1988. In A. Marcel & E. Bisiach (Eds.), Conciousness in Contemporary Society. NY: Oxford University Press.

160

10

Brain modularity: towards a philosophy of conscious experience

Michael S. Gazzaniga

Thinking about thought has a long and distinguished history. It is what philosophers do and it is one of the more difficult human mental activities. To have a philosophy of something is to try to have an understanding of how one comes to know what it is one knows about the subject in question. What makes that so difficult is that philosophical thinking demands working out relations between two different levels of analysis. A philosophy of conscious experience would require knowledge about the content and mechanics of conscious experience and the process by which consciousness was gained. A science of conscious experience, by comparison, is much easier. Students of that enterprise need only worry about representational systems independent of the stuff that sustains those representations and independent of a consideration of how they came to know the ideas expressed in the representation. There are a million things to know within that framework, and there should be little mystery why many scientists investigating the nature of human consciousness are reluctant to engage in the additional chore of considering a philosophy of conscious experience. To achieve the goal of having a philosophy of conscious experience would require, it seems to me, the philosopher of conscious experience to know about the brain. From my perspective, understanding brain logic will illuminate these traditional epistemological issues. I will take as my assignment, therefore, the outlining of what I feel are important brain facts, facts a philosophy of conscious experience ought to incorporate.

My message is that in order to know how we come to know what we know we must learn how and why the human brain seems reflexively given over to the process of generating hypotheses and explanations for events (information) it contacts. Why must self-produced actions, thoughts occurring suddenly in our conscious experience, mood swings, externally occurring events, and other perturbations of the status quo be interpreted? Why does the human species not content itself with simply

recording internal and external actions and leave the possible causal aspects of the experience in question alone? Why must we come to lay claim that we know why an event occurred and gradually transform this thought into a firmly held belief? What is it about us that finds us always transcending a literal contact with the environment and insisting on an interpretive view of events? Our species does all of this with a vengeance. Even fatalists from religious or whatever background have asked the question 'Why?' That they have accepted a stock answer handed to them by a religious system or whatever does not negate the reality of their original question. The interpretation we give to the question 'Why?' starts with analysing such things as simple hand movements, simple moods, and builds into larger culturally based phenomena. It is everywhere in our species, and I think that there are some provocative clues now available from brain research that shed light on this phenomenon.

My approach will be to outline a series of findings on human patients who have undergone brain bisection and to argue that the findings suggest that human brain architecture is organized in terms of functional modules capable of working both co-operatively and independently. These modules can carry out their functions in parallel and outside of the realm of conscious experience. The modules can effect internal and external behaviours, and do this at regular intervals. Monitoring all of this is a left-brain based system called the interpreter. The interpreter considers all the outputs of the functional modules as soon as they are made and immediately constructs a hypothesis as to why particular actions occurred. In fact the interpreter need not be privy to why a particular module responded. None the less, it will take the behaviour at face value and fit the event into the large ongoing mental schema (belief system) that it has already constructed. If a module effects a behaviour that is dissonant with the belief system established through prior interpretive actions, the behaviour will tend to change the belief system. [One quickly sees the importance of not exposing such a brain to an environment that would encourage certain modules to act in a way counter-productive to the current belief system (Gazzaniga 1985).]

It is important to understand how the concept of modularity is being applied in this context. Modularity refers to functional units that can produce behaviours and trigger emotional responses. This differs from the concept of modularity as it is commonly used in cognitive science (Fodor 1983; Kosslyn 1983). In that setting it refers to the identifiable components that are part of the mechanism of specific mental functions such as mental imagery or language. I will discuss modularity from this standpoint as well. The concept of modularity has also been used in the neurosciences where specific brain structures and areas are identified as carrying out specific functional activities. This is yet another way the term is used, and I will also report on studies relevant to this framework.

Overall, my view, driven by brain studies to be outlined below, argues that our species generates what it thinks it knows as a consequence of a special human brain capacity that insists on interpreting events. This interpretive system, which appears tied to the capacity to make inference, is based in the left hemisphere of most humans, and I believe, as will be made clear, that it is found in the distribution of the left, middle cerebral artery. What is not yet determined is whether the kinds of inferences that can be made about a set of events (data) are limited. Does our species's interpretive system have a very finite repertoire of algorithms upon which to draw when inferring the meaning of the data it is considering? I am convinced mine does, and so, for those who believe human inventiveness is infinite, I shall now proceed to report the observations that find my interpreter making the foregoing claims. Perhaps others will process the data differently.

If the brain is organized in the way I suggest, it is easy to imagine that rich dissociations would be potentially demonstrable in patients with brain damage or disconnections. For independently functioning modules, brain damage ought to eliminate their participation in overall cognitive activities. For modules working in co-operation, brain damage or disconnection ought to yield impaired performance in the remaining brain system. In short, studying the neurological patient should illuminate how modular the brain is in the overall construction of our apparent conscious unity.

It should not come as a surprise to discover that particular dissociations are stumbled upon somewhat unexpectedly and rather routinely. The idea of brain modularity is sufficiently undefined at this time that the cataloguing of phenomena that will someday comprise the total picture of modularity will go on for years. The first dissociation I would like to discuss demonstrates the extent to which non-conscious processes can influence behaviour. I will describe this set of experiments in detail as illustrative of our general testing procedures.

Speech without conscious awareness

We are now able to show how a non-conscious system can discreetly govern an overt behaviour (Gazzaniga *et al.* 1987). Until recently, the view that functional brain architecture incorporates non-conscious parallel processes has been more commonly asserted than demonstrated. In the experimental psychological literature on normals, modern studies have focused on how subliminal stimuli are effective in facilitating subsequent perceptual and semantic judgements (Marcel 1983). Studies on the neurological patient have claimed that information presented in a blind field of vision produced by occipital lobe damage can be useful in generating manual and ocular responses (Pöppel *et al.* 1973; Weiskrantz *et al.* 1974), although there is now evidence that not all lesions in primary occipital cortex allow for dissociations between spoken and manual responses under conditions of a forced choice response (Holtzman 1983). Additionally, patients with extinction on double simultaneous stimulation following parietal lobe damage are able to have the information presented in the extinguished field influence cognitive judgements (Volpe *et al.* 1979).

In a new study (Gazzaniga *et al.* 1987), the results suggest that non-conscious processes can control overt behaviour. Specifically, it is possible to show how the right hemisphere can set up a left-hemisphere-specific response without the left hemisphere being able to consciously access the information inserted by the right brain. In short, the findings suggest that response behaviours can be set up and carried out without conscious awareness of the elicited behaviour prior to its occurrence.

The experimental demonstration of the existence of such systems was made possible by means of tests conducted on a patient with a particular brain condition—the existence of an MRI[1]-verified full callosal section. Case JW is a 32-year-old male who underwent staged surgery in 1979. Post-operation, JW evidenced the capacity to comprehend language in both his right and left himispheres. However, JW can produce speech only from his language-dominant left hemisphere (Gazzaniga *et al.* 1984).

For present purposes I will report on two sets of experiments. The first detailed the capacity of the left hemisphere to name visual information strictly lateralized to the right hemisphere. The second set of experiments was directed at ascertaining the left hemisphere's awareness of the knowledge it possessed. The initial period of each trial was common to all conditions: JW was instructed to fixate a point on the centre of the screen and, when the experimenter ascertained that accurate fixation had been achieved, a single digit was presented for 150 msec 6° directly to the left or right of the fixation stimulus. Two seconds then elapsed and a tone sounded. Conditions differed with regard to the sequence of events following the tone.

In the first study demonstrating the crossed speech phenomenon, a target digit was either a '1' or a '2', and JW's task was to report verbally the digit that appeared after the tone. In this test JW's left hemisphere

[1] Magnetic Resonance Imaging.

could accurately verbalize which of the two stimuli appeared in either visual field. In a second study the subject was required to substitute a difficult word-associate for the simple numbers being flashed. In this complex naming condition, which was identical in all respects to the simple naming condition, except for the response that was required, JW was instructed to respond 'indescribable' when the '1' appeared and to respond 'indestructable' when the '2' appeared. In this test, as in the first, JW was able to respond accurately through speech to stimuli presented in both visual fields.

In the final experiment in this set, the target digit '2' was substituted by '9' in the left visual field only. This condition was identical in all other respects to the simple naming condition carried out in the first experiment. Thus either a '1' or a '2' appeared in the right visual field, whereas either a '1' or a '9' appeared in the left visual field. In this test JW verbally responded to the left visual field '9' as if it were a '2', and overall remained highly consistent in naming the stimuli presented in both fields.

Taken together, these experiments show that JW can name from the left hemisphere information presented to the right half-brain. The next set of experiments examines whether or not JW's left hemisphere is aware of this capacity.

In the first experiment in this group, JW was required to make an interfield comparison using a pointing response. Here, at the tone, two vertically aligned digits (1/2 or 2/1) appeared either in the same hemifield as the target (within-field) or in the opposite hemifield (between-field). JW was required to point with his right hand to the digit that matched the target. The results were clear. JW was able to match the sample information to the target number only when the sample information was presented to the same hemisphere that initially saw the information. Thus a stimulus presented to the right brain such as a '1' could be matched by the right brain but not by the left.

Similar results were seen in another experiment that required JW to make an interfield comparison (same/different judgement). For this experiment, all target digits (either '1' or '2') appeared in the left visual field and, at the tone, a probe digit (either a '1' or a '2') appeared for 150 msec in the right visual field. JW was required to report verbally whether the target and probe digits were the 'same' or 'different'. As in the preceding experiment, JW was unable to carry out a comparison task requiring between-field matching.

These results clearly show that JW's left hemisphere was not able to consciously access the information made available to the speech response system of the left hemisphere. It would appear that the information transmitted to the left hemisphere from the right hemisphere establishes a response readiness for one of two possible outcomes. This readiness is established outside the realm of conscious awareness. In follow-up studies, confidence judgements were taken from the left-hemisphere for both the left and right visual field presentations. When the stimuli appeared in the right visual field, the accuracy and the ratings were high. When the stimuli appeared in the left visual field, the accuracy was high but the confidence ratings were low; to borrow terminology established for other visual studies, it could be called 'blind-naming'.

The dramatic finding that a response system such as speech can be prepared and be capable of functioning without the left hemisphere being aware of the information the speech system possesses is consistent with the view that non-conscious processes can be active in the production of behaviours. In this particular set of experiments the split-brain patient is useful in revealing how such organizational features of human cognition operate.

It is not clear how the information presented to the right hemisphere is transmitted to the left hemisphere. Simple cross-cueing strategies seen in other tests do not appear active in JW (Gazzaniga and Hillyard 1971). If cross-cueing were active, the left hemisphere would be aware of the nature of the information and would be able to respond in the between-hemisphere comparison tasks. As a result it would appear that the transfer of information is internal and neural in nature as opposed to the external strategies these patients can use. Consistent with this view are recent observations using evoked potentials on case JW (M. Kutas, S. A. Hillyard, and M. S. Gazzaniga 1985, unpublished observation). It was shown that early responses in the visual evoked potential were different for the '1' as opposed to the '2' when these were flashed in the left visual field. Clearly the information is being encoded in a differential way, and information is transmitted to the left speech system. The route of transmission is unknown, but is presumably subcortical.

This demonstration of how an unconscious process can directly influence a behaviour is also reminiscent of other examples where the triggering stimuli were emotional in nature. I have previously reported a series of studies that showed how stimuli presented to the disconnected right hemisphere can influence the emotional state of the left hemisphere (Gazzaniga, 1970), even though the left hemisphere is not cognizant of the stimulus that triggered the emotional response in the right half-brain. Recently, LeDoux *et al.* (1984) have developed an animal model for studying such conditioned emotional responses and have begun to be able to track the actual neural pathways involved in an auditory conditioned response. These pathways course through the mid-brain and never reach cortical systems. LeDoux can selectively block the learning of the conditioned response by lesioning the pathways in the mid-brain. These startling findings suggest a reason why our emotional life seems so out of control to our cognitive processes. Conversely, we can begin to see a brain mechanism that explains why we construct a story at the conscious level for emotional responses triggered independently at the mid-brain level. Cortical mechanisms have to construct a theory as to why there is a felt state since the brain systems triggering the emotional state do not have direct, neural access to cortical processes. As in the split-brain patients, where we can examine these kinds of mechanisms experimentally, the emotional tone set up by one disconnected half-brain can be transmitted through mid-brain systems over to the other. It remains for the other half-brain to interpret the meaning within its ongoing cognitive context, whether it be positive or negative.

The experimental psychological and brain sciences are now able to move beyond the claim that non-conscious processes influence behaviour and are able to isolate the systems and study them directly. The realization that processes accessible to conscious experience represent only part of the overall process by which consciousness functions complicates the task of identifying all the players in the game of coming to know how we know things. At the same time it liberates us from viewing conscious experience as the product of a totally accessible rational process.

Whole brains and half-brains: modular entities and interactions

A major tenet in human brain science is that there are specialized functions within the cerebral cortex. It has long been known that for most humans the left brain is specialized for language and speech. More tentative but still widely believed is the claim that the right hemisphere is specialized for certain non-verbal skills such as facial recognition, spatial location, and other non-verbal skills. Thus neurologists have been aware for years of the 'modular' nature of the brain and have argued convincingly that any model of brain function that assumes there is something like a unified cognitive mechanism is in error. General problem-solving devices and other highly integrated views of how cognition works (Newell and Simon 1972) simply will not do.

One of the main challenges of human brain science is to attempt to isolate subfunctions of the cognitive system and to assess whether or not there is any biological validity to the cognitive constructs that are proposed. The need to put more ornaments on the modular tree is obvious. In my laboratory, at the Cornell University Medical College, work guided somewhat by the basic idea of modularity continues, and

we continue to unearth many puzzling phenomena, some of which identify new modules and some of which speak to how other features of brain organization emphasize the modules' integrative action.

Studying the split-brain patient allows the examination of one half-brain independent of the major influences of the other half-brain. This is both revealing and masking with respect to our overall objective of identifying modular systems of the cerebral cortex. I will first review what I take to be the most revealing studies. Later we shall see how the study of disconnected brains masks how the two half-brains normally interact to produce what appear to be specialized functions.

Dissociating language and cognition

There are a few split-brain patients who possess language in both the left and the right half-brain. Most patients only possess language in the left hemisphere. The few who possess language in both allow one to examine how the introduction of language to the right hemisphere augments the overall cognitive capacity of that brain structure. To understand the continuum in which these observations are made, it is necessary to know what right hemispheres without language can do and also what I mean by the right-hemisphere possessing language.

In the past, split-brain patients without right-hemisphere language have not been studied as extensively as they might have been. After their post-operative assessment, which quickly reveals the cognitive state, or, better, the lack of cognitive state, in the right brain the patients as a rule have not been followed up. If the right brain is largely unresponsive to the processing of simple or complex stimuli, interest wanes in further delineating the patient's status. None the less, in the several patients we have studied in more detail a disconcerting picture emerges. The range of responsiveness to patterned stimuli ranges from none to the capacity to make simple matching judgements above chance. In the patients with the capacity to make perceptual judgements not involving language, there was no ability to make a simple same/different judgement within the right brain when both the sample and match were lateralized simultaneously. In other words, when a judgement of sameness was required for two simultaneously presented figures, the right hemisphere failed. Also, these same patients were unable to carry out tasks calling upon specialized right-hemisphere skills such as facial recognition tests. This profile is commonly seen in patients of all kinds, including patients of similar and sometimes greater overall intelligence than those who possess some right-hemisphere language.

This minimal profile of capacity stands in marked contrast to the patients with right-hemisphere language. The right brain of these patients is most responsive, and their overall capacity to respond both to language and non-language stimuli has been well catalogued and reported. Perceptual judgments are made easily, as are same/different judgments of all kinds. In some tests, such as facial recognition tasks, these patients demonstrate a superior performance in the left visual field. It was these kinds of findings that led me to believe that the presence of language in the right brain made the difference, and that, moreover, language processes were central to good cognitive operations (Gazzaniga 1980, 1983). It was upon this foundation that we planned a series of experiments that tried to elucidate further the cognitive capacities of the right brain in these patients with language. Our hope was to correlate varying cognitive capacity with the varying competence of language skills within the group of patients who possessed language.

The East Coast series of patients we studied included case JW, who understood language and who had a rich right-brain lexicon as assessed by the Peabody picture–vocabulary test as well as by other special tests (Gazzaniga *et al.* 1984). At the same time, JW has no capacity to speak out of the right brain. Our hope of contrasting JW's performance on a set of cognitive tasks with a more robust right-brain language system was made possible by studies on cases VP and PS. These patients were able both to understand language and to speak from each half-brain. Would this extra skill lend a greater capacity to the right brain's ability to think?

The different language capacities of the two groups consisted primarily of the capacity to speak, to understand some syntactic relationships, and to comprehend sentential strings. JW's right hemisphere is able to understand only individual words as evidenced by his capacity to pick word-associates (Gazzaniga *et al.* 1984). Thus if the word 'fruit' is presented to the right hemisphere, the left hand is able to point to the word 'apple' out of a list. In this manner superordinate and subordinate relations can be tested, as can synonyms/antonyms and so on (Sidtis *et al.* 1981). However, while JW's right hemisphere performs well at picking associates, the right hemisphere appears to have little insight into what it is doing. If a series of words are presented that vary in their categorical quality, such as 'fruit', 'apple', 'hardware', 'hammer', and so on, the right hemisphere is unable to judge whether or not one word is superordinate to another. Thus while the left brain has no problem judging which of the words is a 'category' vs. 'no category' word, the right brain performs barely above chance. It appears that possessing the capacity to correctly pick words that have a relationship to one another does not mean that the responding system knows why it is doing so.

The literalness or concreteness of the right hemisphere can be ascertained from another simple test. If a word, such as 'book', is spelled backwards, so that the right hemisphere sees the string 'koob', it cannot sort it out such that it can pick a simple associate. The left hemisphere under the same tachistocopic conditions has no problem with the task.

Of course, in all tests demonstrating lack of function the possibility always exists that the task was not understood. Yet in these tests as in all of our tests, the task is explained, then demonstrated, and then, under free-field conditions, practice trials are run. In most cases the response mode is identical to that in other tests that are completed with success.

At the same time, JW's right brain seems relatively at ease in understanding simple requests. Quite remarkably, if a picture of something, for example a horse, is flashed to the right brain, the left brain will typically speak out and say that it saw nothing. The examiner can then say things like, 'Don't draw what it is; draw what goes on it'. The patient might say something to the effect of 'What are you talking about; I didn't see anything'. Then the left hand will pick up a pencil and draw a saddle. In this particular case, JW drew an English saddle, a sketch that would appear ambiguous if you did not know the context. JW said that he did not know what he had drawn. He was then asked to draw a picture of what was flashed. The left hand then drew a horse and, after completing the picture, JW grinned and said, 'That must be a saddle'.

JW's right hemisphere, however, has failed to reveal any understanding of syntax. Thus while case VP's right hemisphere can appreciate functors, so that the difference between the triplet 'playing the field' and 'the playing field' is easily detected, JW's cannot. JW has poor overall sentential understanding as compared to VP. For example, if a sentence is read aloud, such as 'He forgot to water his new plant', and is then followed by the question 'Was it . . . ?', again read aloud except for the last missing word, and then the missing word 'dry' was flashed to either the left or right brain, JW scored at chance with the right hemisphere and 87 per cent with the left. VP, on the other hand, scored 77 per cent with the right brain and 92 per cent with the left. Clearly, VP possesses far better language skills that does JW. The exact specification and nature of the difference remains for future research to identify.

None the less, it turns out that the right hemispheres of both patients are poor at making simple inferences (Gazzaniga and Smylie 1984). For example, when shown two pictures one after the other, such as a picture of a match and a picture of a wood pile, the right hemisphere cannot combine the two gnostic elements into a causal relation and choose the proper result; i.e. a picture of a burning wood pile as opposed to a picture of a wood pile and a set of matches. In other testing, simple words were serially presented to the right brain. The task was to infer the causal relation that obtains between the two lexical elements and to pick the answer from a list of six possible answers printed and in full view of the subject. A typical trial would consist of words like 'pin' and 'finger' being flashed to the right brain, with the correct answer being 'bleed'. While the right hemisphere when tested separately could always find a close lexical associate of all the words used, it could not make the inference that 'pin' and 'finger' should result in the answer 'bleed'. All of this goes on, of course, after the right hemisphere has been shown how to do the task under free-field conditions and several examples have been presented. The successful completion of a task under these conditions must mean that the left hemisphere was controlling the response. Still, the right hemisphere was free to inspect and watch how the task was done.

With VP the tests were pursued and further simplified. Instead of two words being flashed to either the left or right visual field, one word was spoken and the other was then lateralized to either the left or right brain. Thus the word 'pin' would be spoken, followed by the word 'finger' being flashed. This simplification seemed to make no difference. The right hemisphere remained poor at carrying out the task.

When another test was administered that reduced still further the cognitive demand, both VP and JW performed poorly with their right hemisphere. This test assessed the capacity of each half-brain to identify a common attribute between two different words. Again, in order to simplify the testing procedure, one word was spoken and the other flashed to either the left or right brain. Thus the word 'fire-truck' was spoken and the word 'elephant' was flashed to either the left or right brain. There were four words in full view of the subject: 'size', 'colour', 'speed', and 'texture'. The right brain scored above chance at about 50 per cent (chance being 25 per cent) for both patients, while the left was near perfect. When the right hemisphere was correct on this task it picked a likely associate to the flashed word.

Similarly, the right hemisphere performs poorly on simple mathematical problems. When flashed a series of numbers and asked to perform simple addition, subtraction, multiplication, and division, the right hemisphere can identify the stimuli but performs poorly on carrying out the required computation.

Finally, the right hemisphere in these three patients also proved to be poor at solving a spatial reasoning task. In this task, a geometric shape with a specific design is lateralized to either the right or left brain. Placed in full view in front of the patient are four other figures, one of which fits exactly into the geometric stimulus that had been lateralized to form a perfect square. The task is exceedingly simple. Yet, while the left hemisphere found the task easy to solve, the right hemisphere performed poorly.

From all these tests we conclude that perhaps language is a data structure, a system called upon to label and express the computations of other cognitive systems. The language system itself is not able to perform cognitive activities, such as inference. In this regard, it is helpful to remember that patients in the early stages of Alzheimer's disease are frequently quite intact with respect to language, but are unable to solve the simplest problems or make the simplest inferences. At the same time, it is also apparent that the presence of language of the kind described in the right hemisphere in these patients correlates with a half-brain that is capable of carrying out many more mental activities than a right hemisphere without language. Understanding this fact is the objective of some new, ongoing studies of ours that compare performance of patients pre- and post-operatively on tasks that draw upon lateralized skills.

Bihemispheric interaction

Over the past 25 years of split-brain research it has been difficult to isolate what the potential costs to cognition might be by having the human cerebrum divided in two. Many earlier studies have shown that there is no change in reaction-time response to simple discriminations (Gazzaniga and Sperry 1966); in the capacity to form hypotheses (LeDoux *et al.* 1977); and in verbal IQ (Campbell *et al.* 1981). There have been some reports that negative effects can be registered on memory function (Zaidel and Sperry 1974), whereas others have not confirmed this concern (LeDoux *et al.* 1977). There are data suggesting that hemispheric disconnection actually allows each half-brain to function without perceptual interference from the other, and thereby confers on the whole brain a super-normal capacity to apprehend perceptual information (Gazzaniga 1970; Holtzman and Gazzaniga 1985). While most prior studies have been carried out in the belief that each half-brain is a functioning, independent system that operates no differently when separated than when connected, new studies are beginning to challenge this original view. The old working assumption was based on the kind of behavioural profile seen in the split-brain cases who possess language in each hemisphere. Each hemisphere seemed capable of responding in its own way to a wide variety of stimuli.

But then there are the other cases in whom right-hemisphere performance after surgery was poor to non-existent. Prior to surgery these epileptic patients performed normally on so-called right-hemisphere tasks. The question became whether these abilities were locked in to the silent right-hemisphere after disconnection from the dominant left half-brain. We plan a large study on this issue, and are encouraged by some early results. Consider the cases EB, DR, and LL. Each is interesting in a different way.

Case EB is a 23-year-old woman who has suffered from epilepsy since the age of 12. Prior to callosal surgery she underwent a right occipital resection in Montreal, with the aim of removing her epileptic focus. This produced a left-visual-field scotoma. Her seizures were not brought under control, and, at the age of 21, she underwent posterior section of the corpus callosum. Prior to this surgery she was examined on a number of tests including the nonsense wire-figure test of Milner and Taylor (1972). In brief, this task requires the matching of irregularly shaped wire figures. Four are placed in front of a subject, out of view. One of the figures is placed in the hand and then removed. Moments later the subject is required to find a match from the group of four. This task is believed to tap into right-hemisphere specialized systems, and case EB was able to perform the task with either hand. It appears that her intact callosum assisted in distributing the information arriving in her left brain from the right hand over to the specialized system in the right hemisphere. Or that, at least, is how we have come to think about these kinds of things.

After the posterior half of the callosum was cut, EB, in typical split-brain fashion, was unable to name objects placed in the left hand. The fibres crucial for the interhemispheric transfer of tactile information had been severed, and, as a result, what the right hand knew the left did not. She also proved to be a patient without right-hemisphere language. While she was able to find points of stimulation on the left hand by touching them with the left thumb, thereby demonstrating good, right-hemisphere, cortical somato-sensory function, she was unable to retrieve with the left hand objects named by the examiner. This task is managed easily by patients with right-hemisphere language. Most importantly, however, EB could no longer perform the wire-figure task with either hand.

Since EB could perform the task pre-operatively, it seems clear that the right hemisphere had the capacity to contribute to solving this kind of task when it was connected to the left. Disconnected from the left, it appears unable to function. This kind of finding suggests that the left hemisphere may normally contribute certain executive functions to specialized systems in the right brain. What was thought to be one module actually is the product of the interaction of at least two modules, each located in a different brain area.

The same general finding was seen in the pre- vs. post-operative scores on the block design test for the two other patients, cases DR and LL.

This test is considered to be a right-hemisphere task, although there are several reports suggesting that left-hemisphere damage can also cause deficits in its performance. Both of the patients underwent full callosal section. Case LL had had a right temporal lobe resection prior to the callosal surgery, carried out in an effort to control his epilepsy. His callosal surgery was performed in two stages. Case DR, a 39-year-old woman, had her surgery carried out in one operation. Prior to the callosal surgery of these patients, their performance on the block design subtest of the WAIS (Wechsler Adult Intelligence Scale) was fast and accurate, well within the normal range. This simple test requires arranging four to nine, red and white coloured blocks in a pattern that matches a picture of arranged blocks. The pre-operative tests were carried out with the right hand. Post-operatively, neither the left nor the right hand of either case could perform the task with ease. The time it took to solve the simplest patterns doubled, and completion of the more difficult patterns was simply not possible. Case LL revealed no other right-hemisphere function except for the capacity to locate with the left hand a point of light flashed in the left visual field. He was unable to carry out with the right hemisphere the simplest match-to-sample test using pictorial or verbal stimuli. Yet it appears that, pre-operatively, the right hemisphere when connected to the left participated in the solving of the block design problem. Also, since the post-operative scores for the left hemisphere were also lowered, the left hemisphere obviously benefited from processes located in the right half-brain.

Case DR had a more responsive right hemisphere. She was able to carry out visual match-to-sample tasks for lateralized visual, but not verbal, stimuli within her right hemisphere. Yet when two geometric shapes were presented sequentially to the right hemisphere, she was unable to make a same/different judgement, thereby indicating that her right hemisphere was not capable of simple problem-solving. At the same time, there is evidence that DR's right hemisphere understands some simple nouns. Yet, even with the far greater capacity to process information within the right brain, neither the left nor the right hand could perform the block design test as well as the right hand had performed it pre-operatively. Here again we see evidence that the normal contribution of the right hemisphere to solving such tasks can be realized only when it is connected to the left. And again, the left hemisphere was also benefiting from right-brain participation prior to the operation.

For future surgeries, a more comprehensive pre- and post-operative battery of tests is planned. However, when the evidence to date is taken together it suggests that there are dissociable factors active in what look to be unified mental activities. In short, one can begin to envisage that there are something like executive controllers that are active in manipulating the data of specialized processing systems. These controllers tend normally to be lateralized in the left brain, and, when the right brain becomes isolated from their influence, the specific functions of the right brain become hard to detect when tested alone.

Windows on cognition: the incomplete callosal section

Deducing the nature of cortical organization and how it relates to cognitive representational systems is a task that receives assistance from many quarters. The newest opportunity for us grows out of the recent observation that MRI studies of the human brain allow for determining the extent of callosal disconnection actually achieved during split-brain surgery. Before this technology was available, reports on the extent of surgery on all patients relied on the accuracy of surgical notes. Now, MRI is able to verify or correct the surgical claims (Gazzaniga *et al.* 1985).

For present purposes, two paradigmatic cases will be reviewed. Case JW was discovered to have a complete callosal section with the unapproached anterior commissure remaining intact. JW does not transfer any perceptual information between the hemispheres. Colour, pattern, and brightness information can not be cross-compared, thereby leaving but one observation of interhemispheric integration. Under conditions of sustained stimulation some crude spatial information can be integrated between the disconnected half-brains (Holtzman 1984). In any event, a spared anterior commissure has not yet proved capable of transmitting any useful cognitive or perceptual information between the hemispheres. It seems reasonable to assume that it transfers something, yet studies to date have failed to identify what this might be.

Case VP, however allows for different insights. MRI revealed sparing of fibres both in the splenium and in the rostrum of the corpus callosum. Sparing in the splenium suggests the possibility that visual pattern and colour information might transfer between the two hemispheres. Yet in test after test in VP there is no such indication. It is too soon to tell whether the failure of simple transfer reflects regional differences of function within the splenium or whether it is related to the number of fibres spared, or both.

Further tests on VP have revealed a most remarkable interaction that was not seen in JW. The task required VP to judge whether or not two words, one presented to each visual field, rhymed. There were four conditions: the words (a) did not look or sound alike, (b) looked alike but did not sound alike, (c) sounded alike but did not look alike or (d) both looked and sounded alike. VP is able to judge correctly whether the words rhyme only when the words both look and sound alike. Such a finding suggests the highly specific way in which the cortex encodes information. It appears that the visual system, which is still marginally interconnected by some fibres, can send some kind of verifying signal that is useful if information has already been transmitted through another modality. Without that bit of redundancy in the system, the information transferred appears to be of no use.

The left-brain interpreter

I have outlined a picture of brain function that reveals its apparent modular organization. The functioning modules do have some kind of physical instantiation, but the brain sciences are not yet able to specify the nature of the actual neural networks involved. It is clear that they operate outside the realm of awareness and express their computational product to the motor system directly. Catching up with and assessing what the brain is doing seems to be a function of an interpretive module residing in the left hemispere. I think it need not always be in the left, but that is where it is for most humans. To watch the interpreter work under strict experimental conditions is most dramatic.

We first revealed the phenomenon using a simultaneous concept test. The patient is shown two pictures, one exclusively to the left hemisphere and one exclusively to the right, and is asked to choose from an array of pictures placed in full view in front of him the ones associated with the pictures lateralized to the left and right brain. In one example of this kind of test, a picture of a chicken claw was flashed to the left hemisphere and a picture of a snow scene to the right hemisphere. Of the array of pictures placed in front of the subject, the obviously correct association is a chicken for the chicken claw and a shovel for the snow scene. PS responded by choosing the shovel with the left hand and the chicken with the right. When asked why he chose these items, his left hemisphere replied: 'Oh, that's simple. The chicken claw goes with the chicken, and you need a shovel to clean out the chicken shed'. Here, the left brain, observing the left hand's response, interprets that response into a context consistent with its sphere of knowledge—one that does not include information about the left-hemifield snow scene.

It is interesting to note that, although the patients possess at least some understanding of their surgery, they never say things like, 'Well, I chose this because I have a split-brain and the information went to the right, non-verbal hemisphere'. Even patients who are brighter than PS, based on IQ testing, view their responses as behaviours emanating from their own volitional selves, and as a result, incorporate these behaviours into a theory to explain why they behave as they do. Certainly one can imagine that at some future point a patient might be studied who chose not to interpret such behaviours in terms of an overlying psychological structure that prevented the response. Or one can imagine a patient learning by rote, as it were, what a 'split-brain' is all about, and why, therefore, a certain behaviour most likely occurred. With that understood they may well not offer an explanation.

There are occasions in which a patient, having trouble controlling his left arm due to a transient state of dyspraxia, will tend to write off anything this arm does under the direction of the right brain, thereby making the foregoing test inappropriate for demonstrating the phenomenon. In such situations, a single set of pictures is presented and only one hand is allowed to make the response. Thus, in this test the word 'pink' is flashed to the right hemisphere and the word 'bottle' is flashed to the left. Placed in front of the patient are pictures of at least 10 bottles of different colour and shape. When this test was run on JW, on a particular day when he kept saying that his left hand was doing what it wanted to do, he immediately pointed to the pink bottle with his right hand. When asked why he had done this JW said: 'Pink is a nice colour'.

Another example of this phenomenon, of the left brain interpreting actions produced by the disconnected right brain, involves lateralizing a written command, such as 'laugh', to the right hemisphere by tachistoscopically presenting it to the left visual field. After the stimulus is presented, the patient laughs and, when asked why, says: 'You guys come up and test us every month. What a way to make a living'. In still another example, if the command 'walk' is flashed to the right hemisphere, the patients will typically stand up and begin to leave the testing van. When asked where he is going, the left brain says: 'I'm going into the house to get a Coke'. However you manipulate this type of test, it always yields the same kind of result (Gazzaniga 1983).

There are many ways to influence the left-brain interpreter. As already mentioned, we wanted to know whether or not the emotional response to stimuli presented to one half-brain would have an effect on the affective tone of the other half-brain. In this particular study, we showed under lateralized stimulus-presentation procedures a series of film vignettes that included either violent or calm sequences. In these studies we used an eye-tracking device which permits prolonged lateralization of visual stimuli while the eyes remain fixated on a point (Holtzman 1984; Gazzaniga and Smylie 1984). The computer based system keeps careful track of the position of the eyes so that if they move from fixation the movie sequence is electronically turned off. For example, in one test a film depicting one person throwing another into a fire was shown to the right hemisphere of patient VP. She reacted: 'I don't really know what I saw; I think just a white flash. Maybe some trees, red trees like in the fall. I don't know why, but I feel kind of scared. I feel jumpy. I don't like this room, or maybe it's you getting me nervous.'

As an aside to a colleague, she then said, out of my earshot, 'I know I like Dr Gazzaniga, but right now I'm scared of him for some reason'. Clearly, the emotional valence of the stimulus has crossed over from the right to the left hemisphere. The left hemisphere remains unaware of the content that produced the emotional change, but it experiences and must deal with the emotion and give it an interpretation.

The same kind of phenomenon is observed when more neutral stimuli are presented, such as scenes of ocean surf, nature walks, and the like. The patient becomes calm and serene. Taken together, these examples show that both covert as well as overt responses are interpreted, and confirm and extend earlier experiments carried out on the California patients (Gazzaniga 1970).

The kind of thing we see in these special patients and under these kinds of laboratory conditions can be related to many everyday experiences. Consider how often we go to bed in a good frame of mind (or the opposite), only to awake feeling depressed and cranky (or the opposite). The cognitive data structure, which is to say the facts about our life, has not changed during the night, so why the change in mood? Could it be that a set of prior memories has become activated and has unleashed biochemical mechanisms that give rise to a specific mood state? The idea here is that the left-brain interpreter would try to make sense out of these feelings, and may well and somewhat gratuitously attribute a cause for them to otherwise innocent concepts also existing in the conscious realm at that time.

In the patients studied to date, the interpreter has been most demonstrably represented in the left hemisphere. A natural question to consider is whether or not the right hemisphere also has an interpreter, or, more likely, could develop one if disconnected from the left. The intact brain would not need two such modules. For a right brain that cannot talk, it would be difficult to gain evidence of such a function. Yet such right brains, when examined non-verbally, as on the inference tests described above, do not perform well. This would suggest that they do not have a functioning interpreter. For the patients with bilateral speech, no clear evidence has yet appeared that the right hemisphere carries out interpretive functions. In the standard tests used to elicit the phenomenon, each hemisphere can quite simply state what it saw and, when asked why, can tell you why. And, as in the patient whose right hemisphere can understand but not produce language, even a right hemisphere that can speak cannot carry out the simple inference tasks.

The idea of a central and crucial mental module or system that interprets the behaviours and activities of other modules comes up in a number of other contexts. Recent developments in the study of amnesia have suggested that patients frequently suffer from so-called 'source amnesia' (Schacter 1986; Schacter *et al.* 1984). Patients remember the content of a prior event but not its source. What they commonly do under a task demanding identification of the source is to make up a source which they quickly believe to be real. In hypnosis research, the interpreter is commonly seen at work when a subject explains why a post-hypnotic suggestion has been carried out (Hilgard 1977).

Conclusions

It is difficult to imagine Descartes insisting today that the only truly knowable subject would be mathematics. It clearly is knowable since the mathematician starts by fiat, setting up the hypothesis to be examined. Yet in the twentieth century there are factual systems being generated all the time that in effect are fiats for the mind's interpreter to play on. Those of us in brain science assume that one day all the characters in the brain play will be known and, as a consequence, that the interpreter will also have its data. In the foregoing I reviewed some new facts in what I assume to be not a hopeless objective, the task of specifying the operating characteristics of the human brain.

The picture that emerges from studying damaged brains, whether they be by the elegant disconnection process used in the control of epilepsy, or by focal lesions produced by stroke or tumour, all point to a brain model that is heavily committed to parallel processes that are co-active in our conscious lives. Their function proceeds, as it must, and as do most other physiological processes, outside of our awareness. Corralling all of these activities and making sense of them appears to be the function of special processes present in the left brain of humans. This function, the interpretive function, works on the products of the modular activities to build a schema that can explain the logic behind all of the ongoing activity that results in a behaviour. Behaving, alas, becomes a powerful determinant in what we come to believe as true.

Acknowledgements

This work was aided by USPHS (United States Public Health Service) grant no. NS-17778-04.05; by the McKnight Foundation; and by the Alfred P. Sloan Foundation.

References

Campbell, A. L., Bogen, J. E., and Smith, A. (1981). Disorganization and reorganization of cognitive and sensorimotor functions in cerebral commissurotomy: compensatory roles of the forebrain commissures and cerebral hemispheres in man. *Brain*, **104**, 493–511.

Fodor, J. (1983). *The modularity of mind*. MIT Press, Cambridge, MA.

Gazzaniga, M. S. (1970). *The bisected brain*. Appleton–Century–Crofts, New York.

Gazzaniga, M. S. (1980). The role of language for conscious experience: observations from split-brain man. In *Motivation, motor and sensory processes of the brain, progress in brain research*, Vol. 54, (ed. H. H. Kornhuber and L. Deecke), pp. 689–96. Elsevier, Amsterdam.

Gazzaniga, M. S. (1983). Right hemisphere language; a twenty year perspective. *The American Psychologist*, **38**, 525–37.

Gazzaniga, M. S. (1985). *The social brain*. Basic Books, New York.

Gazzaniga, M. S. and Hillyard, S. A. (1971). Language and speech capacity of the right hemisphere. *Neuropsychologia*, **9**, 273–80.

Gazzaniga, M. S. and Smylie, C. S. (1984). Dissociation of language and cognition: A psychological profile of two disconnected right hemispheres. *Brain*, **107**, 145–53.

Gazzaniga, M. S. and Sperry, R. W. (1966). Simultaneous double discrimination response following brain bisection. *Psychonomic Science*, **4**, 261–2.

Gazzaniga, M. S., Holtzman, J. D., Gates, J., Deck, M. D. F., and Lee, B. C. P. (1985). MRI assessment of human callosal surgery with neuropsychological correlates. *Neurology*, **35**, 1763–66.

Gazzaniga, M. S., Smylie, C. S., Baynes, K., Hirst, W., and McCleary, C. (1984). Profiles of right hemisphere language and speech following brain bisection. *Brain and Language*, **22**, 206–20.

Gazzaniga, M. S., Holtzman, J. D., and Smylie C. S. (1987). Speech without conscious awareness. *Neurology*, **35**, 682–685.

Hilgard, E. R. (1977). *Divided consciousness: multiple controls in human thought and action*. John Wiley, New York.

Holtzman, J. D. (1984). Interactions between cortical and subcortical visual areas: evidence from human commissurotomy patients. *Vision Research*, **24**, 801–13.

Holtzman, J. D. and Gazzaniga, M. S. (1985) Enhanced dual task performance following callosal commissurotomy in humans. *Neuropsychologia*, **23**, 315–21.

Holtzman, J. D., Volpe, B. T., and Gazzaniga, M. S. (1984). Deficits in visual–motor control despite intact subcortical visual areas, (abstract) *Neurology*, **34**, 187.

Kosslyn, S. M. (1983). *Ghosts in the mind's machine: creating and using images in the brain*. W. W. Norton, New York.

LeDoux, J. E., Risse, G., Springer, S., Wilson, D. H., and Gazzaniga, M. S. (1977). Cognition and commissurotomy. *Brain*, **100**, 87–104.

LeDoux, J. E., Sakaguchi, A., and Reis, D. J. (1984). Subcortical efferent projections of the medial geniculate nucleus mediate emotional response conditioned to acoustic stimuli. *Journal of Neuroscience*, 4, 683–98.

Marcel, A. J. (1983). Conscious and unconscious perception: an approach to the relations between phenomenal experience and perceptual processes. *Cognitive Psychology*, 15, 238–300.

Milner, B. and Taylor, L. (1972). Right hemisphere superiority in tactile pattern-recognition after cerebral commissurotomy: evidence for nonverbal memory. *Neuropsychologia*, **10**, 1–15.

Newell, A. and Simon, H. A. (1972). *Human problem solving*. Prentice-Hall, Englewood Cliffs, NJ.

Pöppel, E., Held E., and Frost D. (1973). Residual visual capacities in a case of cortical blindness. *Cortex*, **10**, 605–12.

Schacter, D. L. (1986). The psychology of memory. In *Mind and brain: dialogues in cognitive neuroscience*, (ed. J. E. LeDoux and W. Hirst), pp. 189–214. Cambridge University Press, New York.

Schacter, D. L., Harbluk, J. L., and McLachlan, D. R. (1984). Retrieval without recollection: an experimental analysis of source amnesia. *Journal of Verbal Learning and Verbal Behavior*, **23**, 593–611.

Sidtis, J. J., Volpe, B. T., Holtzman, J. D., Wilson, D. H., and Gazzaniga, M. S. (1981). Cognitive interaction after staged callosal section: evidence for a transfer of semantic activation. *Science*, **212**, 344–6.

Volpe, B. T., LeDoux, J. E., and Gazzaniga, M. S. (1979). Information processing of visual stimuli in an extinguished field. *Nature*, **282**, 722–4.

Weiskrantz, L., Warrington, E. K., Sanders, M. D., and Marshall, J. (1974). Visual capacity in the hemianopic field following a restricted occipital ablation. *Brain*, **97**, 709–28.

Zaidel, D. and Sperry, R. W. (1974) Memory impairment after commissurotomy in man. *Brain*, **97**, 263–72.