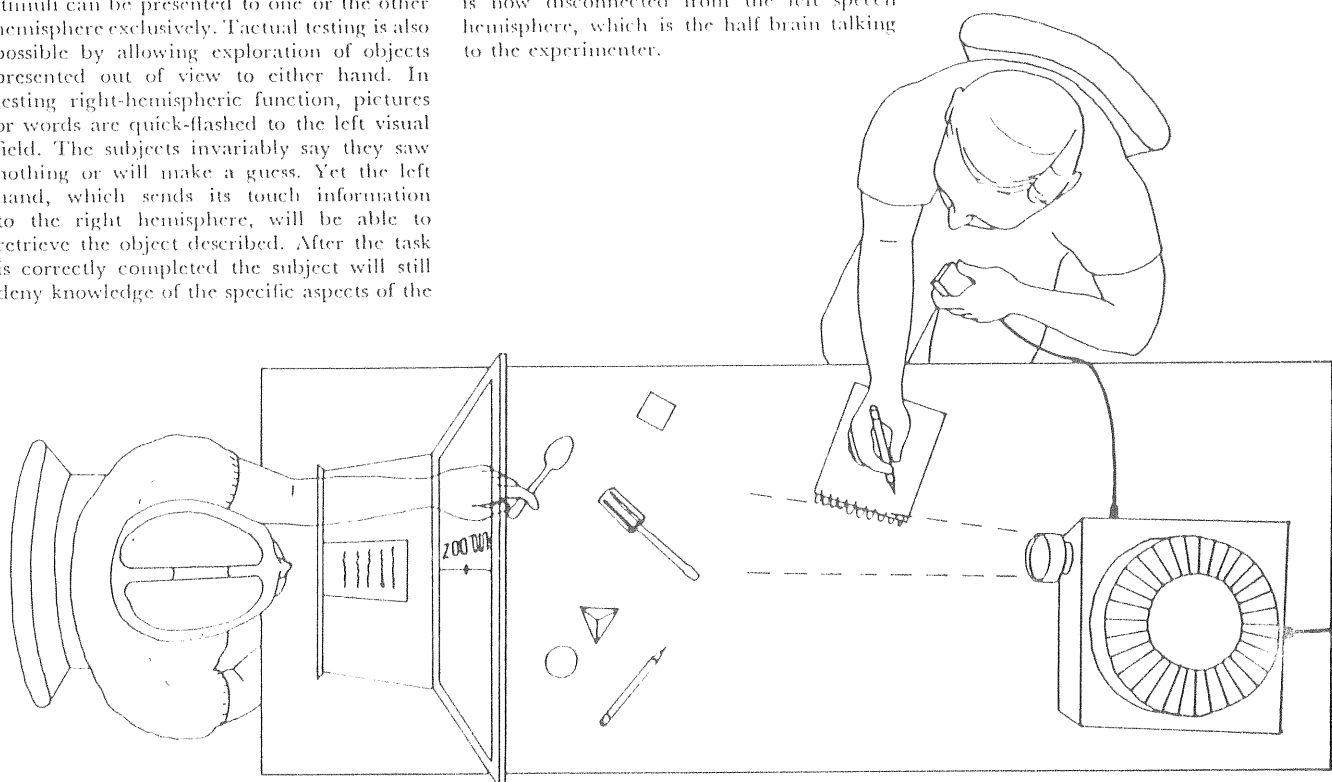
The suggestion that these kinds of observation support the idea of double consciousness (i.e. a separate set of mental controls for each hemisphere) has been challenged by Donald M.

MacKay (19). He raises a crucial and fascinating question. All organisms have, of course, normative systems. Clearly, in split-brain man, at the physical level, basic humoral and electrotonic brainstem influences are unified and intact. In addition, MacKay wonders whether basic psychological systems such as our response priority-determining mechanism exist in duplicate in these patients. This is the system that sets the goals, priorities, and rank order of objectives of an organism. Put differently, it assigns values or response probabilities—one of the most important features of brain activity. Without this mechanism the world would seem flat and any activity would be like any other. MacKay maintains that this system, which he calls the "metaorganizing system," is a leading and basic feature of brain function and that it is rarely if ever in conflict. As a result, he maintains, it falls to us to demonstrate whether or not each half brain has its own priority-determining system that can work independently of the other.

There are seemingly a lot of things going in favor of MacKay's criticism. Hillyard and I (9, 12), for example, have recently shown that the CNV brain wave (i.e. the contingent nega-

Figure 2. Using an apparatus especially designed for testing split-brain patients, visual stimuli can be presented to one or the other hemisphere exclusively. Tactual testing is also possible by allowing exploration of objects presented out of view to either hand. In testing right-hemispheric function, pictures or words are quick-flashed to the left visual field. The subjects invariably say they saw nothing or will make a guess. Yet the left hand, which sends its touch information to the right hemisphere, will be able to retrieve the object described. After the task is correctly completed the subject will still deny knowledge of the specific aspects of the

event, because the activity was carried out by the disconnected right hemisphere, which is now disconnected from the left speech hemisphere, which is the half brain talking to the experimenter.



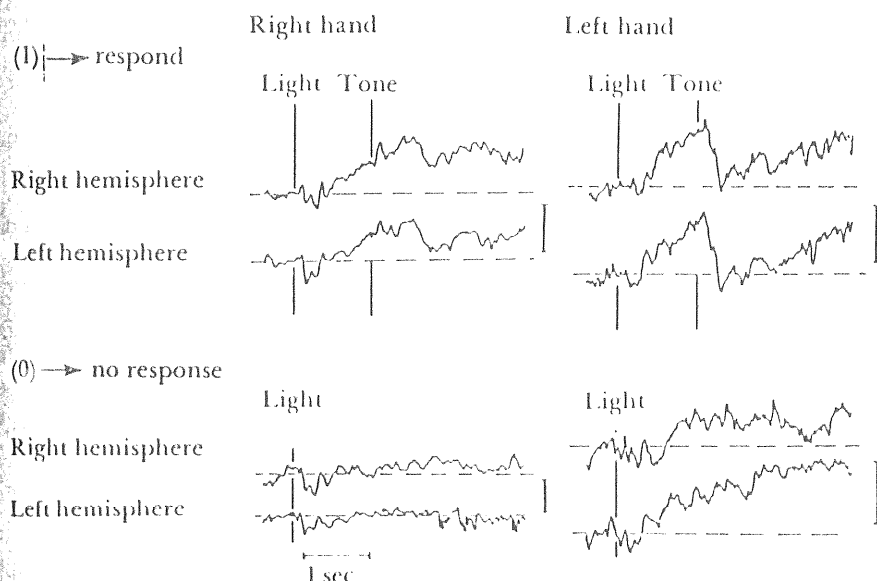


Figure 3. Computer-averaged CNV's ($N = 12$) recorded simultaneously from the scalp over the right and left hemispheres when right or left hand was used and left visual field-right hemisphere was presented the visual discrimination task. Clearly, both hemispheres develop the expectancy wave even

though only one knows what the triggering stimulus was. Nonpolarizing electrodes were placed 5 cm to the right and left of the midline, along the interaural line. Trials containing eye-movement artifacts were excluded from these averages. DC amplification was used; calibrations, 20 μV .

tive variation brain wave that appears over the parietal lobe region prior to a specific motor response) is bilaterally symmetrical, even though only one half brain sees the triggering stimulus (Fig. 3). In this test, recordings were made on each side of the skull while a visual discrimination was flashed to only one hemisphere. The subject was trained to make a manual response to a tone which followed the numeral "one" but did not follow a "zero." Thus, when the "one" appeared the expectancy brain wave develops but does not appear if a "zero" is flashed. When the information was presented in the left visual field, which projects to the right hemisphere, the subject responded appropriately. When subsequently asked what the stimuli were, the subjects said they didn't know—that's the left hemisphere talking. Yet the physiological recordings showed that the normal expectancy wave developed in each hemisphere.

In the past such waves were thought to have a 1-to-1 correspondence to basic psychological processes. While this may still be true, the relation becomes more remote. The separated hemispheres are linked in these parameters but remarkably different in both their subjective and objective reports. The CNV seems to have psychological specificity with respect to the events

that trigger it, but it cannot be indexing a psychological process like attention or expectancy because the non-expectant hemisphere also has the CNV. As a result, what initially looked like a strike for hemisphere unity now appears to be otherwise.

Still the MacKay question is open. Experimentally, the question becomes: Can one environmental situation precipitate two different behavioral responses, each having a different value for each half brain? In other words, could the same rewarding event elicit a different probability of responding in each separate hemisphere?

There is a difference between what I am asking and what has already been shown literally hundreds of times in split-brain cats, monkeys, and humans. A variety of studies have shown that the split-brain organism can learn conflicting visual discriminations. For example, the right hemisphere is trained to learn that the + of a + vs. 0 discrimination will be rewarded in one half brain and the 0 of the + vs. 0 in the other half brain. In this experiment the peanut or reward value is kept constant: the animal has the same probability of responding to it in each half brain. Learning opposing visual discrimina-

tion cues as a less probable contingent response is, you might say, a cognitive detail. It does not put the normative system in conflict for the peanut always remains rewarding.

Again, what we are asking is the more basic question: can the more probable response, namely eating the peanut, have a value X for one hemisphere and a value Y for the other? This question was recently analyzed by J. D. Johnson and myself, using split-brain monkeys (17). During the course of studying the role of reward in learning it became apparent that the positive stimulus of a visual discrimination, which may become a rewarding event in and of itself in one brain, simultaneously elicited neutral responses in the other half brain.

Consider the following. We have shown that when one naive hemisphere observes the errorless performance of the other on a pattern discrimination, it too learns (16). In other words, a half brain need not experience errors to learn a visual discrimination.

Having established that trial and error is not a necessary condition for learning, we next tried to analyze the role of reward. In brief, we taught one half brain a new problem and then advanced the reward schedule to fixed ratio 2 (RF-2). Thus, on every other trial the animal was rewarded (Fig. 4). On the nonrewarded trials, both the trained half brain and the naive half brain were allowed to view the discrimination. On the rewarded trials, only the trained hemisphere saw the problem; the naive half brain saw nothing. Could the naive half brain learn if it only observed correct performance and also never experienced a reward? We supposed that if the normative system (which assigns values or response probabilities to all events) was common to both hemispheres, the monkey would calmly and easily learn the discriminative cues even though there was no primary reward present. The secondary or quasi-reward value of the stimulus ought to register instantly on the naive side.

What happened was most surprising to us. The naive hemisphere not only did not learn the discrimination, but on the nonrewarded trials it actively interfered with the ongoing normal discriminative activity of the trained half brain. In other words, the naive

half brain was not content to observe the performance of the trained side on these trials as it had before when rewards were present. It waived any response tendency that might have transferred and sought its own solution to the problem. As a result, it actively intruded and interfered with behavior.

Clearly, any quasi-reward value of the discrimination *per se* that may have been assigned to the stimulus by the trained half brain did not transfer, and was in no way communicated, to the naive half brain. If it had, the naive half brain would have learned easily and would not have been frustrated. Indeed, when looking at the actual behavior, it was as if two different value systems were competing for control over one response mechanism.

These animal studies are in agreement with recent testing of the split-brain patients on the effects of reward (Fig. 5). We showed that when a reward—say, the appearance of the word “right” for correct responses and “wrong” for incorrect responses—was flashed to one half brain and a visual discrimination was presented exclusively to the other, no learning occurred in over thirty trials (15). In callosus-intact people, the information is immediately synthesized and learning occurs in one or two trials. Johnson went on to show, however, that if the split-brain patient was reprimanded for making an error, quick learning occurred. Here, it is hypothesized, the reward, or feedback, no longer remained cortical. When the “wrong” light appeared the patient would now make an exclamation, sigh, and gesture disgust. On the next trials, learning occurred. Thus when the reward took on more general affective responses the cuing became so massive that the opposite half brain could figure out which stimulus was producing the general negative reaction and which was not. Taken together then, it can be said that higher-order reward information can remain isolated and separate in the split brain. Each hemisphere apparently is free to assign different or even conflicting response probabilities to the same stimulus.

In a more direct physiological approach to these same general questions, Alan Gibson and I have been analyzing the eating behavior controlled by each hemisphere in split-brain monkeys, following unilateral

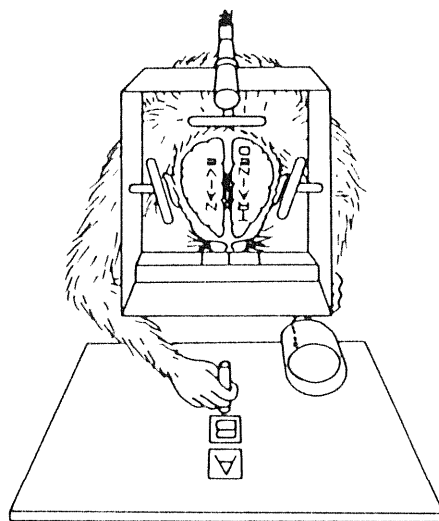


Figure 4. Split-brain monkeys observe a visual discrimination through a specially designed training apparatus which allows for the separate or combined projection of visual information to each eye. Here a naive hemisphere is free to observe the errorless performance of a trained hemisphere.

hypothalamic lesion (14). To date we have seen marked differences between the hemispheres in food intake behavior and response patterns as the result of the lesions. In other split-brain animals, differences were discovered that reflected unilateral damage to the hypothalamus as a result of the surgery. What is apparent is that two completely different response probability systems can coexist in the split organism for something so basic as food. That is, one hemisphere will initiate more activity for food than will the other. This must mean that the cortical system, which is the only neural system disconnected in split-brain surgery, is much more involved in the hypothalamic process than we had ever thought.

Language training

The earlier claim of the existence of double consciousness following transection of the cerebral commissures has received support from other studies. At the time, we largely based the idea on the extensive evidence we had collected on the cognitive capacity of the disconnected right hemisphere in man. This mute, passive cognitive system was shown to be capable of a number of mental operations, as outlined above. One inference from this work was that if the left, dominant hemisphere should ever be damaged in a normal adult, the right side with proper training ought to be able to come to its aid. While this idea has

received little support from huge amounts of clinical data, it nonetheless seemed viable as a result of our studies on the bisected brain.

Recently, working at New York Institute of Rehabilitative Medicine, Andrea Velletri, David Premack, and I were able to teach an 84-year-old global aphasic some basic language operations (11). This woman had had a major stroke involving the left speech and language center that rendered her hemiparalytic and unable to understand or produce natural language. Nonetheless, using the language scheme developed by Premack (22) for chimpanzees, we were able to train her to arrange correctly cut-out paper symbols that were referent to language operations.

Contrary to existing views, which in the main hold that the left hemisphere's language center is specialized for the processing of symbolic information, the subject learned that a variety of paper symbols were each referent to a particular linguistic operation. For example, when two similar objects were placed side by side, the subject could place between them a symbol meaning “same.” When the objects were different, another symbol, representing “different,” would be appropriately placed. The proper use of the “same” and “different” symbols was not restricted to the items used in training but transferred freely to non-training items. A question symbol was introduced in the same-different construction and given the meaning of “missing element”; the subject showed her grasp of the symbol by successfully substituting for it whatever element was missing, predicate as well as object. In addition, the subject could form the negative in the injunctive mode. We have extended these observations by training six more global aphasics. Some have been brought to the level of generating simple sentences using these methods.

While, of course, one cannot completely rule out the possibility that undamaged parts of the left hemisphere are active in carrying out these tasks, it would seem fair to say that a more likely explanation is that the remaining right hemisphere is doing the work. In other words, the original split-brain data we reported on humans that spelled out the boundary condition of mental competence on the right side give support to the notion

that the right hemisphere, separated or not from the left hemisphere, can do many complicated and sophisticated cognitive operations.

These remarkable abilities in severely brain-damaged global aphasics demonstrate that the languageless human being still possesses a conceptual system that can handle the logical tasks outlined in the foregoing. The data suggest, moreover, that there exists in the brain a conceptual system that is separate and independent from the natural language system. Indeed, it could be that this primitive conceptual system may be the primordial cognitive system of primates, from which may have come the language abilities of man. Approaching the problem of cognition in this light suggests the theoretical importance of coming to a better understanding of the brain-damaged human. With the confounding and interwoven language mechanisms put to rest, we can begin to see

how the brain deals with complex logical operations in the raw.

There is other additional support for the view that the right hemisphere has tremendous cognitive powers. We have seen the intact brain at work performing perceptual tasks outside and independent of the normal language system. In some exploratory and preliminary tests (7) carried out at Cornell Medical School, unilateral amytal testing was done on the left hemisphere of two nonaphasic brain-damaged patients subsequent to a required angiogram. Prior to injection of the anesthetic, which has the effect of putting one half brain briefly asleep, an object was placed in the subject's left hand, out of his view. When asked what it was, the subject responded correctly by saying "spoon." This showed that the left hand right hemisphere somesthetic projection system was working as well as the right hemisphere-left hemisphere callosal link to

the speech center. Next, the amytal was administered and the left hemisphere went out. At this time, when the patient is totally unable to use or understand language, another object was placed in the left hand. Since the right hemisphere is exclusively awake, it is free to remember the test object. The subject held it for awhile, and then it was removed. Shortly thereafter, the effects of the drug wore off and the left hemisphere woke up. An exchange followed that went something like this:

"How do you feel?"
 "Fine," said the patient.
 "What did I put in your hand?"
 "I don't know," said the patient.
 "Are you sure?"
 "Yes," said the patient.

Then a series of objects were shown to the subject. "Which one was it?" The left hand immediately pointed to the correct object.

It is still too early to report all the necessary qualifications on this experiment. Other patients, for example, are unable to remember anything at all. Yet, the first result suggests that, when the natural language and speech system is not functioning, perceptually stored information encoded at that time is not subsequently available to the language system upon its return to normal operation. In a way it is like the common experience of being unable to remember events earlier than the age of two or three. It is possible that the brain can remember critical events, which may later play a role in the control of behavior, but because the remembered events occurred prior to the clear establishment of the language system they cannot be subsequently recalled through this system.

Yet the brain is forever confounding its students by continually offering up paradoxes. From some of our recent tests it would seem that the functional capacities of the right hemisphere are present to a different extent when it is tested in the presence of the left hemisphere but disconnected from it versus when it is tested in the presence of a damaged left hemisphere. Many of the positive functions attributed to the right hemisphere come from our studies on split-brain patients. As I have said, simple noun-object discriminations were easily carried out. If we blindfold a subject and tell him to find an object with his left hand,

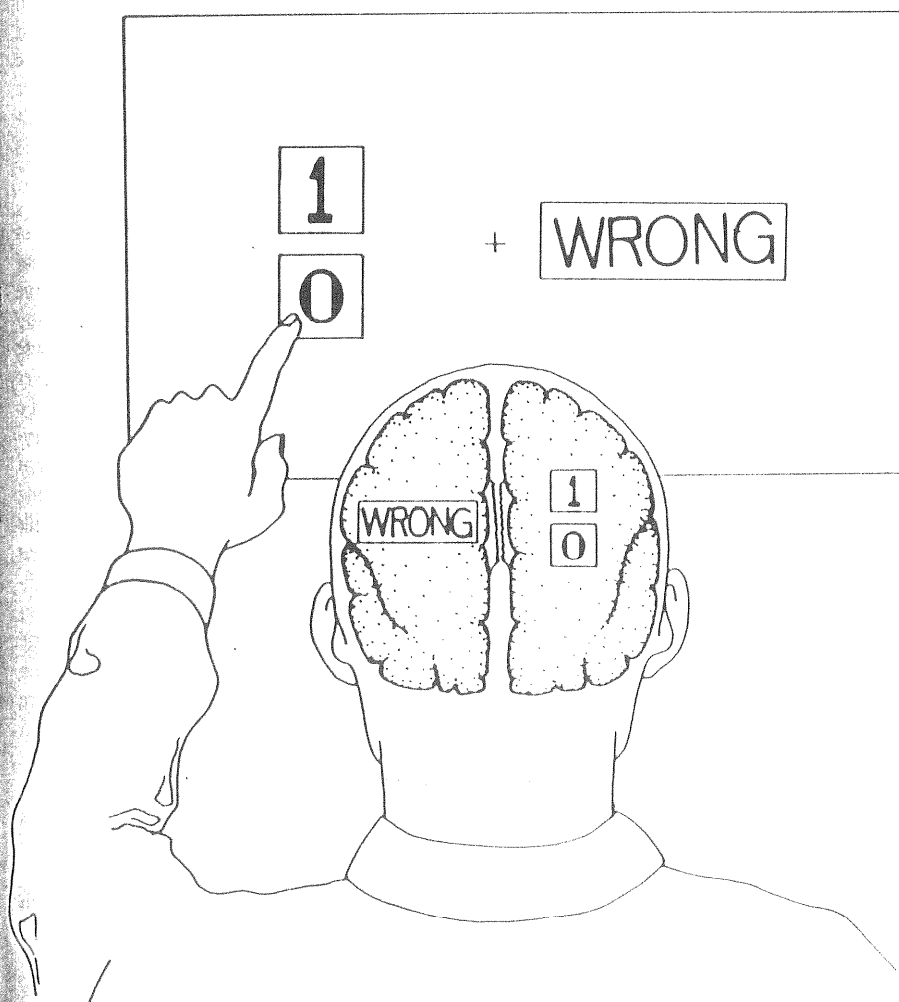


Figure 5. Split-brain subjects are unable to describe verbally from the left hemisphere visual information presented to the right hemisphere (left of fixation). Here a discrimination is presented to the right hemi-

sphere while only the left receives reward information. Normals learn the problem quickly, but a split remains at chance level after 50 trials.

correct performance is invariably seen. Here both hemispheres hear the question while only the right receives the opportunity for answer by stereognostic information from the left hand.

When this test is run on a subject with a minimally damaged left hemisphere no such ability is found (10). We recently examined a 63-year-old man with a crisp and nearly pure auditory agnosia. He has no evidence of bilateral disease. He essentially speaks normally, reads normally, and writes normally, yet he cannot understand a single spoken word and was unable to perform the auditory tactile test described for the subjects with split brains! The real differences in functional expression from the right hemisphere as seen in this case suggest that damage to the left hemisphere plays an important role in limiting or inhibiting the upper capabilities of the right hemisphere.

Brain code and the corpus callosum

It is difficult at this point not to mention a major aspiration coming from this work. Those of us in brain research assume that there is a corollary physical code to our personal psychological experience. It has not been at all clear how and where one would approach this problem in the brain, but it now seems that the corpus callosum might be a good starting point. We know beyond a shadow of a doubt that it is this brain structure which relates the psychological, conscious experiences of one hemisphere to the other. Therefore, if we could succeed in gaining insight into the nature of the callosal transfer mechanism, it is possible that we would also find some answers to the more general question of how the brain encodes and transmits psychological data.

It is in this context that we first examined interhemispheric exchange of information in normals. Obviously, in order to begin to understand the corpus callosum, it is necessary to study people in whom it is still intact. Briefly, the original idea was to use lateralized visual stimuli in combination with reaction-time measures in an effort to determine the timing and transfer properties of this great commissure. By asking for a spoken response in a left hemisphere-dominant person, we had hoped to show a difference between the reaction time to

incoming stimuli that were originally projected to the left hemisphere, as opposed to information originally projected to the right half brain.

In one of our first studies, we found that when a simple dot was flashed to the left hemisphere, subjects responded approximately 30 msec faster using speech than when it was flashed to the right hemisphere (1). The response was to say "yes" when the dot was present and "no" when it was absent. When a trial consisted of a simple flash, the "no" response took approximately 40 msec more than when the left hemisphere was responding to a dot. This was explained by the fact that the left half brain had to wait for a signal from the right as to whether a stimulus had appeared or not. At that time we also showed that there was no reliable difference in this task when a manual response was required.

Along with the dot experiment, we were examining the extent to which each hemisphere in normal man is capable of controlling language processing (6). Here we used the Posner and Mitchell "name identity versus physical identity" tasks and demonstrated that tasks requiring verbal processing were done more quickly when the test material was first presented to the left half brain. In this experiment there were two conditions. In the first part subjects were required to respond manually only to physically identical stimuli. Thus AA or aa would require response whereas AB, Ab, or ab would not. The results showed that there was no difference in response rate as a function of left or right visual field presentation. In other words, either hemisphere could perform this task rather easily.

In the second condition, however, the subject was instructed to respond to name identity only--i.e. whether the two adjacent letters were of the same class, such as Aa. Here there was a difference between the two hemispheres. When the information was presented to the right nondominant hemisphere, the response took longer than when it was flashed to the left speech hemisphere.

We next examined whether the interhemispheric exchange relation could be reversed (13). We thought by taking a visual-spatial task we could now find right-hemisphere superiority.

Using a simple visual pattern task that required subjects to judge which two zig-zag figures were oriented in the same direction, we found that, with a verbal response, the discrimination could be performed much more quickly when presented first to the right hemisphere. When first presented to the left hemisphere, the task takes approximately 14 msec longer to perform. The interpretation is that information needing spatial analysis which is presented to the left hemisphere is first relayed over to the right for decoding and then sent back to the left for the verbal response.

There have been a number of additional observations reported which seem to bear out these early general findings (3, 18, 20, 21, 23). A variety of different tests have been used, and not too surprisingly there have been different observations on the interhemispheric transfer latency. For the most part the tests break down into two main categories: those that deal with the callosal transmission and timing properties and those that are primarily concerned with the different cognitive properties of each hemisphere per se and how they relate to information processing models.

In a sense, of course, these kinds of early studies simply demonstrate that reaction time techniques are sensitive enough to be used to trace information flow in the brain. It remains for these techniques to be used to discover properties of the callosum itself. To this end we have recently been carrying out a series of experiments that require the interhemisphere matching of visual information (7). Using this procedure we quickly discovered that interhemisphere matches using difficult-to-see visual stimuli (subjects indicate whether two words are the same or different) are far less accurate when one word is flashed to one hemisphere and the other to the opposite than when both are flashed to the same hemisphere. If the stimuli are bright, crisp, and clear, no such differences are seen.

At the start then we may be faced with the fact that the callosum is a rather limited communication channel. It normally is engaged in communicating the activities of one half brain to the other in a still unspecified spatial-temporal neural code, and it does not easily encode for transmission weak signals presented to one hemisphere. We

can only make this very general assessment at present, of course, because even if such a code exists, we wouldn't recognize it if it were placed in front of us. Indeed the problem of properly conceptualizing how this system might work is both the challenge and the mystery of the corpus callosum.

Summary and implications

It would seem fair to say that we now know that the physical substrate of conscious experience exists in duplicate in the human brain. For reasons that are not entirely clear, the separate systems are linked together in the normal organism by the corpus callosum. Furthermore, the critical function of assigning values, or response probability, which is certainly a core activity of brain and behavior processes, involves neural systems that can maintain a mutual independence after cortical-cortical disconnection. While it has never been clear what brain areas are involved in these crucial mechanisms in behavior, many researchers have assumed that subcortical systems, which remain functionally interconnected in the cortical commissure-sectioned animal, would have been primarily involved.

But, most importantly, in the normal subject it is the interhemispheric connections which allow for conscious unity. In other words, we can now say that a particular brain structure, the corpus callosum, transmits information responsible for subjective experience. When it is intact, we have our normal sense of conscious unity; without it the private experiences of the right hemisphere go on outside the awareness of the left, and vice versa. As a result of these studies we have succeeded in beginning to tie down highly complex psychological processes to specific neurological systems.

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"Bad news. I hear we're on the endangered species list."