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Consider This …

A 44-year-old man entered a neurology clinic in France complaining of mild leg weakness. His doctors were shocked when they examined images of his brain. Where they had expected to see brain tissue, they found mostly fluid and only a thin strip of brain surrounding the inside of his skull (Feuillet, Dufour, & Pelletier, 2007). The parts of the brain normally necessary for thought, speech, and memory were largely absent and replaced by a massive cavern in his head (Figure 1.1). Although his IQ of 75 was far below average, his social functioning was relatively normal. He was married with two children and had a job as a civil servant. How is it possible that he could speak, remember, carry out everyday tasks, and hold a job, with so much of his brain missing?

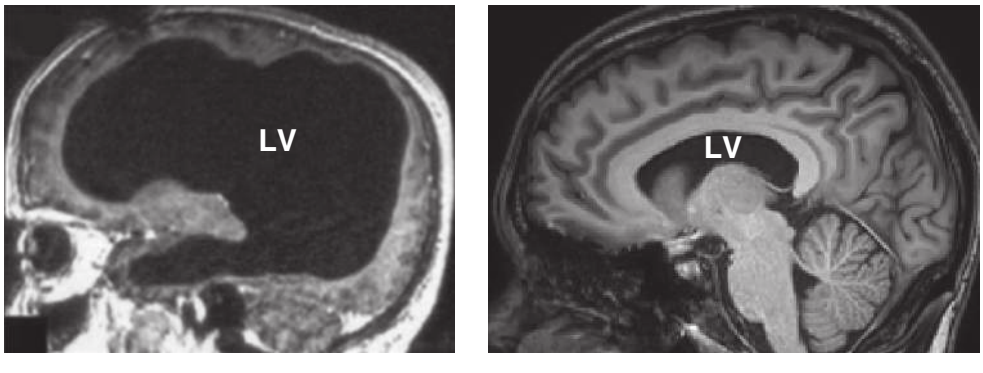

Figure 1.1 The man with a thin strip of brain. The image on the left reveals that areas in the center of the man's brain that would normally be filled with brain tissue were instead filled only with fluid. The image to the right shows a normal brain. LV = lateral ventricle, a fluid-filled compartment. (Left, from Feuillet, Dufour, & Pelletier, 2007, © 2007 Elsevier Ltd. All rights reserved; right, © Sherbrooke Connectivity Imaging Lab (SCIL)/Getty Images.)

The French philosopher René Descartes advocated for **dualism** during the early 1600s. The immaterial (non-physical) mind (Descartes referred to it as the soul) exists separately from the physical brain and body. But how do the two realms interact? Descartes believed that when you decide to lift your right arm, the *immaterial* decision in your mind sets your nerves and muscles in motion. When you listen to music, the *physical* sense organs in the ear cause melodies to arise in your (*immaterial*) mind. But *where* do the mind and the physical brain interact, asked Descartes? He believed the interaction occurred in the pineal gland, a small pine-cone-shaped structure near the center of the brain (Figure 1.2).

> [The] mechanism of our body is so constructed that simply by this [pineal] gland's being moved in any way by the soul … it drives the surrounding spirits towards the pores of the brain, which direct them through the nerves to the muscles; and in this way the gland makes the spirits move the limbs. (Descartes, 1984)

From this point of view, the man in our opening anecdote lacking so much brain tissue might have required no brain at all to generate decisions! So long as the immaterial wishes of his soul could move the pineal gland, the rest of the brain would only need to set in motion physical processes to carry out his actions.

Even if one believed that Descartes had localized the site of mind–body interaction to the pineal gland, many thinkers noticed that a deeper problem remained: If a decision is *non-material*, how can it affect the pineal gland? How can a non-material cause have an effect on a *material* body? To get from the immaterial to the material seems like a bridge one cannot logically cross, and philosophers refer to this problem as the *Cartesian impasse*.

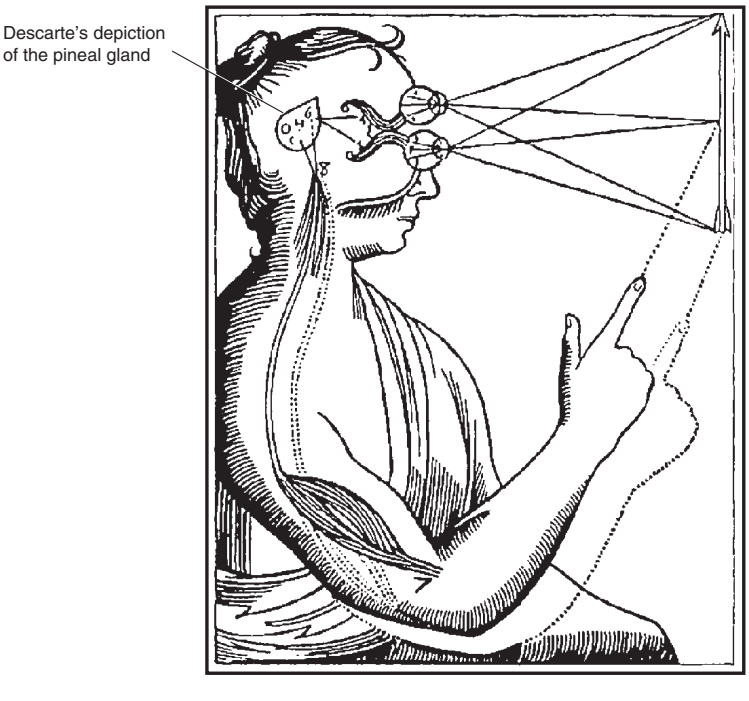

Figure 1.2 Descartes' view of the brain and mind. Descartes believed that visual input enters the eyes, and travels through nerves to cause movement of the teardrop-shaped pineal gland. The immaterial soul detects these movements of the gland, allowing the soul to see the world outside. When deciding to act, the soul moves the pineal gland, and drives wind-like "spirits" to move the limbs and other body parts. (Descartes,1972.)

Let's try a simple experiment right now: Lift your left arm. (Go ahead, play along.) You may not know much (yet) about the how the brain controls arm movements. However, you can imagine the basic idea that neurons send signals from the brain down the spinal cord, and that nerves from the spinal cord activate muscles in the shoulder. Contraction of the proper set of muscles causes the arm to lift. We'll fill in the details in Chapter 4, but you can see that there's nothing particularly puzzling or "spooky" about neurons in the brain controlling an arm movement.

But now let's try something slightly different: Lift one of your arms – you choose which one – but don't do it right away. Exert your free will and *decide upon* the moment when you want to lift it. (Take a moment to do this.) Is your decision material or immaterial? If, like Descartes, you believe it's "immaterial," how did your immaterial decision set in motion the neural activity that ultimately led to the arm movement? This is the Cartesian impasse. How can a non-material decision, located nowhere in particular, produce a physical effect on neurons? This dualist view is commonly held (at least among those who haven't studied neuroscience); but it is kind of spooky.

Dualism is not the view of neuroscience, or of most contemporary philosophy for that matter. The chapters that follow in this book will show that our ability to think, remember, decide, to have any mental experience at all, depends on the activity of the brain. As you'll see in Chapter 4, the very *decision* or *urge* to move a limb at a particular moment depends upon the activity of neurons located in an area of the frontal cortex near the midline of the brain, called the supplementary motor area.

This **monist** perspective rejects the idea of a duality between the mind and the brain. While there are many variants of monism, we're interested here in the monist view that mental phenomena like thoughts and desires arise as products of brain activity – the activation of neurons. How can a thought arise from the activity of neurons? The monist believes that neural activity has various properties. On one hand, neurons produce electrical signals allowing them to communicate with one another; the neuronal activity can be monitored with physical measuring devices. On the other hand, when the neurons are *your* neurons communicating with other neurons in *your* brain, you may experience the neural activity as a thought, desire, or some other mental event. By analogy, a cloud gives a particular impression when viewed from the ground looking up at it; but upon closer inspection, one discovers that the cloud contains various molecules interacting in ways that seem quite "un-cloudlike." From the monist perspective of neuroscience, your decision to move your arm was itself the result of *material* processes, that is, neuronal activity in some part of your brain. Those neurons then activate other neurons, eventually those in your spinal cord, and finally your muscles, causing your arm to lift. There is no logical impasse.

Similarly, from the monist view, the man in the opening scenario owes all his mental and behavioral functions to the small amount of brain tissue that he possesses. Even with much of his brain tissue lost, he retains many mental functions because the brain tissue was lost when he was very young. The human brain is highly **plastic**, that is to say, capable of structural and functional change, especially during our early years. It is likely that the neurons that remained in the man's brain took over some of the cognitive, sensory, and motor functions that were lost as a result of brain damage.

In this chapter, we give an overview of the amazing 3.3-pound mass of soft, gray tissue sitting snugly inside your skull. It is one of the most powerful instruments in the known universe. Its 100 billion or so neurons make an estimated 100 trillion connections among themselves. The human brain and its product, the mind, are responsible for all of our thoughts, emotions, memories, and actions. We'll begin by examining

neurons and glia, the main cells of the nervous system, and then we'll step back to take a bird's eye view of the peripheral nervous system, the spinal cord, and the brain. We'll fill in the details in later chapters.

1.1 THE CELLS OF THE NERVOUS SYSTEM ARE THE NEURONS AND GLIA

Neurons are the fundamental units by which information moves through the nervous system. Sights, sounds, thoughts, memories – all depend upon communication between neurons. The nervous system's other major cell type is the glial cell, which contributes to neuronal function in important ways.

1.1.1 Neurons

Information processing is what sets the brain apart as a wondrous organ capable of generating thoughts, emotions, and behaviors. Neurons carry information through the brain. The four basic parts of the neuron are the dendrites, cell body, axon, and terminal (Figure 1.3A and B). **Dendrites** are branch-like extensions that receive input from other neurons. Some neurons have dendrites that branch wildly, with additional dendrites coming from each branch like branches of a tree (Figure 1.3C). Information travels along the dendrites toward the **cell body** (also called the soma), which can be thought of as the "factory" of the neuron. It has organelles, compartments that generate energy and package chemicals, as well as a nucleus containing the DNA. The DNA is the cell's instructions about the necessary materials (proteins) that the neuron will need to manufacture. Finally, a thread-like **axon** leaves the cell body and carries an electrical signal to the end or **terminal** of the axon. Neurons communicate with one another (or with muscles or organs) primarily by releasing chemicals called **neurotransmitters** (dopamine, serotonin, and others) from the axon terminal. The transmitters cross a **synaptic cleft** (a tiny gap) and bind to neurotransmitter **receptors** on other neurons, muscle fibers, or cells of internal organs (Figure 1.4).

Understanding how neurons send information from one part of the nervous system to another is fundamental to understanding how the brain generates emotions, thoughts, and behavior. In Chapter 2, we will ask how neurons communicate, or send signals, to one another. We will see in many chapters of this book that the strength of connections between neurons are plastic; they can change as a result of experience. We will ask how changes in the strength of synaptic connections between neurons give rise to memories and skills.

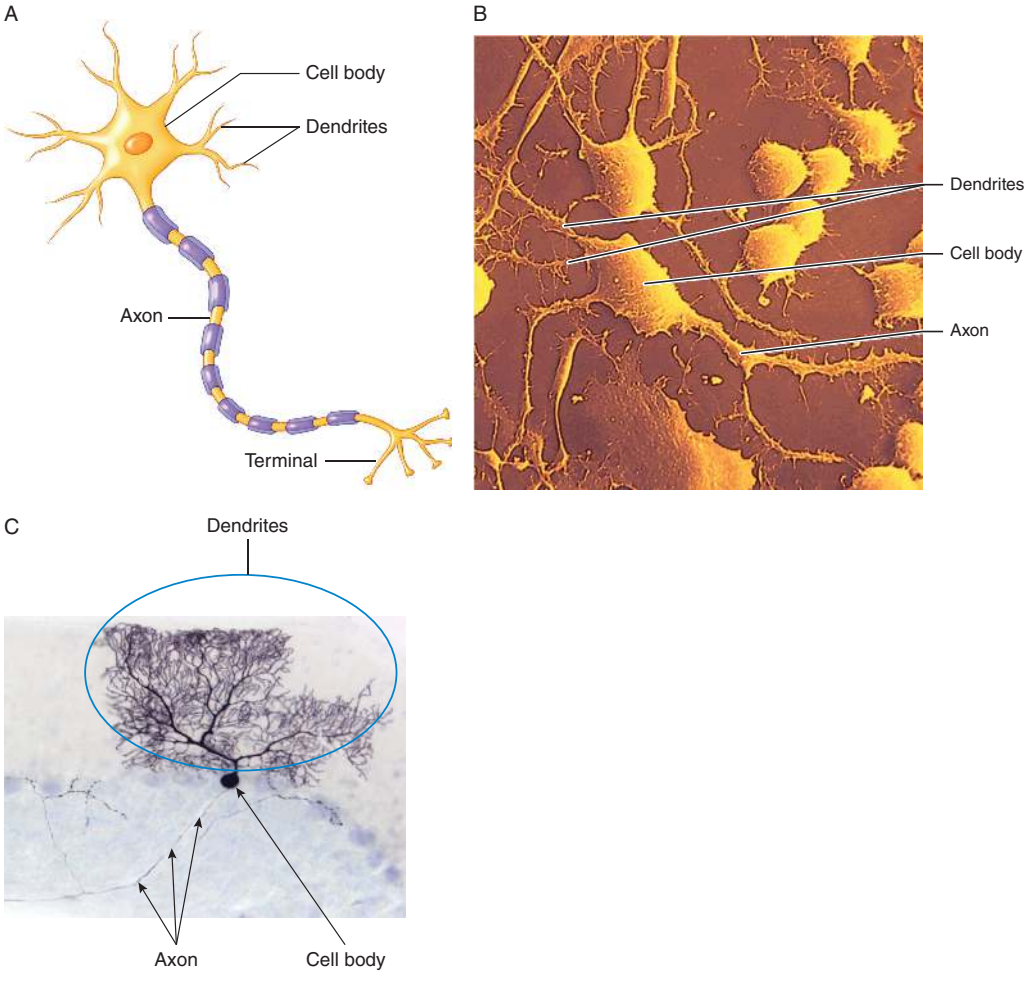

Figure 1.3 The four major components of a neuron. (A) Dendrites receive information, the cell body collects it, and the axon transmits an electrical signal to the terminal. The small circle within the cell body represents the nucleus of the cell. (B) This microscopic image shows that neurons can form dense connections with one another. (David M. Phillips/Visuals Unlimited.) (C) Neurons vary in their morphology (shape). For instance, the neuron in this microscopic image has a huge dendritic tree. (Adapted from Sugihara et al., 2009, fig. 12A, © 2009 Wiley-Liss, Inc.)

1.1.2 Glia

Glia carry out a large number of processes critical to the workings of the nervous system. Let's take a look at five major types of glial cells found in the nervous system: astrocytes, oligodendrocytes, Schwann cells, microglia, and radial glia.

Astrocytes look like stars (hence the name "astro"). They do many things, including bringing nutrients to neurons and storing biochemicals (such as glucose and neurotransmitters) that the neuron can use later. Astrocytes may also enter a brain site to provide assistance when neurons

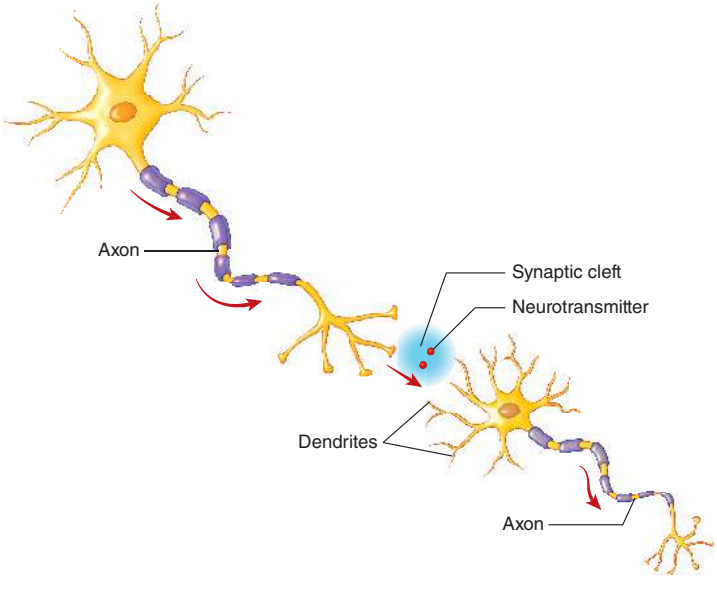

Figure 1.4 **Neurons release neurotransmitters which cross a synapse to communicate with receiving neurons.**

have been damaged. While these glial cells have traditionally been considered a kind of support staff for the health and activity of nearby neurons, research is leading to dramatic changes in how we view astrocytes. Recent evidence suggests that astrocytes may influence the activity of nearby neurons to affect a person's mood, and that abnormalities in astrocyte function may play a role in mood disorders (Zhou et al., 2019). Astrocytes also play a still-mysterious role in learning (see Box 1.1).

Oligodendrocytes form the whitish tissue (**myelin**) that surrounds and insulates axons in the brain and spinal cord to speed information transfer across the axon. Chapter 2 examines what it means for "information" or "signals" to move along an axon. For now, imagine that a bee lands on your shoulder and "information" about this event travels along axons of several neurons to reach brain areas that perceive tactile events. If the axons are myelinated (surrounded by myelin), the information travels along the axons more quickly, perhaps in time for you to move your body before the bee stings you. While oligodendrocytes produce myelin in the brain and spinal cord (the central nervous system), **Schwann cells** are the glial cells that produce myelin in the nerves that target peripheral body parts and organs (i.e., in the peripheral nervous system, discussed below).

Microglia are tiny compared to the other glia (hence the name "micro"). They are the brain's cleanup crew. When neurons die or suffer damage, microglia remove the debris left behind. Lastly, **radial glia** play a critical role in early brain development. They provide cellular scaffolding that guides newly born neurons to their final destination in the brain.

BOX 1.1 Glial Cells Do More than We Thought

Evidence for a role of glial cells in learning came, in part, from an experiment so strange that it seems like science fiction. Investigators at the University of Rochester in New York were studying immature cells that normally develop to become astrocytes (Goldman, Nedergaard, & Windrem, 2015). In their immature form, they are called **glial progenitor cells** or **GPCs**. The experimenters placed human GPCs into the brains of newborn mice (Figure 1.5A), taking steps to ensure that the mouse immune system wouldn't reject the human cells. Sure enough, the immature human cells migrated (traveled) throughout the mouse brain and increased in number. They soon developed into astrocytes, which competed with and replaced most of the mouse astrocytes. *Within about ten months, most of the astrocytes in the mouse brain were human in origin* (Figure 1.5B). Researchers sometimes refer to this procedure as "glial humanization," or more specifically, "astrocytic humanization" of the mouse brain. The mice are described as **chimeric**, for their brains are part mouse, part human. (Chimera were mythical hybrid creatures with body parts from more than one animal.)

The team of neuroscientists trained the mice on a learning task in which a tone came on a few seconds before a mild shock was delivered to the floor of the cage. A group of mice that were not transplanted with foreign astrocytes eventually learned the tone–shock association; they would often "freeze" (become briefly immobilized with fear) when the tone came on, reflecting their expectation of shock. Another group of mice were transplanted with astrocytes *from other mice*. These mice gradually learned the tone–shock association as well. However, the mice with human astrocytes (the "chimeric mice") were by far the fastest learners. After one day of training, they showed better learning than the other mice showed after four days' training (see Figure 1.5C). The long, thin extensions of astroctyes often wrap around synapses between neurons. Evidence suggests that astrocytes enhance synaptic plasticity, the ability of neuronal connections to strengthen, and thereby enhance learning (Han et al., 2013; Hussaini & Jang, 2018). Investigators do not yet understand the precise manner in which astrocytes strengthen synaptic connections and promote learning.

1.1.3 Gray versus White Matter

In many of the chapters to come, you will read about environmental and psychological conditions associated with changes in the brain's **gray matter** (Figure 1.6A). For instance, London cab drivers show increased gray matter in brain areas related to spatial memory (remembering locations), musicians show increased gray matter in auditory areas of the brain, major depression is associated with reduced gray matter in several brain regions, and antidepressant medications restore gray matter. Gray matter is mostly made up of cell bodies, dendrites, and unmyelinated axons of neurons.

As seen in Figure 1.6B, an increase in gray matter within a particular brain region may mean that:

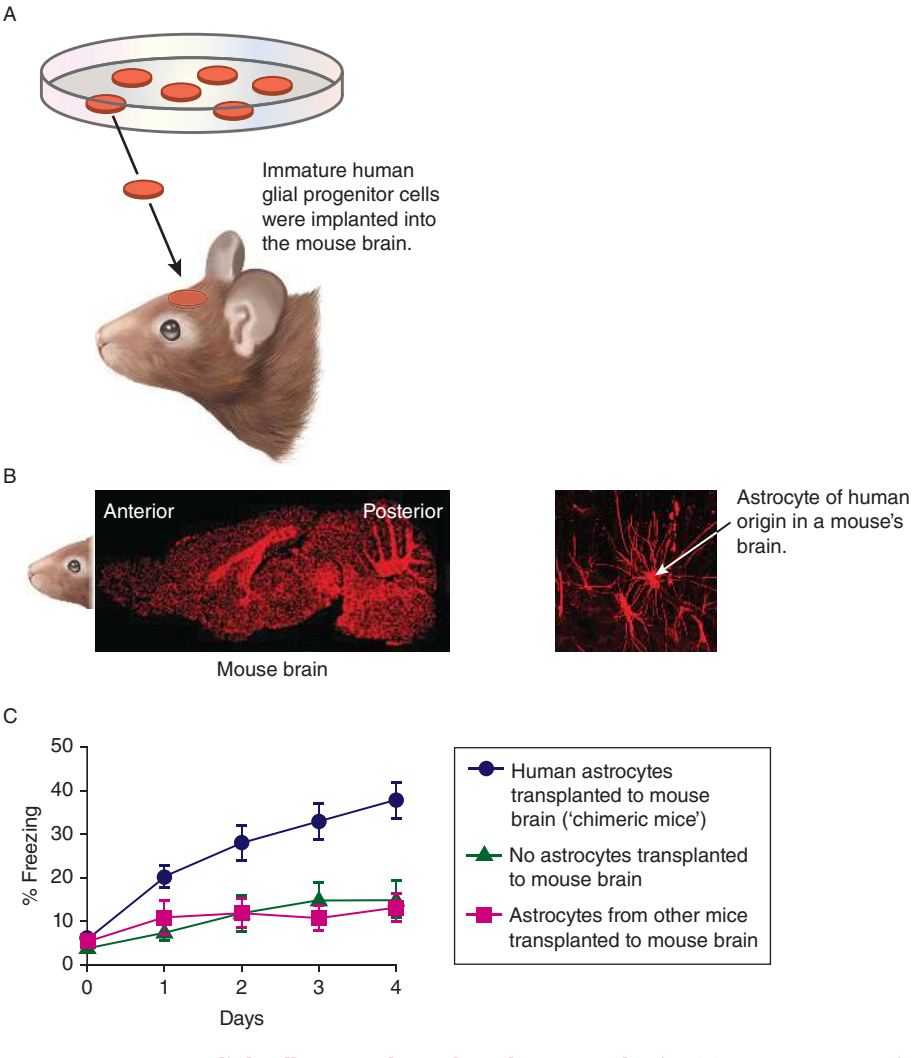

Figure 1.5 Human glial cells transplanted to the mouse brain. (A) Mice were transplanted with human glial progenitor cells (GPCs). (B) The human GPCs (stained red) quickly spread across the entire mouse brain, increased in number, and developed into astrocytes. The photograph of the mouse brain on the left is cut from the anterior to posterior end. (As described later in the chapter, this is called a "sagittal slice.") On the right, an arrow points to a human astrocyte in a mouse's brain. Notice the long, thin extensions radiating outward. Some of these extensions make contact with the much smaller mouse astrocytes. (Left, Goldman et al., 2015, fig. 1; right, Han et al., 2013, fig. 3A, © 2013 Elsevier Inc. All rights reserved.) (C) The *y*-axis shows the percentage of time mice spent freezing in fear during a tone that signaled shock. Mice with human astrocytes learned the tone–shock association quicker than control mice.
(Adapted from Han et al., 2013, fig. 6A, © 2013 Elsevier Inc. All rights reserved.)

- axons have sprouted new branches
- dendrites have grown new branches, and/or
- new neurons have been born (**neurogenesis**, discussed in Chapters 8 and 9).

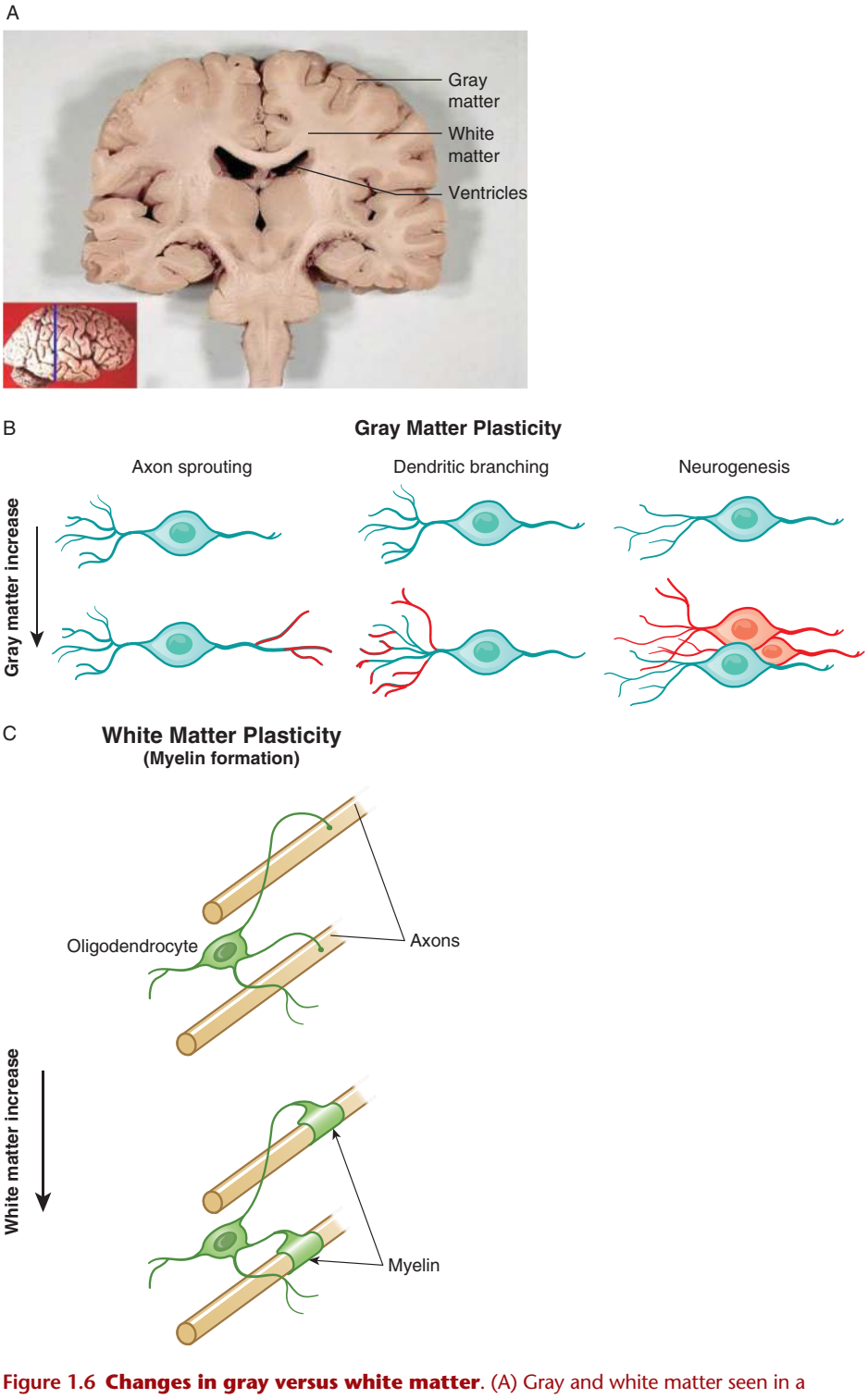

Figure 1.6 Changes in gray versus white matter. (A) Gray and white matter seen in a slice from a human brain. (John Beal, LSU Health Sciences Center.) (Ventricles are discussed later in this chapter.) (B) Increases in gray matter can result from increased branching of axons (left) or dendrites (middle), or from neurogenesis (right). (C) Increases in white matter result from increases in the axon myelination formed by nearby oligodendrocytes.
(B and C adapted from Zatorre, Fields, & Johansen-Berg, 2012, figs. 3A and 3B respectively.)