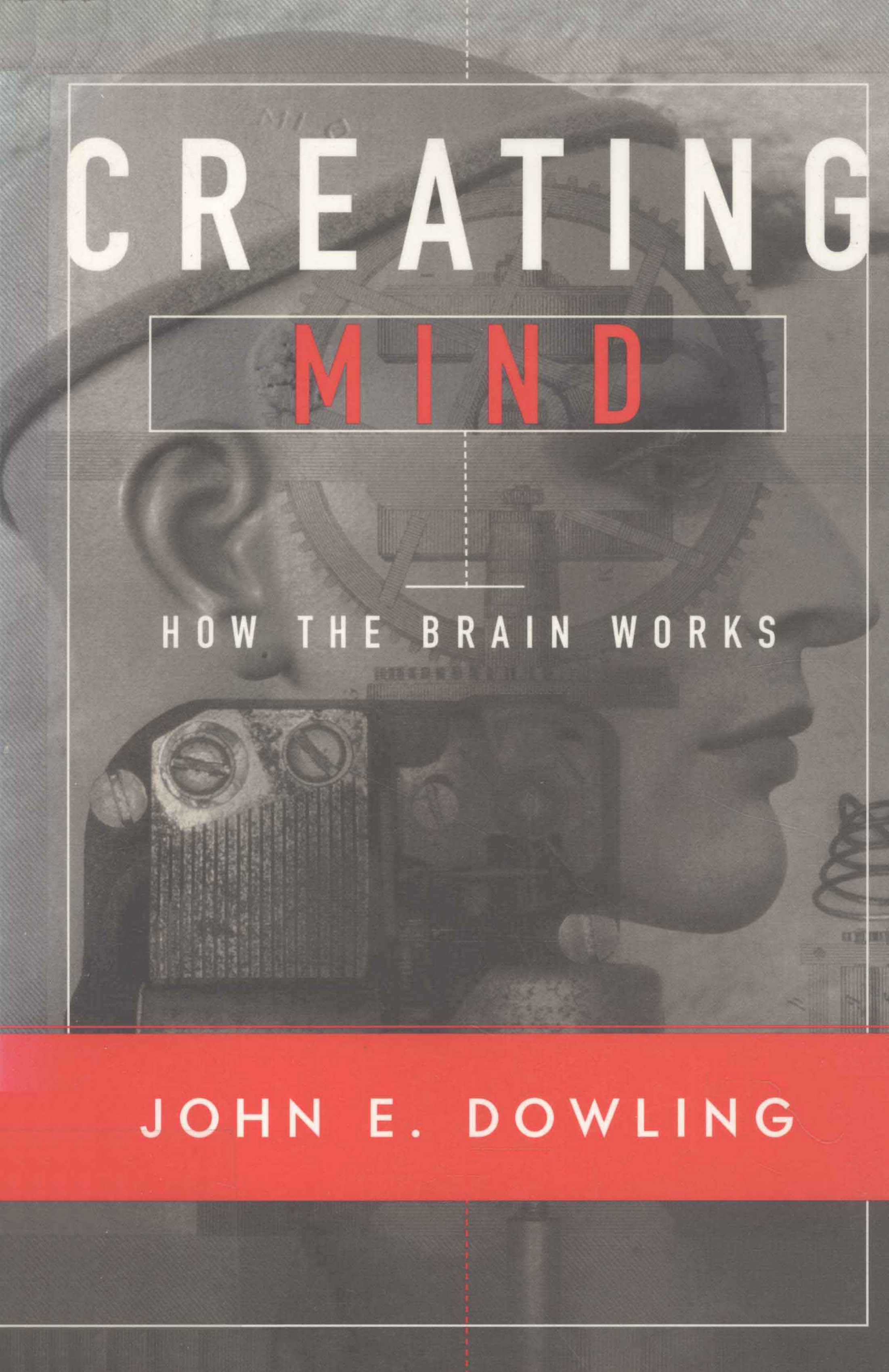

CREATING MIND

HOW THE BRAIN WORKS

JOHN E. DOWLING

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Figure 43: Block, J. R., and Yuker, H. E. *Can You Believe Your Eyes?: over 250 illusions and other visual oddities*. New York: Gardner Press, Inc., 1989. Copyright 1989 by Gardner Press, Inc. Courtesy of T. E. Parks and Peter Thompson, University of York, England.

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Preface

What makes us human and unique among all creatures is our brain. Perception, consciousness, memory, learning, language, and intelligence all originate in and depend on the brain. The brain provides us with wondrous things, from mathematical theories to symphonies, from automobiles and airplanes to trips to the moon. But when it goes awry, we are undone.

Over the past century, our understanding of the brain has raced forward, yet those who study the brain are still scratching the surface, so to speak. What is the mind, after all, and how does it relate to brain function? Most neuroscientists believe the mind originates in brain function, but at the moment no one can define adequately what we mean by mind. Even "consciousness" is an elusive subject, though philosophers and others endlessly talk about what it means.

As a neuroscientist, I am forever peppered with questions about the brain and brain function. This is especially true for friends who know about the exciting discoveries in the brain sciences, yet witness the consequences of mental illness, aging, or brain injury and want to know more about new drug therapies for treating these problems. No field of medicine is untouched by the advances in the brain sciences, especially as we have come to realize how much the course of a disease and even its outcome, perhaps, can be affected by brain function and mental state. Sound body / sound mind is a two-way street; each is profoundly affected by the other.

This book is intended to answer many of the questions about neuroscience I am often asked. At the same time, I hope to convey to the general reader the essence and vitality of the field—the progress we are making in understanding how brains work—and to describe some of our strategies for studying brain function. Whenever possible, I try to relate topics to something relevant such as a disease or a consequence of brain function. Much wonderful work in the field is ignored—to keep the book manageable and, I hope, an interesting read.

The first five chapters provide the nuts and bolts necessary for an up-to-date understanding of the brain. The remainder of the book dips into aspects of brain function—vision, perception, language, memory, emotion, and consciousness—seemingly more relevant to how the brain creates mind. But if an in-depth understanding of these topics is to be gained, the nuts and bolts of brain function must be sorted out. Some readers may wish to start with Chapter 6 or another chapter of particular interest and return to the earlier chapters later for more details of how the brain works. A glossary is provided to help along the way with unfamiliar terms or concepts, but in almost every case further explanation is provided elsewhere in the book.

Chapter 1 describes the general organization of the brain. What are the cells like that are found in the brain? How do they differ from cells elsewhere in the body? Chapter 2 discusses how brain cells receive, process, and transmit information. Neural signals travel along cells electrically but between cells chemically. How do cells accomplish this? How do brain cells generate electrical signals, and how do chemical substances pass information to adjacent cells? Chapter 3 discusses in more detail how brain cells talk to one another and the changes that occur in brain cells when they are contacted by other cells. The chemical substances used to communicate signals in the brain are described and drugs that alter chemical transmission and cause profound alterations in brain function discussed.

Chapter 4 describes how invertebrates—animals without backbones—have been invaluable for elucidating neural mechanisms. Animals from the sea, such as squids, horseshoe crabs, and sea slugs, have been particularly useful, and examples of important findings from these animals are presented. Chapter 5 describes the architecture of the human brain—the various parts of the brain and what roles they play. How do the brains of frogs and fishes differ from our brains? The dominant role of the cerebral cortex in mammals and, especially, man is emphasized.

In Chapter 6, I explore the visual system in depth, from the light-sensitive molecules found in the photoreceptor cells to current ideas about visual perception. We know more about the visual system than about any other brain system; it provides a wealth of clues about brain function. Chapter 7 deals with the development of the brain. How do embryonic brain cells find their way to their targets? How does environment affect the developing brain? The fascinating topics of language, memory, and learning are dealt with in Chapter 8, along with the question of how we discover new things about the human brain. The neurology clinic has long provided instructive examples of patients with specific brain lesions. Today, brain imaging techniques promise a wealth of new information about the human brain.

Chapter 9 turns to matters we associate more with mind—emotions, personality, and rationality. What regions of the brain are involved in emotional behaviors, and what happens when these areas are disrupted? Finally, Chapter 10 discusses consciousness. What do we mean by the word, and what can we say about consciousness from a neurobiological perspective? Throughout the book, I use as examples instances where brain function is compromised by injury or disease. Such examples are not presented simply as curiosities. Rather, these alterations in brain function cast light on normalcy.

Howard Boyer guided the early stages of the book, providing superb suggestions and masterful editing of the first drafts. Laura Simonds Southworth executed the illustrations expertly and beautifully. Richard Mixter enthusiastically saw the book through to publication. Barbara Whitesides made many perceptive suggestions, and last, but certainly not least, Stephanie Levinson provided all the administrative help that a project like this entails.

Contents

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How the Brain Works

CHAPTER 1

The Uniqueness of the Brain

Bob Jones was sixty-two years old when he retired as chief executive officer of a small company. He had always been an effective administrator and was dedicated to his wife and family. Two years earlier, he had become uncharacteristically short-tempered, but this change was attributed by everyone to stress. He also failed on occasion to run promised errands, but his wife assumed he simply did not want to do them. Although retired as CEO, he continued to work for the company.

Over the next few months, Mr. Jones became increasingly forgetful, and finally he went to see his physician, who reassured him that he was just getting a little older. His irritability also increased, eventually to the point that nothing seemed right, and his wife took him back to the physician. No evidence of brain disease was evident, and the physician thought Mr. Jones was experiencing depression. An antidepressant drug was prescribed, along with psychotherapy, and both appeared to help. Mr. Jones seemed better for about a year.

Over the second year, however, Mr. Jones's memory deteriorated significantly, and he began experiencing attention loss and an inability to learn new things. He no longer could work, and a brain scan at this point indicated a significant shrinkage of his brain. A diagnosis of Alzheimer's disease was made.

Mr. Jones's mental abilities now began to deteriorate dramatically. On several occasions, he made a cup of coffee when his wife was out and forgot to turn the stove off. If he left the house, he promptly became lost, and eventually he became lost in his own home. He became so confused about right and left that he could not put on his clothes without help. Difficulty in orienting his arms and head in space eventually made it impossible for him to eat without assistance. His wife cared for him over this time but felt increasingly that it was not her husband she was caring for but a stranger. He had lost virtually all the traits that had made him a unique individual.

—Adapted from David L. Rosenham and Martin E. P. Seligman, *Abnormal Psychology: Casebook and Study Guide* (New York: Norton, 1995)

The human brain weighs no more than 3½ pounds, only about 2–3 percent of our total body weight, but its importance cannot be overstated. It oversees virtually everything we do and makes us what we are. When the brain deteriorates, as happened to Mr. Jones, not only are individuals unable to carry out even simple tasks such as eating, they also lose their uniqueness and individuality.

We are aware of many activities the brain controls; walking, talking, laughing, and thinking are just a few of them. The brain initiates these activities and also controls and regulates them. But, as we go about our daily lives, we are unaware of many other aspects of brain function: the regulation of internal organs, including the heart and vascular system, lungs and respiratory system, and gut and digestive system. The brain also coordinates and integrates movements employing mechanisms that we don't notice, such as the use of abundant sensory information from muscles, tendons, and joints. The extent of muscle contraction is signaled to the brain, yet we are quite unaware ordinarily of the state of our individual muscles.

Of most interest, and most mysterious, are mental functions referred to as "mind." Feelings, emotions, awareness, understanding, and creativity are well-known aspects of mind. Are they created in and by the brain? The consensus today among neuroscientists and philosophers is that mind is an emergent property of brain function. That is, what we refer to as mind is a natural consequence of complex and higher neural processing. Clearly brain injury or disease can severely compromise the mind, as happened to Mr. Jones. At the very least, then, mind depends on intact and healthy brain function.

Do animals have minds? The answer to this question depends mainly on one's definition of mind. Certainly cats, dogs, and monkeys can express emotion, show some understanding, and even apply creative approaches to simple problems, but no animal approaches humans in richness of mind. Is there something unique about human brains relative to those of other organisms? Not that we know. So how do we explain our extraordinary mental abilities?

Is it that human brains represent a higher evolutionary level than the brains of other animals? This is likely so, in part because the cellular mechanisms underlying human brain function appear identical to those operating in other animals, even those that have very elementary nervous systems and exhibit virtually no aspects of mind.

The simple view I espouse is that the human brain is qualitatively similar to the brains of other animals, but quantitatively different. That is, the human brain has more nerve cells than do the brains of other primates, our closest relatives, but also, what is probably more important, the cerebral cortex of the human brain, the seat of higher neural function—perception, memory, language, and intelligence—is far more developed than is the cerebral cortex of any other vertebrate (see Figure 1). *And because of the added neural cells and cortical development in the human brain, new facets of mind emerge.*

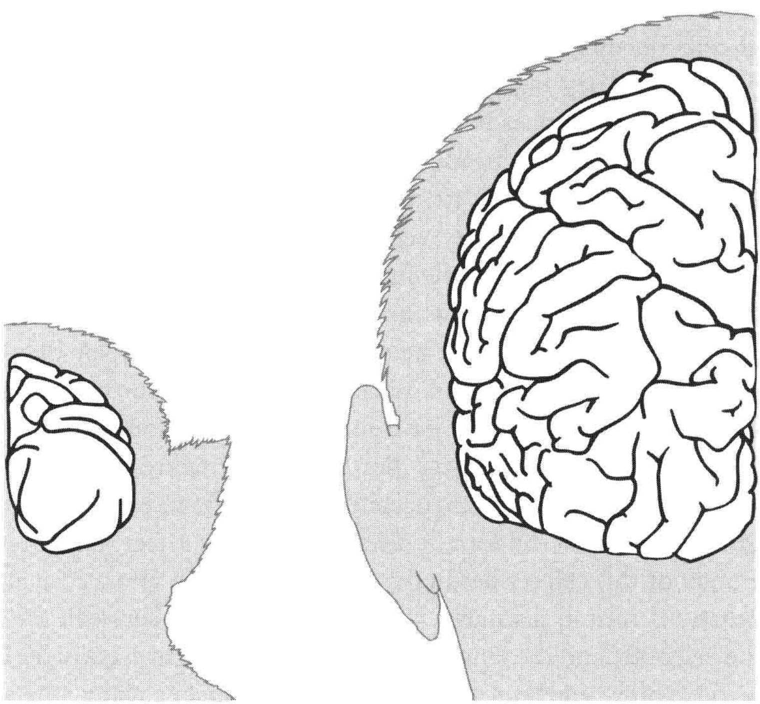

Figure 1 The brain of an adult rhesus monkey compared to that of a human. Not only is the human brain very much larger, its surface is thrown into many more folds, thus increasing the surface (cortical) area of the brain substantially.

An understanding of the brain requires knowing its structure, function, and chemistry. Once we do so, can we truly understand the mind? Can the brain understand itself? No one knows; there is much to learn.

To lay the groundwork for this quest, I'll describe the brain's elements and their structure, how the elements communicate with one another, their special features, and the consequences of these features. This will bring us to a general notion of how the brain is organized.

Cells of the Brain: Neurons

The brain, like other organs, is made up of discrete units or cells. Two classes of cell make up the brain: *neurons*, or nerve cells, whose business is to receive, integrate, and transmit information; and *glia* (derived from the Greek word for glue), which are supporting cells. Glial cells do things like help maintain the neurons and the brain's environment. They regulate the levels of substances needed or used by neurons in the spaces between the cells. They also provide a structural framework for neurons (especially during development), and they insulate the neurons to make them conduct electrical signals more effectively. But the key cells for understanding how the brain works are the neurons, and the brain contains billions of them.

We don't know exactly how many neurons are in the human brain, but the best estimates suggest between 100 billion and 1,000 billion—more cells than there are stars in the Milky Way. Neurons, like glial cells, are also elaborate and have numerous extensions or branches that may extend long distances. For example, a neuron that controls muscles in the foot has a branch, called an *axon*, that extends down the length of the leg to the foot, a distance of about 3 feet (or a meter). The body of this cell resides in the lower part of the spinal cord and is less than 0.1 mm in diameter. To put the difference between the size of the cell body and the length of its axon in perspective, consider how long the axon would be if the cell body were 6 inches wide—the axon would extend almost a mile!

The branches of neurons allow them to contact one another in the brain in complex and intricate ways. Typically, neurons make one hundred to ten thousand connections with other neurons, and one type of neuron (the cerebellar Purkinje cell) makes as many as 100,000 connections.

Neurons have many branches, and so most of the brain consists of neuronal branches. Two kinds of neuronal branches are distinguished anatomically—*dendrites* and *axons* (*see Figure 2*). Dendrites are like the branches of a tree, relatively thick as they emerge from the cell but dividing often and becoming thinner at each branch point. Many dendrites usually extend from each neuron. Axons, in contrast, are thinner at their point of origin on a neuron and remain constant in diameter along most of their length. Neurons usually have just one axon that

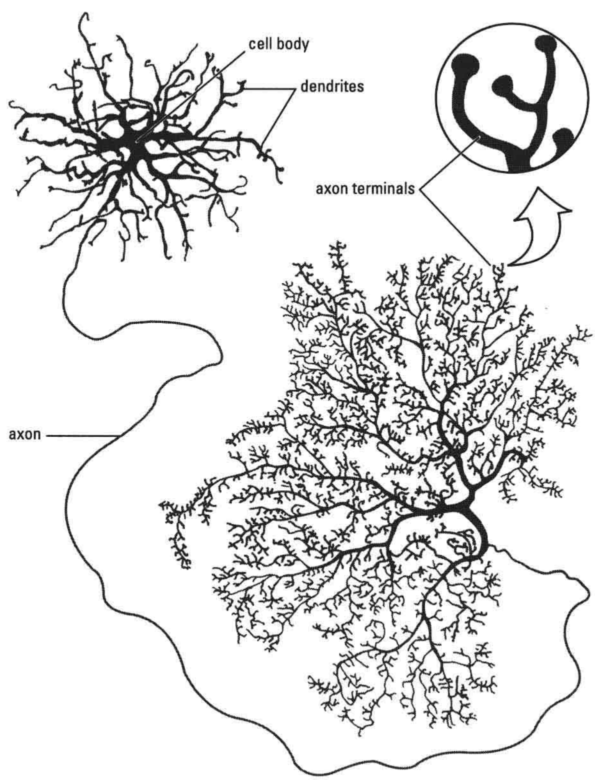

Figure 2 A neuron with a relatively short axon. Input to a neuron is usually onto the dendrites or cell body, whereas the cell's output occurs via the axon terminals. Each tiny branch in both the dendritic and axonal terminal arbors is likely to be a site of synaptic contact.

branches profusely as it terminates. Input to nerve cells is usually via the dendrites; the axon carries the cell's output.

Figure 2 depicts a neuron with a short axon found in the retina of the eye. Each tiny branch in both the dendritic tree and axon terminal complex probably represents a point of functional contact with another cell. And it is likely that a number of contact points were missed by the scientist who drew the cell. The functional contacts between neurons, called *synapses*, operate mainly chemically. That is, at synapses neurons release specific chemical substances that diffuse to an adjacent neuron

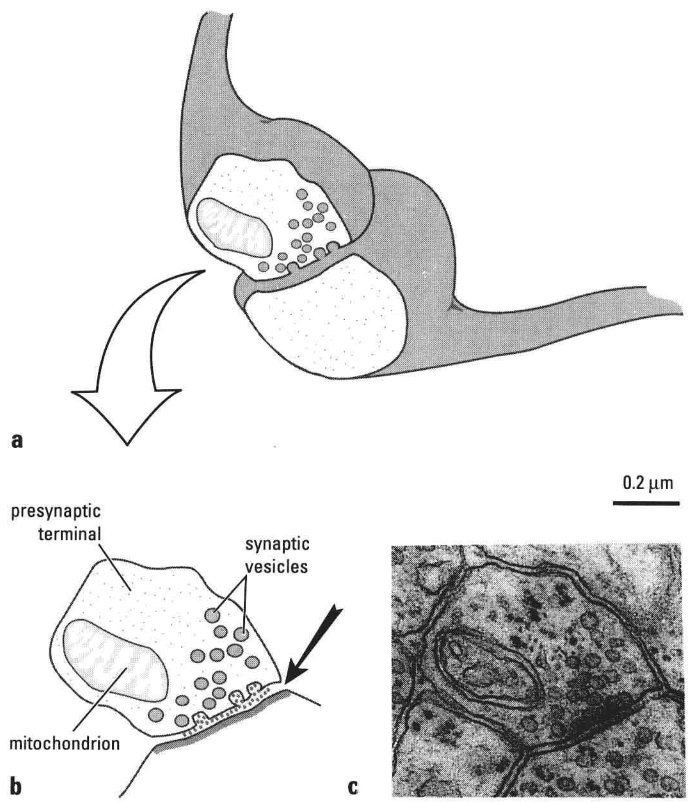

Figure 3 Drawings of a synaptic contact between two neuronal branches (above and below to the left) and an electron micrograph of a synapse (below right). The synaptic vesicles contain substances that are released when the synapse is active. The vesicles attach to the membrane and release their contents into the small space between the two branches (arrow). The substances released can excite, inhibit, or modulate activity in the contacted branch.

contacted by that synapse. This chemical may excite, inhibit, or modulate the contacted neuron.

Synapses have a characteristic structure that can be readily visualized with the high resolving power of an electron microscope. *Figure 3a* is a drawing of a synapse (essentially one of the terminal branches in *Figure 2*). Below to the right is an electron micrograph of a synapse and drawing of it on the left. What you are viewing in the electron micrograph is a slice through the middle of the axon terminal that is shown in the drawing above. A prominent feature of axon terminals is the presence of *synaptic vesicles* within the terminal: tiny vesicles that store the chemicals released at the synapse. The vesicles cluster at the synapse, fuse to the membrane when synapses are active, and release their contents into the small space between the two cells (*arrow in Figure 3*). The chemicals spread across the space and interact with specific molecules (proteins) present within the membrane of the contacted cell. The molecules, when activated by the synaptic chemical, initiate mechanisms that alter the cells.

Neuroscientists focus much attention on synapses because of the general agreement that synaptic interactions between neurons explain much of what the brain does. For example, most drugs that affect states of behavior, such as cocaine, LSD, Prozac, and even Valium, do so by modifying synaptic activity (see Chapter 3, Drugs and the Brain). Furthermore, affective mental disorders, such as schizophrenia, depression, and anxiety, appear to result from impaired synaptic mechanisms in the brain.

How Special Are Neurons?

Neurons employ the same cellular mechanisms as do other cells in the body. Each neuron has a nucleus containing *nucleic acid* (DNA) that specifies the proteins made by the cell. Neurons possess *ribosomes*, structures responsible for assembling proteins, and *mitochondria*, which supply energy-rich molecules that power the cells. Neurons also contain tubules and filaments found in virtually all cells; these are involved in the movement of substances throughout the cell, and they help maintain the complex structure of a neuron.

It is clear from this that the neurons' biochemical mechanisms are similar to those used by all cells. Yet neurons differ from other cells in the body in two significant ways which have important medical consequences: First, brain cells are not replaced or replenished and second, brain cells constantly require oxygen. Once neurons have matured during embryonic development, they can never divide again. This is quite different from most cells in the body that divide and produce new cells in response to injury or disease. A cut on the finger soon heals as cells divide and fill in the injury. The same is true for cells in most organs of the body.

When brain cells are lost because of injury or disease, they are not replaced. The brain of a one-year-old human contains as many cells as it will ever have, and throughout life neurons are lost via normal aging processes. In other organs, dead cells are quickly replaced, but in the brain they are not. And the number of brain cells lost is surprisingly high—maybe as many as 200,000 per day. This estimate comes from the finding that, with age, at least 5–10 percent of brain tissue is lost. If you assume a loss of 7 percent of the brain cells in eighty to one hundred years, with, say, 100 billion cells at the outset, about 200,000 cells are lost per day. With age, the brain also loses neuronal branches and the neurons shrink in size.

If neurons cannot divide once they have matured, how can a brain tumor grow? In adults, most if not all brain tumors are glial cell tumors. Glial cells, unlike neurons, can divide in the adult brain, and when glial cell division becomes uncontrolled, a tumor or cancer can result. Only in children do brain tumors arise from neurons, and, fortunately, these are quite rare.

Because the brain contains so many neurons, most of us can get through life without losing so many cells that we become mentally debilitated. Eventually, though, brain cell loss with age does catch up with us, and eventually mental deterioration takes place in virtually everyone. It's a mystery why some individuals maintain keen mental abilities much longer than do others; indeed, it may be brain cell loss that determines human life span. If we could eliminate heart attacks, cancer, and other fatal diseases, we still might not extend the life span of humans, because brain cells cannot divide and replace themselves.

Although the average life expectancy for humans has increased by