THE FUNCTIONAL ORGANIZATION OF THE BRAIN

A. R. LURIA
March 1970

The functional organization of the human brain is a problem that is far from solved. I shall describe in this article some recent advances in the mapping of the brain. They open up a new field of exploration having to do with the structures of the brain involved in complex forms of behavior.

So far as sensory and motor functions are concerned, the brain, as is well known, has been mapped in precise detail. Studies by neurologists and psychologists over the past century have defined the centers that are responsible for some elementary functions such as seeing, hearing, other sensory functions and the control of the various muscular systems of the body. From outward symptoms or simple tests disclosing a disturbance of one of these functions it is possible to deduce the location of the lesion (a tumor or a hemorrhage, for example) causing the disturbance. Such a finding is of major importance in neurology and neurosurgery. The sensory and motor centers, however, account for only a small part of the area of the cerebral cortex. At least three-quarters of the cortex has nothing to do with sensory functions or muscle actions. In order to proceed further with the mapping of the brain's functions we must look into the systems responsible for the higher, more complex behavioral processes.

It is obvious that these processes, being social in origin and highly complex in structure and involving the elaboration and storage of information and the programming and control of actions, are not localized in particular centers of the brain. Plainly they must be managed by an elaborate apparatus consisting of various brain structures. Modern psychological investigations have made it clear that each behavioral process is a complex functional system based on a plan or program of operations that leads to a definite goal. The system is self-regulating: the brain judges the result of every action in relation to the basic plan and calls an end to the activity when it arrives at a successful completion of the program. This mechanism is equally applicable to elementary, involuntary forms of behavior such as breathing and walking and to complicated, voluntary ones such as reading, writing, decision-making and problem-solving.

What is the organizational form of this system in the brain? Our present knowledge of neurology indicates that the apparatus directing a complex behavioral process comprises a number of brain structures, each playing a highly specific role and all under coordinated control. One should therefore expect that lesions of the structures involved might result in changes in the behavior, and that the nature of the change would vary according to the particular structure that is damaged.

A New Approach

This concept forms the basis of our new approach to exploration of the functional organization of the brain—a study we call neuropsychology. The study has two objectives. First, by pinpointing the brain lesions responsible for specific behavioral disorders we hope to develop a means of early diagnosis and precise location of brain injuries (including those from tumors or from hemorrhage) so that they can be treated by surgery as soon as possible. Second, neuropsychological investigation should provide us with a factor analysis that will lead to better understanding of the components of complex psychological functions for which the operations of the different parts of the brain are responsible.

The human brain can be considered to be made up of three main blocks incorporating basic functions. Let us examine the responsibilities of each block in turn.

The first block regulates the energy level and tone of the cortex, providing it with a stable basis for the organization of its various processes. The brilliant researches of Horace W. Magoun, Giuseppe Moruzzi, Herbert H. Jasper and Donald B. Lindsley located the components of the first block in the upper and lower parts of the brain stem and particularly in the reticular formation, which controls wakefulness. If an injury occurs in some part of the first block, the cortex goes into a pathological state: the stability of its dynamic processes breaks down, there is a marked deterioration of wakefulness and memory traces become disorganized.

I. P. Pavlov observed that when the normal tone of the cortex is lowered, the "law of force" is lost and much of the brain's ability to discriminate among stimuli suffers. Normally the cortex reacts powerfully to strong or significant stimuli and responds hardly at all to feeble or insignificant stimuli, which are easily suppressed. A weakened cortex, on the other hand, has about the same response to insignificant stimuli as to significant ones, and in an extremely weakened state it may react even more strongly to weak stimuli than to strong ones. We all know about this loss of the brain's selectivity from common experience. Recall how diffuse and disorganized our thoughts become when we are drowsy, and what bizarre associations the mind may form in a state of fatigue or in dreams.

Obviously the results of injury to the first block in the brain, namely the loss of the selectivity of cortical actions and of normal discrimination of stimuli, will bring about marked changes in behavior. The control of behavior becomes deranged. In our common work with Macdonald Critchley of England such disturbances have been observed in patients who had tumors of the middle parts of the frontal lobes, and other investigators in our laboratory in Moscow have since reported similar effects from lesions in deep parts of the brain.

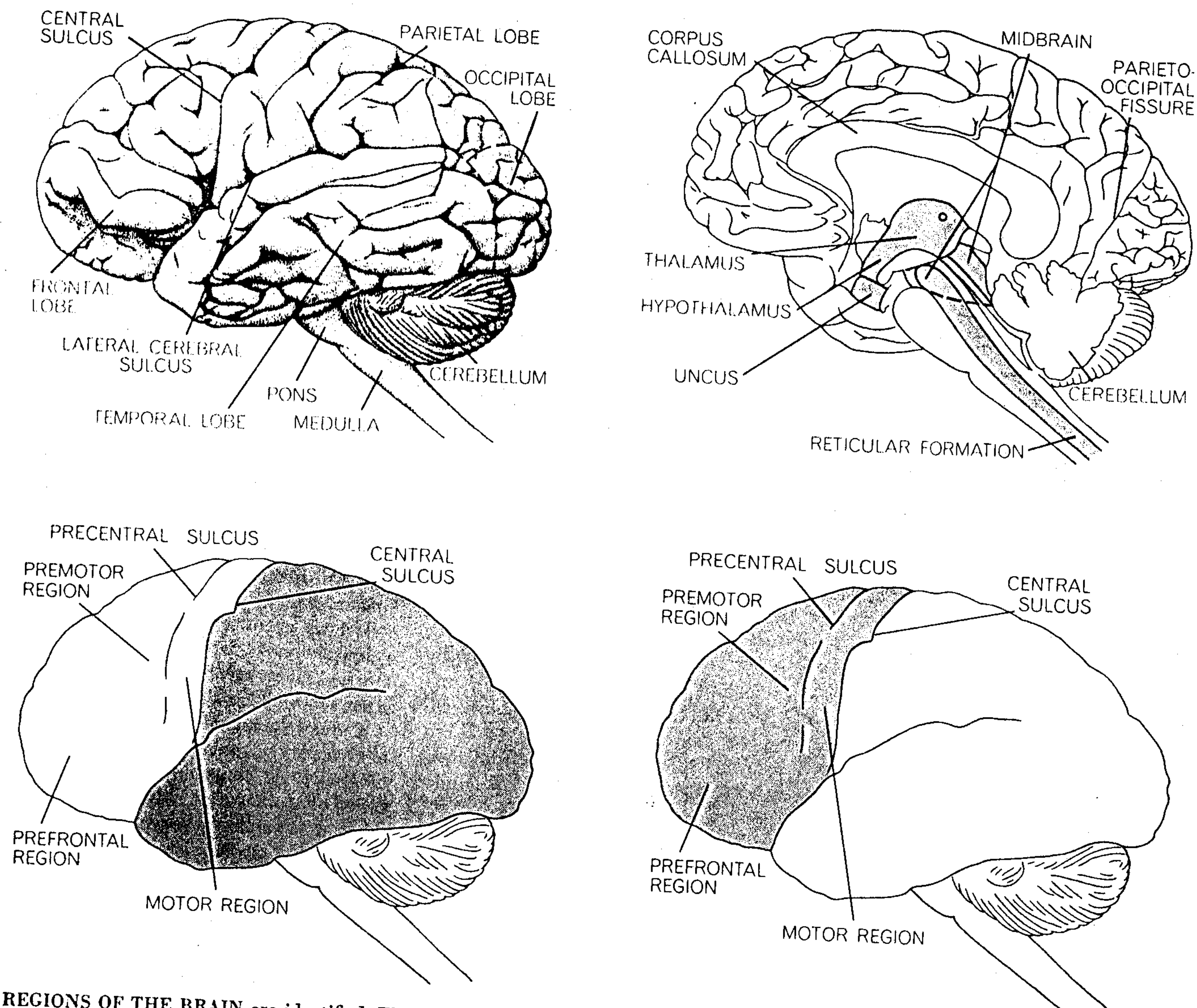
The Second Block

The second block of the brain has received much more study, and its role in the organization of behavior is better known. Located in the rear parts of the cortex, it plays a decisive role in the analysis, coding and storage of information. In contrast to the functions of the first block, which are mainly of a general nature (for example controlling wakefulness), the systems of the second block have highly specific assignments.

We can easily identify areas in the second block that are respectively responsible for the analysis of optic, acoustic, cutaneous and kinesthetic stimuli. Each of these cortical areas has a hierarchical organization: a primary zone that sorts and records the sensory information, a secondary zone that organizes the information further and codes it and a tertiary zone where the data from different sources overlap and are combined to lay the groundwork for the organization of behavior.

Injuries to the parts of the second block produce much more specific effects than lesions in the first block do. An injury in a primary zone of the second block results in a sensory defect (in seeing or hearing, for example); it does not, however, bring about a marked change in complex forms of behavior. A lesion in a secondary zone produces more complicated disturbances. It interferes with analysis of the sensory stimuli the zone receives and, because the coding function is impaired, the lesion leads to disorganization of all the behavioral processes that would normally respond to these particular stimuli. It does not disturb any other behavioral processes, however, which is an important aid for locating the lesion.

Of the various lesions in the second block of the brain those in the tertiary zones are particularly interesting to us as neuropsychologists. Since these zones are responsible for the synthesis of a collection of information inputs from different sources into a coherent whole, a lesion of a tertiary zone can cause such complex disturbances as visual disorientation in space. The lesion seriously im-



REGIONS OF THE BRAIN are identified. The gross anatomy of the human brain is depicted at upper left. The other drawings identify three major blocks of the brain involved in the organization of behavior. The first block (*upper right*) includes the brain stem and the old cortex. It regulates wakefulness and the response to stimuli. The second block (*lower left*) plays a key role in the analysis, coding and storage of information. The third block (*lower right*) is involved in the formation of intentions and programs.

pairs the ability to handle complex problems that entail an organization of input in simultaneous matrixes. That is why these lesions may render a person incapable of performing complex operations with numbers or of coping with a complexity in grammar logic or language structure.

The Third Block

The third block of the brain, comprising the frontal lobes, is involved in the formation of intentions and programs for behavior. Important contributions to elucidation of the functions of the frontal lobes have been made by S. I. Franz, L. Bianchi, Karl H. Pribram and Jerzy Konorski through studies of animals and by V. M. Bekhterev, C. Kleist and Derek E. Denny-Brown through clinical observations. We have devoted much study to the roles of the third block in our laboratory.

The frontal lobes perform no sensory or motor functions; sensation, movement, perception, speech and similar processes remain entirely unimpaired even after severe injury to these lobes. Nevertheless, the frontal lobes of the human brain are by no means silent. Our findings make it clear that they participate to a highly important degree in every complex behavioral process.

Intimately connected with the brain stem, including its reticular formation, the frontal lobes serve primarily to activate the brain. They regulate attention and concentration. W. Grey Walter showed a number of years ago that the activity of the brain could be measured by the appearance of certain slow brain waves in an electroencephalogram; these waves are evoked when a subject is stimulated to active expectancy and disappear when the subject's attention is exhausted [see "The Electrical Activity of the Brain," by W. Grey Walter; SCIENTIFIC AMERICAN Offprint 73]. At about the same time M. N. Livanov, a Russian investigator, found that mental activity is signaled by a complex of electrical excitations in the frontal cortex and that these excitations disappear when the subject subsides to a passive state or is lulled with tranquilizers.

Functional Systems

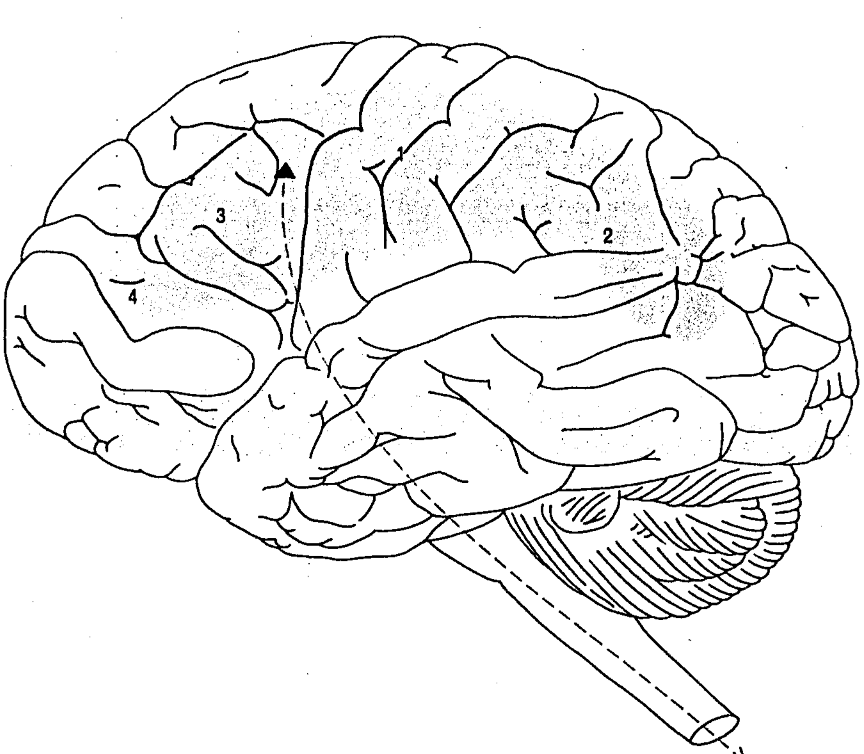
Now that we have reviewed the functions of the brain's basic blocks, let us see what we can learn about the location of specific parts of the various functional systems. It is clear that every complex form of behavior depends on the joint operation of several faculties located in different zones of the brain. A disturbance of any one faculty will affect the behavior, but each failure of a specific factor presumably will change the behavior in a different way. We have explored these effects in detail with a number of psychological experiments.

To illustrate our findings I shall discuss the results of a neuropsychological analysis of two processes. One is voluntary movement; the other is speech and in particular one of its forms, namely writing.

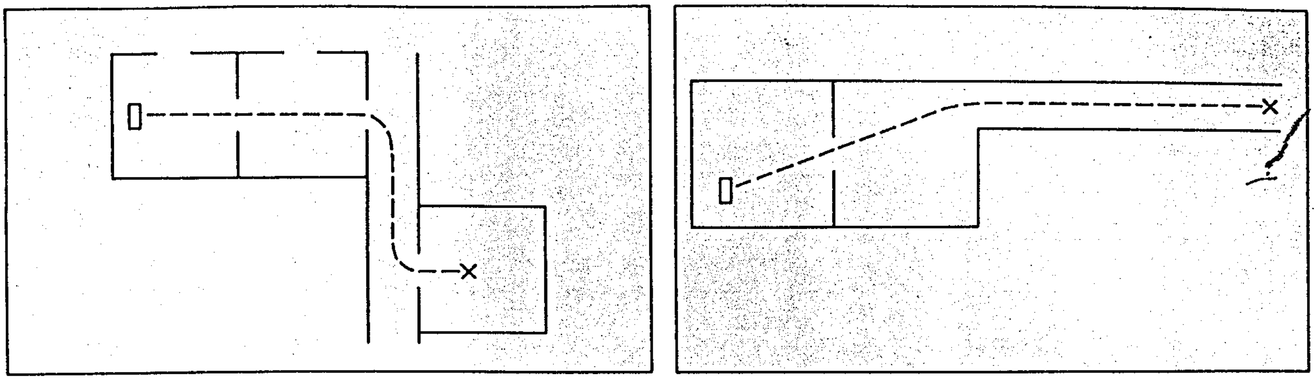
It was long supposed that voluntary movements are a function of the motor cortex, that is, the large pyramidal cells of the cortex of the anterior convolution of the brain. These cells, discovered by the Russian anatomist V. A. Betz more than 100 years ago, have exceptionally long axons that conduct the excitation toward the roots of the spinal cord. Impulses from these cells result in the constriction of muscles and are supposed to be the neurophysiological basis of voluntary movement.

Up to a certain point this is true, but the mechanism of the formation of a voluntary movement is much more complicated. To think that a voluntary action is formed in the narrow field of the motor cortex would be a mistake similar to an assumption that all the goods exported through a terminal are produced in the terminal. The system of cortical zones participating in the creation of a voluntary movement includes a complex of subcortical and cortical zones, each playing a highly specific role in the whole functional system. That is why lesions of different parts of the brain can result in the disturbance of different voluntary movements.

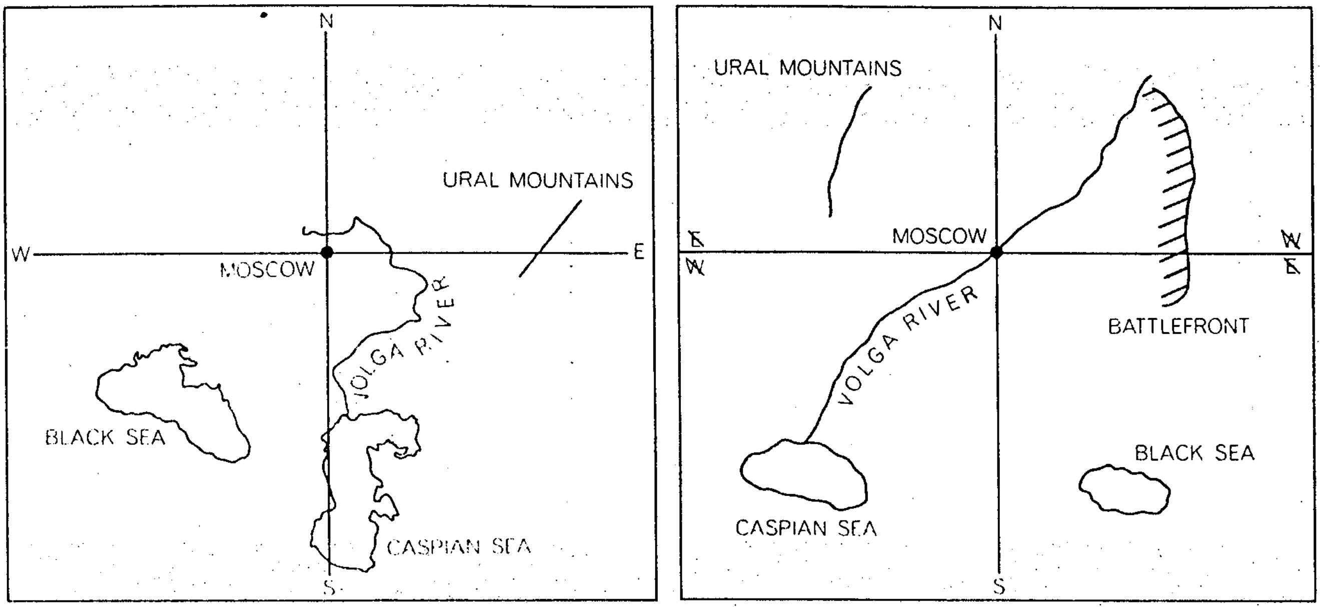
Let us examine the components of voluntary movement and see how it is affected differently by lesions in different parts of the brain. The first component is a precisely organized system of afferent (sensory) signals. The Russian physiologist N. A. Bernstein has shown in a series of studies that it is impossible to regulate a voluntary movement only by way of efferent impulses from the brain to the muscles. At every moment of the movement the position of the limb is different, and so is the density of the muscles. The brain has to receive feedback from the muscles and joints to correct the program of impulses directed to the motor apparatus. One can recognize the nature of the problem by recalling how difficult it is to start a leg movement if



VOLUNTARY MOVEMENT is controlled by a complex of cortical and subcortical zones. The classical theory was that voluntary movement originated with the large pyramidal cells (*arrowhead*) of the cortex; they have long axons that conduct impulses to the spinal cord. It is now known that other zones participating in voluntary movement are the postcentral zone (*1*), which deals with sensory feedback from the muscles; the parieto-occipital zone (*2*), which is involved in the spatial orientation of movement; the premotor zone (*3*), which deals with the separate links of motor behavior, and the frontal zone (*4*), which programs movements. Lesions in different zones give rise to different behavioral aberrations.



SPATIAL DISORGANIZATION is evident in a patient who had a gunshot wound of the right parieto-occipital part of the brain. The patient was asked to depict the layout of his hospital ward. His visualization is at right and the actual layout of the ward is at left.



CONFUSION OVER DIRECTIONS was manifested by another patient with a gunshot wound of the right parieto-occipital zone. He was asked to draw a map of the region of the U.S.S.R. where he had been involved in fighting during World War II. The actual geographical relations are shown at left; the patient's view is at right. The line of battle represented on his map was in fact west of Moscow. In addition to reversing most of the locations, the patient could not make up his mind on the labeling of east and west.

the leg has become numb. This sensory or proprioceptive base is provided by a special part of the brain: the postcentral sensory cortex. If this part of the cortex is destroyed by a wound or other injury, the patient not only loses sensation in the limb but also is unable to fulfill a well-organized voluntary movement.

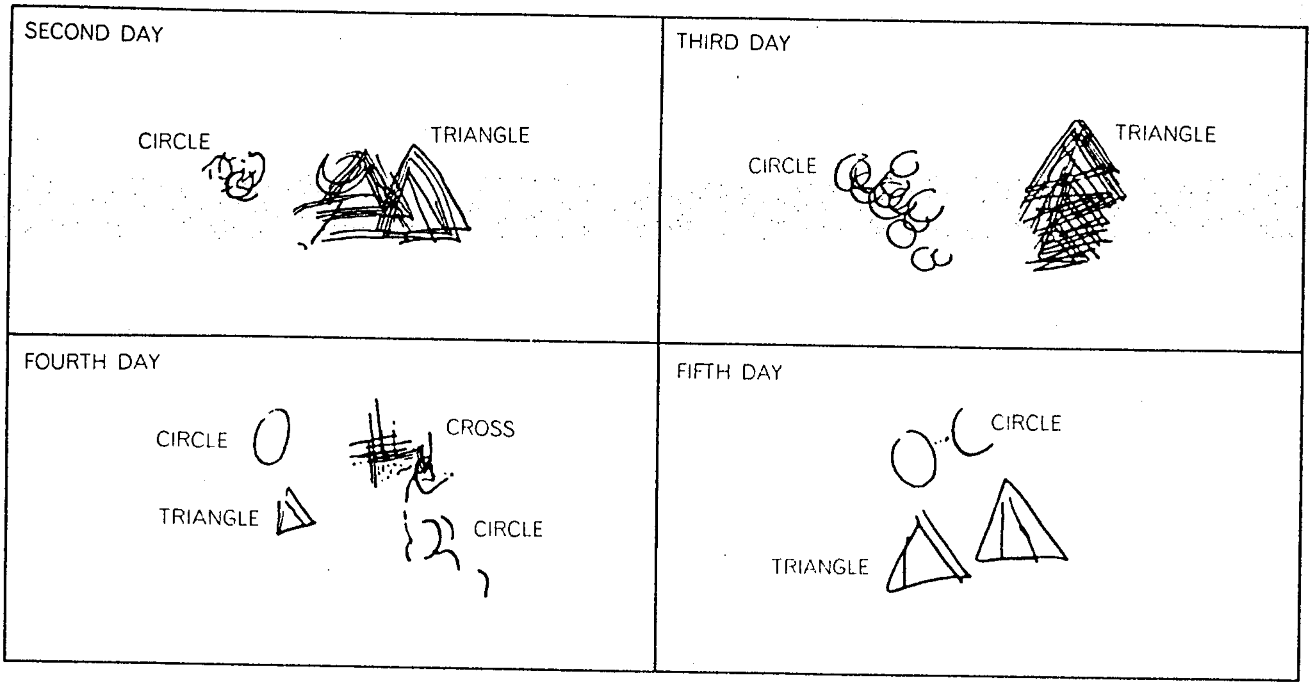
One of our co-workers has studied the physiological mechanism of such a disturbance and has shown that in lesions of the sensory part of the cortex every voluntary impulse loses its specific "address" and arrives equally at all muscles, both flexors and extensors. No organized movement can be elicited in such conditions. That is why neurologists have called this kind of motor disturbance afferent paresis.

A second component of voluntary movement is the spatial field. The movement has to be precisely oriented toward a certain point in space. Spatial analysis is done in another zone of the cortex: the tertiary parts of the parieto-occipital areas. Lesions of these highly complicated parts of the cortex result in a different kind of disturbance of voluntary movement. The sensory base of the movement remains intact, but the patient fails in a precise spatial organization of the movement. He loses the ability to evaluate spatial relations and confuses left and right. Such a patient may be unable to find his way in a familiar place or may be confused in such matters as evaluating the position of the hands of a watch or in distinguishing east and west on a map.

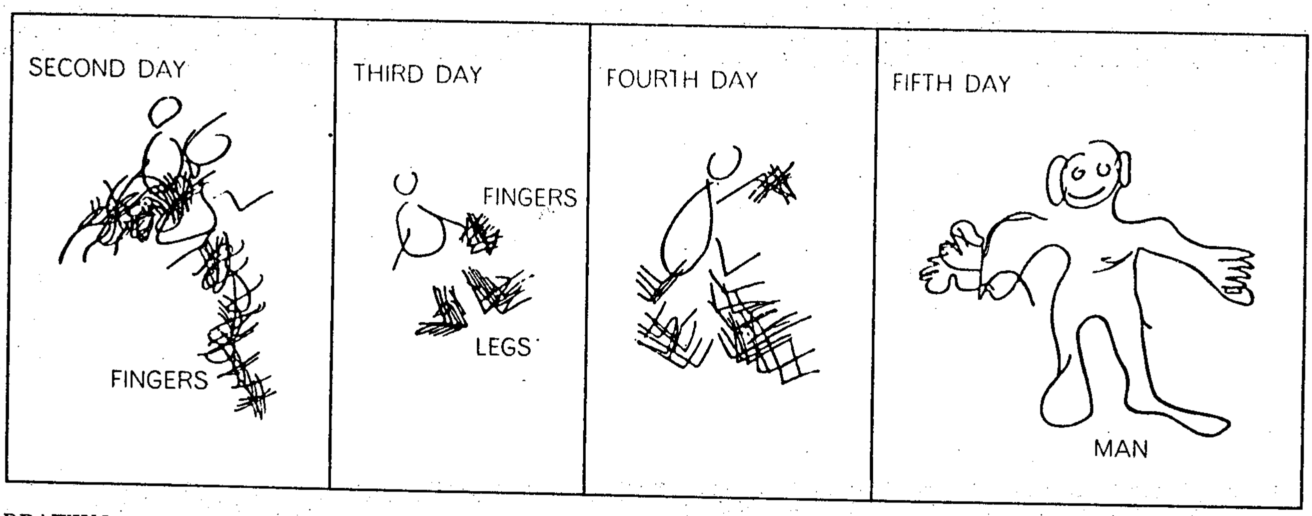
The sensory and spatial factors in the organization of a movement are basic but still insufficient to allow the completion of the movement. A voluntary movement is the result of a sequence of events. A skilled movement is really a kinetic melody of such interchangeable links. Only if one already fulfilled part of the movement is blocked and the impulse is shifted to another link can an organized skilled movement be made.

An important finding, first described by Karl S. Lashley and John F. Fulton and carefully studied in our laboratory for many years, is that a totally different part of the brain—the premotor cortex—is responsible for sequential interchanges of separate links of motor behavior. A skilled movement disintegrates when this part of the brain is injured. Such a patient still has sensory feedback and spatial orientation, but he loses the ability to arrest one of the steps of the movement and to make a transition from one step to the next.

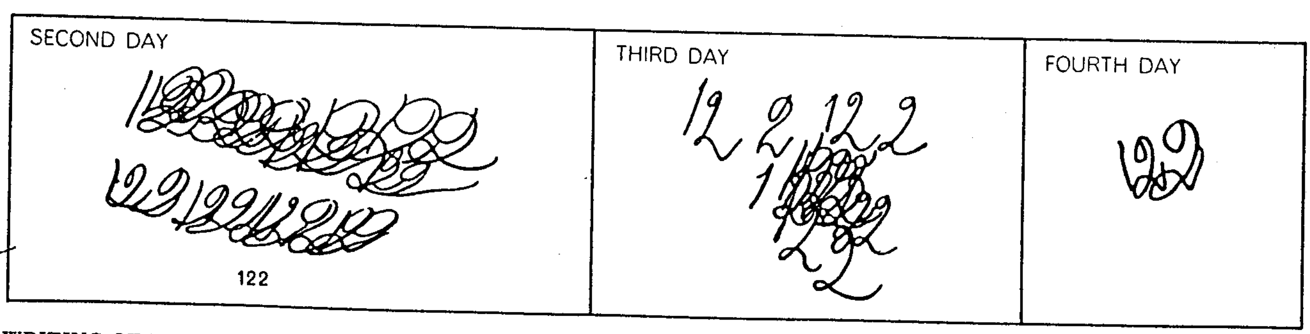
Even now I have not fully described the brain's organization of a voluntary



INFLUENCE OF PREMOTOR REGION on the organization of movement appears in drawings made by a patient after surgery for removal of a meningioma, which is a tumor arising from the meninges, from the left premotor region. On each of the days represented in the illustration the patient was asked to draw simple figures such as those shown here. Performance improved steadily.



DRAWINGS OF A MAN were attempted by the same patient during the postoperative period. At first he drew a head and body, represented by the circles at top center in the drawing at left. Then he drew a second man, whose head is to the right of the first man's body. Then he made a series of stereotyped pen strokes. The ones that trail off at lower right in the first drawing were made on moving paper. On successive days the patient's work improved. Difficulty in stopping a movement often appears in premotor lesions.



WRITING OF NUMBERS was attempted by the same patient on the second, third and fourth day after the operation. As in the other cases the patient at first showed a tendency to repeat part of the task, but the repetition diminished on the following days.

movement. Every movement has to be subordinated to a stable program or a stable intention. They are provided in the prefrontal lobes of the brain (included in the third block). If the frontal lobes are injured, the sensory base, spatial organization and plasticity of the movement remain but goal-linked actions are replaced by meaningless repetitions of already fulfilled movements or impulsive answers to outside stimuli. The whole purposive conduct of the patient is disturbed.

Speech and Writing

Let us now analyze a more complex psychological process: the ability to speak, and particularly the ability to write. It used to be thought that the operation of writing is controlled by a certain area (called Exher's center) in the middle of the premotor zone of the brain's left hemisphere (for a right-handed writer). It has since been learned, however, that this is not the case, and that a broad area of the left hemisphere is involved. We must therefore consider the effects of lesions in all parts of this region on writing.

Let us start by a psychological analysis of the processes involved in writing something in response to an instruction. Suppose one is asked to write a given word. The interpretation of the oral request turns out to be in itself a complex process. A word is composed of individual sounds, or phonemes, each coded by a letter or combination of letters. The recognition of a word may depend on the perception of very slight differences between phonemes, or acoustic cues. Consider, for example, "vine" and "wine," "special" and "spatial," "bull" and "pull," "bark" and "park." The practiced brain readily distinguishes between similar sounds, and to a person brought up in the English language the two words in these pairs sound quite different from each other. Obviously the brain must perform a sharp analysis of phonemes on the basis of learning. We become impressed with this fact when we see how difficult it is to sense distinctions in listening to a foreign language. To an English-speaking or French-speaking person, for example, three words in the Russian language—*pyl*, meaning "ardor," *pyl'* (with the *l* palatalized), meaning "dust," and *pil* (with a hard *l*), meaning "he drank"—sound almost exactly the same, yet a Russian has no difficulty distinguishing these words. Much more remarkable instances of subtle distinctions the mind is called on to make can be cited in other languages. In Chinese *ma* and *ma* have the opposite meaning ("to buy" and "to sell"), although the only difference is in the tone of the vowel. In the Vietnamese language the phoneme *tü* has at least six different meanings, depending on the pitch of the voice!

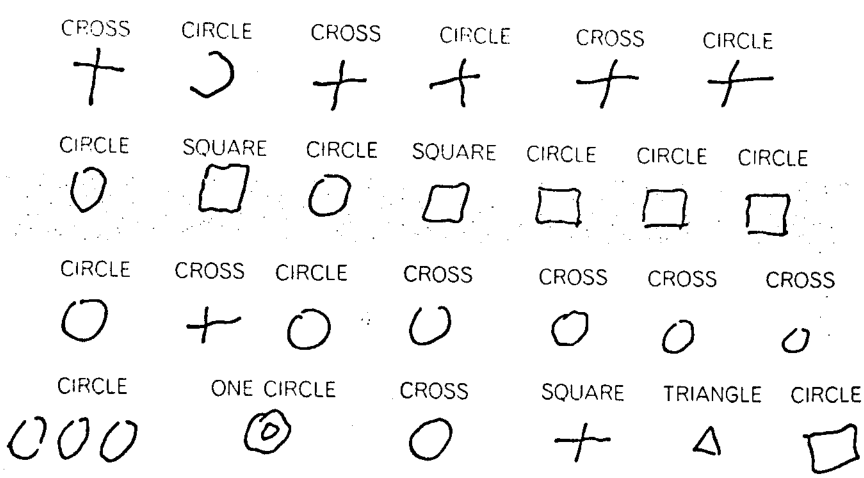
What part of the brain is responsible for recognizing phonemes? Our observations on many hundreds of patients with local brain wounds or tumors who underwent word-writing tests established clearly that the critical region lies in the secondary zones of the left temporal lobe, which are intimately connected with other parts of the brain's speech area. People with lesions in this region cannot distinguish *b* from *p* or *t* from *d*, and they may write "pull" instead of "bull" or "tome" instead of "dome." Moreover, they may make unsuccessful attempts to find the contents of the sounds of words they try to write. Interestingly enough, Chinese patients with severe injury of the acoustic region have no such difficulty, because their writing is based on ideographs instead of on words that call for the coding of phonemes.

Continuing our dissection of the process of word recognition, we must note that people commonly pronounce an unfamiliar word before writing it, and in the case of an unfamiliar name they are likely to ask the person to spell it. Articulation of the sounds helps to clarify the word's acoustic structure. A class of Russian elementary schoolchildren during a lesson in the early stages of learning to write is generally abuzz with their mouthing of the words. To find out if this activity was really helpful, I asked one of my co-workers to conduct an experiment. The children were instructed to hold their mouths open or to immobilize their tongues with their teeth while they wrote. In these circumstances, unable to articulate the words, the children made six times as many spelling mistakes!

It turns out that a separate area of the brain cortex, in the central (kinesthetic) region of the left hemisphere, controls the articulation of speech sounds. People with lesions in this area confuse the sound of *b* with that of *m* (both made with similar tongue and lip movements) and often cannot distinguish between *d, e, n* and *l*. A Russian with such a lesion may write *ston* ("groan") instead of *stol* ("table") and *khadat* (meaningless) instead of *khalat* ("dressing gown").

After evaluation of the speech sounds and recognition of the word, the next step toward writing the word is the coding of the sound units (phonemes) into the units of writing (letters). We find that this step calls into play still other parts of the brain cortex, in the visual and spatial zones. Patients with lesions in these zones (in the occipital and parietal lobes) have a perfectly normal ability to analyze speech sounds, but they show marked difficulty in recognizing and forming written letters. They find it difficult to visualize the required structure of a letter, to grasp the spatial relations among the parts of the letter and to put the parts together to form the whole.

The mental process for writing a word entails still another specialization: putting the letters in the proper sequence to form the word. Lashley discovered many years ago that sequential analysis

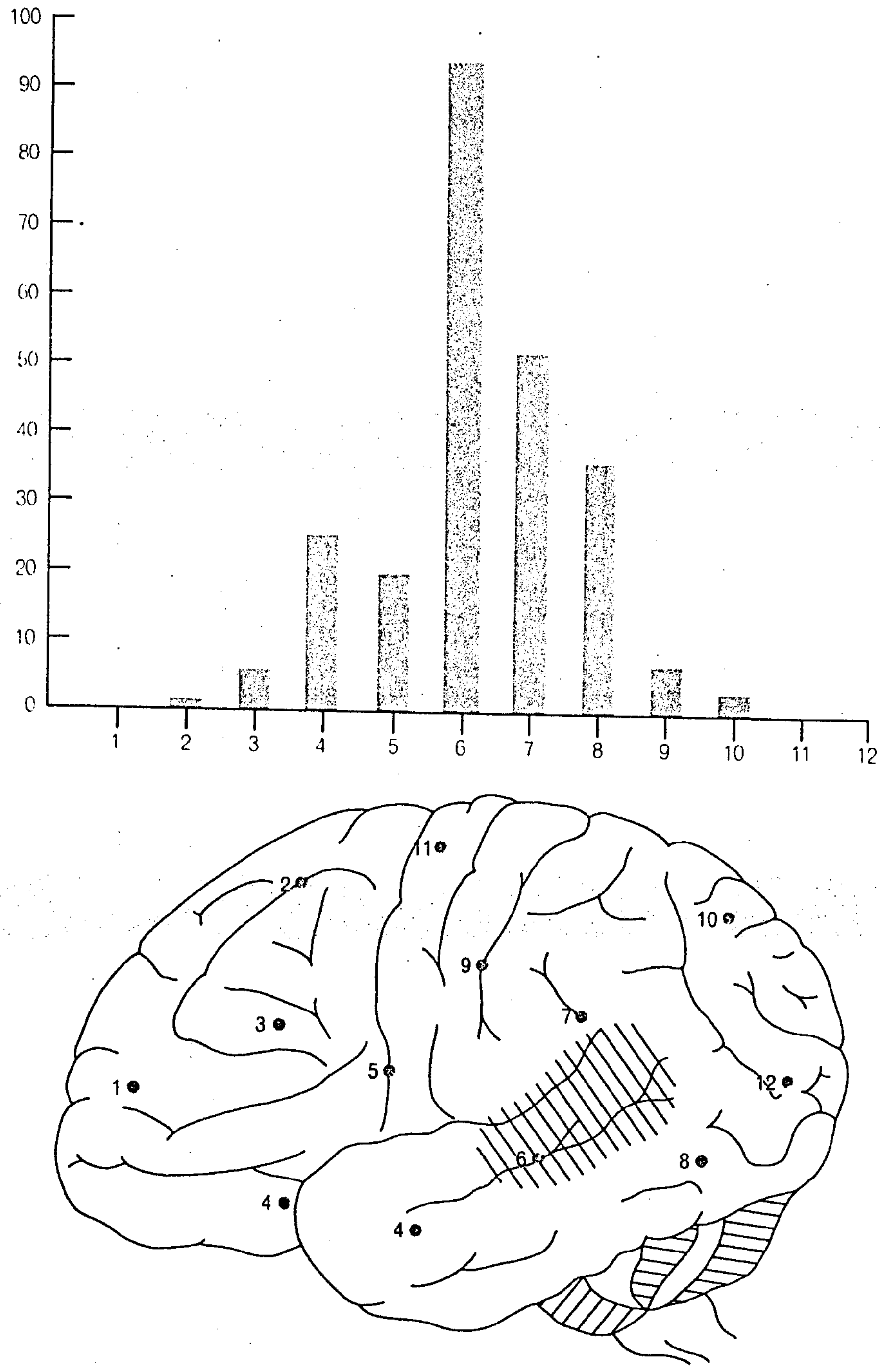


LESIONS OF FRONTAL LOBES interfere with the programming of actions and cause errors such as repetition. On each line of the illustration are drawings made by patients; printed words show what they were asked to draw. The first, second and fourth patient had tumors of the left frontal lobe; the third patient had an abscess of the right frontal lobe.

involved a zone of the brain different from that employed for spatial analysis. In the course of our extensive studies we have located the region responsible for sequential analysis in the anterior region of the left hemisphere. Lesions in the prefrontal region disturb the ability to carry out rhythmic movements of the body, and they also give patients difficulty in writing letters in the correct order. Such patients transpose letters, are unable to proceed serially from one letter to another and often replace the required letter with a meaningless stereotype. If the lesion is located deep in the brain where it interrupts connections between the basal ganglia and the cortex, the patient becomes incapable of writing words at all; he may merely repeat fragments of letters. Yet such a patient, with the higher parts of the cortex undamaged, can recognize phonemes and letters perfectly well.

Finally, there is an overall requirement for writing that involves the apparatuses of the third block of the brain as a whole. This is the matter of writing not merely letters or words but expressing thoughts and ideas. When the third block is damaged by severe lesions of the frontal lobes, the patient becomes unable to express his thoughts either orally or in writing. I shall never forget a letter written to the noted Russian neurosurgeon N. N. Burdenko by a woman with a severe lesion of the left frontal lobe. "Dear Professor," she wrote, "I want to tell you that I want to tell you that I want to tell you..." and so on for page after page!

The analysis of the writing process is just one of the tracers we have used in our psychological exploration of the functional organization of the brain. Over the past three decades investigators in our laboratory and our clinical associates have carried out similar analyses of the brain systems involved in perception, bodily movements, performance of planned actions, memorization and problem-solving. All these studies have demonstrated that detailed investigation of the nature of a behavioral disturbance can indeed guide one to the location of the causative lesion in the brain.



DISRUPTION OF HEARING in patients with bullet wounds in the left hemisphere of the cerebral cortex is charted. Affected areas of the brain are numbered, and the correspondingly numbered bars show the percent of patients who had difficulty recognizing sounds.

Factor Analyses

Obviously the neuropsychological approach provides a valuable means of dissecting mental processes as well as diagnosing illness. It is enabling us to search out the details of the brain's normal operations and capacities. A generation ago L. L. Thurstone of the University of Chicago and C. E. Spearman of the University of London learned some of the details by the statistical technique of factor analysis based on batteries of tests administered to great numbers of subjects. With the neuropsychological technique we can now make factor analyses in individual subjects. When a particular factor is incapacitated by a brain lesion, all the complex behavior processes that involve the factor are disturbed and all others remain normal. We find, for example, that an injury in the left temporal lobe causes the patient to have serious difficulty in analyzing speech sounds, in repeating verbal sounds, in naming objects and in writing, but the person retains normal capacities in spatial orientation and in handling simple computations. On the other hand, a lesion in the left parieto-occipital region that destroys spatial organization does not affect the patient's fluency of speech or sense of rhythm.

Sorting out the various factors and

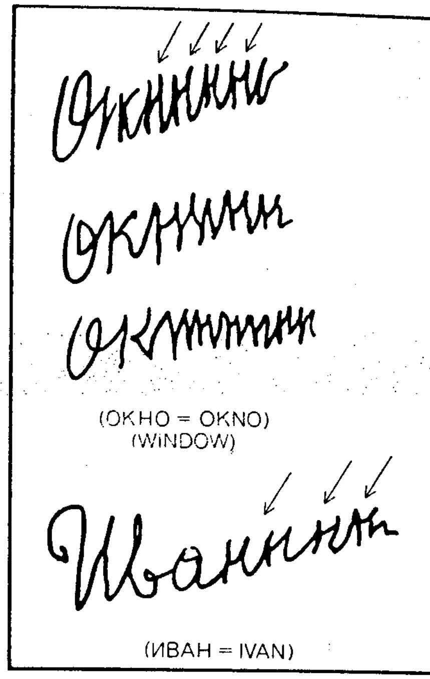
their effects, we arrive at some surprising findings. One is that behavioral processes that seem very similar or even identical may not be related to one another at all. For example, it turns out that the mechanism for perception of musical sounds is quite different from that for verbal sounds. A lesion of the left temporal lobe that destroys the ability to analyze phonemes leaves musical hearing undisturbed. I observed an outstanding Russian composer who suffered a hemorrhage in the left temporal lobe that deprived him of the ability to understand speech, yet he went on creating wonderful symphonies!

On the other hand, behavioral proccesses that seem to have nothing in common may actually be related through dependence on a particular brain factor. What can there be in common between the capacities for orientation in space, for doing computations and for dealing with complexities in grammar logic? Yet all three of these abilities are affected by the same lesion in the lower part of the left parietal lobe. Why so? A close analysis of the three processes suggests an explanation. Computation and the ability to handle language structure depend, like orientation, on the ability to grasp spatial relations. In order to subtract 7 from 31, for example, one first performs the operation $30 - 7 = 23$ and then adds the 1 to this preliminary result. There is a spatial factor here: one indicates unambiguously that the 1 is to be *added* by placing it to the right of the 23. A patient with a lesion disturbing his capacity for spatial organization is unable to cope with the problem because he is at a loss whether to place the 1 to the left or the right—in other words, whether to add it or subtract it.

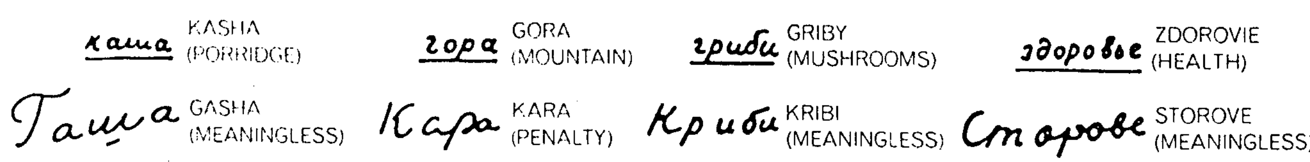
The same principle applies to understanding complex grammatical constructions. In order to grasp the difference between "father's brother" and "brother's father" or between "summer comes after spring" and "spring comes after summer," for example, one must make a clear analysis of the quasi-spatial relations between the elements in each expression.

Finally, the neuropsychological approach gives us a new insight into the effects of learning on the brain's processes. There is a well-known story of a patient of the 19th-century English neurologist Sir William Gowers who, after many unsuccessful attempts to repeat the word "no" in response to his instruction, at last burst out: "No, doctor, I can't say 'no.'" We have observed many cases of automatic performances of this kind in brain-injured patients who could not achieve a given task when they thought about it. One was an old lady who was unable to write a single word on instruction, but when she was asked to write a whole sentence quickly (a kinetic skill), she did so without hesitation. Patients who cannot write from dictation are often able to sign their names readily. It appears, therefore, that training or habituation changes the organization of the brain's activity, so that the brain comes to perform accustomed tasks without recourse to the processes of analysis. That is to say, the task may invoke a stereotype based on a network of cortical zones quite different from the one that was called on originally when the performance required the help of the analytical apparatus.

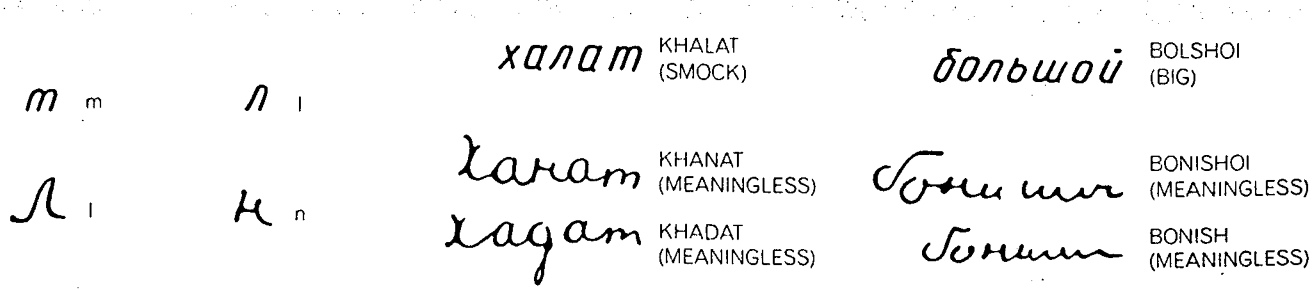
Neuropsychology has put us on a new path in the investigation of how the brain functions, and we can suppose that it is likely to lead the way to substantial changes in the design of psychological research in the future.



WRITING ABERRATION was shown by a patient with a tumor in the deep part of the brain's left premotor zone. He was asked to write the Russian words for window and Ivan, which are printed in Russian and in English transliteration below each example. Arrows show repetition or fragments.



WRITING DISTURBANCES appear in a patient with a lesion of the left temporal area. The patient was writing to dictation; the dictated Russian word, its transliteration and its English meaning are on the top line. The written response of the patient in each case appears below with its transliteration and English meaning in the single instance (*kara*) where the patient wrote a meaningful word.



ERRORS IN WRITING also were shown by a patient with a lesion of the left parietal area. Again the dictated letter or word appears on the top line; the bottom lines show the written response by the patient. None of the words that the patient wrote were meaningful.