The Cerebral Cortex: Crown of the Brain

The cerebral cortex, a 1/4-inch-thick sheet of gray (unmyelinated) cells that form the outermost layer of the human brain, is the crowning achievement of brain evolution. Fish and amphibians have no cerebral cortex, and the progression from more primitive to more advanced mammals is marked by a dramatic increase in the proportion of cortical tissue. In humans, the cortex constitutes fully 80 percent of brain tissue (Nolte, 1998).

The cerebral cortex is not essential for physical survival in the way that the brain stem structures are, but it is essential for a human quality of living. How much so is evident in this description of patients who, as a result of an accident during prenatal development, were born without a cerebral cortex:

> *Some of these individuals may survive for years, in one case of mine for twenty years. From these cases, it appears that the human [lacking a cortex] sleeps and wakes; . . . reacts to hunger, loud sounds, and crude visual stimuli by movement of eyes, eyelids, and facial muscles; . . . may see and hear, . . . may be able to taste and smell, to reject the unpalatable and accept such food as it likes. . . . [They can] utter crude sounds, can cry and smile, showing displeasure when hungry and pleasure, in a babyish way, when being sung to; [they] may be able to perform spontaneously crude [limb] movements. (Cairns, 1952, p. 109)*

Because the cortex is wrinkled and convoluted, like a wadded-up piece of paper, a great amount of cortical tissue is compressed into a relatively small space inside the skull. Perhaps 75 percent of the cortex's total surface area lies within its fissures, or canyonlike folds. Three of these fissures are important landmarks. One large fissure runs up the front and along the top of the brain, dividing it into right and left hemispheres. Another major fissure within each hemisphere divides the cerebrum into front and rear halves, and the third fissure runs from front to rear along the side of the brain. On the basis of these landmarks, neurologists have divided each hemisphere into four lobes: frontal, parietal, occipital, and temporal (Figure 3.15).

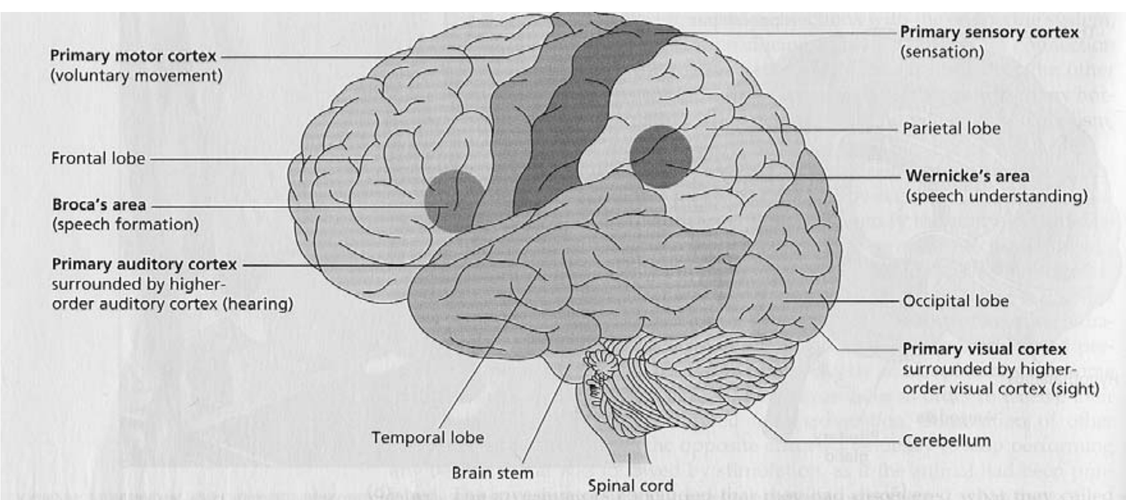

FIGURE 3.15 Division of the brain into frontal, parietal, occipital, and temporal lobes, and localization of sensory and motor functions in the cortex. The remainder is primarily association cortex, consisting of interneurons involved in complex psychological functions, such as perception and reasoning.

Each of the four cerebral lobes is associated with particular sensory and motor functions (also shown in Figure 3.15). Speech and skeletal motor functions are localized in the frontal lobe. The area governing body sensations is located in the parietal lobe immediately behind the central fissure, which separates the frontal and parietal lobes. The brain's visual area is located in the occipital lobe at the back of the brain. Finally, messages from the auditory system are sent to a region in the top of the temporal lobe (Robinson, 1997). The large areas in Figure 3.16 that are not associated with sensory or motor functions (about three-fourths of the cortex) are association cortex involved in mental processes such as thought, memory, and perception.

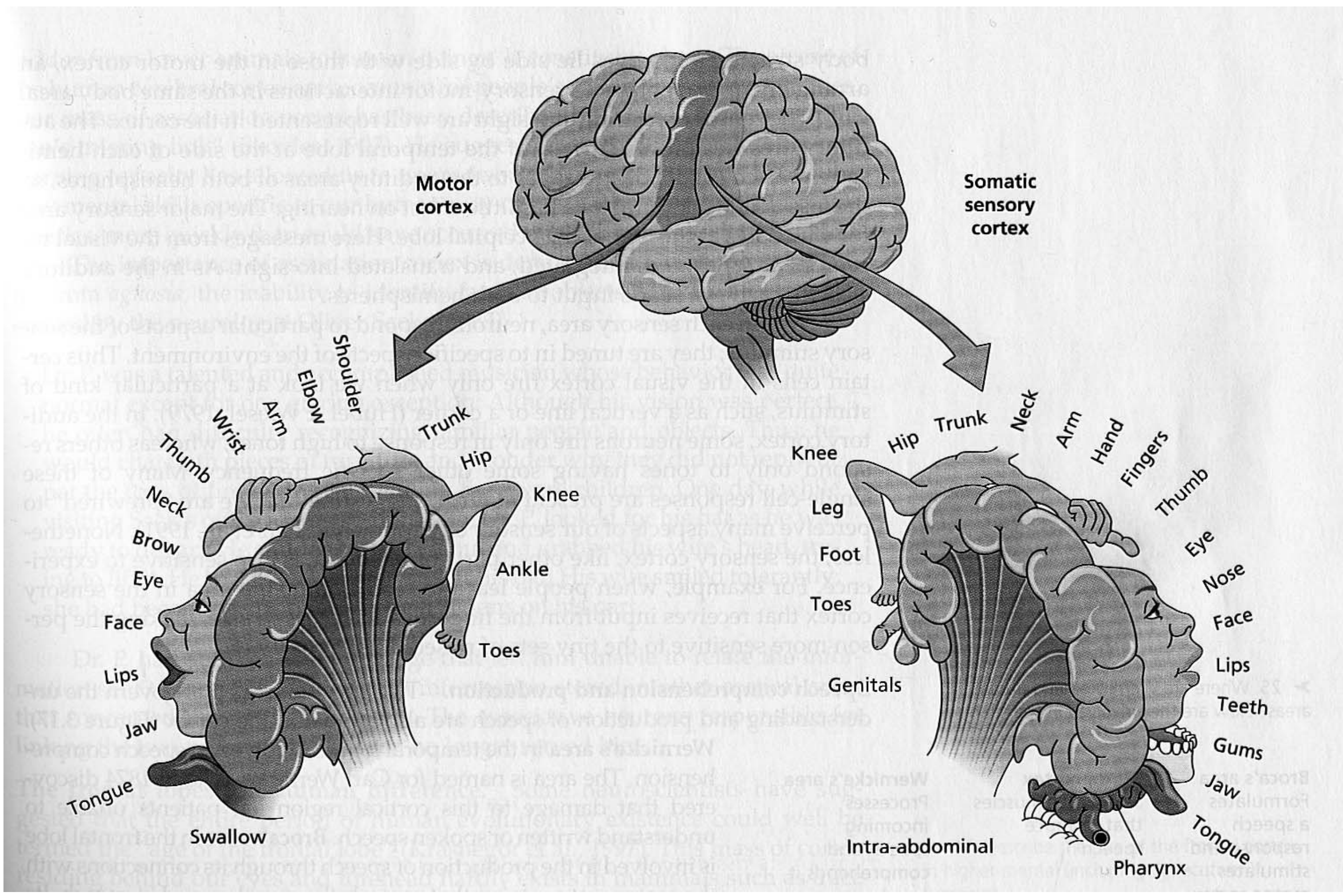

Figure 3.16

Most sensory systems send information to specific regions of the cerebral cortex. Motor systems that control the activity of skeletal muscles are situated in other cortical regions. The basic organization of the cortex's sensory and motor areas is quite similar from rats to humans. Let us explore these regions more closely.

The motor cortex. The motor cortex, which controls the 600 or more muscles involved in voluntary body movements, lies at the rear of the frontal lobe adjacent to the central fissure. Each hemisphere governs movement on the opposite side of the body. Thus severe damage to the right motor cortex would produce paralysis in the left side of the body.

The left side of Figure 3.16 shows the relative organization of function within the motor cortex. As you can see, specific body areas are represented in different parts of the motor cortex, and the amount of cortex devoted to each area depends on the complexity of the movements that are carried out by the body part. Note, for example, that the amount of cortical tissue devoted to your fingers is far greater than that devoted to your torso, even though your torso is much larger. If we electrically stimulate a particular point on the motor cortex, movements occur in the muscles governed by that part of the cortex.

The sensory cortex. Specific areas of the cortex receive input from our sensory receptors. With the exception of taste and smell, at least one specific area in the cortex has been identified for each of the senses.

The somatic sensory cortex receives sensory input that gives rise to our sensations of heat, touch, cold, and our senses of balance and body movement (kinesthesis). It lies in the parietal lobe just behind the motor cortex, separated from it by the large fissure that divides the frontal lobe from the parietal lobe. As in the case of the motor system, each side of the body sends sensory input to the opposite hemisphere. Like the motor area next to it, the somatic sensory area is basically organized in an upside-down fashion, with the feet being represented near the top of the brain. Likewise, the amount of cortex devoted to each body area is directly proportional to that region's sensory sensitivity. The organization of the sensory cortex is shown on the right side of Figure 3.16, as is the proportion of cortex devoted to each body area. As far as your sensory cortex is concerned, you are mainly fingers, lips, and tongue. Notice also that the organization of the sensory cortex is such that the body structures it serves lie side by side with those in the motor cortex, an arrangement that enhances sensory-motor interactions in the same body area.

The senses of hearing and sight are well represented in the cortex. The auditory area lies on the surface of the temporal lobe at the side of each hemisphere. Each ear sends messages to the auditory areas of both hemispheres, so the loss of one temporal lobe has little effect on hearing. The major sensory area for vision lies at the rear of the occipital lobe. Here messages from the visual receptors are analyzed, integrated, and translated into sight. As in the auditory system, each eye sends input to both hemispheres.

Within each sensory area, neurons respond to particular aspects of the sensory stimulus; they are tuned in to specific aspects of the environment. Thus certain cells in the visual cortex fire only when we look at a particular kind of stimulus, such as a vertical line or a comer (Hubel & Wiesel, 1979). In the auditory cortex, some neurons fire only in response to high tones, whereas others respond only to tones having some other specific frequency. Many of these single-cell responses are present at birth, suggesting that we are "prewired" to perceive many aspects of our sensory environment (Shair et al., 1991). Nonetheless, the sensory cortex, like other parts of the brain, is also sensitive to experience. For example, when people learn to read Braille, the area in the sensory cortex that receives input from the fingertips increases in size, making the person more sensitive to the tiny sets of raised dots (Pool, 1994).

Speech comprehension and production. Two specific areas that govern the understanding and production of speech are also located in the cortex (Figure 3.16). Wernicke's area in the temporal lobe is involved in speech comprehension. The area is named for Carl Wernicke, who in 1874 discovered that damage to this cortical region left patients unable to understand written or spoken speech. Broca's area in the frontal lobe is involved in the production of speech through its connections with the motor cortex region that controls the muscles used in speech. Its discoverer, Paul Broca, found that damage to this frontal area left patients with the ability to comprehend speech but not to express themselves in words or sentences. These two speech areas normally work in concert when you are conversing with another person. They allow you to comprehend what the other person is saying and to express your own thoughts (Werker & Tees, 1992). In this example, input is sent from the ears to the auditory cortex and is routed to Wernicke's area for comprehension. When you decide to reply, nerve impulses are sent from Wernicke''s area to Broca's area, and impulses passed on from Broca's area to the motor cortex result in the mouthing of a verbal response. This sequence illustrates a key action principle of brain functioning: even relatively simple acts usually involve the coordinated action of several brain regions. These structures lie in the left hemisphere for most people.

Association cortex. The association cortex is critically involved in the highest level of mental functions, including perception, language, and thought. These areas are sometimes referred to as "silent areas" because electrically stimulating them does not give rise to either sensory experiences or motor responses. This fact has probably helped promote the widely cited myth that most humans use only 10 percent of their brain power. Nothing could be farther from the truth.

Damage to specific parts of the association cortex causes disruption or loss of functions such as speech, understanding, thinking, and problem solving. As we might expect if the association cortex is involved in higher mental processes, the amount of association cortex increases dramatically as we move up the brain ladder from lower animals to human beings. It constitutes about 75 percent of the human cerebral cortex and accounts for people's superior cognitive abilities. Our mass of association cortex has been described by one scientist as "evolution's missing link" (Skoyles, 1997). He suggests that its mental flexibility and learning capacity has allowed us to upgrade our cognitive skills and to acquire new mental skills specific to our human way of life, such as reading and mathematics, more quickly than could have occurred through natural selection alone.

The importance of association cortex is demonstrated in people who suffer from agnosia, the inability to identify familiar objects. One such case is described by the neurologist Oliver Sacks (1985).

> *Dr. P. was a talented and accomplished musician whose behavior was quite normal except for one glaring exception: Although his vision was perfect, he often had difficulty recognizing familiar people and objects. Thus, he would chat with pieces of furniture and wonder why they did not reply, or pat the tops of fire hydrants, thinking they were children. One day, while visiting Sack's office for an examination, Dr. P. looked for his hat as he was ready to depart. He suddenly reached out and grabbed his wife's head, trying to lift it. He*

had mistaken his wife for his hat! His wife smiled tolerantly; she had become accustomed to such actions on his part.

Dr. P. had suffered brain damage that left him unable to relate the information sent to the visual cortex with information stored in other cortical areas that concerned the nature of objects. The associative neurons responsible for linking the two types of information no longer served him.

The frontal lobes: **The human difference.** Some neuroscientists have suggested that the entire period of human evolutionary existence could well be termed the "age of the frontal lobe" (Krasnegor et aL, 1997). This mass of cortex residing behind our eyes and forehead hardly exists in mammals such as mice and rats. The frontal lobes comprise about 3.5 percent of the cerebral cortex in the cat, 7 percent in the dog, and 17 percent in the chimpanzee. In a human, the frontal lobes constitute 29 percent of the cortex. The site of such human qualities as self-awareness, planning, initiative, and responsibility, the frontal lobes are in some respects the most mysterious and least understood part of the brain.

Much of what we know about the frontal lobes comes from detailed studies of patients who have experienced brain damage. Frontal lobe damage results not so much in a loss of intellectual abilities as in an inability to plan and carry out a sequence of actions, even when patients can verbalize what they should do. This can result in an inability to correct actions that are clearly erroneous and self-defeating (Shallice & Burgess, 1991).

The frontal cortex is also involved in emotional experience. In people with normal brains, PET scans show increased activity in the frontal cortex when people are experiencing feelings of happiness, sadness, or disgust (Lane et al, 1997). In contrast, patients with frontal lobe damage often exhibit attitudes of apathy and lack of concern. They literally don't seem to care about anything.

A region of the frontal lobe known as the prefrontal cortex has received increasing attention in recent years. The prefrontal cortex, located just behind the forehead, is the seat of the so-called executive functions. Executive functions, mental abilities involving goal setting, judgment, strategic planning, and impulse control, allow people to direct their behavior in an adaptive fashion. Deficits in executive functions seem to underlie a number of problem behaviors. People with prefrontal cortex disorders seem oblivious to the future consequences of their actions and seem to be governed only by immediate consequences (Bechara et al, 1994). As you may have guessed by now, Phineas Gage, the railroad foreman described elsewhere, suffered massive frontal lobe damage when the spike tore through his brain. Thereafter he exhibited classic symptoms of disturbed executive functions, becoming behaviorally impulsive and losing his capacity for future planning.

A more ominous manifestation of prefrontal dysfunction was discovered by Adrian Raine and his coworkers (1997). Using brain-imaging techniques, the researchers studied 41 violent murderers who had pleaded not guilty by reason of insanity. The murderers' PET scans showed clear evidence of reduced activity in the prefrontal cortex. Their murderous acts, which were often random and impulsive in nature, showed parallel evidence of failure in executive functions such as judgment, foresight, and impulse control. Raine suggested that people with similar prefrontal dysfunction may have a neural predisposition to impulsive violence.

During the 1940s and 1950s many thousands of psychiatric patients who suffered from disturbed and violently emotional behavior were subjected to operations called prefrontal lobotomies (Shorter, 1998). The operation was performed by inserting an instrument with sharp edges into the brain, then wiggling it back and forth to sever the nerve tracts that connected the frontal lobes with the subcortical regions connected with emotion. The calming effect was so dramatic that Egas Moniz, the developer of the technique, was awarded a Nobel Prize. However, the devastating side effects on mental functions that occurred as the executive functions were destroyed were equally dramatic, and the development of antipsychotic drugs resulted in an abandonment of this form of "treatment."

Hemispheric Lateralization: The Left and Right Brains

The left and right cerebral hemispheres are connected by a broad white band of myelinated nerve fibers. The corpus callosum is a neural bridge that acts as a major communication link between the two hemispheres and allows them to function as a single unit. Despite the fact that they normally act in concert, however, there are important differences between the psychological functions that are represented in the two cerebral hemispheres. Lateralization refers to the relatively greater localization of a function in one hemisphere or the other.

Medical studies of patients who suffered various types of brain damage provided the first clues that certain complex psychological functions were lateralized on one side of the brain or the other. The deficits observed in people with damage to either the left or right hemisphere suggested that for most people, verbal abilities and speech are localized in the left hemisphere, as are mathematical and logical abilities (Springer, 1997).

When Broca's or Wernicke's speech areas are damaged, the result is aphasia, the partial or total loss of the ability to communicate. Depending on the location of the damage, the problem may lie in recognizing the meaning of words, in communicating verbally with others, or in both functions. C. Scott Moss, a clinical psychologist who became aphasic in both ways for a time as a result of a left hemisphere stroke, described what it was like for him.

> *I recollect trying to read the headlines of the Chicago Tribune but they didn't make any sense to me at all. I didn't have any difficulty focusing; it was simply that the words, individually or in combination, didn't have meaning, and even more amazing, I was only a trifle bothered by that fact. . . . I think part of the explanation was that I had [also] lost the ability to engage in self-talk. In other words, I didn't have the ability to think about the future-to worry, or anticipate or perceive it-at least not with words. (Moss, 1972, pp. 4-5)*

When the right hemisphere is damaged, the clinical picture is quite different. Language functions are not ordinarily affected, but the person has great difficulty in performing tasks that demand the ability to perceive spatial relations. A patient may have a hard time recognizing faces and may even forget a well traveled route or, as in the case of Dr. P., mistake his wife for a hat (Sacks, 1985). It appears that mental imagery, musical and artistic abilities, and the ability to perceive and understand spatial relationships are primarily right-hemisphere functions (Ornstein, 1997).

The two hemispheres differ not only in the cognitive functions that reside there, but also in their links with particular types of emotions. EEG studies have shown that the right hemisphere is relatively more active when negative emotions such as sadness and anger are being experienced. Positive emotions such as joy and happiness are accompanied by relatively greater left-hemisphere activation (Fox & Davidson, 1991; Tomarken et al., 1992).

The split brain: two minds in one body? Despite the lateralization of specific functions in the two cerebral hemispheres, the brain normally functions as a unified whole because the two hemispheres communicate with one another through the corpus callosum. But what would happen if this communication link between the two hemispheres were cut? Would we, in effect, produce two different and largely independent minds in the same person? A series of Nobel Prize-winning studies by Roger Sperry (1970) and his associates addressed this question.

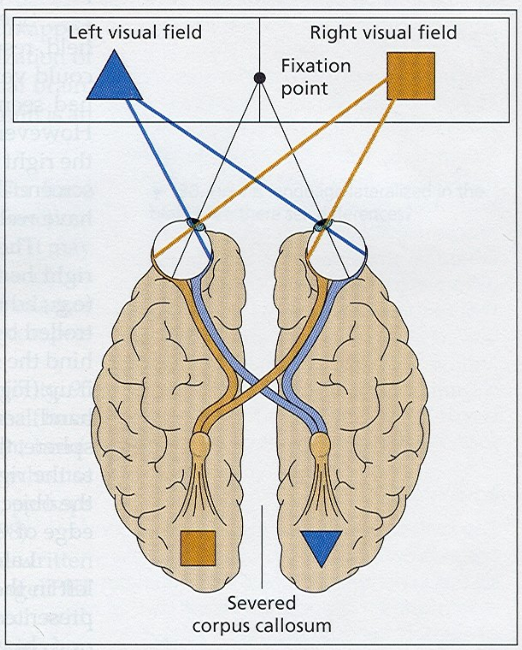

FIGURE 3.18 The visual system's anatomy made studies of split-brain subjects possible. Images entering the eye are reversed by the lens. Optic nerve fibers from the inner portion of the retina (toward the nose) cross over at the optic chiasma, whereas the fibers from the outer portion of the retina do not. As a result, the right side of each eye's visual field projects to the visual cortex of the left hemisphere, whereas the left visual field projects to the right hemisphere. When the corpus callosum is cut, the two hemispheres no longer communicate with each other. By presenting stimuli to either side of the visual fixation point, researchers can control which hemisphere receives the information.

Like many scientific advances, this discovery resulted from natural human misfortune. Some patients suffer from a form of epilepsy in which a seizure that begins as an uncontrolled electrical discharge of neurons on one side of the brain spreads to the other hemisphere. Years ago, neurosurgeons found that by cutting the nerve fibers of the corpus callosum, they could prevent the seizure from spreading to the other hemisphere. Moreover, the operation did not seem to disrupt other major psychological functions. Sperry's studies of patients who had had such operations involved some ingenious ways to test the functions of the two hemispheres after the corpus callosum was cut.

Split-brain research was made possible by the way in which our visual input to the brain is "wired." To illustrate, extend your two hands straight out in front of you, separated by about one foot. Now focus on the point between them. You'll find that you can still see both hands in your peripheral division, and that you have a unified view of the scene. It therefore might surprise you to know that your left hand is being "seen" only by your right hemisphere and your right hand only by your left hemisphere. To see how this occurs, examine Figure 3.18, which shows that some of the fibers of the optic nerve from each eye cross over at the optic chiasma and travel to the opposite brain hemisphere. Fibers that transmit messages from the right side of the visual field project to the left hemisphere; fibers from the visual field's left half project to the right hemisphere. Despite this arrangement, we experience a unified visual world (as you did when you looked at your hands) rather than two half-worlds because the hemispheres' visual areas are normally connected by the corpus callosum. When the corpus callosum is cut, however, visual input to one hemisphere can be restricted by projecting the stimulus to either the right side of the visual field (in which case the image goes only to the left hemisphere) or to the left side of the visual field, which sends it to the right hemisphere.

In Sperry's experiments, split-brain patients basically did what you did with your hands: They focused on a fixation point, a dot on the center of a screen, while slides containing visual stimuli (words, pictures, and so on) were flashed to the right or left side of the fixation point (Figure 3.19).

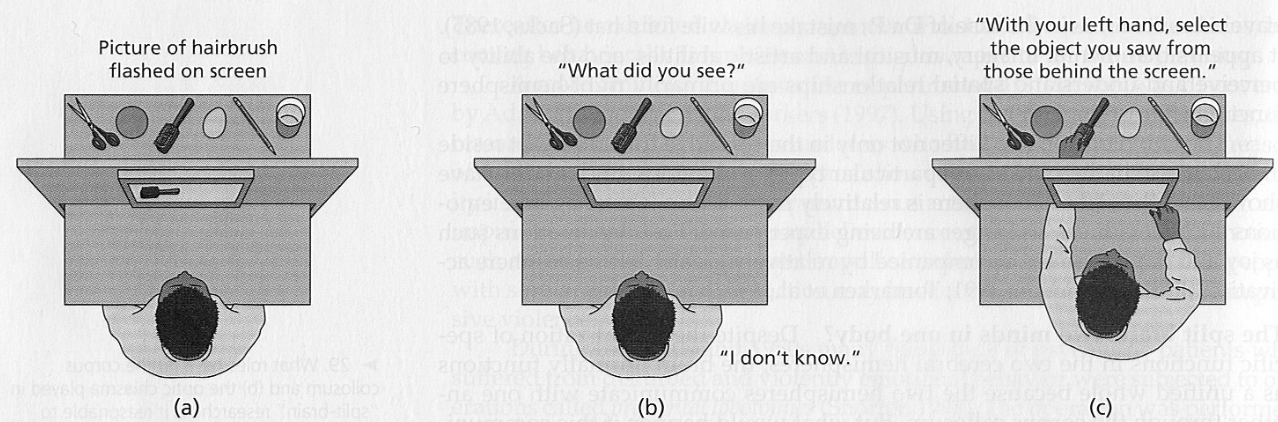

FIGURE 3.19 A split-brain patient focuses on the fixation point in the center of the screen. In (a), a picture of a hairbrush is briefly projected to the left side of the visual field, thus sending the information to the right hemisphere. In (b), the patient is asked to state verbally what she saw. She cannot name the object. In (c), she is asked to select the object she saw, and is able to find it with her left hand. If the object were transferred to her right hand or if the word were flashed to the right side of the visual field, the information would be sent to the language-rich left hemisphere, and she would be able to name the object.

Sperry found that when words were flashed to the right side of the visual field, resulting in their being sent to the language-rich left hemisphere, subjects could verbally describe what they had seen. They could also write what they had seen with their right hand (which is controlled by the left hemisphere). However, if words were flashed to the left side of the visual field and sent on to the right hemisphere, the subjects could not describe what they had read on the screen. This pattern of findings indicated that the right hemisphere does not have well-developed language abilities.

The inability to describe stimuli verbally did not mean, however, that the right hemisphere was incapable of recognizing them. If a picture of an object (e.g., a hairbrush) was flashed to the right hemisphere and the left hand (controlled by the right hemisphere) was allowed to feel many different objects behind the screen, the person's hand would immediately select the brush and hold it up (Figure 3.19c). As long as the person continued to hold the brush in the left hand, sending sensory input about the object to the "nonverbal" right hemisphere, the person was unable to name it. However, if the brush was transferred to the right hand, the person could immediately name it. In other words, until the object was transferred to the right hand, the left hemisphere had no knowledge of what the right hemisphere was experiencing.

Later research showed the right hemisphere's definite superiority over the left in the recognition of patterns. In one study, three split-brain patients were presented with photographs of similar-looking faces projected in either the left or right visual fields. On each trial, they were asked to select the photo they had just seen from a set of 10 cards. On this task, the spatially oriented right hemisphere was far more accurate than the linguistic left hemisphere in correctly identifying the photos . Apparently, the faces were too similar to one another to be differentiated very easily by left-hemisphere verbal descriptions, but the spatial abilities of the right hemisphere could differentiate among them (Gazzaniga & Smylie, 1983).

Some psychologists have suggested that what we call the conscious self resides in the left hemisphere, because consciousness is based on our ability to verbalize about the past and present. Is the right hemisphere, then, an unconscious (nonverbal) mind? Yes, these psychologists answer, except when it communicates with the left hemisphere across the corpus callosum (Ornstein, 1997). But when the connections between the two hemispheres are cut, each hemisphere, in a sense, can have a "mind of its own," as this example shows.

> *One split-brain patient learned to use Scrabble letters to communicate from his right hemisphere using his left hand. To test the dual-mind hypothesis, researchers asked the two hemispheres the same questions-and found that the answers often disagreed. For example, when asked what occupation he would prefer, the left hemisphere responded verbally, "a draftsman." But the right hemisphere used the Scrabble pieces to spell out, "race car driver." (LeDoux and others, 1977)*

Keep in mind that in daily life, the split-brain patients could function adequately because they had learned to compensate for their disconnected hemispheres. For example, they could scan the visual environment so that visual input from both the left and right visual fields got into both hemispheres. The "split-mind" phenomena shown in the laboratory appeared because the patients were tested under experimental conditions that were specifically designed to isolate the functions of the two hemispheres. Nonetheless, the results of split-brain research were so dramatic that they led some people (and even some scientists) to promote a conception of brain functions as being highly localized and restricted to one hemisphere or the other. Even today, we hear about "right brain" education programs and the untapped potentials that they can release. Certainly, there is some degree of localization of brain functions, but a far more important principle is that in the normal brain, most functions involve many areas of the brain working together. The brain is an exquisitely integrated system, not a collection of localized functions.

Hemispheric lateralization of language. For many years, scientists have known that for most people language is primarily a left-hemisphere function. Why language tends to be localized in the left hemisphere is not clear, but it may have some undiscovered evolutionary significance. The brain of the chimpanzee, our genetically closest relative in the animal kingdom, also has a larger left hemisphere in the region that corresponds with Wernicke's speech comprehension area in the human brain (Gannon et al., 1998).

About 90 percent of people are right-handed, and among this majority, 95 percent have left hemisphere language dominance. Among left-handers, half have language in the left hemisphere, 25 percent have it localized in the right hemi- sphere, and the rest have language functions in both hemispheres. Those who use both hemispheres for language functions have a larger corpus callosum, perhaps because more interhemispheric communication is required (Springer, 1998).

Left-hemisphere laterialization is the case not only for spoken and written language, but also for nonverbal kinds of language, such as sign language. PET scans of neural activity show that just as hearing people process speech with their left hemisphere, deaf people use the left hemisphere to decipher sign language. Likewise, a left-hemisphere stroke affects their ability to understand or produce sign language (Corina et al., 1992).

Realize, however, that even if your left hemisphere is dominant for language, this does not mean that your right hemisphere lacks language ability. PET scan studies measuring cerebral blood flow in the brains of normal people indicate that both hemispheres are involved in speaking, reading, and listening (Leondes, 1997; Raichle, 1994). One notable finding, however, is that males and females may differ in the extent to which certain language functions are lateralized, or located, on one side of the brain.

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