Paul Giovanopoulos, *Five Senses*, 1990

Chapter 1

1 Introduction

"WHAT IS REAL? HOW DO YOU DEFINE REAL? If you're talking about what you can feel, what you can smell, what you can taste and see, then real is simply electrical signals interpreted by your brain. This is the world that you know." This is Morpheus's answer to Neo in the 1999 movie *The Matrix*, starring Laurence Fishburne and Keanu Reeves (Figure 1.1). You are about to engage in a journey to discover how we feel, how we see and hear, and how we smell and taste. Throughout this book, you will learn what has been discovered about how we know what is real, or at least, how we know what we *think* is real.

Early Philosophy of Perception

As you may know or suspect, people have asked these questions for a very long time, perhaps as long as humans have existed. *The Matrix* was actually inspired by "The Allegory of the Cave" in Plato's *Republic*, written in about 380 BCE. In this story, **Plato** (428–348 or 347 BCE) (Figure 1.2) compares our ordinary sense of reality to prisoners in a cave (Figure 1.3). He describes prisoners tethered together since childhood, able to see only the wall in front of them. Far behind them is a fire, and between the fire and the backs of the prisoners are men, sometimes talking and sometimes not, carrying statues and other objects. All that the prisoners ever see are shadows on the wall in front of them. This is the prisoners' complete reality. Plato paints this imaginary picture to emphasize how critically our conception of reality depends on what we can learn about the world through our senses. You not do have to think of yourself as a prisoner tied up in front of a wall, but you should appreciate the fact that almost everything that you think is true about the world around you depends on what you can learn through your eyes, ears, nose, tongue, and skin. As you read this book, you will learn how you know what you know about the world around you.

Perception and your sense of reality are the products of evolution. Human senses have evolved to help us act in ways that encourage our survival. It is no accident that only animals have eyes and ears. This is because being able to gain information about the world is critical to being able to move through the environment. In general, our senses have evolved to match just the sorts of energy in the environment that are most important for our survival. However, the energy that humans can sense is a small subset of the energy that surrounds us (Figure 1.4).

For example, human vision is restricted to light a very narrow band of the electromagnetic energy. Bees (Figure 1.4*a*) can see ultraviolet light that reveals patterns in flowers otherwise invisible to us (see Figure 5.24). Using a special organ in front of each eye, rattlesnakes and other pit vipers (Figure 1.4*b*) sense infrared energy that we cannot see, and they use this sense to locate their prey. Dogs (Figure 1.4*c*) and cats, not to mentions bats,

FIGURE 1.1 In the movie *The Matrix*, Morpheus talks to Neo about the nature of reality.

can hear sounds with higher frequencies than you can hear. Many birds, turtles, and amphibians are able to use magnetic fields to navigate. Elephants can hear very low-frequency sounds, and they may use this ability to communicate over long distances. As you sit quietly reading this book, you are being bombarded by many types of energy to which you are not sensitive. Although not as limited as the imaginary case of Plato's prisoners in a cave, your understanding of reality, and even your sense of imagination, is restricted to those things that you can perceive through your senses.

More than two millennia before the field of psychology existed and the first formal perception experiments were conducted, philosophers pondered the ways in which our perception of reality depends on our sensory experiences. **Heraclitus** (about 540–480 BCE), a very influential early Greek philosopher, lived about a century before Plato. He is best known for his famous statement, "You can never step into the same river twice." Heraclitus used this metaphor to stress his view that everything is always changing. Because the river flows continually past, the water a person steps into once is not the same water the next time. The same is true of our own perceptual experiences. No two experiences can ever be identical, because experiencing the first event changes the way we experience the same event a second time.

Several important facts follow from Heraclitus's simple observation. Perception does not depend *only* on energy and events that change in the world. Perception *also* depends on the qualities of the perceiver. Even when exactly the same event happens twice, it will not be perceived the same way twice, because the perceiver has changed following the first event. Experience with the world around us plays a very large role in the way perception works, beginning very early in life. Even before birth, the sounds that the fetus hears will shape later listening. The structure of the environment around us, including cultural differences such as the speech and music we hear, molds the way perception works.

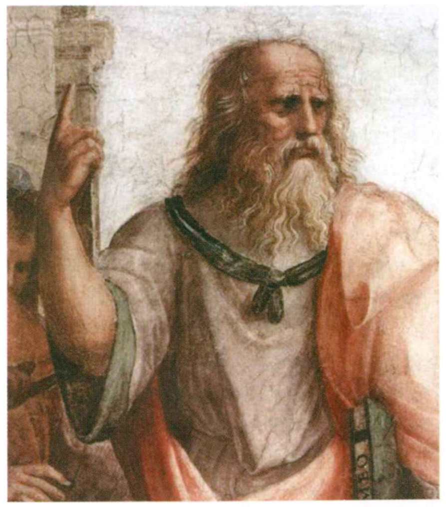


FIGURE 1.2 Plato lived during the golden age of Greece. Then, philosophers often were celebrities. Plato was an especially colorful person. Naked and covered in oil, he competed in the original Olympic Games. (He was younger then!)

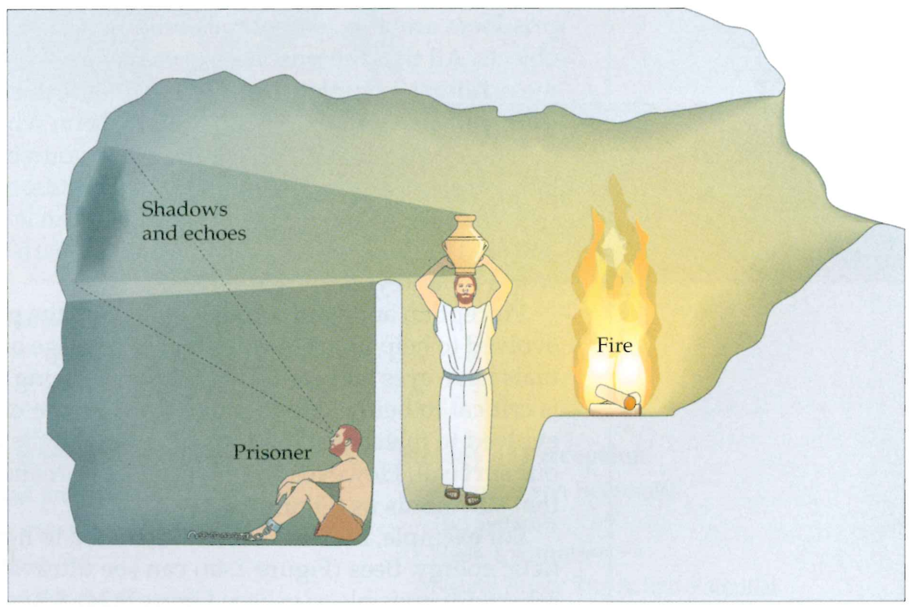


FIGURE 1.3 Prisoners in Plato's imaginary cave could learn about their world only from shadows on, and echoes from, the wall in front of them.

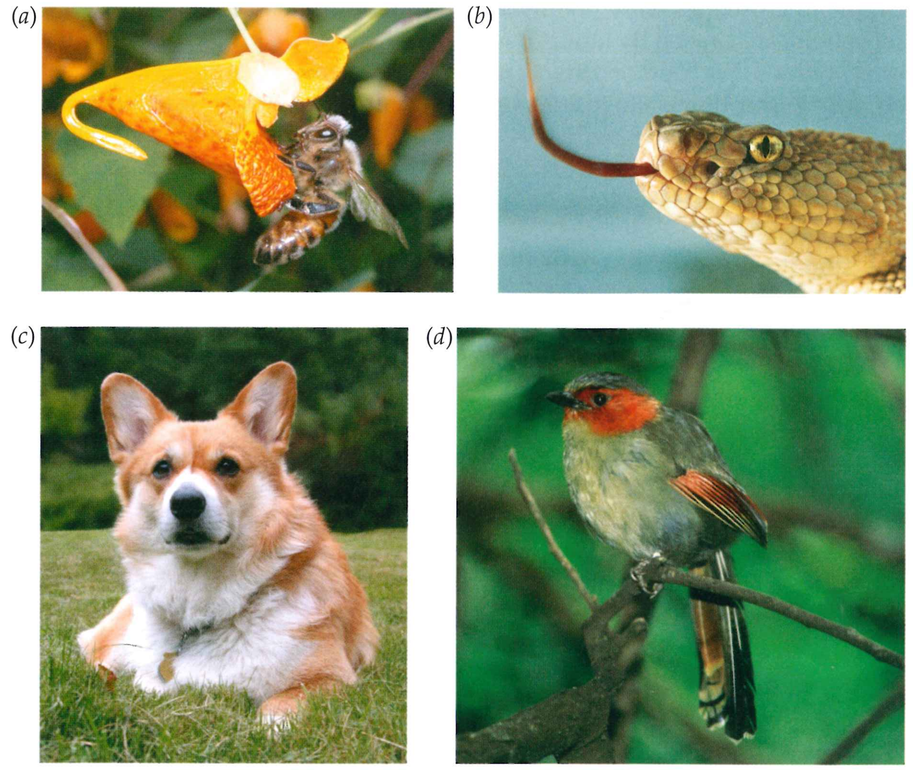


FIGURE 1.4 Our senses are capable of gaining information about only a tiny fraction of the energy and events that occur all around us. Honeybees, snakes, dogs, and birds are able to sense a variety of stimuli that humans cannot (see text).

The idea that the world is continually changing is important for perception in another way. Perceptual systems are acutely sensitive to change. In many different ways, every sense highlights and emphasizes changes around us. In fact, we tend to be quite unaware of things in our environment that do not change. Things that move draw our attention. Ambulance sirens continuously change in pitch so that drivers are more likely to hear them. The flip side is that perception quickly comes to ignore anything that stays the same for very long. The general mechanism is known as **adaptation**. All of our senses adapt to constant stimulation. For example, when you first arrive at someone's house, you may quickly detect a strong odor—perhaps mothballs, perfume, or dinner. Even though the odor was readily apparent to you, your olfactory system (smell) soon adapts to it, and you no longer notice it as much, if at all. Adaptation and other perceptual processes, render things that are steady or predictable in the environment much less salient than things that are changing.

Unlike his contemporary, Plato, the Greek philosopher, **Democritus** (about 460–370 BCE), had almost complete trust in the senses. This trust arose from his radical idea that the world is made up of atoms that collide with one another. Of course, he couldn't see these. It would be 2000 years before even

adaptation A reduction in response caused by prior or continuing stimulation.

sensory transducer A receptor that converts physical energy from the environment into neural activity.

nativism The idea that the mind produces ideas that are not derived from external sources, and that we have abilities that are innate and not learned.

simple microscopes were invented. Nevertheless, Democritus believed that sensations are caused by atoms leaving objects and making contact with our sense organs. For Democritus, this meant that our senses should be trusted because perception is the result of the physical interaction between the world and our bodies. He thought that the most reliable senses were those that detect the weight or texture of objects, because we are in direct contact with things when we make judgments of weight and texture. Democritus held that all the other qualities were secondary because they had to involve atoms moving from the object to interact with atoms of the perceiver.

Despite being way ahead of his time in suggesting the existence of atoms, Democritus did get some things wrong. It is light reflected from an object that allows us to see the object; there are no atomic films peeling off of visible objects. When we hear speech, our ears are detecting sound pressure waves, not atoms from a person's mouth. Taste and olfaction, our sense of smell, come closest to Democritus's theory. In those *chemical senses*, we detect molecules (not isolated atoms, but close enough) binding to receptors on the tongue or deep inside the nose.

Democritus made the distinction between *primary qualities* that can be directly perceived (weight, texture) and *secondary qualities* that require interaction between atoms from objects and atoms in the perceiver. Today, we might distinguish between low-level sensations and higher-level perception. The distinction is not always clear, but we can usually understand low-level sensations quite well by knowing about the functions of sense organs such as eyes, ears, skin, taste buds, and olfactory surfaces. At these early levels, we learn about **sensory transducers**. A transducer is any substance or structure that changes energy from one form to another form. For every sense, first there are transducers that transform information about the world—whether light, sound, pressure, or chemical composition—into neural signals that can be interpreted by the brain. Higher-level aspects of perception are more likely to involve higher brain structures, and they are generally more dependent on experience. Some examples of higher-level perception include recognizing particular objects like horses, understanding spoken words, or identifying your mother by the smell of her perfume. When you learn about all of the senses throughout this book, you will always learn both about the very early stages, including transducers and neural pathways, and about the complex perceptions that make up our understanding of the world.

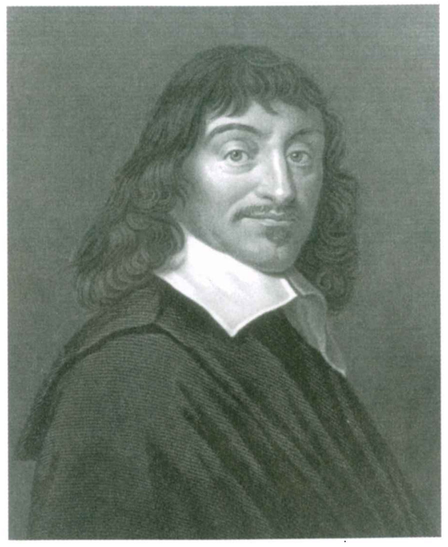


FIGURE 1.5 René Descartes was one of the most important philosophers of all time, and he was equally famous as a physicist, physiologist, and mathematician.

Nativism and Empiricism

Plato used "The Allegory of the Cave" to emphasize limitations on what we can know about reality from our senses. He went on to claim that the truest sense of reality comes from deep within people's minds and souls. Plato thought that there were two worlds: the world of Opinion and the world of Knowledge. The world of Opinion was taken to be incomplete because it is limited by information conveyed to us through our senses. This is all that Plato's prisoners could know. In contrast, Plato thought that real Truth (with a capital *T*) is found in the world of Knowledge. The world of Knowledge is where souls reside, and according to Plato, each soul is joined to a body for a lifetime. Plato's idea that certain mental abilities must be innate is known as **nativism**. Like many realms of psychology, the study of sensation and perception raises the distinction between nature (nativism) and nurture (experience). Plato's division between soul and body is maintained today in many religions and cultures around the world, but it will not enter extensively into our discussion of the senses.

René Descartes

Much later, nativist **René Descartes** (1596–1650) (Figure 1.5) came to a similar conclusion concerning the relationship between mind and body. He argued that only humans have mind. In his view, similarities between humans and animals would be restricted to bodily structures and functions. Modern research on animal cognition indicates that he was wrong about this. For present purposes, our interest is in Descartes's **dualist** view of the mind. He considered the mind to be quite separate from the body. For Descartes, the mind is unextended (does not take up space) and has no substance. It is distinct from the body and survives the death of the body (like a soul). Like Plato, Descartes thought that all true ideas must come from the mind, and he did not trust his senses. Unlike Plato, the Olympic athlete, Descartes was said to have been a very lazy young man. The monks at his church school used to throw buckets of water on young René to get him out of bed, where he would spend much time awake but pondering. Perhaps his attraction to the sedentary life was related to his most famous philosophical statement: *Cogito ergo sum* ("I think, therefore I am"). By this, Descartes asserts that his thinking mind, and not his experiences, is what defines and proves his existence.

Thus far, the distinction between mind and body might strike you as sensible and consistent with the way you think about yourself and humans in general. People typically think of themselves as having a mind that takes in information about the world through the senses before choosing to act in particular ways on the basis of that information. Indeed, Paul Bloom believes that children come into the world ready to hold the dualist belief that humans have both material bodies and immaterial minds (Bloom, 2004). The logical alternative to dualism is that humans, and the rest of the universe for that matter, are made up of only one kind of stuff. This position is known as **monism**. If you hold that everything is matter, you are embracing **materialism**. If, on the contrary, you hold that everything is mind, that is **mentalism**.

However natural a separation between mind and body may seem, there is a problem with **mind–body dualism**: How does that mind, having no substance and occupying no space, have any effect on the physical body? Philosophers continue to struggle with this problem.

dualism The idea that both mind and body exist.

monism The idea that mind and matter are formed from, or reducible to, a single ultimate substance or principle of being.

materialism The idea that physical matter is the only reality, and everything including the mind can be explained in terms of matter and physical phenomena. Materialism is a type of monism.

mentalism The idea that the mind is the true reality, and objects exist only as aspects of the mind's awareness. Mentalism is a type of monism.

mind–body dualism Originated by René Descartes, the idea positing the existence of two distinct principles of being in the universe: spirit/soul and matter/body.

empiricism The idea that experience from the senses is the only source of knowledge.

British Empiricism

You may ask what, if anything, all this has to do with learning about perception. As it turns out, much of the development of thinking about perception grew out of questions concerning the relationship between mind and body. The British philosopher **Thomas Hobbes** (1588–1679) (Figure 1.6) took this problem quite seriously and concluded that, for him, the only sensible answer is that only matter exists. Hobbes rejected the concept of spirit, or God, because such things would have no matter or bodies. Instead, he provided a mechanical model of humans and of society more broadly. In Hobbes's universe of matter alone, he argued that all knowledge must arise from the senses: "For there is no conception in a man's mind, which hath not at first, totally, or in parts, been begotten upon the organs of the Sense" (Hobbes, 1651/1914, p. 3). In short, Hobbes rejects the nativist ideas of Plato and Descartes. Instead, Hobbes is an **empiricist**, which means that his model of human nature relies entirely on experience.

Because Hobbes viewed all mental activity as a consequence of experience, he had what you may find to be an especially dim view of memory, thinking,

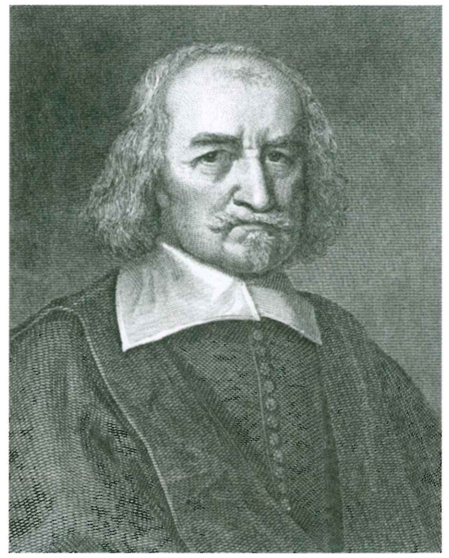


FIGURE 1.6 Thomas Hobbes believed that everything that could ever be known or even imagined had to be learned through the senses.

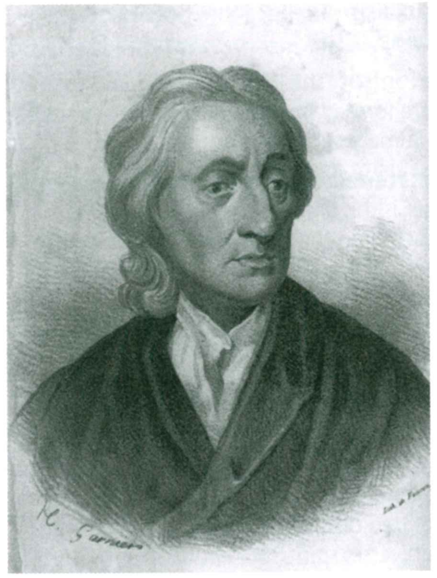


FIGURE 1.7 John Locke sought to explain how all thoughts, even complex ones, could be constructed from experience with a collection of sensations.

and imagination. He thought memories were simply sense experiences that were old and faded. And thinking was little more than connections between memories. Because there would be nothing to the mind other than sensory experiences, imagination was not thought to be creative at all. Instead, Hobbes wrote that imagination "is nothing but *decaying sense*" (Hobbes, 1651/1914, p. 5).

John Locke (1632–1704) (Figure 1.7), another British philosopher, provided us with empiricism's most vivid image: that of the newborn mind as a *tabula rasa*, or "blank slate," on which experience writes. Like Hobbes, Locke suggested that all ideas must be created through experience. Our rich experiences of the world around us, and our subsequent ideas about that world, all begin when the simple stimulation of our sense organs (eyes, ears, skin, nose, tongue) is conveyed to the mind. These first sensory impressions were called "simple ideas," and they may be thought of as primary qualities. Because they are simple and cannot be divided further, these sensory impressions are not the same as the experiences that we normally have with the world. For example, when we perceive a cat, our experience is the combination of different simple qualities, such as seeing the color, hearing the purr, feeling the fur, and smelling Meow Mix. The combination of these simple qualities comes only through experience.

Locke's ideas led to a famous exchange with the Irish scientist William Molyneux. Locke and Molyneux agreed that people who were born without sight but later gained the ability to see would not be able to recognize objects that they had previously only touched or heard because they had never seen the world with their eyes. To test this speculation, one would need to restore the blind to sight. This doesn't happen frequently. In some cases, however, the optics of the eye are opaque or translucent, and surgery can be performed to remove tissue and restore vision. In the days before anesthesia, operations on such patients were very rare. One famous case was that of a 13-year-old boy, operated on by William Cheselden (1688–1752) in 1728. There have been a modest collection of cases since then. Locke and Molyneux probably overstated the visual problems of these individuals, but such individuals do have real trouble with some aspects of vision (notably the ability to use cues to depth; Fine et al., 2003). Interestingly, and sadly, many of these individuals are not made happier by being able to see. Some become quite depressed with their suddenly new world and even wish they were blind again (Gregory and Wallace, 1963; Sacks, 1993).

The city of Berkeley, California, is named after another famous philosopher who was quite attracted to what was then the New World. Irishman **George Berkeley** (1685–1753) (pronounced "Barkley," like Charles, the famous basketball player) (Figure 1.8*a*) traveled to Newport, Rhode Island, with hopes of starting a college. Young Berkeley did not receive the money he needed, so he headed home and became a bishop in Ireland. Instead of starting a college, Berkeley thought a lot about perception, and about what perception tells us about the way minds operate. During the early 1700s, Berkeley was inspired by Molyneux's questions about blind people being able to see again, and he was led to think seriously about how vision works. He began by asking the seemingly simple question of how we know how near or far objects are from us when we see them. As you will learn in Chapter 6, Berkeley (1837 [1709]) was on the right track when he argued that there is no single strategy that will always tell you how distant something is (Figure 1.8*b*). Instead, observers must use several visual cues to perceive distance. Berkeley concluded that we learn how to perceive distance by experiencing many objects and scenes in the world. When we do this, we learn how different visual cues change together

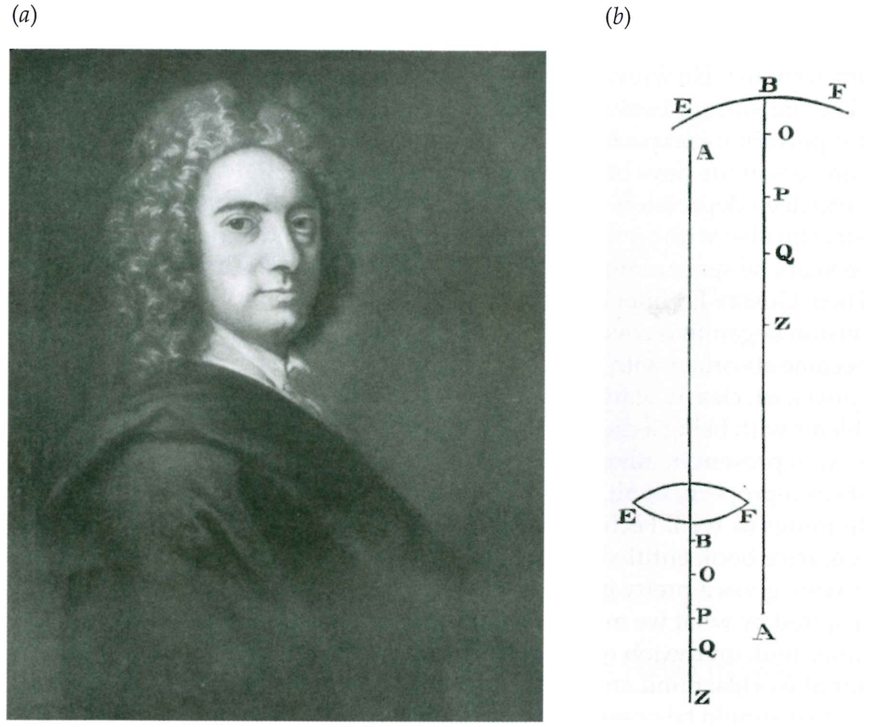


FIGURE 1.8 (*a*) Bishop George Berkeley studied ways in which perception, such as perception of distance, is limited by the information available to us through our eyes. Nevertheless, he was convinced that everything we know must come from our sensory experience, no matter how limited it may be. (*b*) One of Berkeley's own drawings illustrating how difficult it is to know the distance of an object on the basis of light entering the eyes. (From Berkeley, 1709.)

at different distances. Through experience we learn how to use multiple visual cues to arrive at a pretty good estimate of where things are.

When Berkeley thought about perceiving distance, as well as seeing other parts of our visual world, he became convinced that the most important part of perception was experience with the world. Like Plato, Berkeley appreciated the limitations of perception, no matter how much experience the perceiver has. Unlike Plato, Berkeley agreed with Hobbes and Locke. He concluded that all of our knowledge about the world must come from experience, no matter how limited perception may be. So strong was Berkeley's conviction that he disagreed with Descartes' "I think therefore I am" stating instead *Esse est percipi* ("to be is to be perceived") the world exists only to the extent that it is perceived. You've heard the question, "If a tree fell in the forest and no one was there to hear it, did it make a sound?" For Berkeley, if no one was there to hear (or see) it, the tree never existed in the first place.

The Dawn of Psychophysics

The previous discussion shows us that ideas of philosophy such as the nature of reality and the existence of the mind have deep connections to the study of perception; connections that extend to the very first recorded thinking about such things. Eventually these philosophical issues would inspire not only *thinking* about perception; they would give birth to the scientific study of perception. To see how, we begin with the very interesting and versatile German scientist-philosopher **Gustav Fechner** (1801–1887) (Figure 1.9). Fechner is sometimes considered to be the true founder of experimental psychology (Boring, 1950), even if that title is usually given to Wilhelm Wundt (1832–1920), who began his work sometime later. Before making his first contributions to psychology, Fechner had an eventful personal history. Young Fechner earned his degree in medicine, but his interests turned from biological science to

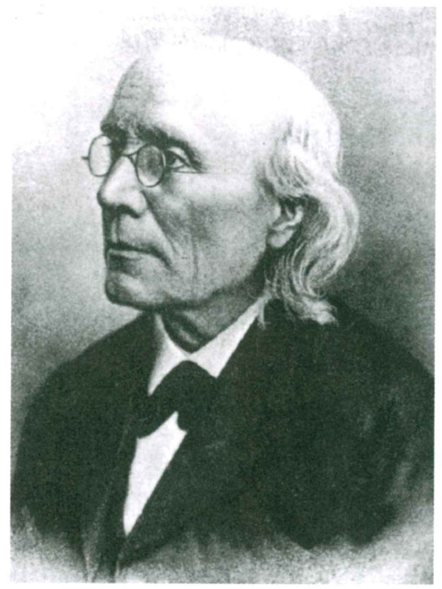


FIGURE 1.9 Gustav Fechner invented psychophysics and is thought by some to be the true founder of experimental psychology. Fechner is best known for his pioneering work relating changes in the physical world to changes in our psychological experiences.

FIGURE 1.10 Ernst Weber discovered that the smallest change in a stimulus, such as the weight of an object, that can be detected is a constant proportion of the stimulus level. This relationship later became known as "Weber's law."

physics and mathematics. Though this might seem to be an unlikely way to get to psychology, events proved otherwise. Fechner was a very hardworking young scientist. He worked himself to exhaustion. In addition to being overworked, he suffered severe eye damage from gazing too much at the sun while performing experiments (a not uncommon problem for curious vision researchers in the days before reliable bright artificial light sources). Fechner fell into deep depression. Not only did he resign from his position at the university; he also withdrew from almost all of his friends and colleagues. For three years he spent almost all of his time alone with his thoughts.

Then, Gustav Fechner experienced what he believed to be a miracle when his vision began to recover quickly. His religious convictions deepened, and he became absorbed with the relationship between mind and matter. Fechner, the physicist, clearly wanted both mind and matter to exist, but he knew the problems with being a dualist. Fechner proposed that the mind, or consciousness, was present in all of nature. This idea, called **panpsychism**, that mind exists as a property of all matter, extended not only to animals, but to inanimate things as well. Fechner described his philosophy of panpsychism in a provocative book entitled *Nanna, or Concerning the Mental Life of Plants*. This title alone gives a pretty good idea of what Fechner had in mind.

Inspired by what we might consider to be somewhat unconventional ideas, Fechner took on the job of explaining the relation between the spiritual and material worlds: mind and body. From his experience as a physicist, Fechner thought it should be possible to describe the relation between mind and body using mathematics. His goal was to formally describe the relationship between sensation (mind) and the energy (matter) that gave rise to the sensation. He called both his methods and his theory **psychophysics** (*psycho* for mind, and *physics* for matter).

In his effort, Fechner was inspired by the findings of one of his Leipzig colleagues, **Ernst Weber** (1795–1878) (Figure 1.10), an anatomist and physiologist who was interested in touch. Weber tested the accuracy of our sense of touch using a device much like the compass you used when learning geometry. With this device, he could measure the smallest distance between two points that was required for a person to feel two points instead of one. Later, Fechner would call the distance between the points the **two-point threshold**. You will learn more about two-point thresholds and touch in Chapter 12.

For Fechner, Weber's most important findings involved judgments of lifted weights. Weber would ask people to lift one standard weight (a weight that stayed the same over experimental trials) and one comparison weight that differed from the standard in incremental amounts. He found that the ability of a subject to detect the difference between the standard and comparison weights depended greatly on the weight of the standard. When the standard was relatively light, people were much better at detecting a small difference when they lifted the comparison weight. When the standard was heavier, people needed a bigger difference before they could detect the change. He called the difference required for detecting a change in weight the **just noticeable difference**, or **JND**. Another term for JND, the smallest change in a stimulus that can be detected, is the **difference threshold**.

As we learned in the preceding example, the absolute size of the JND changes depending on the weight being lifted. When weights are relatively light, the JND is small. When weights are heavier, the JND is larger. Weber noticed that JNDs change in a systematic way. The smallest change in weight that could be detected was always close to one-fortieth of the standard weight. Thus, a 1-gram change could be detected when the standard weighed 40 grams, but a 10-gram change was required when the standard weighed 400 grams.

panpsychism The idea that all matter has consciousness.

psychophysics The science of defining quantitative relationships between physical and psychological (subjective) events.

two-point threshold The minimum distance at which two stimuli (e.g., two simultaneous touches) are just perceptible as separate.

just noticeable difference (JND) The smallest detectable difference between two stimuli, or the minimum change in a stimulus that can be correctly judged as different from a reference stimulus. Also called *difference threshold*.

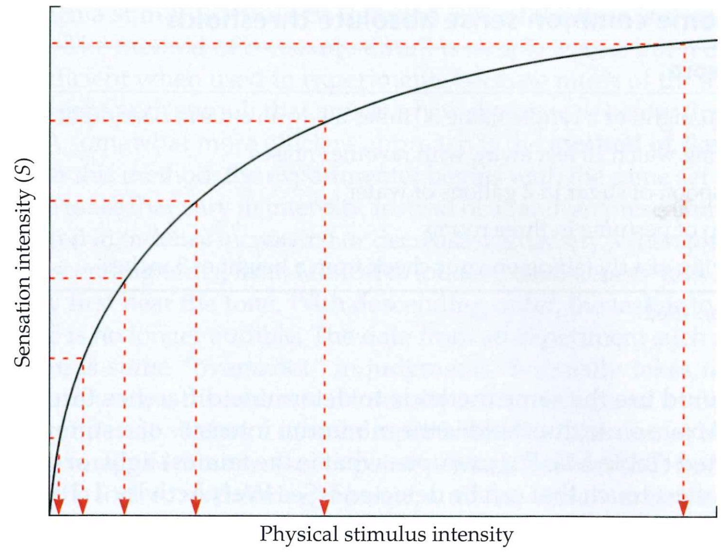


FIGURE 1.11 This illustration of Fechner's law shows that, as stimulus intensity grows larger, larger changes are required for the changes to be detected by a perceiver.

$$\frac{\Delta 1}{40} = 1:40 \qquad \frac{\Delta 10}{400} = 1:40 \qquad \frac{\Delta I}{I} = K = \text{Weber fraction}$$

$$\text{JND} = 1 \qquad \text{JND} = 10$$

Weber went on to test JNDs for a few other kinds of stimuli, such as judging the lengths of two lines, for which the ratio was only 1:100. For virtually every measure—whether brightness, pitch, or time—constant ratios describe our ability to detect change fairly well, except when intensities are very small or very large nearing the minimum and maximum of our senses. Fechner called these ratios, such as 1:40 and 1:100, **Weber fractions** in recognition of Weber's discovery. He also gave Weber's observation a mathematical formula. Fechner named the general rule—that the size of the detectable difference (ΔI) is a constant proportion (K) of the level of the stimulus (I)—**Weber's law**.

In Weber's findings, Fechner found what he was looking for: a way to describe the relationship between mind and matter. Fechner assumed that the smallest detectable change in stimulus (ΔI) could be considered a unit of the mind because this is the smallest bit of change that is perceived. Fechner then made some mathematical extensions of Weber's law to create what became known as **Fechner's law** (Figure 1.11), which is

$$S = k \log R$$

where S is the psychological sensation, which is equal to the logarithm of the physical stimulus level (log R) multiplied by a constant k. This equation describes the fact that your psychological experience of the intensity of light, sound, smell, taste, or touch increases less quickly than the actual physical stimulus increases. With this equation, Fechner provided a mathematical expression that formally demonstrated a relationship between psyche and physics (psychophysics). As you learn about the senses when reading this book, you will find that we typically make a distinction between units of physical entities (light, sound) and measures of people's perception. For example, we measure the physical intensity of a sound in decibels, but we refer to our sensation as "loudness."

Fechner invented new ways to measure what people see, hear, and feel. All of these methods are still in use today. In explaining these methods here, we will use **absolute threshold** as an example because it is simpler to under-

Weber fraction The constant of proportionality in Weber's law.

Weber's law The principle that the just noticeable difference (JND) is a constant fraction of the comparison stimulus.

Fechner's law A principle describing the relationship between stimulus magnitude and resulting sensation magnitude such that the magnitude of subjective sensation increases proportionally to the logarithm of the stimulus intensity.

absolute threshold Minimum amount of stimulation necessary for a person to detect a stimulus 50% of the time.

method of constant stimuli A psychophysical method in which many stimuli, ranging from rarely to almost always perceivable (or rarely to almost always perceivably different from a reference stimulus), are presented one at a time. Participants respond to each presentation: "yes/no," "same/different," and so on.

method of limits A psychophysical method in which the particular dimension of a stimulus, or the difference between two stimuli, is varied incrementally until the participant responds differently.

TABLE 1.1 Some common sense absolute thresholds

SENSE	THRESHOLD
Vision	Stars at night, or a candle flame 30 miles away on a dark, clear night
Hearing	A ticking watch 20 feet away, with no other noises
Taste	A teaspoon of sugar in 2 gallons of water
Smell	A drop of perfume in three rooms
Touch	The wing of a fly falling on your cheek from a height of 3 inches

Source: From Galanter, 1962.

stand, but we would use the same methods to determine difference thresholds such as ΔI. An absolute threshold is the minimum intensity of a stimulus that can be detected (Table 1.1). For example, what is the faintest light, or quietest sound, or softest touch that can be detected? (See **Web Activity 1.1 Psychophysics**.)

Psychophysical Methods

One method of measuring people's sensations, known as the **method of constant stimuli**, requires creating many stimuli with different intensities in order to find the tiniest intensity that can be detected (Figure 1.12). If you have had a hearing test, you may recall having to report when you could and could not hear a tone that the audiologist played to you over headphones. To do this test, intensities of all of the tones would be relatively low, not too far above or below the intensity where we think your threshold would be. The tones, varying in intensity, would be presented randomly, and tones at each intensity would be presented multiple times. The task for the listeners would be to report whether they heard a tone or not. Listeners would always report hearing a tone that was relatively far above threshold, and they would almost never report hearing a tone that was well below threshold. In between, however, some tone intensities would be more likely to be heard than not heard, and other lower intensities would be heard on only a few presentations. In general, the point at which a stimulus would be detected 50% of the time is chosen as the threshold. The method of constant stimuli is simple to use, but it can be somewhat inefficient when used in experiments because much of the subject's time can be spent with stimuli that are clearly well above or below threshold.

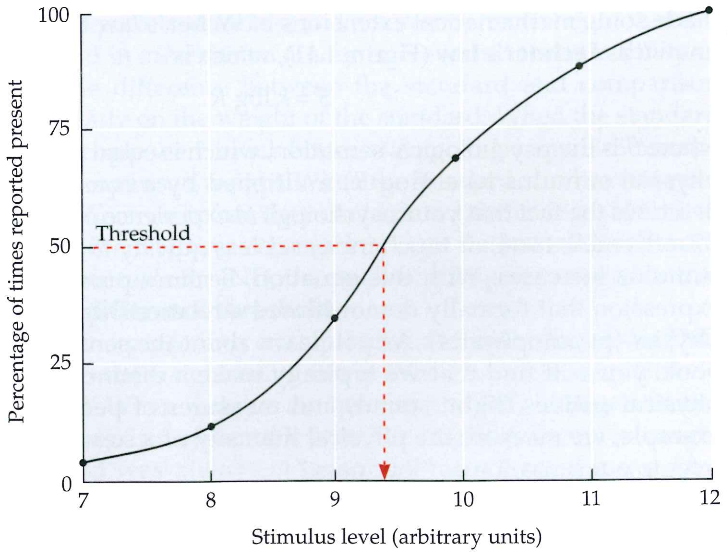


FIGURE 1.12 The method of constant stimuli. Hypothetical data from an experiment measuring absolute threshold. Note that a threshold is not a sharp change in detection. Instead, a point on the curve where subjects are more likely than not to report detecting a stimulus is designated as the threshold.

A somewhat more efficient approach is the **method of limits** (Figure 1.13). With this method, the experimenter begins with the same set of stimuli, in this case tones that vary in intensity. Instead of a random presentation, tones are presented in order of increasing or decreasing intensity. When tones are presented in ascending order, from faintest to loudest, the listeners' task is to report when they first hear the tone. With descending order, the task is to report when the tone is no longer audible. The data from an experiment such as this show that there is some "overshoot" in judgments. It usually takes more intensity to report hearing the tone when intensity is increasing, and it takes more decreases in intensity before a listener reports that the tone cannot be heard. We take the average of these crossover points—when listeners shift from reporting hearing the tone to not hearing the tone, and vice versa—to be the threshold.

The third and final of these classic measures of thresholds is the **method of adjustment**. This method is just like the method of limits, except the subject is the one who steadily increases or decreases the intensity of the stimulus. The method of adjustment may be the easiest method to understand because it is much like day-to-day activities such as adjusting the volume dial on a stereo or the dimmer switch for a light. Although easiest to understand, however, the method of adjustment is not usually used to measure thresholds. The reason, as we have learned from the method of constant stimuli and the method of limits, is that a threshold is not a distinct point. Instead, we see that the threshold is actually a statistical measure, and we simply choose to call the 50% crossover the threshold because the probability of detecting something is greater beyond the threshold and lesser below the threshold.

Because thresholds are probabilistic, not really absolute, more sophisticated methods are required if we are to measure how sensitive people are to different stimuli. Let's think a bit about why subjects' responses might not necessarily yield clear cutoffs in what they detect and do not detect. Perhaps the fact that people are not entirely consistent in their detection of the same stimulus says something more about the person than about just the stimulus.

One reason why thresholds change from trial to trial may be that subjects change from trial to trial. The stimulus being presented to a subject is not the only source of activity in the perceptual system. Our auditory and visual systems actually create energy, or "noise." One quick way to demonstrate this is to plug your ears with earplugs, or even just your fingertips. You will notice that you hear a rumbling noise generated inside your head. Similarly, if you close your eyes in a dark room, you still see something—a mottled pattern of grey with occasional brighter flashes. When you are trying to detect a faint sound or flash of light, you must detect it above and beyond any activity that is going on in your head in the first place.

Signal Detection Theory

Observers complicate the measurement of thresholds in another way as well: by bringing their own biases to a perception task. They might be more prepared or more motivated to hear or see some things more than others. The overshoot that is found with the method of limits is one indicator of such a bias. When subjects are "tuned in" to detecting the stimulus, they are more likely to continue reporting that they detect the stimulus as the intensity of the stimulus is steadily decreased. The exact opposite happens when the

Trial series

Intensity (arbitrary units)	↓1	↑2	↓3	↑4	↓5	↑6	↓7	↑8
20	Y						Y	
19	Y		Y		Y		Y	
18	Y		Y		Y		Y	
17	Y		Y		Y		Y	
16	Y		Y		Y		Y	Y
15	Y	Y	Y	Y	Y	Y	Y	Y
14	Y	N	Y	N	Y	Y	Y	Y
13	N	N	Y	N	Y	N	N	Y
12		N	N	N	N	N		N
11		N		N		N		N
10		N		N		N		N
	13.5	14.5	12.5	14.5	12.5	14.5	13.5	12.5

Crossover values (average = 13.5)

FIGURE 1.13 The method of limits. Here the subject attends to multiple series of trials. For each series, the intensity of the stimulus is gradually increased or decreased until the subject detects (Y) or fails to detect (N), respectively, the stimulus. For each series, an estimate of the threshold is taken to be the average of the stimulus level just before and after the change in perception.

method of adjustment The method of limits for which the subject controls the change in the stimulus.

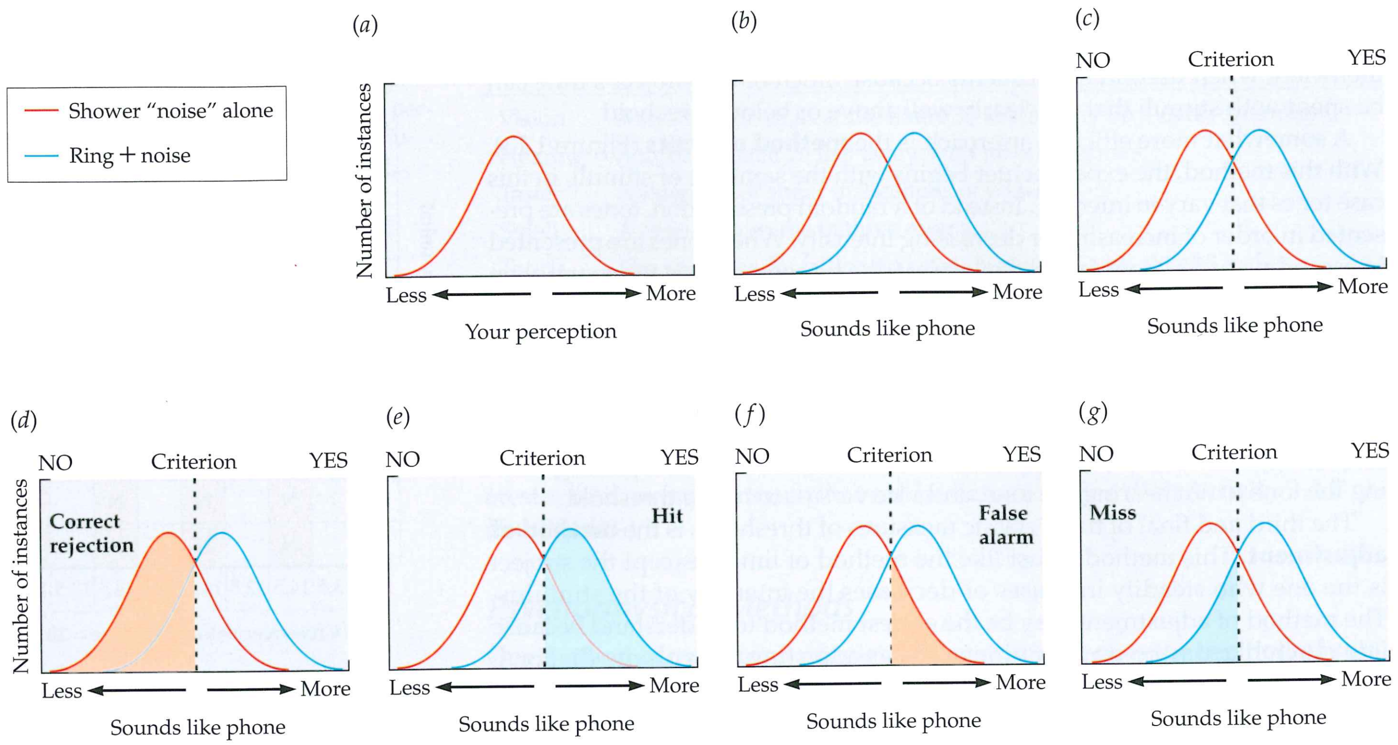


FIGURE 1.14 Detecting a stimulus, the Signal Detection Theory (SDT) approach. (*a*) SDT assumes that all perceptual decisions must be made against a background of noise (the red curve) generated in the world or in your nervous system. (*b*) Your job is to distinguish nervous system responses due to noise alone (red) or signal plus noise (blue). (*c*) The best you can do is to establish some criterion (dotted line) and declare that you detect something if the response is above that criterion. That leads to four classes of response: (*d*) correct rejections, you say "no" and there is, indeed, nothing there; (*e*) hits, you say "yes" and there is a signal; (*f*) false alarm errors, you say "yes" to nothing; (*g*) miss errors, you say "no" to a real signal.

subjects begin with stimuli that they cannot detect. It is easy to think of situations in which you would like observers to be especially biased toward detecting something. For example, we hope that a radiologist looking at X-rays is quite biased toward seeing defects when diagnosing whether or not you broke your leg. The cost of missing even a tiny crack could be very high when you try to walk away from your visit.

To get a feeling for the interaction of the stimulus and the observer, consider the following situation. You are in the shower. The water is making a noise that we will, imaginatively, call *noise*. Sometimes the noise will sound louder to you. Sometimes it will seem softer. We could plot the distribution of your perception of noise as shown in Figure 1.14*a*.

Now the phone rings. We will call that the *signal*. Your perceptual task is to detect the signal in the presence of the noise. That signal is added to the noise, so we can imagine that now we have two distributions of responses in your nervous system: a noise-alone distribution and a signal-plus-noise distribution (Figure 1.14*b*).

For the sake of simplicity, let's suppose that more response means that it sounds more like the phone is ringing. So now your job is to decide if it is time to jump out of the shower and answer what might be the phone. The problem is that you have no way of knowing at any given moment whether you are hearing noise alone or signal plus noise. The best you can do is to set up a criterion level of response (Figure 1.14*c*) that you will call a ring and jump out of the shower if the stimulus exceeds that response level. If the level is below the criterion, you will decide that it is not a ring and stay in the shower.

There are four possible outcomes (Figure 1.14*d–g*): You might say "no" when there was no ring; that is a *correct rejection* (1.14*d*). You might say "yes" when there was a ring; that is known as a *hit* (1.14*e*). Then there are the errors. If you jump out of the shower when there is no ring, that is a *false alarm* (1.14*f*). If you miss the call, that is a *miss* (1.14*g*).

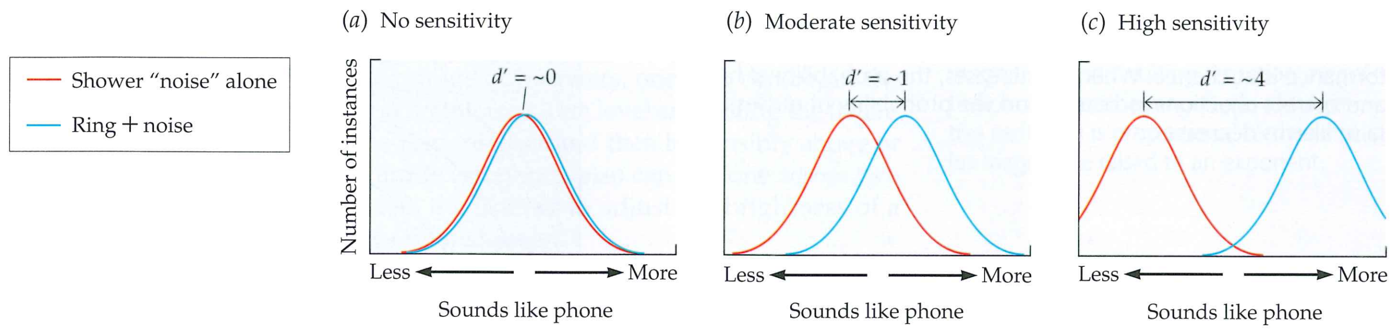


FIGURE 1.15 Your sensitivity to a stimulus is illustrated by the distance between the distributions of your response to noise alone and to signal plus noise. This is captured by the measure, *d′* ("*d*-prime"). If the distributions completely overlap (*a*), *d′* = 0 and you have no ability to detect the signal. If *d′* is intermediate (*b*), you have some sensitivity but you performance will be imperfect. If *d′* is big (*c*), then it is trivial to tell signal from noise.

How sensitive are you to the ring? On the graphs of Figure 1.14, the sensitivity is shown as the separation between the noise-alone and signal-plus-noise distributions. If the distributions are on top of each other (Figure 1.15*a*), then you can't tell noise-alone from signal-plus-noise. A false alarm is just as likely as a hit. By knowing the relationship of hits to false alarms, you can calculate a sensitivity measure known as *d′* (*d*-prime), which would be zero in Figure 1.15*a*.

In Figure 1.15*c*, we see the case of a large *d′*. Here you could detect essentially all the rings and never make a false alarm. The situation we have been discussing is in between (Figure 1.15*b*).

Now suppose you're waiting for a call. You *really* don't want to miss this call, but you can't make yourself more sensitive. All you can do is to move the criterion level of response, as shown in Figure 1.16*a*.

If you shift your criterion to the left, you won't miss many calls, but you will make lots of false alarms (Figure 1.16*a*). If you shift to the right, you won't make those annoying false alarms, but now you will miss most of the calls (Figure 1.16*c*). For a fixed value of *d′*, changing the criterion changes the hits and false alarms in predictable ways. If you plot hits against false alarms for different criterion values, you get a curve known as a **receiver operating characteristic (ROC) curve** (Figure 1.17).

receiver operating characteristics (ROC) curve The graphical plot of the hit rate as a function of the false alarm rate. If these are the same, points fall on the diagonal, indicating that the observer cannot tell the difference between the presence and absence of the signal. As the observer's sensitivity increases, the curve bows upward toward the upper left corner. That point represents a perfect ability to tell signal from noise (100% hits, 0% false alarms).

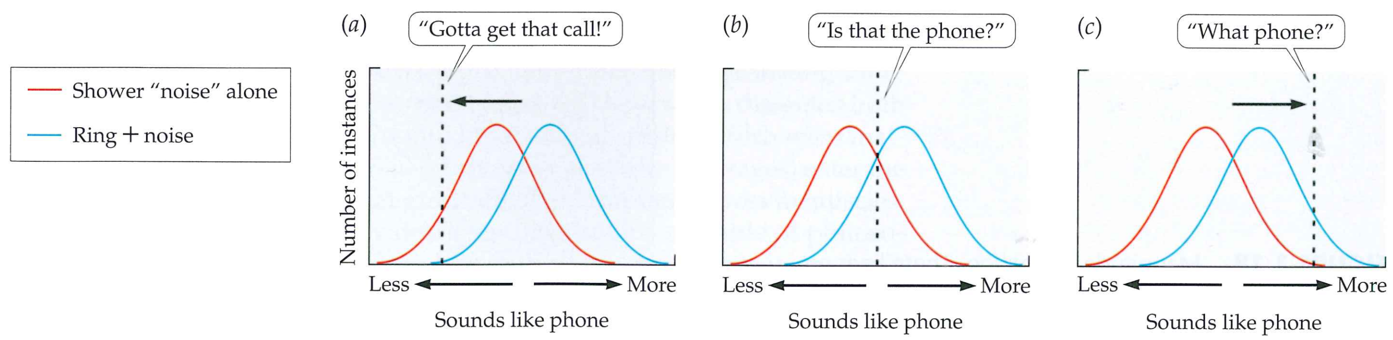


FIGURE 1.16 For a fixed *d′*, all that you can do is change the pattern of your errors by shifting your response criterion. If you don't want to miss any signals, you move your criterion to the left (*a*) but then you make more false alarms. If you don't like false alarms, move to the right (*c*) but then you make more miss errors. In all these case (*a–c*), your sensitivity, *d′*, remains the same.

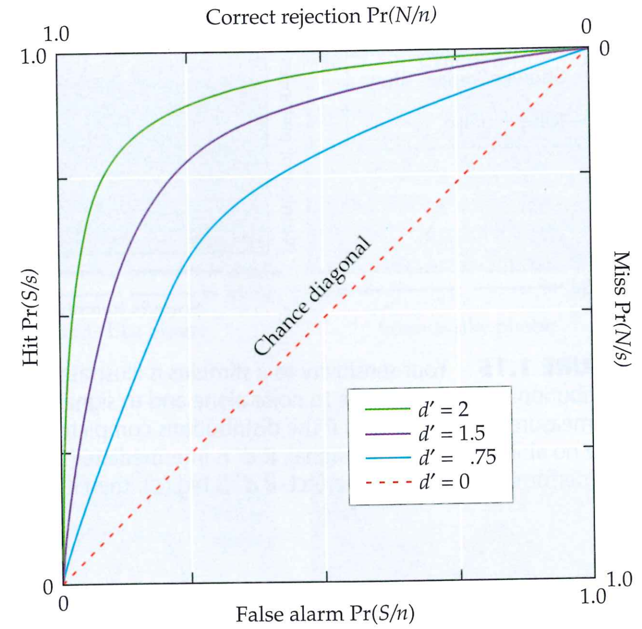


FIGURE 1.17 Theoretical receiver operating characteristics (ROC) curves for different values of d'. Note that $d' = 0$ when performance is at chance. When d' increases, the probability of hits and correct rejections increases, and the probability of misses and false alarms decreases.

signal detection theory A psychophysical theory that quantifies the response of an observer to the presentation of a signal in the presence of noise. Measures attained from a series of presentations are sensitivity (d') and criterion of the observer.

magnitude estimation A psychophysical method in which the participant assigns values according to perceived magnitudes of the stimuli.

The body of research that studies the detection of signals in noise in this manner is known as **signal detection theory** (D. M. Green and Swets, 1966). To learn about how to calculate d', and ROC curves, there are many useful websites and numerous texts (e.g., Macmillan and Creelman, 2005).

Before leaving our discussion of psychophysical methods, we should describe one more method. A very straightforward way to address how strong a sensation is would be simply to ask subjects how they rate it. If, for example, we play tones with different intensities varying from very soft to quite loud, what can the subject simply tell us? The methods to do this are called **magnitude estimation** (Figure 1.18). When using magnitude estimation, we might ask listeners to simply assign a number of their choice to each sound level. The

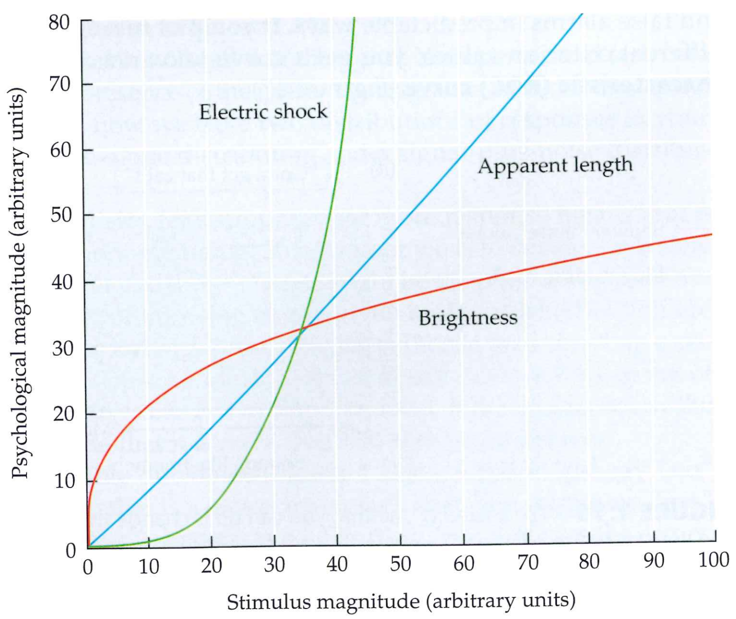


FIGURE 1.18 Magnitude estimation. These lines on this graph plot data from magnitude estimation experiments using electric shocks of different currents, lines of different lengths, and lights of different brightnesses. The exponents that describe these lines are 3.5, 1.1, and 0.33, respectively. For exponents greater than 1, such as for electric shock, Fechner's law does not hold, and Stevens' power law must be used instead. (From S. Stevens, 1961.)

only requirement is that the numbers make sense for the listener (e.g., they are bigger for louder tones). Although this approach actually works pretty well with subjects choosing their own range of numbers, one also can begin the experiment by playing one tone at an intermediate level and telling the listener that this level is a 10. All of the responses should then be sensibly above or below this standard of 10. Magnitude estimation also can be done across two senses. For example, we might ask the listener to adjust the brightness of a light until it matches the loudness of the tone.

Harvard psychologist S. S. Stevens (1962, 1975) invented magnitude estimation and found some interesting cases for which Fechner's law would not work. Following Weber's law, the larger a stimulus becomes, the larger the difference that is necessary to be detected. This is true for most measures, but Stevens found some judgments that work differently. Consider, for example, your sense of electric shock. As the amount of electrical current increases, you actually need less of an increase in order to notice the change. Unlike loudness and brightness, your sensation of shock increases faster than the physical increase in electricity. The painful conclusion is that Fechner's law will not work for these cases because logarithms apply only when sensation grows more slowly than the stimulus does. Weber fractions still can be used, but the fractions would be greater than one.

Stevens' power law A principle describing the relationship between stimulus magnitude and resulting sensation magnitude, such that the magnitude of subjective sensation is proportional to the stimulus magnitude raised to an exponent.

Stevens proposed what is now known as **Stevens' power law**: $S = aI^b$. It stated that the sensation (S) is related to the stimulus intensity (I) by an exponent (b). So, for example, sensation might be intensity squared ($I \times I$). Stimuli like lights that followed Fechner's law quite closely have exponents less than 1 in Stevens' law (about 0.3 for brightness, for example). In the painful case of electric shock, the pain grows with I^3, so an increase of 10-fold in the voltage is 1000-fold in the pain! Properties like length have exponents near 1, so, a 12-inch-long stick looks twice as long as a 6-inch stick.

Biology of Perception

During the eighteenth century, when Weber and Fechner were initiating the experimental study of perception, physiologists also were hard at work learning how the senses, and the brain itself, operate. Because some of this research would involve animals as models, developments in both philosophy and biology helped pave the way.

One of the intellectual developments that encouraged the study of animals can be attributed to Descartes. Because of his philosophy of body and mind, Descartes made the claim that animals were in most ways very similar to humans. His only distinction between humans and animals was that humans have minds and souls, so studying animals was a good way to learn about the material parts of humans. Descartes was very interested in learning more about the inner structure of bodies and brains, and he actually dissected both bodies and brains. Descartes proposed that animal spirits (which were matter, not mind—somewhat like mineral spirits or alcoholic beverages) enter the brain and exit through pores that guide this fluid through nerves to muscles. Of course, Descartes had many details wrong, but his example of philosophers developing a good understanding of the latest developments in physiology was maintained strongly for many years, and even today, many philosophers continue in this tradition, even though they rarely perform their own dissections or surgeries.

Even more encouragement for studying animals to understand how brains work came from the development of the theory of evolution. During the 1800s, Charles Darwin (1809–1882) proposed his revolutionary theory in *The*

FIGURE 1.19 Johannes Müller was a nineteenth-century physiologist who formulated the doctrine of specific nerve energies, which says that we are aware only of the activity in our nerves, and we cannot be aware of the world itself. For this reason, what is most important is *which* nerves are stimulated, not *how* they are stimulated.

doctrine of specific nerve energies A doctrine formulated by Johannes Müller stating that the nature of a sensation depends on which sensory fibers are stimulated, not on how fibers are stimulated.

cranial nerves Twelve pairs of nerves (one for each side of the body) that originate in the brain stem and reach sense organs and muscles through openings in the skull.

olfactory (I) nerves The first pair of cranial nerves, which conduct impulses from the mucous membranes of the nose to the olfactory bulb.

optic (II) nerves The second pair of cranial nerves, which arise from the retina and carry visual information to the thalamus and other parts of the brain.

auditory (VIII) nerves The eighth pair of cranial nerves, which connect the inner ear with the brain, transmitting impulses concerned with hearing and balance. The auditory nerve is composed of the cochlear nerve and the vestibular nerve and therefore is sometimes referred to as the "vestibulocochlear nerve."

oculomotor (III) nerves The third pair of cranial nerves, which innervate all the extrinsic muscles of the eye except the lateral rectus and the superior oblique muscles, and which innervate the elevator muscle of the upper eyelid, the ciliary muscle, and the sphincter muscle of the pupil.

trochlear (IV) nerves The fourth pair of cranial nerves, which innervate the superior or oblique muscles of the eyeballs.

abducens (VI) nerves The sixth pair of cranial nerves, which innervate the lateral rectus muscle of each eye.

Origin of Species (1859). Although many of the ideas found in that book had been brewing for some time, controversy expanded with vigor following Darwin's provocative arguments about how humans evolved from apes in *The Descent of Man* (1871). If humans share a rich genetic heritage with primates and other mammals, then we can learn much about the biology of human perception by studying the structure and function of our nonhuman relatives.

At the same time that Darwin was at work in England, the German physiologist **Johannes Müller** (1801–1858) (Figure 1.19) was writing a very influential book, his *Handbook of Physiology* (1838/1912). In addition to including most of what was then known about physiology, it was in this book that Müller formulated the **doctrine of specific nerve energies**. The central idea of this doctrine was expressed well in Morpheus's statement to Neo at the very beginning of this chapter: We are aware only of the activity in our nerves, and we cannot be aware of the world itself. Further, what is most important is *which* nerves are stimulated, and not *how* they are stimulated. For example, we see because the optic nerve leading from the eye to the brain is stimulated, but it does not matter whether light, or something else, stimulated the nerve. To prove to yourself that this is true, close your eyes and press very gently on the outside corner of one eye through the lid. (This works better in a darkened room.) You will see a spot of light toward the inside of your visual field by your nose. Despite the lack of stimulation by light, your brain interprets the input from your optic nerve as informing you about something visual.

The **cranial nerves** leading into and out of the skull illustrate the doctrine of specific nerve energies (Figure 1.20). The pair of optic nerves is one of 12 pairs of cranial nerves that pass through small openings in the bone at the base of the skull. The cranial nerves are dedicated mainly to sensory and motor systems. Cranial nerves are labeled both by name and by the Roman numeral that roughly corresponds to the order of their locations beginning from the front of the skull. Three of the cranial nerves—**olfactory (I)**, **optic (II)**, and **auditory (VIII)**—are exclusively dedicated to sensory information. Three more—**oculomotor (III)**, **trochlear (IV)**, and **abducens (VI)**—are dedicated to muscles that move the eyes. The other six cranial nerves either are exclusively motor (spinal accessory [XI] and hypoglossal [XII]) or convey both sensory and motor signals (trigeminal [V], facial [VII], glossopharyngeal [IX], and vagus [X]). With respect to our study of perception, later we will return to the first six cranial

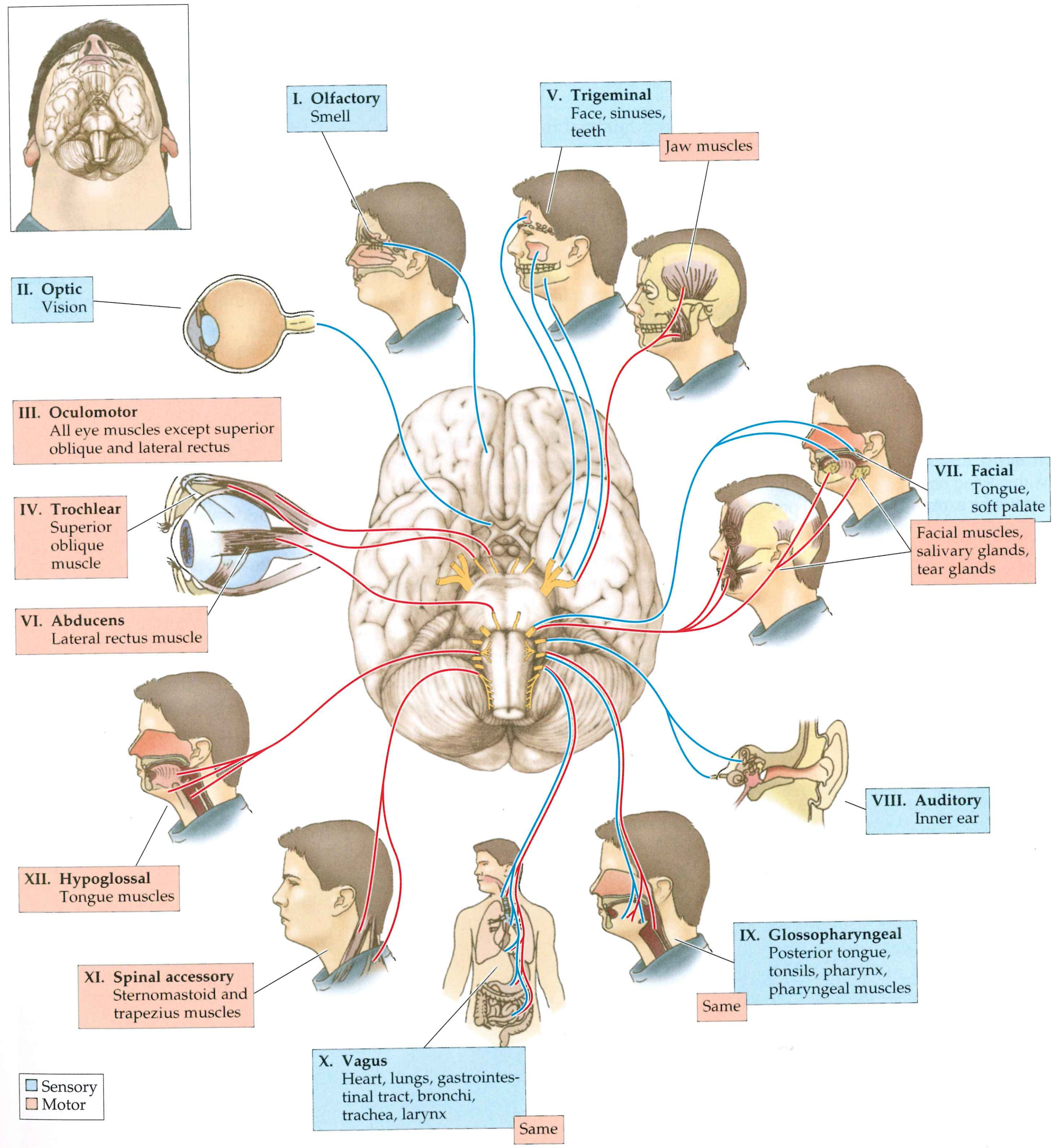


FIGURE 1.20 Twelve pairs of cranial nerves pass through small openings in the bone at the base of the skull. All of these nerves conduct information for sensation, motor behavior, or both. (After Rosenzweig, Breedlove, and Watson, 2005.)

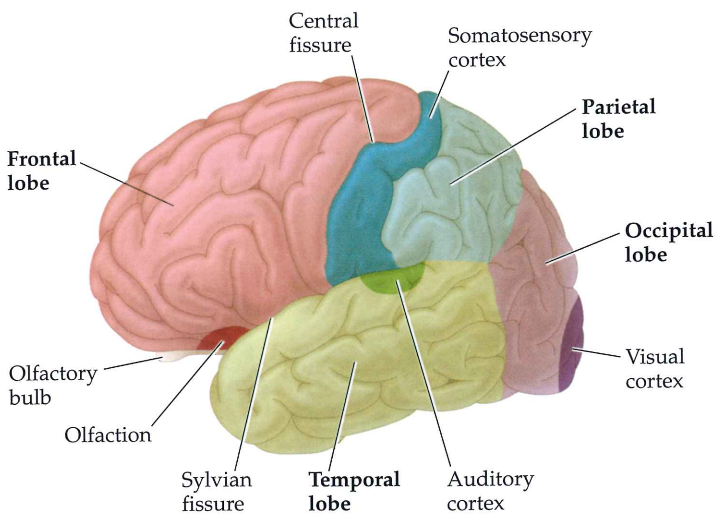


FIGURE 1.21 Cortex of the human brain. Some areas are dedicated primarily to processing information for individual senses.

polysensory A blending of multiple sensory systems.

vitalism Idea that "vital forces" are active within living organism, and these forces cannot be explained by physical processes of matter more generally.

nerves described here, because each one plays an important role in our ability to use our senses to learn about the world around us.

Just as cranial nerves are dedicated to individual sensory and motor tasks, areas of the brain stem and cerebral cortex are similarly dedicated to particular tasks. You will learn that areas of the cortex dedicated to perception actually are much larger than the darkened areas in Figure 1.21. The areas depicted here are primary sensory areas, and more complex processing is accomplished across cortical regions that spread well beyond these primary areas. For example, visual perception uses cortex that extends both anteriorly (forward) into parietal cortex and ventrally (lower) into regions of the temporal lobe. In addition, as processing extends beyond primary areas, cortex often becomes **polysensory**, meaning that information from more than one sense is being combined in some manner. (See **Web Activity 1.2 Sensory Areas in the Brain**.)

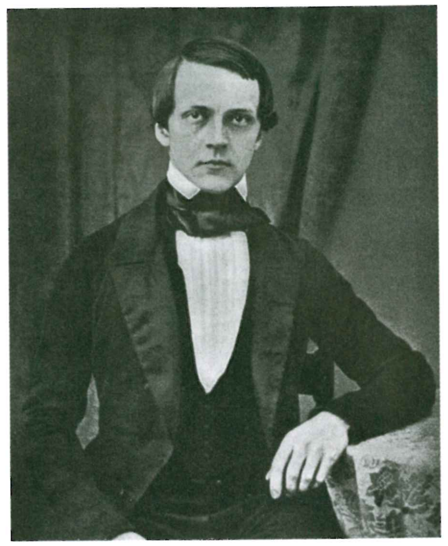


FIGURE 1.22 Hermann von Helmholtz was one of the greatest scientists of all time. He made many important discoveries in physiology and perception.

Hermann von Helmholtz

Hermann Ludwig Ferdinand von Helmholtz (1821–1894) (Figure 1.22), one of the greatest scientists of the nineteenth century, was greatly influenced by Müller at the University of Berlin. Young Helmholtz really wanted to study physics, but he could not afford to go to school to do so. Instead, he studied at a Berlin medical institution where he could attend for free on the condition that he later serve as a surgeon in the Prussian Army. This arrangement was much like the arrangement we have today for students who join the Reserve Officers' Training Corps (ROTC) as a way to pay their tuition. Even though Helmholtz was not a student at the university, he seized opportunities to attend lectures by Müller. When his time as an army surgeon was over and he was finally free to pursue what he really loved, Helmholtz became a junior professor of physiology at the University of Königsberg.

Although Helmholtz was initially inspired by Johannes Müller, he truly disliked one of Müller's ideas. Müller believed in **vitalism**, the idea that there is a force in life that is distinct from physical entities. You can see how vitalism fit well with the dualism of Descartes or, perhaps, the panpsychism of Fechner. Remember that Helmholtz really wanted to be a physicist, not a surgeon. He was an empiricist, in the tradition of Hobbes, Locke, Hume, and Berkeley. Like Thomas Hobbes, Helmholtz thought that all behavior should be explained by only physical forces. Vitalism violated the physical law of conservation of energy, and Helmholtz wanted the brain and behavior to obey purely physical laws. He chose a very smart place to begin his attack on vitalism. Müller had claimed that the nerve impulse could never be measured experimentally. So, Helmholtz set out to show that the activity of neurons obeys normal rules of physics and chemistry, by being the first to effectively measure how fast neurons transmit their signals. (See **Web Activity 1.3 Neurons**.)

When thinking about perception, it is very important to understand how long it takes for our brains to know what is happening in the world, and this requires knowing how fast nerve impulses are. At the time of Helmholtz's work, estimates ranged from 150 feet per second to as fast as 57,600 million feet per second—nearly 60 times the speed of light! Helmholtz thought that the fastest estimates must surely be wrong. If neurons truly were that fast, they would violate normal laws of physics and Müller could be right about vitalism.

In an early effort, Helmholtz estimated that the speed of signal transmission in the nerves in frog legs was only about 90 feet per second. Later he concluded that sensory nerves in people transmitted at between 165 and 330 feet per second. In all cases, this transmission was slower than many people believed at the time. Helmholtz emphasized this point when he noted that a "whale probably feels a wound near its tail in about one second, and requires another second to send back orders to the tail to defend itself" (Koenigsberger, 1906/1965, p. 72). As you may already have guessed, not all neurons are equal when it comes to speed; some are faster than others. It's still interesting to realize that you stub your toe a measurable amount of time before you feel that you have stubbed your toe.

Helmholtz became interested in vision, and again, he invented something completely new to study vision: the ophthalmoscope. You've seen your doctor or optometrist use this device to look directly at the retina, the sheet of blood vessels, receptors, and neurons across the back of your eye. In addition to assisting in diagnosing problems with the eye, the ophthalmoscope allows us to see the only part of the central nervous system that is visible from outside the skull. This invention was extremely valuable to physicians, and Helmholtz did well financially by selling ophthalmoscopes.

Helmholtz also made major discoveries about hearing. His book *On the Sensations of Tone* (1863/1954) begins as the study of music and perception. True to Helmholtz's love of physics, the text also became the classic book on

FIGURE 1.23 Helmholtz teamed up with Rudolph Koenig to create these resonators, now known as "Helmholtz resonators." Each resonator is tuned precisely to a certain frequency of vibration, and when the thin end is held at the ear, listeners can pick out a specific frequency from a complex sound. (Courtesy of Thomas B. Greenslade, Jr.)

(a)

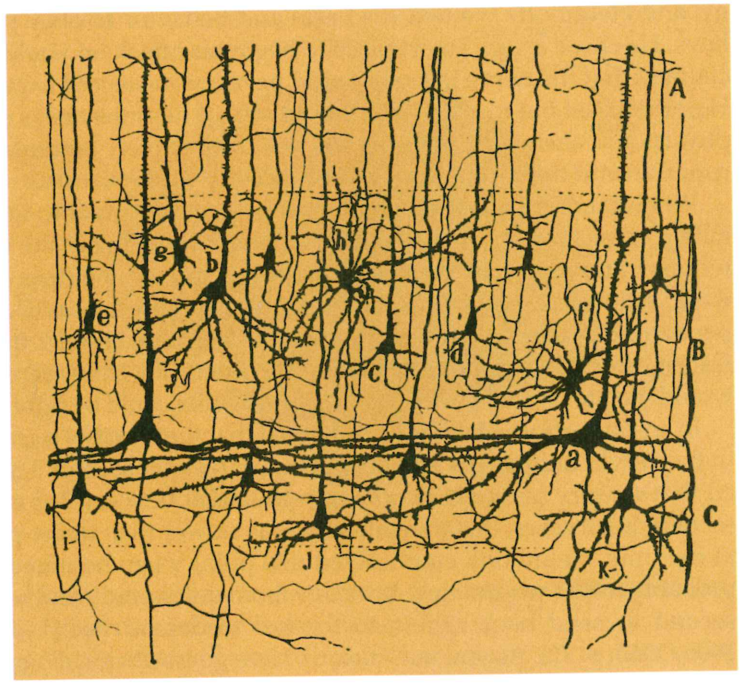

(b)


FIGURE 1.24 (*a*) Santiago Ramón y Cajal created these drawings (*b*) of brain neurons while peering into a microscope for many hours. Because of his painstaking care and accuracy, his early drawings are still cited today. (From Rosenzweig, Breedlove, and Watson, 2005.)

synapse The junction between neurons that permits information transfer.

vibration, particularly vibration in sound. Helmholtz conducted many listening experiments using resonators (Figure 1.23), and he was the first to hypothesize that our ability to hear sounds with different pitches depends on where sounds cause the most activity along the cochlea, a tiny snail-shaped structure of the ear that you will learn about in Chapter 9.

The Synapse

During the second half of the nineteenth century, when Helmholtz was making stunning discoveries concerning vision and hearing, other scientists were learning a great deal about how neurons and brains work. After nearly dying of malaria in Cuba, the Spaniard **Santiago Ramón y Cajal** (1852–1934) (Figure 1.24*a*) returned to his homeland to create some of the most painstaking and breathtaking insights into the organization of neurons in the brain. Spending many hours over a microscope, he created spectacular detailed drawings of neurons and their connections ever created. Figure 1.24*b* shows an example. Ramón y Cajal's drawings suggested that neurons do not actually touch one another. Instead, neurons are separate cells with tiny gaps between them. **Sir Charles Sherrington** (1857–1952) (Figure 1.25) named the tiny gap between the axon of one neuron and the dendrite of the next a **synapse** (Figure 1.26), from the Greek word meaning "to fasten together." Sherrington made very careful measurements demonstrating that the speed of neural transmission decreased at synapses, and this work helped us understand that something special happens at this junction where neurons meet to communicate.

FIGURE 1.25
Sir Charles Sherrington.

Neurotransmitters

For some time, people thought that some sort of electrical wave travels across the synapse from one neuron to the next. **Otto Loewi** (1873–1961) (Figure

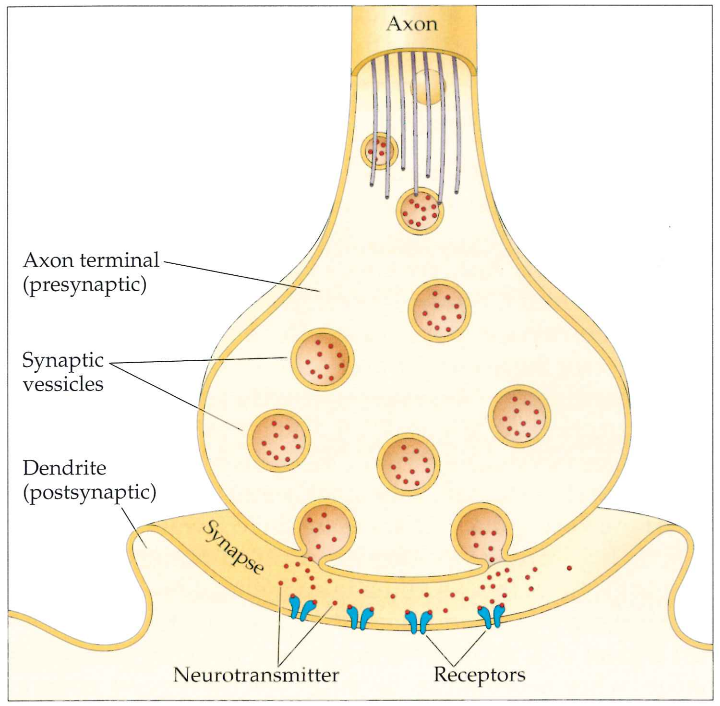


FIGURE 1.26 An axon terminal (presynaptic) binds to the dendrite (postsynaptic). Neurotransmitters are released by synaptic vesicles in the axon and fit into receptors on the dendrite on the other side of the synapse, thus communicating from the axon of the first neuron to the dendrite of the second neuron.

1.27), however, was convinced that this could not be true. One reason is that some neurons increase the response of the next neuron (that is, they are excitatory), but other neurons decrease the response of the next (they are inhibitory). Loewi began thinking that something chemical, instead of electrical, might be at work at the synapse. In the middle of the night before Easter in 1920, he suddenly awoke with an idea for an experimental test of his chemical hypothesis. Unfortunately, the notes that he scribbled then were indecipherable to poor Otto on Easter morning. As luck would have it, at 3:00 a.m. the next morning, he awoke again with the same idea. Not wishing to make the same mistake, instead of scribbling notes, Loewi headed to his laboratory to test his idea.

neurotransmitter A chemical substance used in neuronal communication at synapses.

Loewi's experiment is really quite elegant. He took advantage of the fact that frog hearts continue to beat for some time if they are placed in Ringer solution, a mixture of saltwater (saline) and other chemicals that preserve tissue function. He took two frog hearts, one with the vagus nerve attached and one with it removed. Stimulating the vagus nerve causes heart muscles to beat more slowly. He stimulated the vagus nerve of the one heart, thus slowing it down. Next he took the Ringer solution from this first heart and poured it over the second heart. The beating of the second heart quickly decreased in frequency, as if the vagus nerve had been stimulated. From this simple, pioneering experiment, Loewi demonstrated that stimulation of the vagus nerve released a chemical that slowed the activity of heart muscle.

This simple bit of Easter inspiration launched many studies about molecules that travel from the axon across the synapse to the dendrite of the next neuron. These molecules are called **neurotransmitters**. There are many different kinds of neurotransmitters in the brain, and individual neurons are selective with respect to which neurotransmitters excite or inhibit them from firing. Drugs that are psychoactive, such as amphetamines, work by increasing or decreasing the effectiveness of different neurotransmitters. Today, scientists

FIGURE 1.27 Otto Loewi.

FIGURE 1.28
Sir Alan Hodgkin.

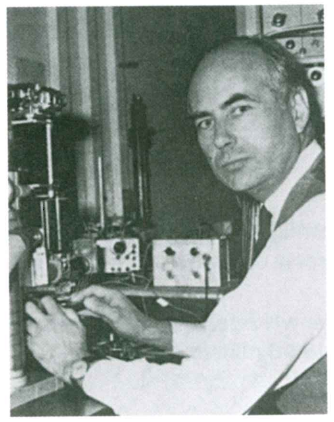


FIGURE 1.29
Sir Andrew Huxley.

use chemicals that influence the effects of neurotransmitters in efforts to understand pathways in the brain, including those that are used in perception.

Neural Firing: The Action Potential

Later, scientists learned what it really means to have a neuron "fire." The greatest early advances were made by taking advantage of the fact that some squids have giant neurons that are as thick as 1 mm. **Sir Alan Hodgkin** (1914–1998) (Figure 1.28) and **Sir Andrew Huxley** (born 1917) (Figure 1.29) conducted experiments in which they could isolate a single neuron from the giant squid and test how the nerve impulse travels along the axon. With such large axons, they could pierce the axon with an electrode to measure voltage, and they could even inject different chemicals inside. They learned that neural firing is actually electrochemical (Figure 1.30). Voltage increases along the axon are caused by changes in the membrane of the neuron that permit positively charged sodium ions (Na^+) to rush very quickly into the axon from outside. Then the membrane very quickly changes again in a way that pushes positively charged potassium ions (K^+) outside the axon, restoring the neuron to its initial resting voltage. All of this—sodium in and potassium out—occurs in about one one-thousandth of a second every time a neuron fires.

We have learned a great deal about how our senses work by measuring these electrical changes when neurons fire. Because even the biggest axons in mammals are much much smaller than the giant squid axon, it is difficult and even rare to be able to insert an electrode inside of a neuron. Usually we measure electrical changes from close outside of mammalian neurons. By measuring the speed and timing of neurons firing, we can learn about how individual neurons encode and transmit information from sense organs through higher levels of the brain.

It is through these tiny electrochemical signals that we learn about the world around us. Or, as Morpheus would say, "If you're talking about what you can feel, what you can smell, what you can taste and see, then real is simply electrical signals interpreted by your brain. This is the world that you know."

Now that you know a little about the very long history and philosophy of thinking and experimenting about perception, it's time to move forward. Just as Neo says at the very end of *The Matrix*, "I didn't come here to tell you how this is going to end. I came here to tell you how it's going to begin." We hope you enjoy learning how we know what is real, or at least, how we know what we think is real.

Refer to the ***Sensation and Perception*** website (www.sinauer.com/wolfe) for activities, essays, study questions, and other study aids.

Summary

1. Since the time of the earliest writings by philosophers, it has been clear that our perception of reality is limited by what we can learn from our five senses. We are capable of detecting and using only a tiny fraction of the energy and events that occur all around us.
2. Nativists address the limitations on our sensory systems by suggesting that much or most true knowledge is innate within individuals.
3. Empiricists concede that all we can ever know must be learned through our sensory experiences. Part of being an empiricist is acknowledging that some things are simply unknowable because we cannot learn about them through our senses.
4. Another enduring philosophical question that matters for perception is the relationship between mind and body. One common idea is dualism, the assumption that people have material bodies, and that they also have immaterial minds.

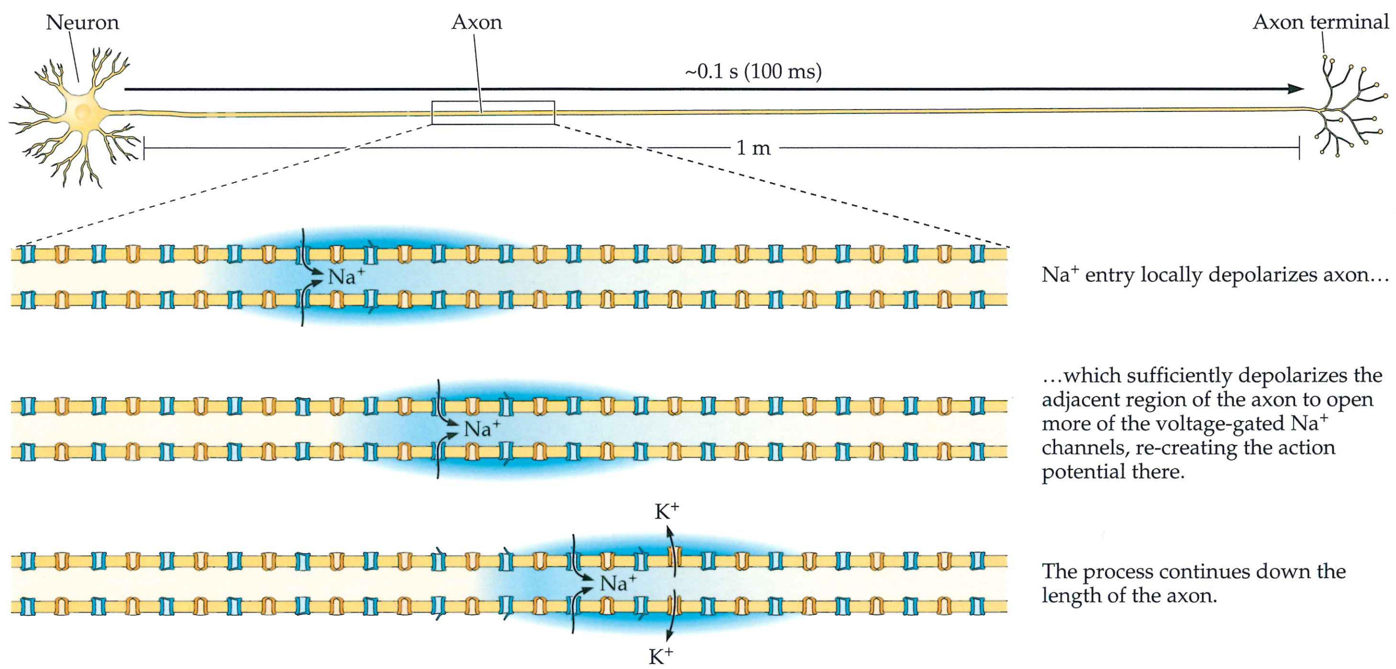


FIGURE 1.30 An action potential (firing) of a neuron is created when the membrane of the neuron permits sodium ions (Na^+) to rush into the cell, thus increasing the voltage. Very quickly afterward, potassium (K^+) flows out of the cell, bringing the voltage back to resting voltage. This process occurs along the length of the axon until the action potential reaches the axon terminal.

One challenge for dualism is to explain how the immaterial mind, which has no mass and takes up no space, can affect the material body. Gustav Fechner invented psychophysics as part of his efforts to scientifically establish the relationship between mind and matter.

5. Gustav Fechner invented several clever methods for measuring the relationship between physical changes in the world and consequent psychological changes in observers. These methods remain in use today.
6. A more recent development for understanding performance—signal detection theory—permits us to simulate changes in the perceiver (e.g., internal noise and biases) in order to understand perceptual performance better.
7. We learn a great deal about perception by understanding the biological structures and processes that are involved. One early observation—the doctrine of specific nerve energies—expresses the fact that people are aware only of the activity of our nervous systems. For this reason, what matters is which nerves are stimulated, not how they are stimulated. The central nervous system reflects specializations for the senses from cranial nerves through to areas of the cerebral cortex involved in perception.
8. The essential activities of all neurons, including those involved in sensory processes, are chemical and electrochemical. Neurons communicate with each other through neurotransmitters, molecules that cross the synapse from the axon of one neuron to the dendrite of the next. Nerve impulses are electrochemical; voltages change along the axon as electrically charged ions (sodium and potassium) pass in and out of the membranes of nerve cells.