1 • Sherringtonian Alternatives—Two Fundamental Elements or Only One?

My professional career was shaped, I suppose, in the neurophysiological laboratory of Professor Sherrington at Oxford. Eventually it was continued in the wards and operating rooms of the Montreal Neurological Institute. Other preoccupations were many and varied, but beneath them all was the sense of wonder and a profound curiosity about the mind. My planned objective, as I turned from studying the animal brain to that of man, was to come to understand the mechanisms of the human brain and to discover whether, and perhaps how, these mechanisms account for what the mind does.

My teacher, Sir Charles Sherrington, received the Nobel Prize for his studies of reflexes and his analysis of the integrative action of the nervous system. His interest had been focused largely on the inborn reflexes, but, on retiring from the Chair of Physiology at Oxford in 1935, at the age of seventy-eight, he turned from animal experimentation to a scholarly and philosophical consideration of the brain and the mind of man.*

In the end, he could only say that "we have to regard the relation of mind to brain as still not merely unsolved, but still devoid of a basis for its very beginning." In June 1947, he wrote a foreword to his book, *The Integrative Action of the Nervous System*, which was then being republished in his honor by the Physiological Society.[32] The

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* In 1937–1938, he delivered the Scottish Gifford Lectures, and published them in 1940 under the title *Man—On His Nature*.[31] (Thoughout the book, these superscript numerals refer to the numbered entries in the Bibliography, which follows the Afterthoughts.)

last paragraph of his foreword expresses his conclusion of it all:

> That our being should consist of two fundamental elements offers, I suppose, no greater inherent improbability than that it should rest on one only.

It is a quarter of a century since Sherrington wrote these words. We have learned a good deal about man since then, and it is exciting to feel, as I do, that the time has come to look at his two hypotheses, his two "improbabilities." Either brain action explains the mind, or we must deal with two elements.*

Perhaps we may take a step toward understanding, if we strive to fit each of the two hypotheses in turn to the physiological evidence that presents itself today. A good scientist is neither a monist nor a dualist while conducting his research. His chosen task is to explain everything he can by critical examination of nature and of the brain, and by planned experimentation. He will account, thus, for what he can about the universe and about man himself, having put his preconceptions out of mind. But he must stop to reconsider, too, and to rationalize from time to time.

Lord Adrian, who shared the Nobel Prize with Sherrington, spoke as a neurophysiologist in 1966 when he said: "As soon as we let ourselves contemplate our own place in the picture, we seem to be stepping outside of the boundaries of natural science." I agree with him; nevertheless, we must step across that boundary from time to

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* Sherrington did not consider the third hypothesis, proposed by Bishop Berkley, that there was only one element, the mind, which explained all. The Berklian explanation assumed that matter had no existence except for its place in the mind.

time, and there is no reason to assume that critical judgment does not go with us.

Writing this book presents the author with a very exciting challenge. Accepting this, I can only give an account of my own experience, describing it simply for the clinician, the physiologist, the philosopher, and the interested layman, with apologies to each for the fact that I have not written for him separately.

A remarkable body of material has come into my hands and I have stumbled on exciting discoveries. I did summarize the material and I recorded it during and at the close of my professional career. But I turned then with great enthusiasm to authorship of another sort, perhaps unwisely. Perhaps it is one's duty to do more than make a record. In answer, I may plead that I can see it all in more mature perspective after an interval, even in the seventh and eighth decades. Is it an effort, if I may paraphrase Hamlet, to lay a "flattering unction to my soul"?

However that may be, as I turn back now to the material and reconsider a life's experience, I seem to see more clearly and understand a little better. So, I shall give the reader a brief account of this pilgrim's progress. It is a story of stumbling upon unexpected revelations, of consequent puzzlement and misconception, and of reaching higher ground to look out on thrilling new vistas of understanding. In the end I shall draw conclusions that are scientific, and present hypotheses that are obvious. After that, because these data are important in other disciplines of thought, I shall pass on to rationalization and a consideration of man's being from the point of view of a layman, and, as far as I can understand it, the point of view of philosopher and even theologian.

Can the brain explain the man? Can the brain achieve by neuronal action all that the mind accomplishes? The evidence that a clinical physiologist can gather should help to answer these questions in the end.

To see the problem of the nature of the mind more clearly, consider with me this universe of ours in long perspective. It was only after the middle millennia that life appeared—first in unicellular organisms, then gradually in more and more complicated forms, first in the sea and then on the land. It was a very recent event, as seen in this long perspective, when evidence appeared of the individual's self-awareness and purpose. Today man, with his amazing mind and his vastly complicated brain, seeks to understand the universe about him, and even the nature of life and of consciousness.

Physiologists have thrown what light they could on these things from their study of mechanisms within the body and the brain in higher and lower living organisms. They have studied sensation and movement, reflex action, and memory and behavior. Karl Lashley[7] spent thirty years of his industrious life striving to discover the nature of the "memory trace" in the animal brain, beginning with experimental investigations of the rat's brain and ending with the chimpanzee. He was hunting for the engram, the record; that is to say: "the structural impression that psychical experience leaves on protoplasm." He failed to find it and ended by laughing cynically at his own effort and by pretending to question whether, after all, it was possible for animals or even man to learn at all.

But consciousness and the relationship of mind to brain are problems difficult to study in animals. Clinical physicians, on the other hand, in their approach to man, may hope with reason to push on toward an understanding of the physiology of memory and the physical basis of the mind and of consciousness.

2 • To Consciousness the Brain Is Messenger

Hippocrates, the Father of Scientific Medicine, began to teach in the fifth century B.C. on the little Greek island of Cos. In that time, philosophers such as Empedocles and Democritus were proclaiming each his own explanation of the universe and the nature of man. Hippocrates defied what he called the "unproven hypotheses" of the philosophers, and declared that only the study and observation of nature and of man would point the way to truth.

He studied man in health and in disease, making of medicine a science and an art. But he saw in man something beyond any discovery that can be made elsewhere in nature, and thus added a moral code, a religion of medical service. In the oath that he required of his disciples there were such phrases as this: "I will use treatment to help the sick according to my ability and judgment, but never with a view to injury or wrongdoing. . . . I will keep pure and holy both my life and my art." Thus, he recognized the moral and the spiritual as well as the physical and the material.[6]

Hippocrates left behind him only a single discussion of the function of the brain and the nature of consciousness. It was included in a lecture delivered to an audience of medical men on epilepsia, the affliction that we still call epilepsy. Here is an excerpt from this lecture, this amazing flash of understanding: "Some people say that the heart is the organ with which we think and that it feels pain and anxiety. But it is not so. Men ought to know that from the brain and from the brain only arise our pleasures, joys, laughter and tears. Through it, in particular, we think, see, hear and distinguish the ugly from the beautiful, the bad from the good, the pleasant from the unpleasant. . . . To consciousness the brain is messenger." And again, he said: "The brain is the interpreter of consciousness." In another part of his discussion he remarked, simply and accurately, that epilepsy comes from the brain "when it is not normal."

Actually, his discussion constitutes the finest treatise on the brain and the mind that was to appear in medical literature until well after the discovery of electricity. It was the evidence of conduction of the brain's energy along the nerves of animals that led to the discovery of electricity itself.

In retrospect, it is abundantly clear that Hippocrates came to his conclusions by listening to epileptic patients when they told him their stories, and by watching them during epileptic seizures. The reader will come to understand, in the pages that follow, that epilepsia still has secrets to reveal. She has much to teach us if we will only listen.

Some of the notes that Hippocrates made after examining his patients were copied and recopied through the centuries. They are models of brevity and insight. Epileptic patients of a certain type, not infrequently, re-live some previous experience in which they see, perhaps, and hear what they have seen and heard at an earlier time in their lives. Realizing, as Hippocrates did, that "epilepsy comes from the brain 'when it is not normal,' " he must have guessed the truth—that the engram of experience is a structured record within the brain.*

* Although Hippocrates, because of his teaching, is to be considered the founder of biological science, his life and personality have been almost completely lost in the course of time. This led me, during the last five years of my career as an operating neuro-

It was the common understanding in those days that the soul, or consciousness, was located in the heart. For example, four hundred years later, these familiar words appeared in the Christian Gospel according to Luke: "Mary kept all these things and pondered them in her heart." When men did finally abandon the idea that thinking was carried out in the heart, and realized that the brain was the master organ, the words of Hippocrates had long been forgotten. Men thought that the brain acted somehow as a mysterious whole, sending out and receiving spirit messengers in accordance with the teaching of the physician Galen (A.D. 131–201). Long after Galen, came the discovery of animal electricity by Galvani (A.D. 1791), which banished the spirit messengers forever.

We know now that the brain does not act mysteriously, as a simple and uncomplicated whole. It has within it many partly separable mechanisms, each of them activated by the passage of electric currents along insulated

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surgeon, to devote many of the days or weeks or months, when I could be spared from clinical responsibility, to the writing of a historical novel about the man as he must have been. It grew into a fictional presentation. I hoped, thus, that I might bring to light the real hero. (*The Torch*, Little, Brown and Co., Boston, 1960; also George Harrap & Co., London, 1961.) It was translated into some other languages, and Mr. Guram Kveladze, Chief Editor of Sabchota Sakartvelo Publishing House, who translated it into Georgian, and published it in Georgia, wrote the following to me on April 5, 1968: "The interest of Georgian readers was greater because of the fact that Hippocrates had visited Georgia and given a description of Kolhidian tribes. So the Georgian reader met in this book a highly respected and widely known personage!" Since I have had no time to follow up this interesting observation and shall not have, perhaps some Georgian scholar, seeing my note, will inform his fellow physicians in the West, how it was that Hippocrates came to cross the Black Sea, and more about his visit to Georgia.

nerve fibers. I shall point out presently that there is a specific mechanism that must be active to make consciousness and thought possible.

Can I discuss this mechanism understandably if I leave behind the technical phrase and speak the language of the unspecialized but educated man? I dare say Benjamin Franklin, founder of the American Philosophical Society, explained in easily understood excitement to the first members of that society how it is that electricity passes down the wet string of a kite. I wish I had been there. Perhaps I would have understood the nature of this all-important wonder called electricity. It seems to me that, somehow, it is like the mind in the sense that one cannot assign to the mind a position in space and yet it is easy to see what it does and where it does it.*

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* Hans Berger, the discoverer of electroencephalography, when he hoped (vainly) to record the activity of the mind electrically, may have had in mind this similarity.

3 • Neuronal Action within the Brain

Definitions are useful at the beginning of an essay—although the text, in this case, will certainly show them to be inadequate. The *mind* (or spirit) is, to quote from Webster's Dictionary: "the element . . . in an individual that feels, perceives, thinks, wills, and especially reasons."

The *brain* is the vastly complicated master organ within the body that makes thought and consciousness possible. In its integrative and coordinating action, it resembles in many ways an electrical computer. An individual *brain-mechanism* is a functional unit that plays a somewhat specialized role in the total integrative action of the brain.

Each nerve cell, or *neurone*, is capable of developing its own electrical charge. Each has one branch called the axone, among its many branches. The axone carries a current of neuronal impulses outward, away from the cell, to other cells. The arriving impulses stimulate each target cell to flash the message onward, or they check activity in the target cell producing inhibition of cell activity.

The cell bodies are collected together, forming islands, or blankets of *gray matter*. The branching connections form the *white matter*. This whole system vibrates, one might say, with an energy that is normally held in disciplined control, like that of a vast symphony orchestra, while millions of messages flash back and forth, to as many functional targets.

However, when some abnormality presents itself within the skull, and becomes a chronic abnormality that irritates the gray matter, it forms a focus of irritation and may cause a recurring disorderly explosion of energy involving many cells at once, like lightning from a miniature thunder cloud. Each time this happens, an *epileptic fit* comes to some unfortunate victim. The attack varies in outward character according to the function of the gray matter in which the discharge takes place. If it occurs in the cells of the gray matter that forms a part of one of the sensory circuits, a sensation is felt; if it occurs in cells of the motor system, movement follows. *Epilepsy*, which is the name for the tendency to these attacks, is as old as the history of man. Indeed, it is probably much older, since it attacks animals far more primitive than man.

When the Montreal Neurological Institute opened its doors in 1934, we had available, at last, facilities for studying the human brain as well as for treating its disabilities. I had learned to operate on epileptic patients like those who taught Hippocrates so much. In some cases, we could remove the cause or remove the altered portion of brain in which the epilepsy-producing discharge began.

Our purpose, of course, was always to cure. And the patient, who remained awake and alert through long operations, carried out in the hope of cure, did guide the surgeon's hand. More than that, the patient taught us much in the process.*

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* These operations could be done safely, and with a reasonable chance of cure, only when the surface of one hemisphere of the brain was exposed widely for careful study and possible excision. There was less danger to life and a better chance to understand each patient's problem if consciousness could be preserved throughout the procedure. Local analgesic was therefore injected into the scalp to prevent pain, and no sedative or anesthetic was given. To be successful, as well as humane, it was

Since a gentle electric current interferes with the patient's use of a convolution of the brain and sometimes produces involuntary expression of its function, a stimulating electrode could be used to map out the cortex and to identify the convolutions as the patient described his sensations and thoughts. Also, the electrode, if used with discretion, would sometimes reproduce the beginning of the patient's epileptic seizure and, thus, disclose the site of brain irritation. By talking to the patient and by listening to what came into his mind each time the electrode was applied to the cortex, we stumbled upon new knowledge. If we removed convolutions as treatment for the fits, we learned about brain function in another way as soon as the nature of the patient's loss was determined after the operation.

The observations to be presented in the following discussions, Chapters 4 through 9, have been published from time to time with the help of a succession of able associates in the Montreal Neurological Institute, not all of whom are named in the bibliography.

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essential for the surgeon to explain each step. Indeed, he must take time for talk before and during the operation. He must, in fact, be the patient's trusted friend.

4 • Sensory and Voluntary-Motor Organization

Here, then, is a brief outline of the sensory and motor mechanisms and of some of the inborn reflexes that play roles in the *integrative action* of the brain of man and other mammals. I hope it may serve as a preparation for some readers and a review or revision for others, before I pass on to the discussion of brain-mechanisms that are more closely related to the action of the mind.

The brain-stem and the spinal cord provide man with inborn reflexes, as they do the other mammals. They regulate such things as muscle tone, maintenance of posture, mechanics of walking, temperature control and sleep-rhythm, breathing, and coughing (see Figure 1).

The cerebral hemispheres that make up the telencephalon, or new brain, grow out of the diencephalon, which may be called the higher brain-stem or old brain. The hemispheres increase in proportional size from the lower vertebrates on up to man. The inflow of nerve impulses carrying pain sensation, for example, passes inwards and upwards through the spinal cord and lower brain-stem to a nucleus of gray matter within the diencephalon. This is the target-gray matter for pain. Pain differs from other forms of sensation since it makes no detour to the cerebral cortex. But the other bundles of fibers carrying sensory impulses that will be converted into discriminatory sensation make important detours. These streams provide information for appreciation of touch, position, vision, hearing, taste, and smell. Each stream comes to a first cellular interruption in the gray matter within the higher brain-stem, but continues on (with the possible exception of smell) in a detour out to a second cellular inter-

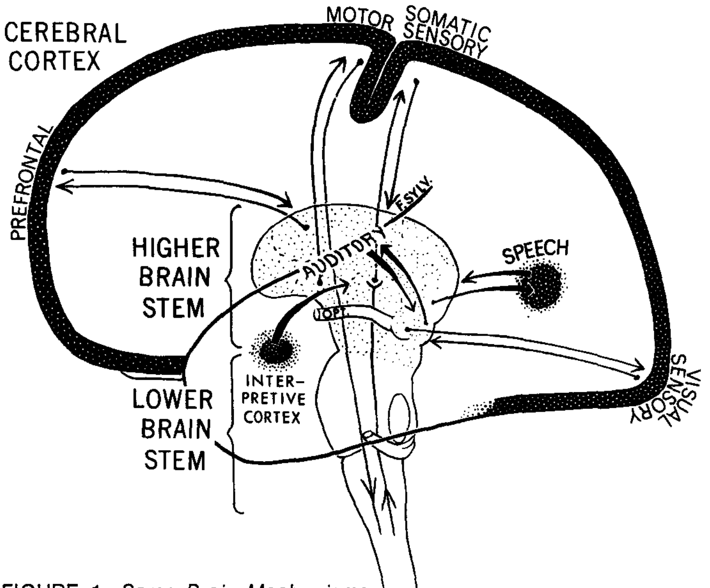

FIGURE 1. *Some Brain-Mechanisms.*

The cortex of the left hemisphere of the human brain is shown in stippled black, the brain-stem and spinal cord are shown in outline within. The principal direction of flow of electrical potentials to and from subdivisions of the cortical gray matter is indicated by the arrows in certain mechanisms as follows: *Motor*—from higher brain-stem to motor cortex and on down to motor cells in the lower brain-stem or spinal cord, producing voluntary movement; *Somatic Sensory*—from eye, ear, body, and limbs upward to higher brain-stem, then in a detour out to somatic sensory convolution and back to higher brain-stem; *Visual Sensory*—from retina through brain-stem (optic thalamus) to visual sensory convolutions of the cortex and back to brain-stem; *Auditory*—from inner ear through brain-stem (medial geniculate body) to Heschl's auditory convolutions and back to the higher brain-stem; *Speech*—from higher brain-stem to speech cortex and back again; *Prefrontal*—from higher brain-stem to prefrontal cortex and back; *Interpretive*—the arrow indicates one part of a circuit yet to be fully demonstrated. This part, as proven by electrode stimulation of interpretive cortex, activates gray matter apparently located in the higher brain-stem. The result is a "flashback" from the record of past experience.

In general, the cerebral cortex seems to play a role in the elaboration of function in each mechanism. The higher brain-stem initiates activity in the mechanism or receives the flow of electrical potentials for further integrative action.

ruption in the gray matter of the cerebral cortex. From there it returns directly to the target-nucleus of cells within the gray matter of the higher brain-stem.

Man's auditory cortex (Heschl's gyrus within the fissure of Sylvius, as shown in Figures 1 and 8) is committed to serve the purposes of auditory sensation. The stream of neuronal information from the ear comes to the higher brain-stem and detours out to Heschl's gyrus. After a cellular junction in the gray matter of that convolution, it flows back into the higher brain-stem. The same is true of the visual sensory cortex, as can be seen in Figure 1. It is a way station between the eye and higher brain-stem.

In this brief outline of the afferent sensory circuits, I have made no reference to the reticular formation described in the brain-stem by Moruzzi and Magoun. Time will doubtless show the functional importance of this system during centrencephalic integration.[8,9]

Recent studies show that each sensory input, whether auditory or visual, or from the great somatic sensory systems of the body, gives off collateral branches on its way to the thalamus, the uppermost nucleus in the brain-stem. These collaterals feed into the reticular formation of the brain-stem. This may well give the reticular formation a means of inhibiting or reinforcing incoming sensory messages in relation to the thalamic or cortical reception of those messages.

This is all part of the centrencephalic system of functional integration that makes possible sensory-motor reaction, as well as conscious reaction and planned action.

In general, it is clear that all sensory data that could inform the individual about his environment are conducted by afferent streams of electrical potentials to gray matter of the higher brain-stem, directly or indirectly.

The word *afferent* means a carrying toward an objective. *Efferent* is to carry away from a source. When considering the functional organization of the brain, afferent suggests movement toward gray matter in the higher brain-stem.

On the other hand, the stream of nerve impulses that controls voluntary activity is efferent. It passes from gray matter in the higher brain-stem outward, making its own detour out to the motor convolutions of the cerebral cortex. After a cellular break there, it passes directly back to the lower brain-stem and spinal cord for a final cellular break before it reaches the muscles. This motor outflow directs activity that may be planned or voluntary.

The sensory and the motor convolutions in man and other mammals are committed as to function at birth. The hippocampal zone (see Figure 8), on the undersurface of each temporal lobe, is likewise committed to its function. It plays a certain role in scanning the record of past experience and in memory recall. On the other hand, some of the convolutions that are used eventually for what may be called psychical functions are uncommitted to their exact function at the time of birth as well, as will be explained presently.

5 • The Indispensable Substratum of Consciousness

Gradually it became quite clear in neurosurgical experience, that even large removals of the cerebral cortex could be carried out without abolishing consciousness. On the other hand, injury or interference with function in the higher brain-stem, even in small areas, would abolish consciousness completely.

An invitation to give the Harvey Lecture at the New York Academy of Medicine caused me to review and reconsider functional localization in 1938.[14] In summary, this was the conclusion:

> There is much evidence of a level of integration within the central nervous system that is (functionally) higher than that to be found in the cerebral cortex, evidence of a regional localization of the neuronal mechanism involved in integration. I suggest that this region lies not in the new brain (the cortex) but in the old (the brain-stem).

And again this: "The *indispensable substratum* of consciousness lies outside the cerebral cortex, probably in the diencephalon (the higher brain-stem)." The realization that the cerebral cortex, instead of being the "top," the "highest level" of integration, was an elaboration level, divided sharply into areas for distinct functions (sensory, motor, or psychical), came to me like a bracing wind. It blew the clouds away and I saw certain *brain-mechanisms* begin to emerge more clearly, and they included those of the mind.[15,16]

Somewhat later I realized that man has convolutions that are new from the point of view of evolution, and not committed to motor or sensory function. They are to be programmed as to function after birth. As compared with other mammals, man has a very considerable enlargement of the cerebral hemispheres in two major areas: a) prefrontal, and b) temporal, as shown in Figure 2. Both additions have to do with what one may call the transactions of the mind.

a) One may surmise something about the function of the first-mentioned addition if it is stated that a major removal of the anterior portion of the frontal lobe results in a defect in the patient's "capacity for planned initiative" (Penfield and Evans,[23] 1940).

b) The second addition enlarges man's temporal lobes. New convolutions appear there between the auditory sensory-cortex and the visual sensory-cortex, crowding those two sensory areas right off the surface in each hemisphere and into the depth of the fissures, and forming a temporal pole in front and below.

When a child is born, the new convolutions of the temporal lobe are uncommitted and unconditioned as far as function is concerned. During the initial learning period of childhood, some of these convolutions will be programmed for *speech* on one side or the other, usually the left side in right-handed individuals. The rest of them will be devoted to interpretation of present experience in the light of past experience. This we have labeled the *interpretive cortex*. These new areas of cerebral cortex, both frontal and temporal, are employed in the mechanisms of mind-action after the early period of what may be called conditioning or programming. This is explained in the next chapters.

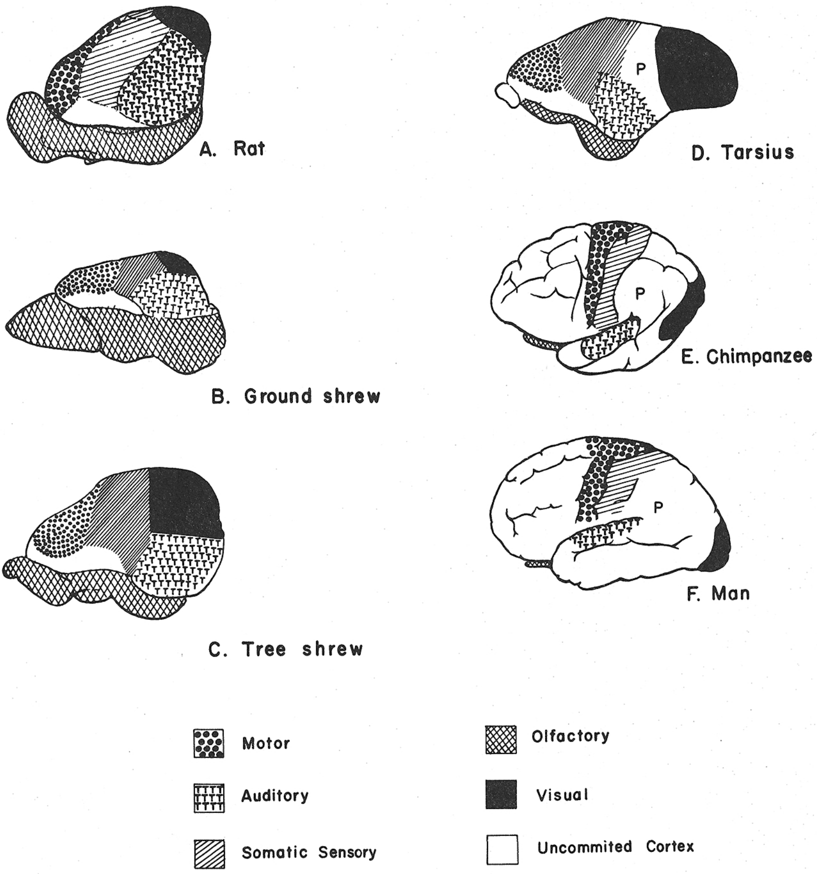

FIGURE 2. *Uncommitted Cortex.*

Functional diagrams of the cerebral cortex of some mammals. The blank areas suggest the approximate extent of gray matter that is not committed to motor or sensory function at birth. In man, for example, the auditory sensory-cortex has really been crowded off the external surface of the brain into the fissure of Sylvius. For this figure, I am indebted to the late Stanley Cobb.

6 • The Stream of Consciousness Electrically Reactivated

In the course of surgical treatment of patients suffering from temporal lobe seizures (epileptic seizures that are caused by a discharge that originates in that lobe), we stumbled upon the fact that electrical stimulation of the interpretive areas of the cortex occasionally produces what Hughlings Jackson had called "dreamy states," or "psychical seizures" (Jackson[3,4]). Sometimes the patient informed us that we had produced one of his "dreamy states" and we accepted this as evidence that we were close to the cause of his seizures.* It was evident at once that these were not dreams. They were electrical activations of the sequential record of consciousness, a record that had been laid down during the patient's earlier experience. The patient "re-lived" all that he had been aware of in that earlier period of time as in a moving-picture "flashback."

On the first occasion, when one of these "flashbacks" was reported to me by a conscious patient (1933), I was incredulous. On each subsequent occasion, I marvelled. For example, when a mother told me she was suddenly aware, as my electrode touched the cortex, of being in her kitchen listening to the voice of her little boy who

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* Electrical exploration was a particularly helpful guide to our surgical procedures before the development of electroencephalography and electrocorticography. Herbert Jasper came to the Montreal Neurological Institute in 1935, bringing with him this new electrographic technique and his invaluable neurophysiological collaboration. This constructive cooperation was to result in a book, *Epilepsy and the Functional Anatomy of the Human Brain*, in 1954.[25]

was playing outside in the yard. She was aware of the neighborhood noises, such as passing motor cars, that might mean danger to him.

A young man stated he was sitting at a baseball game in a small town and watching a little boy crawl under the fence to join the audience. Another was in a concert hall listening to music. "An orchestration," he explained. He could hear the different instruments. All these were unimportant events, but recalled with complete detail.

D.F. could hear instruments playing a melody. I re-stimulated the same point thirty times (!) trying to mislead her, and dictated each response to a stenographer. Each time I re-stimulated, she heard the melody again. It began at the same place and went on from chorus to verse. When she hummed an accompaniment to the music, the tempo was what would have been expected.

In other cases, different "flashbacks" might be produced from successive stimulations of the same point. Perhaps it may add realism if I describe here one illustrative case briefly, although it has been published already.[18] For the sake of those who are not clinicians, I shall even include a photograph of the patient in position for operation.

M.M., a young woman of twenty-six (Figure 3), had minor attacks that began with a sense of familiarity followed by a sense of fear and then by "a little dream" of some previous experience. When the right hemisphere was exposed at operation, as shown in Figure 4, I explored the cerebral cortex with an electrode, placing numbered squares of paper on the surface of the brain to show the position each time a positive response was obtained. At point 2 she felt a tingling in the left thumb; at point 3, tingling in the left side of the tongue; at 7 there was movement of the tongue. It was clear then that

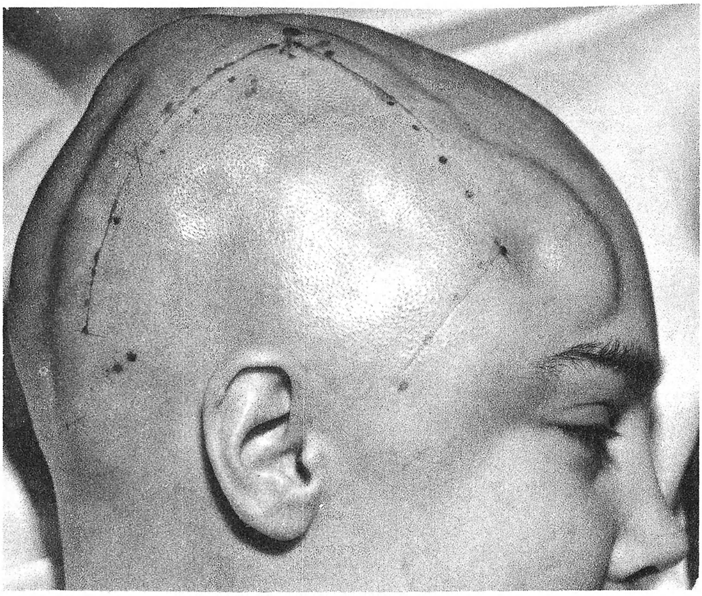

FIGURE 3. *Case M.M.*

The patient is lying on the operating table. A local analgesic has been injected into the scalp and the incision has been marked out by scratches on the skin. See Bibliography.[19]

This photograph is introduced to remind the reader that although surgeon and patient are hidden from each other by a sterile sheet during operation, they are near each other. Sympathy and mutual understanding have helped these patients to discuss their thoughts and feelings freely during electrical stimulation of the brain and removal of scarred convolutions. Although the brain is not sensitive in itself, and cannot give rise to pain, the operations are sometimes long and dangerous and very tiring. The intelligent interest and accurate reporting of these invariably gallant friends has contributed greatly to this study of the physiology of the mind.

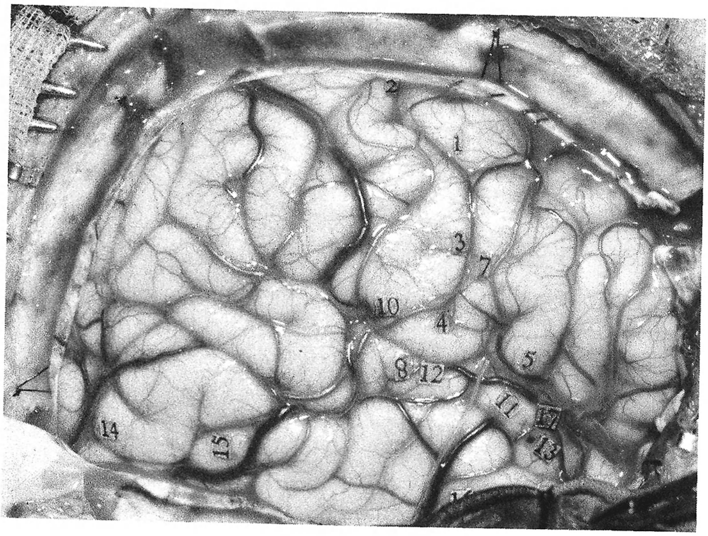

FIGURE 4. *Case M.M.*

Right hemisphere exposed. The numbered tickets mark points where there were responses to the surgeon's stimulating electrode.

3 had been placed on the somatic sensory convolution and 7 on the motor convolution (Figure 5). It is now obvious that 11 marks the first temporal convolution below the fissure of Sylvius. My postoperative sketch, seen in Figure 5, shows the position of all the stimulation points that gave rise to positive responses. The stimulating current was increased from two to three volts. The succeeding responses from the temporal lobe were "psychical" instead of sensory or motor. They were activations of the stream of consciousness from the past as follows:

> 11—"I heard something, I do not know what it was."
>
> 11—(repeated without warning) "Yes, Sir, I think I heard a mother calling her little boy somewhere. It seemed to be something that happened years ago." When asked to explain, she said, "It was somebody in

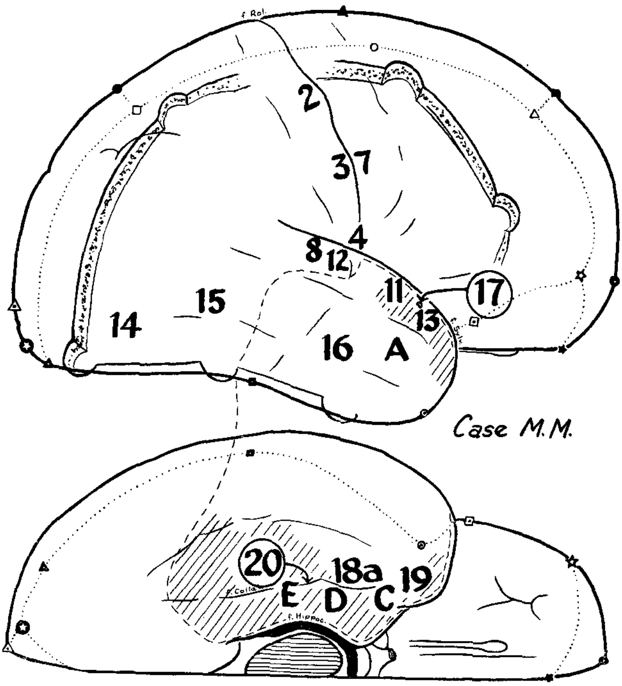

FIGURE 5. *Case M.M.*

Diagram of the operative field and the points of positive response. The broken line shows the extent of removal of the temporal lobe in treatment of the focal epilepsy. Shading indicates the area of sclerosis and atrophy due, in all probability, to pressure upon the brain at the time of birth.

the neighborhood where I live." Then she added that she herself "was somewhere close enough to hear."

12—"Yes. I heard voices down along the river somewhere—a man's voice and a woman's voice calling . . . I think I saw the river."

15—"Just a tiny flash of a feeling of familiarity and a feeling that I knew everything that was going to happen in the near future."

17c—(a needle insulated except at the tip was

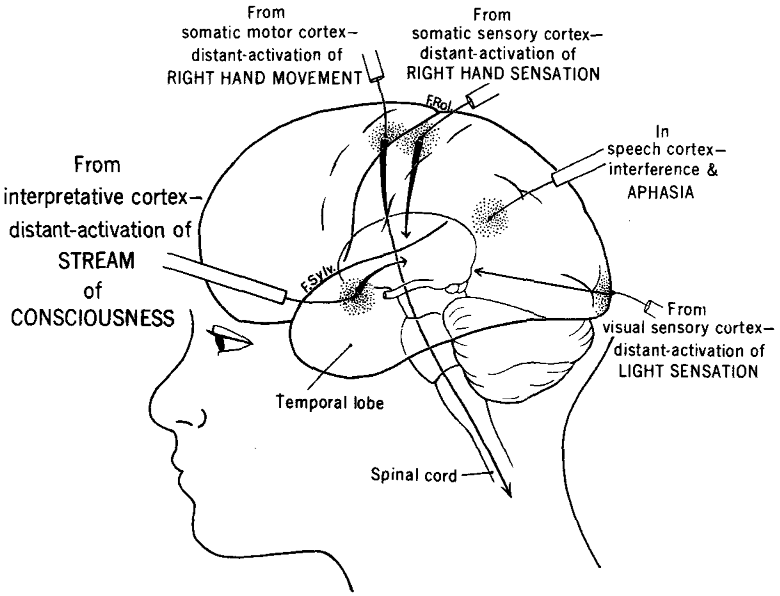

FIGURE 6. *Activation of the Brain's Record of Consciousness and Some Other Results of Stimulation.*

The left hemisphere of the brain is outlined, with the brain-stem and spinal cord shown beneath, to illustrate the results of electrode stimulation of the cortex in motor, sensory, and what may be called psychical areas for the recall of past experience. The dotted zone about each stimulating electrode tip (unipolar) suggests the area of interference in which local cortical elaborative action is arrested by electrical interference. In addition to this interference, a positive response is described from each of these electrodes, except the one on the area where speech is localized. Stimulation of the speech cortex produces only interference aphasia. The positive responses, on the other hand, are caused by normal axonal conduction from cells near the electrode to a distant but functionally related area of gray matter. Thus, the active response is a physiological activation of that distant gray matter. In the case of stimulation of the interpretive cortex, it is the sequential record of successive conscious states from the past that is activated. In the case of motor cortex the target of activation is gray matter in lower brain-stem or spinal cord. In the case of sensory areas the target is in the higher brain-stem.

> inserted to the superior surface of the temporal lobe, deep in the fissure of Sylvius, and the current was switched on) "Oh! I had the same very, very familiar memory, in an office somewhere. I could see the desks. I was there and someone was calling to me, a man leaning on a desk with a pencil in his hand."
>
> I warned her I was going to stimulate, but I did not do so. "Nothing."
>
> 18a—(stimulation without warning) "I had a little memory—a scene in a play—they were talking and I could see it—I was just seeing it in my memory."

I was more astonished, each time my electrode brought forth such a response. How could it be? This had to do with the mind! I called such responses "experiential" and waited for more evidence. Meanwhile, through the early years, we were very busy charting out the sensory, the motor, and the speech areas of the human cortex.[29,30]*

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* The first of the books referred to, *The Cerebral Cortex of Man*,[29] published in 1950, was the result of a collaborative review of all our evidence in the Montreal Neurological Institute up to that date drawn, for the most part, from mapping studies of the cortex with a stimulating electrode. The evidence was amplified by careful excisions of convolutions in the treatment of epilepsy. Theodore Rasmussen, as Director of the Montreal Neurological Institute, continued these studies of the sensory and motor cortex and continues to do so now that he has retired as Director in favor of William Feindel.

In the production of the book *Speech and Brain-Mechanisms*[30] in 1959, my collaboration with Lamar Roberts continued over a ten-year period. It showed that in the adult the speech mechanism consists in three cortical areas (temporal, inferior frontal and mid-frontal), coordinated by one gray matter center in a thalamic nucleus of the higher brain-stem. Integration of this amazingly well-localized speech mechanism, with the *highest brain-mechanism* and the *automatic sensory and motor mechanism*, as will be shown in subsequent chapters, is carried out by a *centrencephalic coordinating system.*

7 • Physiological Interpretation of an Epileptic Seizure

In 1958, after I had accumulated considerable clinical experience, I reconsidered critically the physiology involved in the electrical exploration of the human brain. This was reported in the Sherrington Lecture.[18] I realized that when an electrode passes a current into the cerebral cortex, the current interferes completely with the patient's normal use of that area of gray matter. In some areas, there is no evidence of any further effect. For example, as shown in Figure 6, an electrode on one of the three areas of speech cortex causes aphasia. But, in other areas, as explained in Table I, stimulation gives a positive re-

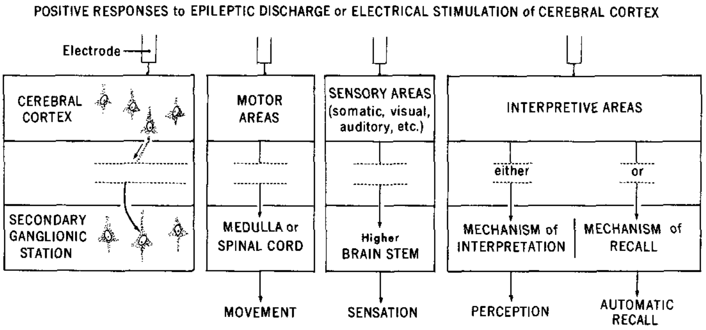


TABLE I. *Positive Responses.*

Electrical stimulation (or epileptic discharge) interferes with function of gray matter locally. It produces an active response only when the electrode is applied to an area of cerebral cortex from which axonal conduction along a functional tract normally activates some *distant* ganglionic station. Cortical responses are of four types: muscular movement, sensation, interpretive perception, and recall of conscious experience.

sponse as well. Such positive responses are produced not by activation of the local gray matter near the electrode, but by neuronal conduction along insulated axones to a distant area of gray matter that is beyond the interfering influence of the electrode's current.

Let me repeat: The activation is of the distant gray matter. See in Figure 6 stimulations of motor cortex, also, somatic sensory-cortex and visual sensory-cortex. There is always interference in the normal use of the local gray matter. If there is also a positive response, it is due to functional activation of distant gray matter. Consequently, when the electrode is applied to the hand area of the motor cortex, the delicate movements of the hand, which the cortex makes possible, are paralyzed, but the secondary station of gray matter in the spinal cord is activated, and crude movements, such as clutching, movements of which an infant is capable, are carried out.

In clinical epilepsy, the spontaneous discharge occurs, in the great majority of cases, either in the gray matter of the cortex or in the gray nuclei of the higher brain-stem. It never occurs in white matter. If it occurs in a so-called silent area of the cortex, there may be no manifestation of it unless an electroencephalogram is being taken.

In any fit, focal discharge begins in some local region of gray matter. If a positive manifestation occurs, it is produced, as in the case of electrical stimulation (see Table I), by axone-conduction to a distance. It is due, then, to neuronal activation of some distant secondary ganglionic station (see Figure 6). An epileptic discharge continues until the discharging local neurones are exhausted. The secondary distant response, which it produced, also stops then, but the local paralytic interference in the primary area of discharge continues after the discharge is over until there is recovery from the cell exhaustion. The distant response, if any, is a physiological phenomenon and stops, as I have said, as soon as axonal conduction to it stops.

There is always a danger, in electrical exploration, that stimulation by the electrode may bring to the cortex a current that is too strong. The local gray matter then goes into epileptic discharge. When the electrode is withdrawn there is an after-discharge and a local seizure. There is also added danger then that axonal conduction from the local gray to some distant gray matter may have increased enough to become a bombardment, and so produce a secondary epileptic explosion.

Spread of the local discharge in any fit may occur in one of two ways: (1) by a "Jacksonian march" into contiguous gray matter, or (2) at a distance (as just explained) by neuronal conduction to a functionally related area of gray matter. Spread of discharge, and, thus, of the epileptic fit, occurs when that conduction turns into a too violent bombardment. The physiological activation of the distant gray matter is then replaced by discharge in that distant area. That causes a new local functional interference at a distance instead of activation.*

* If this is a true statement of the physiological principles involved in epileptic seizures, and I believe it is, it calls for the thoughtful attention of clinicians and electroencephalographers.

8 • An Early Conception of Memory Mechanisms — And a Late Conclusion

This late understanding of the physiology of electrical stimulation, and of the pattern of neuronal discharge in an epileptic seizure, led at once to a clearer understanding of what is taking place in each *experiential response* to electrical stimulation. It called for a reconsideration of the "flashbacks." Consequently, after the close of my own career as an operating neurosurgeon in 1960, we reconsidered and published every detail of the experiential responses so others might judge their meaning for themselves. These were presented by Penfield in the Lister Oration, Royal College of Surgeons, in 1961, and published in full with Phanor Perot in 1963.[28]

There were 1,132 patients for us to reconsider. The brain of each had been explored under local anesthesia in the course of an operation for radical treatment of epilepsy. In 520, the temporal lobe was exposed and explored. The experiential responses came only from the temporal lobe, never from any other part of the brain. Of the temporal explorations 40, or 7.7 percent, gave experiential responses; 53 patients, or 10 percent, had complained of dreamlike attacks, in which past memories came to mind, before operation.

In 1951,[16] I had proposed that certain parts of the temporal cortex should be called "memory cortex," and suggested that the neuronal record was located there in the cortex near the points at which the stimulating electrode may call forth an experiential response. This was a mistake, as shown clearly in 1958 during my Sherrington Lecture.[18] The record is *not* in the cortex. Nevertheless, the initial hypothesis proposed at that time is still tenable: "It is tempting to believe," I wrote, "that a synaptic facilitation is established by each original experience." If so, that permanent facilitation could guide a subsequent stream of neuronal impulses activated by the electric current of the electrode even years later.

Since then, as I have already pointed out, we have come to call the "memory cortex" by another name—the "interpretive cortex." Its boundaries and those of the major speech area may be seen in Figures 7 and 8. And today, we realize that stimulation of the interpretive cortex activates a record located at a distance from that

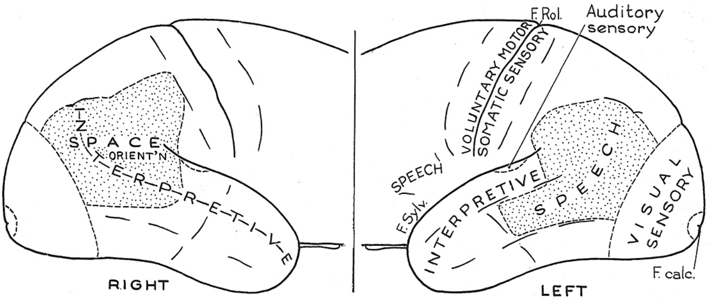
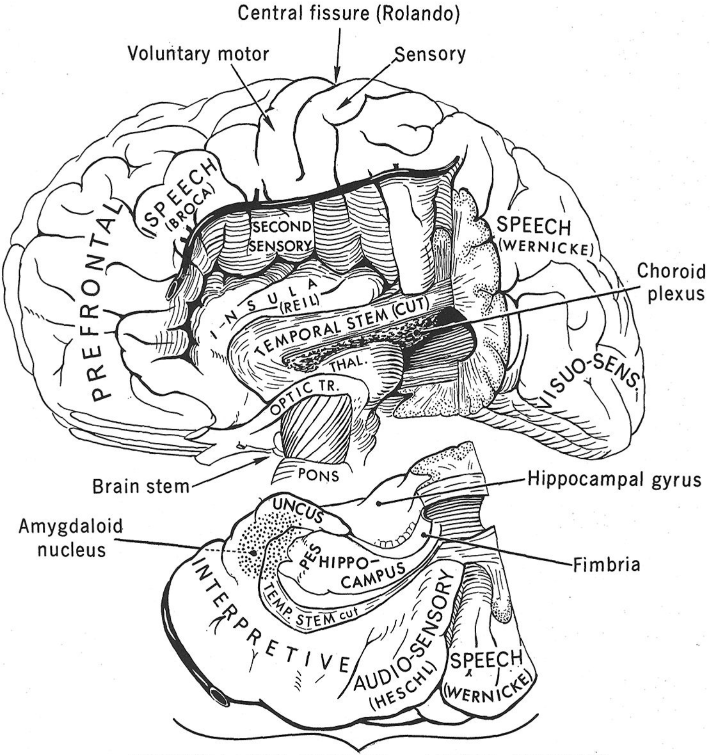


FIGURE 7. *Interpretive Cortex and Speech Cortex (see also Figure 8).*

Lateral surfaces of the posterior parts of both hemispheres of a human adult. On the dominant, or speech side, interference aphasia is produced by stimulating in the area marked *speech.* Both experiential and interpretive responses are produced by stimulating in the interpretive cortex. The area marked *space orientation* on the non-dominant side (right) was outlined by study of the results of cortical excision. Complete removal of this area produced permanent spatial disorientation without aphasia.*

* This figure is from Penfield.[22] For evidence in regard to the frontiers of the temporal speech area (Wernicke), and also for that on space orientation, see Penfield and Roberts.[30] For the localization of the interpretive cortex, see Penfield.[19]

cortex, in a secondary center of gray matter. Putting this together with other evidence makes it altogether likely that the activated gray matter is in the diencephalon (higher brain-stem), as I shall describe below.



TEMPORAL LOBE SUPERIOR and MESIAL SURFACES

FIGURE 8.

Left cerebral hemisphere. The temporal lobe was dissected free at autopsy by opening the fissure of Sylvius. It was then cut across and turned down. Note that the hidden audiosensory gyrus of Heschl is seen to be bounded by speech cortex posteriorly and interpretive cortex anteriorly. (This drawing, like most of the preceding ones, was made by Miss Eleanor Sweezey.)

9 · The Interpretive Cortex

Let me marshal and reconsider the evidence now presented to us by epilepsy and the electrode, after which we may go on to a consideration of the relationship of mind to brain, in Chapters 10 to 16.*

Two related mechanisms are revealed by stimulation of the interpretive cortex (Figures 7 and 8). Each of them was activated in Case M.M. above:

(a) There is a brain mechanism, the function of which is to send neuronal signals that interpret the relationship of the individual to his immediate environment. The action is automatic and subconscious, but the signal appears in consciousness. Such signals as this: these things are "familiar" or "frightening." They are "coming nearer" or "going away," and so on.[10,19]

(b) Secondly, there is another, related, brain mechanism that is revealed in experiential responses like those described in the case of M.M. (Chapter 6) and the others. The mechanism is capable of bringing back a strip of past experience in complete detail without any of the fanciful elaborations that occur in a man's dreaming.[19,28] In ordinary life, the automatic signal that informs one that present experience is familiar comes to all of us, I suppose. If it is accurate, and it usually is, one must be

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* I began to do this in a chapter of the book entitled *Basic Mechanisms of the Epilepsies* (edited by my former associates, Herbert Jasper, Arthur Ward, and Alfred Pope).[22] It led me to a discussion of a specific mechanism for the mind. I shall now push the argument through to a conclusion.

using an automatic mechanism that can scan a record of the past, a record that has not faded but seems to remain as vivid as when the record was made.*

The gray matter of the interpretive-cortex is part of a mechanism that presents interpretations of present experience to consciousness. In a sense, it would seem that the interpretive-cortex does for perception of non-verbal concepts what the speech-cortex and the speech-mechanism do for speech. The localization of areas devoted to speech is reasonably clear. Although much work has yet to be done on the recognition of non-verbal concepts, I shall refer to the mechanism now as the non-verbal concept mechanism. These mechanisms, the one verbal and the other non-verbal, form a remarkable memory file to be opened either by a conscious call or by an automatic one.[18,19,20]

There is much more to be said about the temporal lobes and memory when time permits. That mysterious doubled structure, the hippocampus, may well have much to do with memory of smell in some lower mammals, but in man, it is concerned with memory of other things. It can be removed on one side with impunity when the remaining hippocampus is functioning normally. But, if it is removed on both sides, the ability to reactivate the record of the stream of consciousness, voluntarily or

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* Although the great majority of experiences thus recalled has been strongly visual or strongly auditory, or both, the perception of familiarity is not limited to auditory or visual experience at all, but apparently applies to all that enters consciousness. A person seen may be labeled as "seen before" (*déjà vu*), a bar of music as "heard before," a sequence of events as "happened before."

automatically, is lost. The hippocampi seem to store keys-of-access to the record of the stream of consciousness. With the interpretive cortex, they make possible the scanning and the recall of experiential memory. See Penfield and Mathieson.[27]

And now there opens before us an exciting vista in which the automatic mechanisms of the brain interact with, and may be separated from, the brain's machinery-for-the-mind.

As I have pointed out, epileptic discharge may, and frequently does, confine itself selectively to one functional system, one functional mechanism within the brain. When it does so, it paralyzes that mechanism for any normal function. If the function of gray matter is highly complicated and only partially automatic, such as in the speech area of the human cerebral cortex, the epileptic discharge in it produces nothing more than paralytic silence, e.g., aphasia.

And so it is that the mechanism in the higher brain-stem, whose action is indispensable to the very existence of consciousness, can be put out of action selectively! This converts the individual into a *mindless automaton.* It happens when epileptic discharge occurs in gray matter that forms an integral part of that mechanism. The tentative localization of that gray matter is shown in Figure 9. If the discharge occurs there, primarily, the patient's attack is called *petit mal* automatism. But as I have already pointed out, the temporal cortex and the prefrontal cortex have much to do with the transactions of the mind, and a seizure discharge, which begins locally in temporal cortex or in the anterior frontal cortex, may spread by violent distant bombardment to this gray matter in the higher brain-stem and, thus, produce an attack of autom-

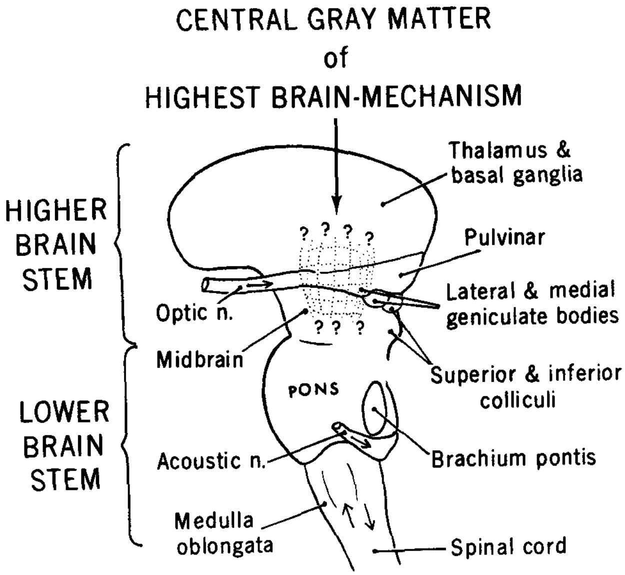

FIGURE 9. *The Highest Brain-Mechanism.*

The site of the central gray matter of this brain-mechanism, the normal action of which constitutes the physical basis of the mind, is shown by the dotted lines. The question marks indicate only that the detailed anatomical circuits involved are yet to be established, not that there is any doubt about the general position of this area in which cellular inactivation produces unconsciousness. Such inactivation may be brought about variously by pressure, trauma, hemorrhage, and local epileptic discharge; it occurs normally in sleep. (Drawing by Eleanor Sweezey.)

atism that differs little in character from that of *petit mal.**

These attacks of epileptic automatism show clearly

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* The direct connections of the higher brain-stem with these two areas of cerebral cortex (prefrontal and interpretive cortex) are indicated in Figure 1. This direct connection is with the gray matter of the mind's mechanism, not with the automatic sensory-motor mechanism, as will be pointed out. Anatomical verification of this important direct relationship is to be found in the recent studies of Walle Nauta.[12]

the automatic, complex performance of which man's computer is capable. In an attack of automatism the patient becomes suddenly unconscious, but, since other mechanisms in the brain continue to function, he changes into an automaton. He may wander about, confused and aimless. Or he may continue to carry out whatever purpose his mind was in the act of handing on to his automatic sensory-motor mechanism when the highest brain-mechanism went out of action. Or he follows a stereotyped, habitual pattern of behavior. In every case, however, the automaton can make few, if any, decisions for which there has been no precedent. He makes no record of a stream of consciousness. Thus, he will have complete amnesia for the period of epileptic discharge and during the period of cellular exhaustion that follows.

Patients are quite unable to predict when these absences of the mind will come. I shall cite a few examples. One patient, whom I shall call A., was a serious student of the piano and subject to automatisms of the type called *petit mal.* He was apt to make a slight interruption in his practicing, which his mother recognized as the beginning of an "absence." Then he would continue to play for a time with considerable dexterity. Patient B. was subject to epileptic automatism that began with discharge in the temporal lobe. Sometimes the attack came on him while walking home from work. He would continue to walk and to thread his way through busy streets on his way home. He might realize later that he had had an attack because there was a blank in his memory for a part of the journey, as from Avenue X to Street Y. If Patient C. was driving a car, he would continue to drive, although he might discover later that he had driven through one or more red lights.

In general, if new decisions are to be made, the automaton cannot make them. In such a circumstance, he may become completely unreasonable and uncontrollable and even dangerous.

The behavior of these temporary automatons throws a brilliant light then, on a second mechanism, clearly distinguishable from the one that serves the mind. It is the *automatic sensory-motor mechanism.* It, too, has centrally placed gray matter in the higher brain-stem where it must have a close functional interrelationship with the mechanism for the mind. The sensory-motor mechanism has its primary localization in the higher brain-stem (see Figure 10), but the mechanism has, quite obviously, a direct relationship to the sensory and motor portions of the cerebral cortex in both hemispheres. Thus, there are two brain mechanisms that have strategically placed gray matter in the diencephalon or brain-stem, viz.: (a) the *mind's mechanism* (or highest brain-mechanism); and (b) the *computer* (or automatic sensory-motor mechanism).

When an epileptic discharge occurs in the cerebral cortex in any of the sensory or motor areas, and if it spreads by bombardment to the higher brain-stem, the result is invariably a major convulsive attack, *never,* in our experience, an attack of automatism. On the other hand, as mentioned above, a local discharge in prefrontal or temporal cortex may develop into automatism.* This is a matter of considerable functional significance, and one that has been largely overlooked. We were first aware of the differences in the manner of spread of epileptic discharge from cerebral cortex to diencephalon when

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* Herbert Jasper and I showed that local epileptic discharge in the prefrontal cortex, occurring either spontaneously or when we had set it off by the electrode, might spread to the diencephalon and cause an attack of automatism that was very like the automatism of *petit mal.*[25]

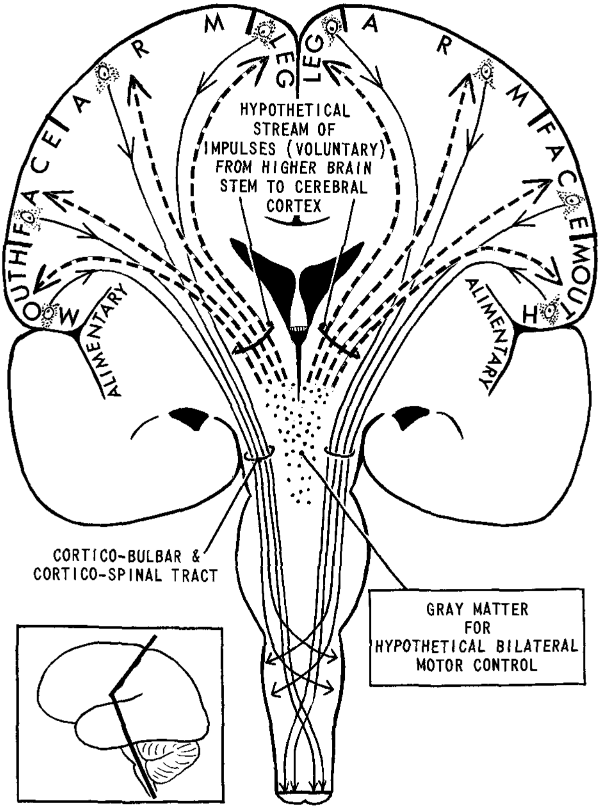

FIGURE 10. *The Automatic Sensory-Motor Mechanism.*

This much-simplified diagram outlines only the direction of the executive, or motor, messages of the mechanism that takes bilateral control of the body either under direction of the mind or automatically. It makes use of the motor cell-stations in the precentral gyrus of both sides, as shown here from leg down to face and mouth. The entire mechanism is a portion of the centrencephalic integration and coordination that makes effective mind-action possible. One may call it "man's computer." It makes available the many skills (including that of speech) that have been learned and recorded in the individual's past. It controls the behavior of the "human automaton" while the mind is otherwise occupied, or when the highest brain-mechanism is selectively inactivated, as in epileptic automatism. On the other hand, epileptic discharge within its central gray matter produces interference with its function, and calls forth active responses from the motor centers in the cortex of both hemispheres, thus producing a generalized convulsion (*grand mal*). (Drawing by Eleanor Sweezey.)

Kristian Kristiansen made his study in 1951. After examining ninety-five cases in our clinic, he pointed out that there were twenty-nine examples of seizures that began with local epileptic discharge in a motor convolution, fifty-five somatic sensory, and eleven visual sensory seizures. None developed automatism during the evolution of their attacks. Many, however, went occasionally from localized sensory or motor manifestations directly to generalized seizures.[26]

William Feindel showed that automatism is frequent (78 percent) among patients who are subject to epileptic discharges in the temporal lobe.[2] He and I showed that automatism could be produced by stimulation if the electrode was passed into the temporal lobe and on into or near the amygdaloid nucleus (see Figure 8). But this occurred only when one continued to stimulate until local epileptic discharge was produced. We assumed that this caused interference in the hippocampus on both sides and perhaps neuronal bombardment of gray matter in the higher brain-stem that went on to epileptic discharge.

Thus, from a practical point of view, a clinician may find it useful to remember that local epileptic discharge in motor or sensory gray matter areas of the cortex may spread by bombardment and so cause epileptic discharge in gray matter of the automatic sensory-motor mechanism in the higher brain-stem. This produces a major convulsion because of its activation of all the motor areas of the cortex. The cortex of one side, being pitted against the other, causes the patient to stiffen the body and limbs rather than to turn. The sensory-motor mechanism exerts activating control from its gray matter in the higher brain-stem. This acts upon the secondary gray matter in the cerebral cortex of each hemisphere, and on the tertiary gray matter in the lower brain-stem and the spinal cord. The major functional outflow of axone conducted energy is carried to the muscles in one efferent stream. During any generalized *grand mal* seizure only the automatic control of breathing, which is located in the lower brain-stem, escapes and continues its function.

When a local discharge occurs in prefrontal or temporal areas of the cortex, it may spread directly to the highest brain-mechanism by bombardment (the *mind's mechanism*). When it does this, it produces automatism. On the other hand, the sensory and motor convolutions of the cortex, when overcharged electrically, bombard the automatic sensory-motor mechanism (the *computer's mechanism*) in the higher brain-stem. One may surmise then that there must be a mind's mechanism that has direct access to prefrontal and temporal cortex but has only indirect access to sensory and motor mechanisms of the cerebral cortex.

Thus, when bombardment from the motor or sensory convolutions of the cortex becomes excessive, it may produce secondary discharge in the computer and thus a major convulsive seizure, but not an attack of automatism. When bombardment from the prefrontal or temporal areas of the cortex becomes excessive, it may produce interference in the highest brain-mechanism (the mind's mechanism) and thus cause an attack of automatism. Or it may produce a major convulsive seizure because of an additional direct connection with the computer.

No functional conclusions should be drawn from these facts except perhaps to suggest that

(1) the highest brain mechanism has direct connection with the newer temporal and prefrontal areas of cerebral cortex, and

(2) its functional connection with the older motor and sensory areas of the cortex must be an indirect one, perhaps interrupted in the computer.