4

CHAPTER FOUR

# Sensation and Perception


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**WHERE DO YOU STAND?** Perception and Persuasion


N *is sort of . . . rubbery . . . smooth,* L *is sort of the consistency of watery paint . . . Letters also have vague personalities, but not as strongly as numerals do.*
—Julieta

*The letter* A *is blue,* B *is red,* C *is kind of a light gray,* D *is orange. . . .*
—Karen

*I hear a note by one of the fellows in the band and it's one color. I hear the same note played by someone else and it's a different color. When I hear sustained musical tones, I see just about the same colors that you do, but I see them in textures.*
—Jazz musician Duke Ellington (George, 1981, p. 226)

*Basically, I taste words.*
—Amelia

THESE COMMENTS ARE NOT FROM A recent meeting of the Slightly Odd Society. They're the remarks of otherwise perfectly normal people describing what seem to be perfectly bizarre experiences except to them; they think these experiences are quite commonplace and genuine. After all, if you can't trust Duke Ellington, an internationally acclaimed jazz composer and bandleader, who can you trust? Perhaps Stevie Wonder? Eddie Van Halen? Vladimir Nabokov, the author of *Lolita*? Franz Liszt, the classical composer? Richard Feynman, the Nobel Prize–winning physicist? Take your pick because these and many other notable people have at least one thing in common: Their perceptual worlds seem to be quite different from most of ours. ■

*What do these people have in common? Duke Ellington, Stevie Wonder, Eddie Van Halen, and Franz Liszt are all musicians, but Richard Feynman was a physicist. All of these people are men, but that has little to do with it. Some are living; some are dead. In fact, all of these people have fairly well-documented experiences of synesthesia, the experience of one sense that is evoked by a different sense.*

*Duke Ellington* METRONOME/GETTY IMAGES
*Stevie Wonder* EVERETT KENNEDY BROWN/EPA/CORBIS
*Eddie Van Halen* MARK DAVIS/GETTY IMAGES
*Franz Liszt* W. & D. DOWNEY/GETTY IMAGES
*Richard Feynman* SHELLEY GAZIN/CORBIS
©ISTOCKPHOTO

These unusual perceptual events are varieties of *synesthesia*, the perceptual experience of one sense that is evoked by another sense (Hubbard & Ramachandran, 2003). For some synesthetes, musical notes evoke the visual sensation of color. Other people with synesthesia see printed letters (**FIGURE 4.1**) or numbers in specific, consistent colors (always seeing the digit 2 as pink and 3 as green, for example). Still others experience specific tastes when certain sounds are heard.

A B C D E

(a) Usual appearance

A B C D E

(b) Appearance to a person with synesthesia

**FIGURE 4.1** **Synesthesia** *Most of us see letters printed in black as they appear in (a). Some people with synesthesia link their perceptions of letters with certain colors and perceive letters as printed in different colors, as shown in (b). In synesthesia, brain regions for different sensory modalities cross-activate one another.*

For those of us who don't experience synesthesia, the prospect of tasting sounds or hearing colors may seem unbelievable or the product of some hallucinogenic experience. Indeed, for many years scientists dismissed synesthesia as either a rare curiosity or a case of outright faking. But recent research indicates that synesthesia is far more common than previously believed: some forms of synesthesia may be found in as many as 1 in every 100 people (Hubbard & Ramachandran, 2005).

Recent research has documented the psychological and neurobiological reality of synesthesia. For example, a synesthete who sees the digits 2 and 4 as pink and 3 as green will find it easier to pick out a 2 among a bunch of 3s than among a bunch of 4s, whereas a nonsynesthete will perform these two tasks equally well (Palmieri, Ingersoll, & Stone, 2002). Brain-imaging studies also show that in some synesthetes, areas of the brain involved in processing colors are more active when they hear words that evoke color than when they hear tones that don't evoke color; no such differences are seen among people in a control group (Nunn, Gregory, & Brammer, 2002).

So, synesthesia may indicate that in some people, the brain is "wired" differently than in most, so that brain regions for different sensory modalities cross-activate one another (Ramachandran & Hubbard, 2003). Whatever the ultimate explanations for these fascinating phenomena, this recent wave of research shows that synesthesia is a mindbug that can shed new light on how the brain is organized and how we sense and perceive the world.

In this chapter, we'll explore key insights into the nature of sensation and perception. These experiences are basic to survival and reproduction; we wouldn't last long without the ability to accurately make sense of the world around us. Indeed, research on sensation and perception is the basis for much of psychology, a pathway toward understanding more complex cognition and behavior such as memory, emotion, motivation, or decision making. Yet sensation and perception also sometimes reveal mindbugs, ranging from the complexities of synesthesia to various kinds of perceptual illusions that you might see at a science fair or in a novelty shop. These mindbugs are reminders that the act of perceiving the world is not as simple or straightforward as it might seem.

## The Doorway to Psychology

**Sensation** is *simple awareness due to the stimulation of a sense organ.* It is the basic registration of light, sound, pressure, odor, or taste as parts of your body interact with the physical world. After a sensation registers in your central nervous system, **perception** takes place at the level of your brain: It is *the organization, identification, and interpretation of a sensation in order to form a mental representation.* As an example, your eyes are coursing across these sentences right now. The sensory receptors in your eyeballs are registering different patterns of light reflecting off the page. Your brain, however, is integrating and processing that light information into the meaningful perception of words, such as *meaningful, perception,* and *words.* Your eyes—the sensory organ—aren't really seeing words; they're simply encoding different shapes and patterns of ink on a page. Your brain—the perceptual organ—is transforming those shapes into a coherent mental representation of words and concepts.

**sensation** Simple awareness due to the stimulation of a sense organ.

**perception** The organization, identification, and interpretation of a sensation in order to form a mental representation.

**transduction** What takes place when many sensors in the body convert physical signals from the environment into neural signals sent to the central nervous system.

If all of this sounds a little peculiar, it's because from the vantage point of your conscious experience, it *seems* as if you're reading words directly; sensation and perception feel like one continuous, seamless event. If you think of the discussion of brain damage in Chapter 3, however, you'll recall that sometimes a person's eyes can work just fine, yet the individual is still "blind" to faces she has seen for many years. Damage to the visual-processing centers in the brain can interfere with the interpretation of information coming from the eyes. The senses are intact, but perceptual ability is compromised. Sensation and perception are related—but separate—events.

We all know that sensory events involve vision, hearing, touch, taste, and smell. Arguably, we possess several more senses besides these five. Touch, for example, encompasses distinct body senses, including sensitivity to pain and temperature, joint position and balance, and even the state of the gut—perhaps to sense nausea via the autonomic nervous system. Despite the variety of our senses, they all depend on the process of **transduction**, which is *the conversion, by sensors in the body, of physical signals from the environment into neural signals sent to the central nervous system*.

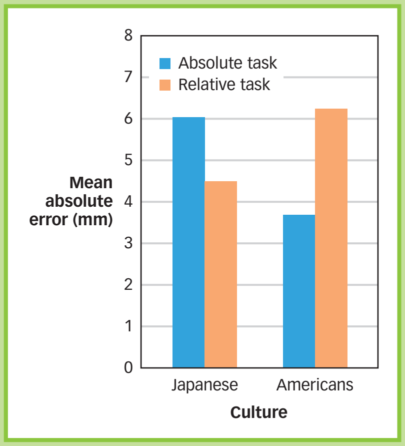
**What role does the brain play in what we see and hear?**

In vision, light reflected from surfaces provides the eyes with information about the shape, color, and position of objects. In audition, vibrations (from vocal cords or a guitar string, perhaps) cause changes in air pressure that propagate through space to a listener's ears. In touch, the pressure of a surface against the skin signals its shape, texture, and temperature. In taste and smell, molecules dispersed in the air or dissolved in saliva reveal the identity of substances that we may or may not want to eat. In each case physical energy from the world is converted to neural energy inside the central nervous system. We've already seen that synesthetes experience a mixing of these perceptions; however, even during synesthesia the processes of transduction that begin those perceptions are the same. Despite "hearing colors," your eyes simply can't transduce sound waves, no matter how long you stare at your stereo speakers!

## Culture & Community

### Our Brains Interpret Messages from Our Senses and Transform Them into Meaningful Words, Images, and Concepts. Is This Process Universal, or Might Culture Influence Perception?

In an experiment, researchers gave Japanese and American participants a sheet of paper with a square drawn on it, within which was printed a single vertical line (Kitayama et al., 2003). The participants were then given the task of reproducing the single line within a second, smaller box in (a) absolute terms (reproducing the exact length of the line from the original box) and (b) relative terms (reproducing a line proportional to the new height of the surrounding box).




In support of the researchers' hypothesis, Japanese were significantly more accurate at the relative task than the absolute task, whereas Americans were significantly more accurate at the absolute task than the relative task. Interestingly, when testing Americans living in Japan or Japanese living in America, the participants tended to show an increase in the skill appropriate to their host nation.

## Psychophysics

It's intriguing to consider the possibility that our basic perceptions of sights or sounds might differ fundamentally from those of other people. One reason we find synesthetes fascinating is because their perceptual experiences are so different from most of ours. But we won't get very far in understanding such differences by simply relying on casual self-reports. As you learned in Chapter 2, to understand a behavior, researchers must first *operationalize* it, and that involves finding a reliable way to measure it.

Any type of scientific investigation requires objective measurements. Measuring the physical energy of a stimulus, such as the color and brightness of a light, is easy enough: You can probably

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*You can enjoy a tempting sundae even if you do not know that its sweet taste depends on a complex process of transduction, in which molecules dissolved in saliva are converted to neural signals processed by the brain.*

buy the necessary instruments online to do that yourself. But how do you quantify a person's private, subjective *perception* of that light? The structuralists, led by Wilhelm Wundt, tried using introspection to measure perceptual experiences (see Chapter 1). They failed miserably at this task. After all, you can describe your experience to another person in words, but that person cannot know directly what you perceive when you look at a sunset. You both may call the sunset "orange" and "beautiful," but neither of you can directly perceive the other's experience of the same event. Evoked memories and emotions intertwine with what you are hearing, seeing, and smelling, making your perception of an event—and therefore your experience of that event—unique.

**Why is the perception of any event unique to yourself?**

Given that perception is different for each of us, how could we ever hope to measure it? This question was answered in the mid-1800s by the German scientist and philosopher Gustav Fechner (1801–1887). Fechner developed an approach to measuring sensation and perception called **psychophysics:** *methods that measure the strength of a stimulus and the observer's sensitivity to that stimulus* (Fechner, 1966/1860). In a typical psychophysics experiment, researchers ask people to make a simple judgment—whether or not they saw a flash of light, for example. The psychophysicist then relates the measured stimulus, such as the brightness of the light flash, to each observer's yes-or-no response.

**TABLE 4.1**

**Approximate Sensory Thresholds**

| Sense | Absolute Threshold | |
|---|---|---|
| Vision | A candle flame 30 miles away on a clear, dark night |  JANOS MISETA FEATUREPICS |
| Hearing | A clock's tick 20 feet away when all is quiet |  RAINFORESTAUSTRALIA ISTOCKPHOTO |
| Touch | A fly's wing falling on the cheek from one centimeter away |  TYLER OLSON FEATUREPICS |
| Smell | A single drop of perfume diffused through an area equivalent to the volume of six rooms |  MARCO ANDRAS EST AGEFOTOSTOCK |
| Taste | A teaspoon of sugar dissolved in two gallons of water |  FOODFOLIO ALAMY |

*Source:* Adapted from Galanter (1962).

## Measuring Thresholds

The simplest quantitative measurement in psychophysics is the **absolute threshold,** *the minimal intensity needed to just barely detect a stimulus.* A *threshold* is a boundary. The doorway that separates the inside from the outside of a house is a threshold, as is the boundary between two psychological states ("awareness" and "unawareness," for example). In finding the absolute threshold for sensation, the two states in question are *sensing* and *not sensing* some stimulus. **TABLE 4.1** lists the approximate sensory thresholds for each of the five senses.

To measure the absolute threshold for detecting a sound, for example, an observer sits in a soundproof room wearing headphones linked to a computer. The experimenter presents a pure tone (the sort of sound made by striking a tuning fork), using the computer to vary the loudness or the length of time each tone lasts and recording how often the observer reports hearing that tone under each condition. Investigators typically define the absolute threshold as the loudness required for the listener to say she or he has heard the tone on 50% of the trials.

If we repeat this experiment for many different tones, we can observe and record the thresholds for tones ranging from very low pitch to very high. It turns out that people tend to be most sensitive to the range of tones corresponding to human conversation. If the tone is low enough, such as the lowest note on a pipe organ, most humans cannot hear it at all; we can only feel it. If the tone is high enough, we likewise cannot hear it, but dogs and many other animals can.

**Why can parents identify their own child's cry over others?**

The absolute threshold is useful for assessing how sensitive we are to faint stimuli, but most everyday perception involves detecting differences among stimuli that are well above the absolute threshold. Most people are pretty adept at noticing that a couch is red, but they're likely to want to know if the couch is redder than the drapes they're considering. Similarly, parents can usually detect their own infant's cry from the cries of other babies, but it's probably more useful to be able to differentiate the "I'm hungry" cry from the "I'm cranky" cry from the "Something is biting my toes" cry. In short, the human perceptual system excels at detecting *changes* in stimulation rather than the simple onset or offset of stimulation.

As a way of measuring this difference threshold, Fechner proposed the **just noticeable difference**, or **JND**—*the minimal change in a stimulus that can just barely be detected*. The JND is not a fixed quantity; rather, it is roughly proportional to the magnitude of the standard stimulus. This relationship was first noticed in 1834 by a German physiologist named Ernst Weber, and it is now called **Weber's law**, which states that *the just noticeable difference of a stimulus is a constant proportion despite variations in intensity.* As an example, the JND for weight is about 2%. If you picked up a one-ounce envelope, then a two-ounce envelope, you'd probably notice the difference between them. But if you picked up a five-pound package, then a five-pound, one-ounce package, you'd probably detect no difference at all between them. In fact, you'd probably need about a five-and-a-half-pound package to detect a JND. When calculating a difference threshold, it is the proportion between stimuli that is important; the measured size of the difference, whether in brightness, loudness, or weight, is irrelevant.

**psychophysics** Methods that measure the strength of a stimulus and the observer's sensitivity to that stimulus.

**absolute threshold** The minimal intensity needed to just barely detect a stimulus.

**just noticeable difference (JND)** The minimal change in a stimulus that can just barely be detected.

**Weber's law** The just noticeable difference of a stimulus is a constant proportion despite variations in intensity.

**signal detection theory** An observation that the response to a stimulus depends both on a person's sensitivity to the stimulus in the presence of noise and on a person's response criterion.

## Signal Detection

Measuring absolute and difference thresholds requires a critical assumption: that a threshold exists! But much of what scientists know about biology suggests that such a discrete, all-or-none change in the brain is unlikely. Humans don't suddenly and rapidly switch between perceiving and not perceiving; in fact, the transition from *not sensing* to *sensing* is gradual. The very same physical stimulus, such as a dim light or a quiet tone, presented on several different occasions, may be perceived by the same person on some occasions but not on others. Remember, an absolute threshold is operationalized as perceiving the stimulus 50% of the time . . . which means the other 50% of the time it might go undetected.

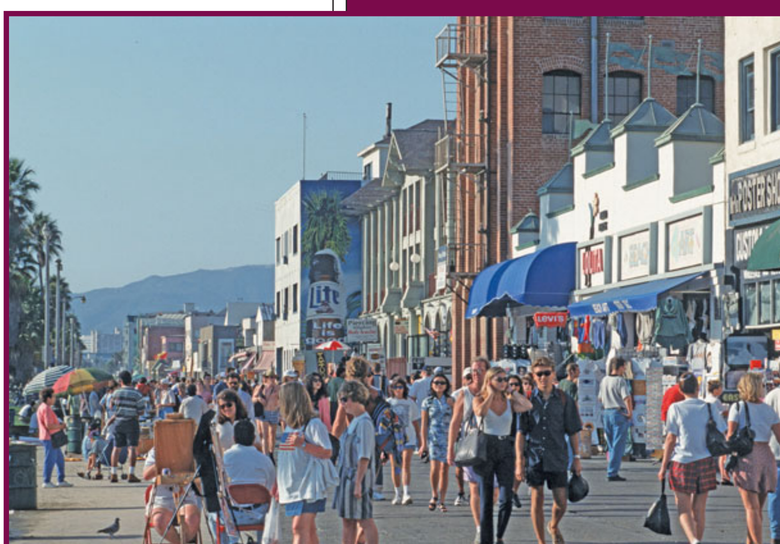
Our accurate perception of a sensory stimulus, then, can be somewhat haphazard. Whether in the psychophysics lab or out in the world, sensory signals face a lot of competition, or *noise,* which refers to all the other stimuli coming from the internal and external environment. Memories, moods, and motives intertwine with what you are seeing, hearing, and smelling at any given time. This internal "noise" competes with your ability to detect a stimulus with perfect, focused attention. Other sights, sounds, and smells in the world at large also compete for attention; you rarely have the luxury of attending to just one stimulus apart from everything else. As a consequence of noise, you may not perceive everything that you sense, and you may even perceive things that you haven't sensed.

● How accurate and complete are our perceptions of the world?

An approach to psychophysics called **signal detection theory** holds that *the response to a stimulus depends both on a person's sensitivity to the stimulus in the presence of noise and on a person's response criterion*. That is, observers consider the sensory evidence evoked by the stimulus and compare it to an internal decision criterion (Green & Swets, 1966; Macmillan & Creelman, 2005). If the sensory evidence exceeds the criterion, the observer responds by saying, "Yes, I detected the stimulus"; if it falls short of the criterion, the observer responds by saying, "No, I did not detect the stimulus."

Signal detection theory is a more sophisticated approach than was used in the early days of establishing absolute thresholds. Back then, it might have been assumed that everyone (or at least a majority of observers)

*Cluttered environments such as this promenade in Venice Beach, California, present our visual system with a challenging signal detection task.*



ERNST WRBA/ALAMY

**sensory adaptation** Sensitivity to prolonged stimulation tends to decline over time as an organism adapts to current conditions.

heard a tone or saw a flickering candle flame with equal facility. Signal detection theory, in contrast, explicitly takes into account observers' response tendencies, such as liberally saying, "Yes," or reserving identifications only for obvious instances of the stimulus.

For example, a radiologist may have to decide whether a mammogram shows that a patient has breast cancer. The radiologist knows that certain features, such as a mass of a particular size and shape, are associated with the presence of cancer. But noncancerous features can have a very similar appearance to cancerous ones. The radiologist may decide on a strictly liberal criterion and check every possible case of cancer with a biopsy. This decision strategy minimizes the possibility of missing a true cancer but leads to many false alarms. A strictly conservative criterion will cut down on false alarms but will miss some treatable cancers.

These different types of errors have to be weighed against one another in setting the decision criterion. Signal detection theory offers a practical way to choose among criteria that permit decision makers to take into account the consequences of hits, misses, false alarms, and correct rejections (McFall & Treat, 1999; Swets, Dawes, & Monahan, 2000). (For an example of a common everyday task that can interfere with signal detection, see the Real World box, on the next page.)

## Sensory Adaptation

When you walk into a bakery, the aroma of freshly baked bread overwhelms you, but after a few minutes the smell fades. If you dive into cold water, the temperature is shocking at first, but after a few minutes you get used to it. When you wake up in the middle of the night for a drink of water, the bathroom light blinds you, but after a few minutes you no longer squint. These are all examples of **sensory adaptation**, the observation that *sensitivity to prolonged stimulation tends to decline over time as an organism adapts to current conditions*.

● What conditions have you already adapted to today? Sounds? Smells?

Sensory adaptation is a useful process for most organisms. Imagine what your sensory and perceptual world would be like without it. When you put on your jeans in the morning, the feeling of rough cloth against your bare skin would be as noticeable hours later as it was in the first few minutes. The stink of garbage in your apartment when you first walk in would never dissipate. If you had to constantly be aware of how your tongue feels while it is resting in your mouth, you'd be driven to distraction. Our perceptual systems respond more strongly to changes in stimulation rather than to constant stimulation. A stimulus that doesn't change usually doesn't require any action; your car probably emits a certain hum all the time that you've gotten used to. But a change in stimulation often signals a need for action. If your car starts making different kinds of noises, you're not only more likely to notice them, but you're also more likely to do something about it.

### summary quiz [4.1]

1. Sensation and perception
   a. are basically the same process.
   b. are two completely different and unrelated processes.
   c. are related but separate events.
   d. feel like two distinct events.

2. The minimal intensity needed to just barely detect a stimulus is called the
   a. just noticeable difference.
   b. receptive field.
   c. absolute threshold.
   d. difference threshold.

3. Dr. Gonzalez, a radiologist, uses a very liberal criterion when she reads mammograms. She recommends a biopsy for every possible case of cancer. This decision strategy

a. maximizes the chances of missing a true cancer and also leads to many false alarms.
b. minimizes the chances of missing a true cancer but also minimizes false alarms.
c. minimizes the chances of missing a true cancer but also leads to many false alarms.
d. maximizes the chances of missing a true cancer but minimizes the chances of false alarms.

4. If you dive into cold water, the temperature seems chilling at first, but after a few minutes you don't notice it. This is an example of
a. accommodation.
b. Weber's law.
c. sensory adaption.
d. signal detection.

[THE REAL WORLD]

## Multitasking

By one estimate, using a cell phone while driving makes having an accident four times more likely (McEvoy et al., 2005). In response to highway safety experts and statistics such as this, state legislatures are passing laws that restrict, and sometimes ban, using mobile phones while driving. You might think that's a fine idea . . . for everyone else on the road. But surely *you* can manage to punch in a number on a phone, carry on a conversation, or maybe even text-message while simultaneously driving in a safe and courteous manner. Right?

In a word, *wrong.* The issue here is *selective attention,* or perceiving only what's currently relevant to you. Try this. Without moving a muscle, think about the pressure of your skin against your chair right now. Effortlessly you shifted your attention to allow a sensory signal to enter your awareness. This simple shift shows that your perception of the world depends both on what sensory signals are present and on your choice of which signals to attend to and which to ignore. Perception is an active, moment-to-moment exploration for relevant or interesting information, not a passive receptacle for whatever happens to come along.

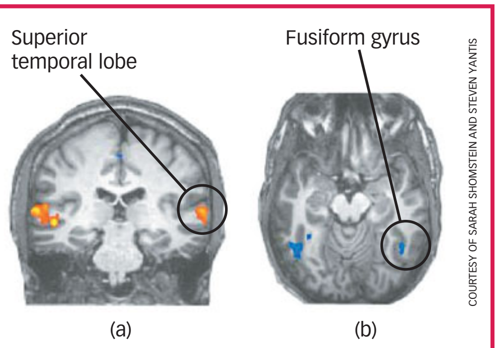
Talking on a cell phone while driving demands that you juggle two independent sources of sensory input—vision and audition—the same time. Normally this kind of *multitasking* works rather well. It's only when you need to react suddenly that your driving performance may suffer. Researchers have tested experienced drivers in a highly realistic driving simulator, measuring their response times to brake lights and stop signs while they listened to the radio or carried on phone conversations about a political issue, among other tasks (Strayer, Drews, & Johnston, 2003)

These experienced drivers reacted significantly slower during phone conversations than during the other tasks. This is because a phone conversation requires memory retrieval, deliberation, and planning what to say and often carries an emotional stake in the conversation topic. Tasks such as listening to the radio require far less attention or none at all.

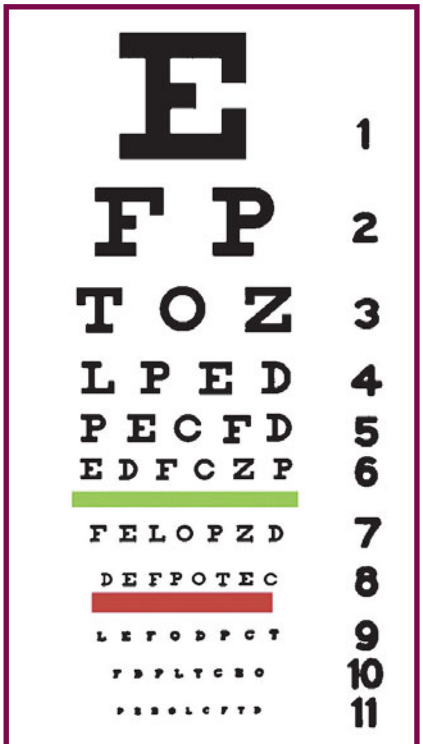
The tested drivers became so engaged in their conversations that their minds no longer seemed to be in the car. Their slower braking response translated into an increased stopping distance that, depending on the driver's speed, would have resulted in a rear-end collision. Whether the phone was handheld or hands free made little difference. This suggests that laws requiring drivers to use hands-free phones may have little effect on reducing accidents.

Other researchers have measured brain activity using fMRI while people were shifting attention between visual and auditory information. When attention was directed to audition, activity in visual areas decreased compared to when attention was directed to vision (Shomstein & Yantis, 2004). It was as if the participants could adjust a mental "volume knob" to regulate the flow of incoming information according to which task they were attending to at the moment.

So how well do we multitask in several thousand pounds of metal hurtling down the highway? Experienced drivers can handle divided attention to a degree, yet most of us have to acknowledge that we have had close calls due to driving while distracted. Unless you have two heads with one brain each—one to talk and one to concentrate on driving—you might do well to keep your eyes on the road and not on the phone.




**Shifting Attention** Participants received fMRI scans as they performed tasks that required them to shift their attention between visual and auditory information. (a) When focusing on auditory information, a region in the superior (upper) temporal lobe involved in auditory processing showed increased activity (yellow/orange). (b) In striking contrast, a visual region, the fusiform gyrus, showed decreased activity when participants focused on auditory information (blue).




*The Snellen chart is commonly used to measure visual acuity. Chances are good you've seen one yourself on more than one occasion.*

# Vision: More Than Meets the Eye

You might be proud of your 20/20 vision, even if it is corrected by glasses or contact lenses. *20/20* refers to a measurement associated with a Snellen chart, named after Hermann Snellen (1834–1908), the Dutch ophthalmologist who developed it as a means of assessing **visual acuity**, *the ability to see fine detail;* it is the smallest line of letters that a typical person can read from a distance of 20 feet. By comparison, hawks, eagles, owls, and other raptors have much greater visual acuity than humans—in many cases, about eight times greater, or the equivalent of 20/2 vision. That's handy if you want to spot a mouse from a mile away, but if you simply need to see where your roommate left the big bag of Fritos, you can probably live with the fact that no one ever calls you "Ol' Eagle Eye."

Although you won't win any I Spy contests against a hawk, your sophisticated visual system has evolved to transduce visual energy in the world into neural signals in the brain. Humans have sensory receptors in their eyes that respond to wavelengths of light energy. Understanding vision, then, starts with understanding light.

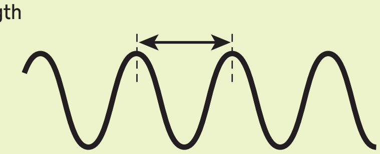
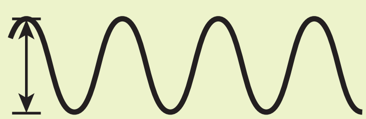
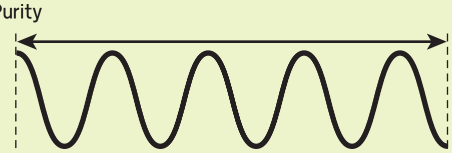
## Sensing Light

Visible light is simply the portion of the electromagnetic spectrum that we can see, and it is an extremely small slice. You can think about light as waves of energy. Like ocean waves, light waves vary in height and in the distance between their peaks, or *wavelengths,* as TABLE 4.2 (below) shows.

Light waves have three properties, each of which has a physical dimension that produces a corresponding psychological dimension. The *length* of a light wave determines its hue, or what humans perceive as color. The intensity or *amplitude* of a light wave—how high the peaks are—determines what we perceive as the brightness of light. The third property is *purity,* or the number of wavelengths that make up the light. Purity corresponds to what humans perceive as saturation, or the richness of colors (see FIGURE 4.2, on page 97). In other words, light doesn't need a human to have the properties it does: Length, amplitude, and purity are properties of the light waves themselves. What humans perceive from those properties are color, brightness, and saturation.

**TABLE 4.2**

**Properties of Light Waves**

| Physical Dimension | Psychological Dimension |
|---|---|
| Length  | Hue, or what we perceive as color |
| Amplitude  | Brightness |
| Purity  | Saturation or richness of color |

**visual acuity** The ability to see fine detail.

**retina** Light-sensitive tissue lining the back of the eyeball.

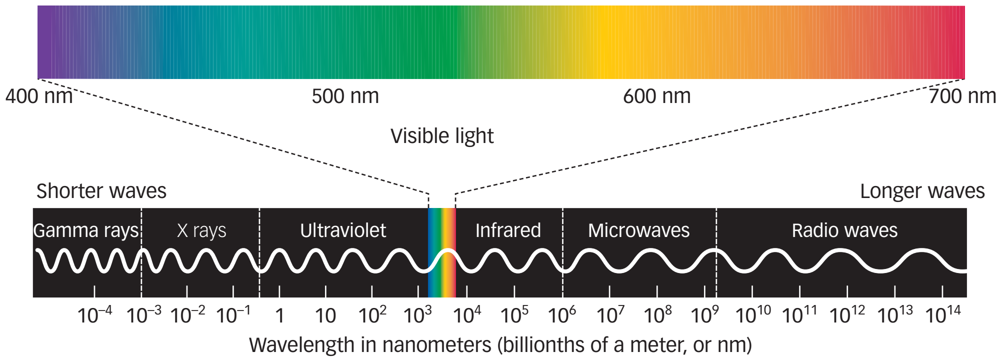



**FIGURE 4.2** **Electromagnetic Spectrum** *The sliver of light waves visible to humans as a rainbow of colors from violet-blue to red is bounded on the short end by ultraviolet rays, which honeybees can see, and on the long end by infrared waves, on which night vision equipment operates. Someone wearing night vision goggles, for example, can detect another person's body heat in complete darkness. Light waves are minute, but the scale along the bottom of this chart offers a glimpse of their varying lengths, measured in nanometers (nm; 1 nm = 1 billionth of a meter).*

## The Human Eye

Eyes have evolved as specialized organs to detect light. Light that reaches the eyes passes first through a clear, smooth outer tissue called the *cornea*, which bends the light wave and sends it through the *pupil,* a hole in the colored part of the eye (**FIGURE 4.3**, below). This colored part is the *iris,* which is a translucent, doughnut-shaped muscle that controls the size of the pupil and hence the amount of light that can enter the eye.

Immediately behind the iris, muscles inside the eye control the shape of the *lens* to bend the light again and focus it onto the **retina**, *light-sensitive tissue lining the back of the eyeball*. The muscles change the shape of the lens to focus objects at different distances, making the lens flatter for objects that are far away or rounder for nearby objects. This is called *accommodation,* the process by which the eye maintains a clear image on the retina. **FIGURE 4.4a** (page 98) shows how accommodation works.

If your eyeballs are a little too long or a little too short, the lens will not focus images properly on the retina. If the eyeball is too long, images are focused in front of the retina, leading to nearsightedness (*myopia*), which is shown in **FIGURE 4.4b** (page 98). If the eyeball is too short, images are focused behind the retina, and the result is farsightedness (*hyperopia*), as shown in **FIGURE 4.4c** (page 98). Eyeglasses, contact lenses, and surgical procedures can correct either condition. For example, eyeglasses and contacts both provide an additional lens to help focus light more appropriately, and procedures such as LASIK physically reshape the cornea.

● **How do eyeglasses actually correct vision?**

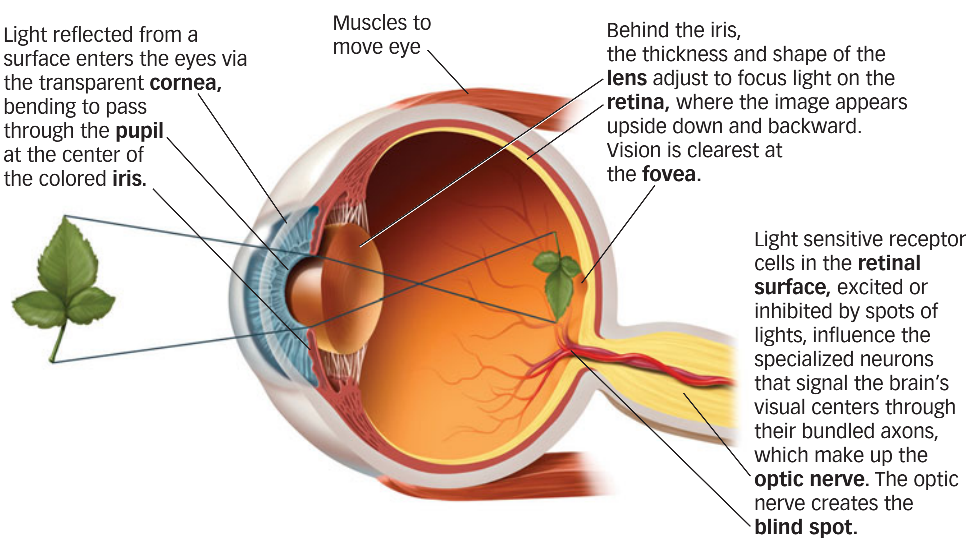



**FIGURE 4.3** **Anatomy of the Human Eye** *Light reflected from a surface enters the eye via the transparent cornea, bending to pass through the pupil at the center of the colored iris. Behind the iris, the thickness and shape of the lens adjust to focus the light on the retina, where the image appears upside down and backward. Basically, this is how a camera lens works. Light-sensitive receptor cells in the retinal surface, excited or inhibited by spots of light, influence the specialized neurons that convey nerve impulses to the brain's visual centers through their axons, which make up the optic nerve.*

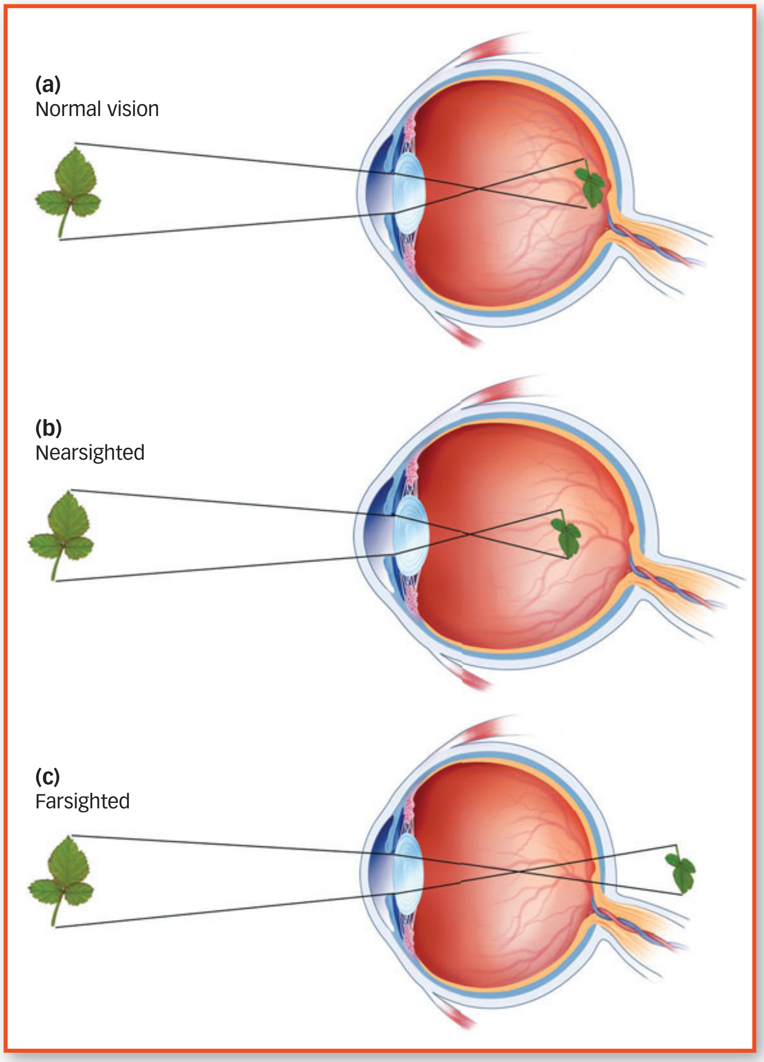



FIGURE 4.4 **Accommodation** *Inside the eye, the lens changes shape to focus nearby or faraway objects on the retina. (a) People with normal vision focus the image on the retina at the back of the eye, both for near and far objects. (b) Nearsighted people see clearly what's nearby, but distant objects are blurry because light from them is focused in front of the retina, a condition called myopia. (c) Farsighted people have the opposite problem: Distant objects are clear, but those nearby are blurry because their point of focus falls beyond the surface of the retina, a condition called hyperopia.*

## Phototransduction in the Retina

The retina is the interface between the world of light outside the body and the world of vision inside the central nervous system. Two types of *photoreceptor cells* in the retina contain light-sensitive pigments that transduce light into neural impulses. **Cones** *detect color, operate under normal daylight conditions, and allow us to focus on fine detail.* **Rods** *become active only under low-light conditions for night vision* (see FIGURE 4.5, on the next page).

Rods are much more sensitive photoreceptors than cones, but this sensitivity comes at a cost. Because all rods contain the same photopigment, they provide no information about color, and sense only shades of gray. Think about this the next time you wake up in the middle of the night and make your way to the bathroom for a drink of water. Using only the moonlight from the window to light your way, do you see the room in color or in shades of gray?

Rods and cones differ in several other ways as well, most notably in their numbers. About 120 million rods are distributed more or less evenly around each retina except in the very center, the **fovea**, *an area of the retina where vision is the clearest and there are no rods at all.* The absence of rods in the fovea decreases the sharpness of vision in reduced light, but it can be overcome. For example, when amateur astronomers view dim stars through their telescopes at night, they know to look a little off to the side of the target so that the image will fall not on the rod-free fovea but on some other part of the retina that contains many highly sensitive rods.

**cones** Photoreceptors that detect color, operate under normal daylight conditions, and allow us to focus on fine detail.

**rods** Photoreceptors that become active only under low-light conditions for night vision.

**fovea** An area of the retina where vision is the clearest and there are no rods at all.

**blind spot** An area of the retina that contains neither rods nor cones and therefore has no mechanism to sense light.

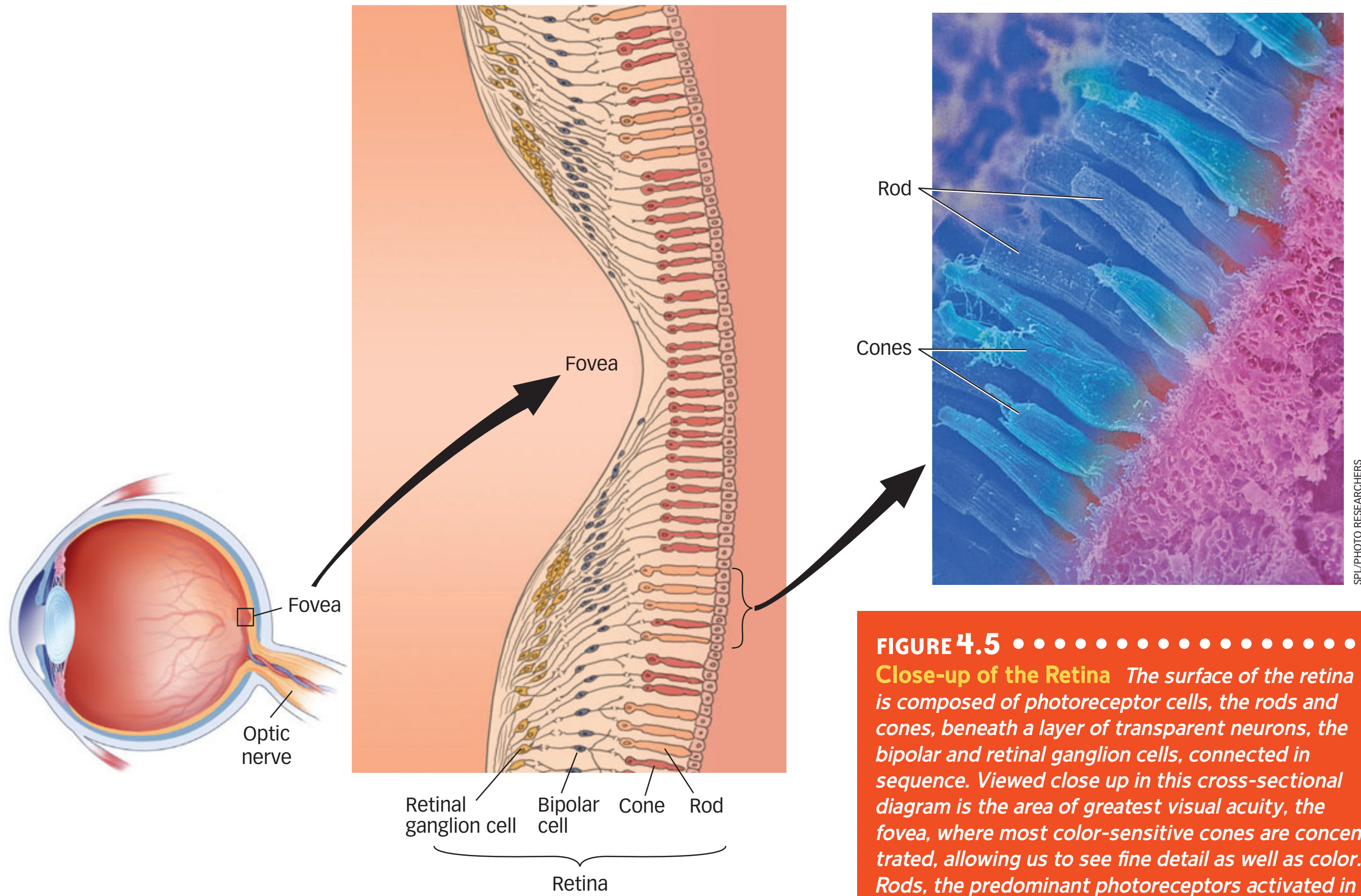


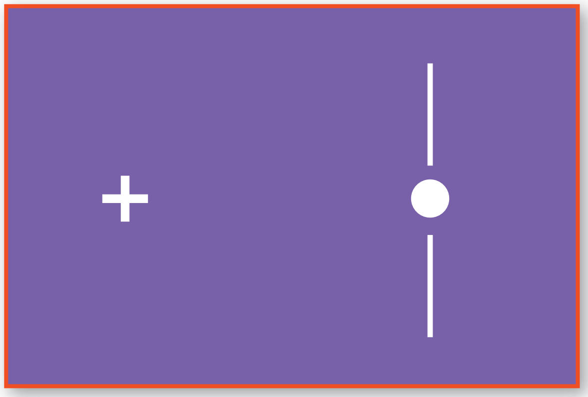

**FIGURE 4.5** **Close-up of the Retina** *The surface of the retina is composed of photoreceptor cells, the rods and cones, beneath a layer of transparent neurons, the bipolar and retinal ganglion cells, connected in sequence. Viewed close up in this cross-sectional diagram is the area of greatest visual acuity, the fovea, where most color-sensitive cones are concentrated, allowing us to see fine detail as well as color. Rods, the predominant photoreceptors activated in low-light conditions, are distributed everywhere else on the retina.*

In contrast to rods, each retina contains only about 6 million cones, which are densely packed in the fovea and much more sparsely distributed over the rest of the retina, as you can see in **FIGURE 4.5**. The high concentration of cones in the fovea directly affects visual acuity and explains why objects off to the side, in your *peripheral vision,* aren't so clear. The light reflecting from those peripheral objects has a difficult time landing in the fovea, making the resulting image less clear. The more fine detail encoded and represented in the visual system, the clearer the perceived image. The process is analogous to the quality of photographs taken with a six-megapixel digital camera versus a two-megapixel camera.

The retina is thick with cells. The photoreceptor cells (rods and cones) form the innermost layer. The middle layer contains *bipolar cells,* which collect neural signals from the rods and cones and transmit them to the outermost layer of the retina, where neurons called *retinal ganglion cells* (RGCs) organize the signals and send them to the brain. The bundled RGC axons—about 1.5 million per eye—form the *optic nerve,* which leaves the eye through a hole in the retina called the **blind spot,** which *contains neither rods nor cones and therefore has no mechanism to sense light.* Try the demonstration in **FIGURE 4.6** to find the blind spot in each of your own eyes.


*The full-color image on the left is what you'd see when your rods and cones were fully at work. The grayscale image on the right is what you'd see if only your rods were functioning.*

FIGURE 4.6
**Blind Spot Demonstration** *To find your blind spot, close your left eye and stare at the cross with your right eye. Hold the book 6 to 12 inches (15 to 30 centimeters) away from your eyes, and move it slowly toward and away from you until the dot disappears. The dot is now in your blind spot and so is not visible. At this point the vertical lines may appear as one continuous line because the visual system fills in the area occupied by the missing dot. To test your left-eye blind spot, turn the book upside down and repeat with your right eye closed.*



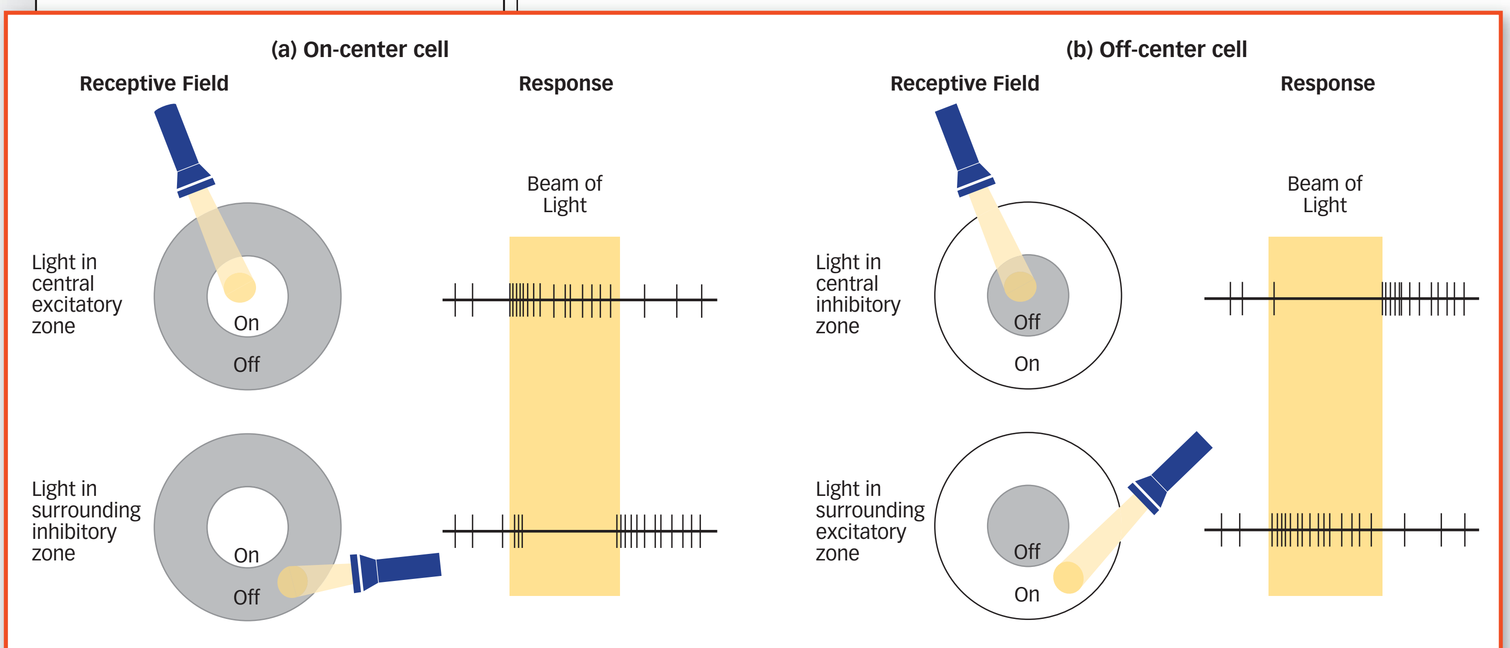
## Receptive Fields

Most RGCs respond to input not from a single retinal cone or rod but from an entire patch of adjacent photoreceptors lying side by side, or laterally, in the retina. A particular RGC will respond to light falling anywhere within that small patch, which is called its **receptive field**, *the region of the sensory surface that, when stimulated, causes a change in the firing rate of that neuron.* Although we'll focus on vision here, the general concept of receptive fields applies to all sensory systems. For example, the cells that connect to the touch centers of the brain have receptive fields, which are the part of the skin that, when stimulated, causes that cell's response to change in some way.

A given RGC responds to a spot of light projected anywhere within a small, roughly circular patch of retina (Kuffler, 1953). Most receptive fields contain either a central excitatory zone surrounded by a doughnut-shaped inhibitory zone, which is called an *on-center cell,* or a central inhibitory zone surrounded by an excitatory zone, which is called an *off-center cell* (see FIGURE 4.7). The doughnut-shaped regions represent patches of retina.

Think about the response of an on-center retinal ganglion cell when its receptive field is stimulated with spots of light of different sizes (FIGURE 4.7a). A small spot shining on the central excitatory zone increases the RGC's firing rate. When the spot exactly fills the excitatory zone, it elicits the strongest response, whereas light falling on the surrounding inhibitory zone elicits the weakest response or none at all. The response of an

FIGURE 4.7
**RGC Receptive Fields Viewed End-on** *(a) An on-center ganglion cell increases its firing rate when the receptive field is stimulated by light in the central area but decreases its firing rate when the light strikes the surrounding area. Both neural response levels are shown in the right column. (b) The off-center ganglion cell decreases its firing rate when its receptive field is stimulated by light in the central area but increases its firing rate when the light strikes the surrounding area. Both responses are shown at the right.*



off-center cell, shown in **FIGURE 4.7b** (previous page), is just the opposite. A small spot shining on the central inhibitory zone elicits a weak response, and a spot shining on the surrounding excitatory zone elicits a strong response in the RGC. The retina is organized in this way to detect edges—abrupt transitions from light to dark or vice versa. Edges are of supreme importance in vision. They define the shapes of objects, and anything that highlights such boundaries improves our ability to see an object's shape, particularly in low-light situations.

**receptive field** The region of the sensory surface that, when stimulated, causes a change in the firing rate of that neuron.

## Perceiving Color

We thrill to the burst of colors during a fireworks display, "ooh" and "aah" at nature's palette during sunset, and marvel at the vibrant hues of a peacock's tail feathers. These rich experiences of color depend critically on our perception of light's wavelength (see **FIGURE 4.8**). We perceive the shortest visible wavelengths as deep purple. As wavelengths increase, the color perceived changes gradually and continuously to blue, then green, yellow, orange, and, with the longest visible wavelengths, red. This rainbow of hues and accompanying wavelengths is called the *visible spectrum,* illustrated in **FIGURE 4.8**.

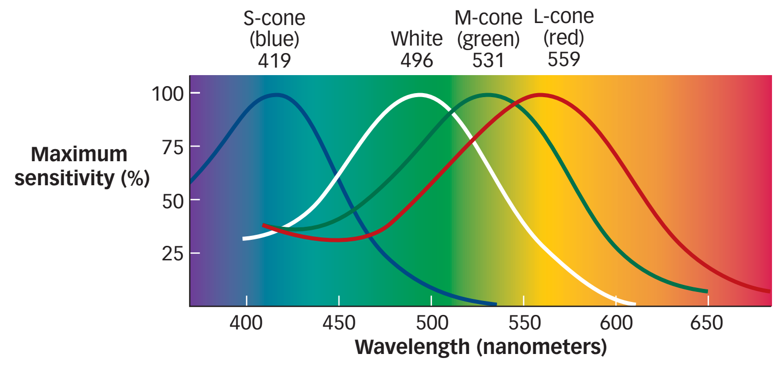
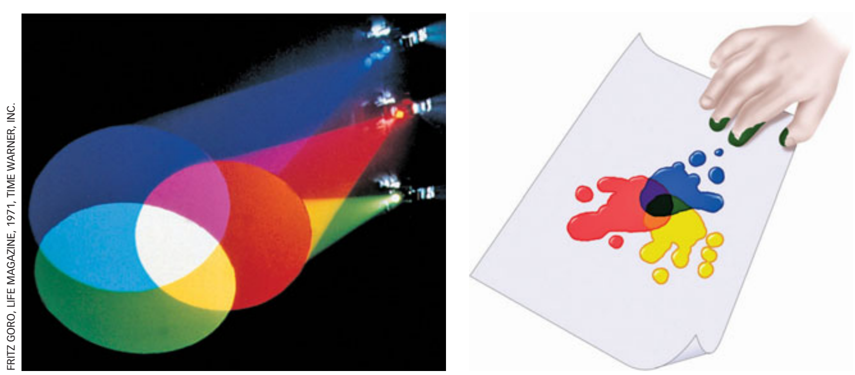



**FIGURE 4.8** **Seeing in Color** *We perceive a spectrum of color because objects selectively absorb some wavelengths of light and reflect others. Color perception corresponds to the summed activity of the three types of cones. Each type is most sensitive to a narrow range of wavelengths in the visible spectrum—short (bluish light), medium (greenish light), or long (reddish light). Rods, represented by the white curve, are most sensitive to the medium wavelengths of visible light but do not contribute to color perception.*

You'll recall that all rods contain the same photopigment, which makes them ideal for low-light vision but bad at distinguishing colors. Cones, by contrast, contain any one of three types of pigment. Each cone absorbs light over a range of wavelengths, but its pigment type is especially sensitive to visible wavelengths that correspond to red (long-wavelength), green (medium-wavelength), or blue (short-wavelength) light. Red, green, and blue are the primary colors of light; color perception results from different combinations of the three basic elements in the retina that respond to the wavelengths corresponding to the three primary colors of light. For example, lighting designers add primary colors of light together, such as shining red and green spotlights on a surface to create a yellow light, as shown in **FIGURE 4.9a** (below). Notice that in the center of the figure, where the red, green, and blue lights overlap, the surface looks white. This demonstrates that a white surface really is reflecting all visible wavelengths of light. Increasing light to create color in this way is called *additive color mixing*.

You may have discovered a similar process for yourself when mixing paints: you can re-create any color found in nature simply by mixing only three colors: red, blue, and yellow. This *subtractive color mixing* works by removing light from the mix, such as when you combine yellow and red to make orange or blue and yellow to make green, shown in **FIGURE 4.9b**. The darker the color, the less light it contains, which is why black surfaces reflect no light.




(a) Additive color mixing (red, blue, green)

(b) Subtractive color mixing (red, blue, yellow)

**FIGURE 4.9** **Color Mixing** *The millions of shades of color that humans can perceive are products not only of a light's wavelength but also of the mixture of wavelengths a stimulus absorbs or reflects. We see a ripe banana as yellow because the banana skin reflects the light waves that we perceive as yellow but absorbs the wavelengths that we perceive as shades of blue to green and those that make us see red. (a) Additive color mixing works by increasing the reflected wavelengths—by adding light to stimulate the red, blue, or green photopigments in the cones. When all visible wavelengths are present, we see white. (b) Subtractive color mixing removes wavelengths, thus absorbing light waves we see as red, blue, or yellow. When all visible wavelengths are absorbed, we see black.*

Light striking the retina causes a specific pattern of response in the three cone types (Schnapf, Kraft, & Baylor, 1987). The pattern of responding across the three types of cones provides a unique code for each color. Researchers can "read out" the wavelength of the light entering the eye by working backward from the relative firing rates of the three types of cones. A genetic disorder in which one of the cone types is missing—and, in some very rare cases, two or all three—causes a *color deficiency* (sometimes referred to as *color blindness*, although people missing only one type of cone can still distinguish many colors). Color deficiency is sex linked, affecting men much more often than women.

● What happens when the cones in your eyes get fatigued?

You can create a sort of temporary color deficiency by exploiting the idea of sensory adaptation. Just like the rest of your body, cones need an occasional break, too. Staring too long at one color fatigues the cones that respond to that color, producing a form of sensory adaptation called *color afterimage*. To demonstrate this effect for yourself, follow these instructions for **FIGURE 4.10**:

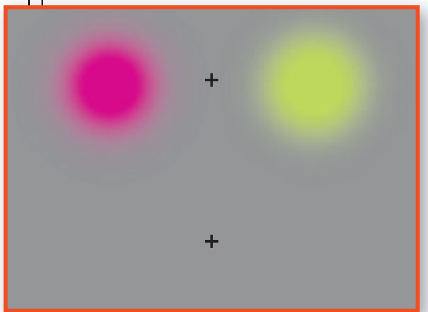



**FIGURE 4.10** **Color Afterimage Demonstration** *Follow the accompanying instructions in the text, and sensory adaptation will do the rest. When the afterimage fades, you can get back to reading the chapter.*

- Stare at the small cross between the two color patches for about 1 minute. Try to keep your eyes as still as possible.
- After a minute, look at the lower cross. You should see a vivid color aftereffect that lasts for a minute or more. Pay particular attention to the colors in the afterimage.

Were you puzzled that the red patch produces a green afterimage and the green patch produces a red afterimage? This result may seem like nothing more than a curious mind-bug, but in fact it reveals something important about color perception. When you view a color—let's say, green—the cones that respond most strongly to green become fatigued over time. Fatigue leads to an imbalance in the inputs to the red-green color-opponent neurons, beginning with the retinal ganglion cells. The weakened signal from the green-responsive cones leads to an overall response that emphasizes red.

## The Visual Brain

A great deal of visual processing takes place within the retina itself, including the encoding of simple features such as spots of light, edges, and color. More complex aspects of vision, however, require more powerful processing, and that enlists the brain.

Streams of action potentials containing information encoded by the retina travel to the brain along the optic nerve. Half of the axons in the optic nerve that leave each eye come from retinal ganglion cells that code information in the right visual field, whereas the other half code information in the left visual field. These two nerve bundles link to the left and right hemispheres of the brain, respectively (see **FIGURE 4.11**, on page 103). The optic nerve travels from each eye to the *lateral geniculate nucleus* (*LGN*), located in the thalamus. As you will recall from Chapter 3, the thalamus receives inputs from all of the senses except smell. From there the visual signal travels to the back of the brain, to a location called **area V1**, the *part of the occipital lobe that contains the primary visual cortex*. Here the information is systematically mapped into a representation of the visual scene. There are about 30 to 50 brain areas specialized for vision, located mainly in the occipital lobe at the back of the brain and in the temporal lobes on the sides of the brain (Orban, Van Essen, & Vanduffel, 2004; Van Essen, Anderson, & Felleman, 1992).

One of the most important functions of vision involves perceiving the shapes of objects; our day-to-day lives would be a mess if we couldn't distinguish individual shapes from one another. Imagine not being able to reliably differentiate between a warm doughnut with glazed icing and a straight stalk of celery and you'll get the idea; breakfast could become a traumatic experience if you couldn't distinguish shapes.

**area V1** The part of the occipital lobe that contains the primary visual cortex.

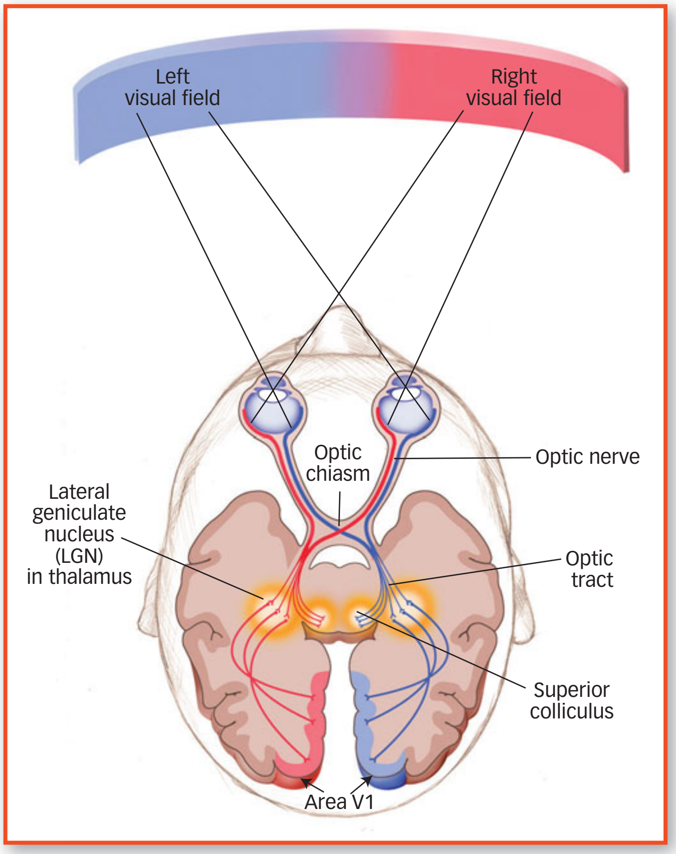



**FIGURE 4.11** **Visual Pathway from Eye through Brain** *Objects in the right visual field stimulate the left half of each retina, and objects in the left visual field stimulate the right half of each retina. The optic nerves, one exiting each eye, are formed by the axons of retinal ganglion cells emerging from the retina. Just before they enter the brain at the optic chiasm, about half the nerve fibers from each eye cross. The left half of each optic nerve, representing the right visual field, runs through the brain's left hemisphere via the thalamus, and the right halves, representing the left visual field, travel this route through the right hemisphere. So information from the right visual field ends up in the left hemisphere, and information from the left visual field ends up in the right hemisphere.*

Perceiving shape depends on the location and orientation of an object's edges. It is not surprising, then, that area V1 is specialized for encoding edge orientation.

As you read in Chapter 3, neurons in the visual cortex selectively respond to bars and edges in specific orientations in space (Hubel & Weisel, 1962, 1998). In effect, area V1 contains populations of neurons, each "tuned" to respond to edges oriented at each position in the visual field. This means that some neurons fire when an object in a vertical orientation is perceived, other neurons fire when an object in a horizontal orientation is perceived, still other neurons fire when objects in a diagonal orientation of 45 degrees are perceived, and so on (see **FIGURE 4.12**). The outcome of the coordinated response of all these feature detectors contributes to a sophisticated visual system that can detect where a doughnut ends and celery begins.

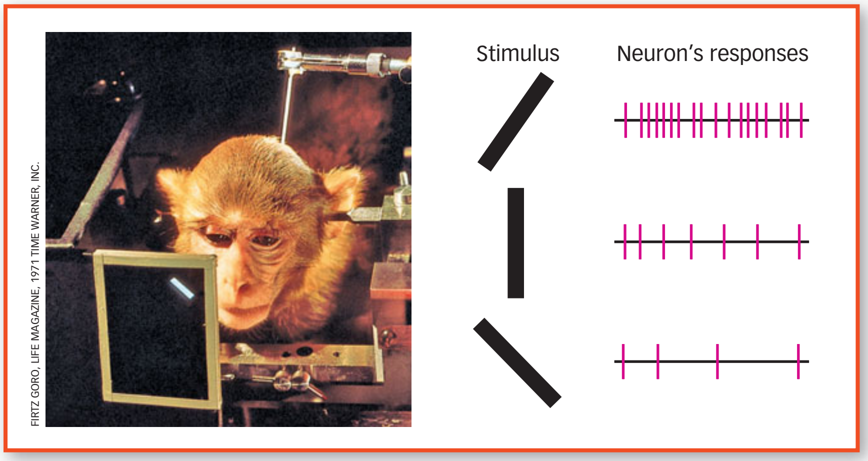
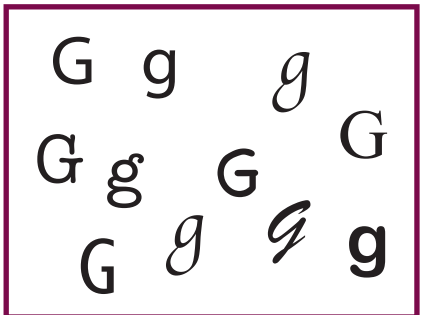



**FIGURE 4.12** **Single Neuron Feature Detectors** *Area V1 contains neurons that respond to specific orientations of edges. Here a single neuron's responses are recorded (at right) as the monkey views bars at different orientations (left). This neuron fires continuously when the bar is pointing to the right at 45 degrees, less often when it is vertical, and not at all when it is pointing to the left at 45 degrees.*




A quick glance and you recognize all these letters as G, but their varying sizes, shapes, angles, and orientations ought to make this recognition task difficult. What is it about the process of object recognition that allows us to perform this task effortlessly?

## Recognizing Objects by Sight

Take a quick look at the letters in the accompanying illustration. Even though they're quite different from one another, you probably effortlessly recognized them as all being examples of the letter *G*. Now consider the same kind of demonstration using your best friend's face. Suppose one day your friend gets a dramatic new haircut—or adds glasses, hair dye, or a nose ring. Even though your friend now looks strikingly different, you still recognize that person with ease. Just like the variability in *G*s, you somehow are able to extract the underlying features of the face that allow you to accurately identify your friend.

This thought exercise may seem trivial, but it's no small perceptual feat. If the visual system were somehow stumped each time a minor variation occurred in an object being perceived, the inefficiency of it all would be overwhelming. We'd have to effortfully process information just to perceive our friend as the same person from one meeting to another, not to mention laboring through the process of knowing when a *G* is really a *G*. In general, though, object recognition proceeds fairly smoothly, in large part due to the operation of the feature detectors we discussed earlier.

### Representing Objects and Faces in the Brain

How do feature detectors help the visual system get from a spatial array of light hitting the eye to the accurate perception of an object, such as your friend's face? Some researchers argue for a *modular view:* that specialized brain areas, or modules, detect and represent faces or houses or even body parts. Using fMRI to examine visual processing in healthy young adults, researchers found a subregion in the temporal lobe that responds selectively to faces compared to just about any other object category, while a nearby area responds selectively to buildings and landscapes (Kanwisher, McDermott, & Chun, 1997). This view suggests that we not only have detectors to aid in visual perception but also "face detectors," "building detectors," and possibly other types of neurons specialized for particular types of object perception (Kanwisher & Yovel, 2006).

Other researchers argue for a more *distributed representation* of object categories. In this view, it is the pattern of activity across multiple brain regions that identifies any viewed object, including faces (Haxby et al., 2001). Each of these views explains some data better than the other one, and researchers are continuing to debate their relative merits.

One perspective on this issue is provided by experiments designed to measure precisely where epileptic seizures originate; these experiments have provided insights on how single neurons in the human brain respond to objects and faces (Quiroga et al., 2005). Electrodes were placed in the temporal lobes of people who suffer from epilepsy. Then the volunteers were shown photographs of faces and objects as the researchers recorded their neural responses. The researchers found that neurons in the temporal lobe respond to specific objects viewed from multiple angles and to people wearing different clothing and facial expressions and photographed from various angles. In some cases, the neurons also respond to the words for the objects they prefer. For example, a neuron that responded to photographs of the Sydney Opera House also responded when the words *Sydney Opera* were displayed but not when the words *Eiffel Tower* were displayed (Quiroga et al., 2005).

Taken together, these experiments demonstrate the principle of **perceptual constancy:** *Even as aspects of sensory signals change, perception remains consistent.* Think back once again to our discussion of difference thresholds early in this chapter. Our perceptual systems are sensitive to relative differences in changing stimulation and make allowances for varying sensory input. This general principle helps explain why you still recognize your friend despite changes in hair color or style or the addition of facial jewelry. It's not as though your visual perceptual system responds to a change with "Here's a new and unfamiliar face to perceive." Rather, it's as though it responds with "Interesting . . . here's a deviation from the way this face usually looks." Perception is sensitive to changes in stimuli, but perceptual constancies allow us to notice the differences in the first place.

**How do we recognize our friends, even when they're hidden behind sunglasses?**

**ONLY HUMAN**

**I KNOW IT'S AROUND HERE SOMEPLACE**
A 44-year-old man was arrested for DUI in Australia's Northern Territory after he asked a police officer how to get to the hard-to-miss Uluru (Ayers Rock, the huge, 1,000-foot-high rock formation that appears red in sunlight), which was about 300 feet in front of him, illuminated in his headlights.

## Principles of Perceptual Organization

Of course, before object recognition can even kick in, the visual system must perform another important task: to group the image regions that belong together into a representation of an object. The idea that we tend to perceive a unified, whole object rather than a collection of separate parts is the foundation of Gestalt psychology, which you read about in Chapter 1. Gestalt principles characterize many aspects of human perception. Among the foremost are the Gestalt *perceptual grouping rules,* which govern how the features and regions of things fit together (Koffka, 1935). Here's a sampling:

- *Simplicity:* A basic rule in science is that the simplest explanation is usually the best. When confronted with two or more possible interpretations of an object's shape, the visual system tends to select the simplest or most likely interpretation: It's easier to interpret the object in **FIGURE 4.13a** (below) as a single arrow than as a triangle placed carefully on top of a rectangle.
- *Closure:* We tend to fill in missing elements of a visual scene, allowing us to perceive edges that are separated by gaps as belonging to complete objects. Thus, in **FIGURE 4.13b** we see a single arrow shape, not four unrelated sets of bent lines.
- *Continuity:* Edges or contours that have the same orientation have what the Gestaltists called "good continuation," and we tend to group them together perceptually. Thus, in **FIGURE 4.13c**, we see one curved line crossing another curved line.
- *Similarity:* Regions that are similar in color, lightness, shape, or texture are perceived a belonging to the same object; thus, in **FIGURE 4.13d**, we tend to see one column of circles, surrounded by two columns of triangles, rather than three rows each containing two triangles and a circle.
- *Proximity:* Objects that are close together tend to be grouped together. Thus, in **FIGURE 4.13e**, we tend to see three clusters of dots.
- *Common fate:* Elements of a visual image that move together are perceived as parts of a single moving object. Thus, a sign such as the one shown **FIGURE 4.13f**, where the blinking arrows come on and off in a sequence from left to right, we tend to see an arrow moving from left to right.

Perceptual grouping is a powerful aid to our ability to recognize objects by sight. Grouping involves visually separating an object from its surroundings. In Gestalt terms, this means identifying a *figure* apart from the (back)*ground* in which it resides. For example, the words on this page are perceived as figural: They stand out from the ground of the sheet of paper on which they're printed. Similarly, your instructor is perceived as

**perceptual constancy** A perceptual principle stating that even as aspects of sensory signals change, perception remains consistent.

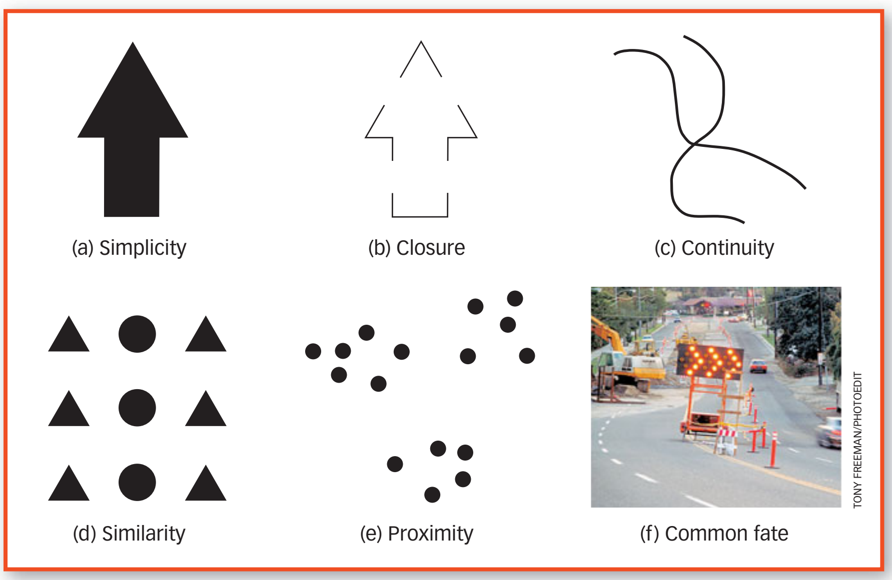



**FIGURE 4.13** **Perceptual Grouping Rules** *Principles first identified by Gestalt psychologists and now supported by experimental evidence demonstrate that the brain is predisposed to impose order on incoming sensations. One neural strategy for perception involves responding to patterns among stimuli and grouping like patterns together.*

**monocular depth cues** Aspects of a scene that yield information about depth when viewed with only one eye.

**binocular disparity** The difference in the retinal images of the two eyes that provides information about depth.

the figure against the backdrop of all the other elements in your classroom. You certainly can perceive these elements differently, of course: The words *and* the paper are all part of a thing called "a page," and your instructor *and* the classroom can all be perceived as "your learning environment." Typically, though, our perceptual systems focus attention on some objects as distinct from their environments.

Size provides one clue to what's figure and what's ground: Smaller regions are likely to be figures, such as tiny letters on a big paper. Movement also helps: Your instructor is (we hope) a dynamic lecturer, moving around in a static environment. Another critical step toward object recognition is *edge assignment*. Given an edge, or boundary, between figure and ground, to which region does that edge belong? If the edge belongs to the figure, it helps define the object's shape, and the background continues behind the edge. Sometimes, though, it's not easy to tell which is which.

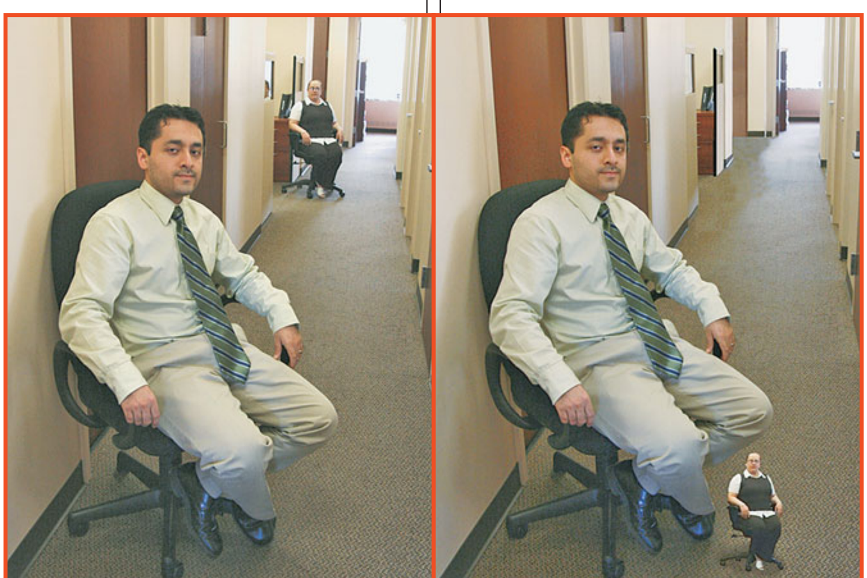
FIGURE 4.14 **Ambiguous Edges** *Here's how Rubin's classic reversible figure-ground illusion works: Fixate your eyes on the center of the image, and your perception will alternate between a vase and facing silhouettes, even as the sensory stimulation remains constant.*

This ambiguity drives the famous illusion shown in FIGURE 4.14. You can view this figure in two ways, either as a vase on a black background or as a pair of silhouettes facing each other. Your visual system settles on one or the other interpretation and fluctuates between them every few seconds. This happens because the edge that would normally separate figure from ground is really part of neither: It equally defines the contours of the vase as it does the contours of the faces. Evidence from fMRI scans shows, quite nicely, that when people are seeing the Rubin image as a face, there is greater activity in the face-selective region of the temporal lobe that we discussed earlier than when they are seeing it as a vase (Hasson et al., 2001).

## Perceiving Depth and Size

Objects in the world are arranged in three dimensions—length, width, and depth—but the retinal image contains only two dimensions, length and width. How does the brain process a flat, two-dimensional retinal image so that we perceive the depth of an object and how far away it is? The answer lies in a collection of *depth cues* that change as you move through space. Monocular and binocular cues help visual perception (Howard, 2002).

FIGURE 4.15 **Familiar Size and Relative Size** *When you view images of people, such as the men in the left-hand photo (below), or of things you know well, the object you perceive as smaller appears farther away. With a little image manipulation, you can see in the right-hand photo that the relative size difference projected on your retinas is far greater than you perceive. The image of the person who is brought forward in the second photo is exactly the same size in both photos.*

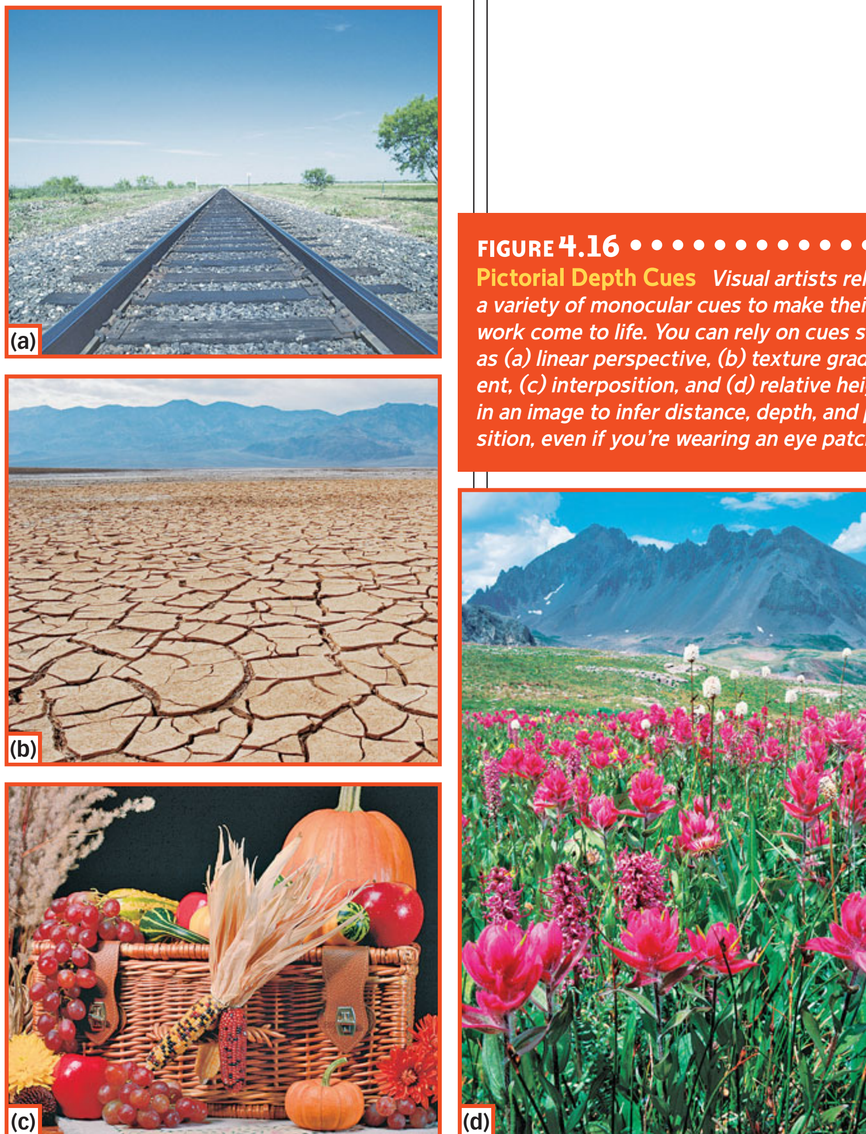




**Monocular depth cues** are *aspects of a scene that yield information about depth when viewed with only one eye.* These cues rely on the relationship between distance and size. Even with one eye closed, the retinal image of an object you're focused on grows smaller as that object moves farther away and larger as it moves closer. Our brains routinely use these differences in retinal image size, or *relative size,* to perceive distance. This works particularly well in a monocular depth cue called *familiar size*. Most adults, for example, fall within a familiar range of heights (perhaps five to seven feet tall), so retinal image size alone is usually a reliable cue to how far away they are. Our visual system automatically corrects for size differences and attributes them to differences in distance. FIGURE 4.15 demonstrates how strong this mental correction for familiar size is. In addition to relative size and familiar size, there are several more monocular depth cues:

- *Linear perspective,* which describes the phenomenon that parallel lines seem to converge as they recede into the distance (see **FIGURE 4.16a**).
- *Texture gradient,* which arises when you view a more or less uniformly patterned surface because the size of the pattern elements, as well as the distance between them, grows smaller as the surface recedes from the observer (see **FIGURE 4.16b**).
- *Interposition,* which occurs when one object partly blocks another (see **FIGURE 4.16c**). You can infer that the block*ing* object is closer than the block*ed* object. However, interposition by itself cannot provide information about how far apart the two objects are.
- *Relative height in the image* depends on your field of vision (see **FIGURE 4.16d**). Objects that are closer to you are lower in your visual field, while faraway objects are higher.

We also obtain depth information through **binocular disparity**, *the difference in the retinal images of the two eyes that provides information about depth.* Because our eyes are slightly separated, each registers a slightly different view of the world. Your brain computes the disparity between the two retinal images to perceive how far away objects are, as shown in **FIGURE 4.17** (on page 108). Viewed from above in the figure, the images of the more distant square and the closer circle each fall at different points on each retina. The View-Master toy works by presenting a pair of photos, taken from two horizontally displaced locations; when viewed, one by each eye, the pairs of images evoke a vivid sense of depth. 3-D movies are based on this same idea.



PHOTODISC
AGE FOTOSTOCK/SUPERSTOCK
ROB BLAKERS/GETTY IMAGES
ROB BLAKERS/GETTY IMAGES

**FIGURE 4.16** **Pictorial Depth Cues** *Visual artists rely on a variety of monocular cues to make their work come to life. You can rely on cues such as (a) linear perspective, (b) texture gradient, (c) interposition, and (d) relative height in an image to infer distance, depth, and position, even if you're wearing an eye patch.*


CORBIS/ALAMY
KODAK COLLECTION/SSPL/THE IMAGE WORKS

*The View-Master has been a popular toy for decades. It is based on the principle of binocular disparity: Two images taken from slightly different angles produce a stereoscopic effect.*

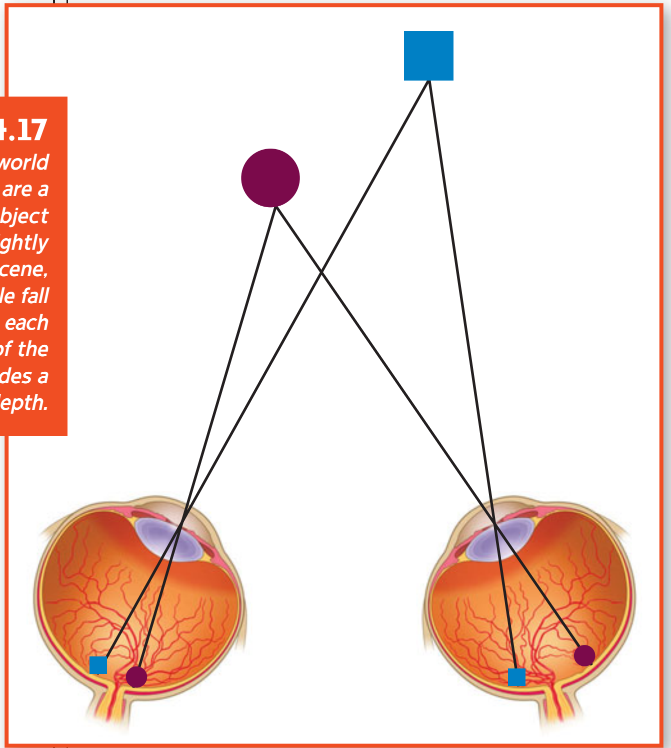


FIGURE 4.17
**Binocular Disparity** *We see the world in three dimensions because our eyes are a distance apart and the image of an object falls on the retinas of each eye at a slightly different place. In this two-object scene, the images of the square and the circle fall on different points of the retina in each eye. The disparity in the positions of the circle's retinal images provides a compelling cue to depth.*

Most of the time, these mechanisms for depth perception work effortlessly and well to help us compute the size and distance of objects. But we are all vulnerable to *illusions,* mindbugs in which our perceptions differ from reality. The relation between size and distance has been used to create elaborate illusions that depend on fooling the visual system about how far away objects are. One of the most famous of these is the *Ames room,* constructed by the American ophthalmologist Adelbert Ames in 1946. The room is trapezoidal in shape rather than square: Only two sides are parallel (see **FIGURE 4.18a** on page 109). A person standing in one corner of an Ames room is physically twice as far away from the viewer as a person standing in the other corner. But when viewed with one eye looking through the small peephole placed in one wall, the Ames room looks square because the shapes of the windows and the flooring tiles are carefully crafted to *look* square from the viewing port (Ittelson, 1952). The visual system perceives the far wall as perpendicular to the line of sight so that people standing at different positions along that wall appear to be at the same distance, and the viewer's judgments of their sizes are based directly on retinal image size. As a result, a person standing in the right corner appears to be much larger than a person standing in the left corner (see **FIGURE 4.18b** on page 109).

● What does the Ames room tell us about how the brain can be fooled?

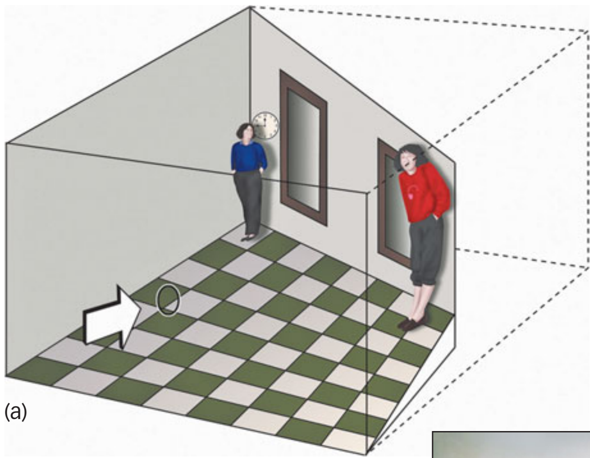
## Perceiving Motion

You should now have a good sense of how we see what and where objects are, a process made substantially easier when the objects stay in one place. But real life, of course, is full of moving targets; objects change position over time. To sense motion, the visual system must encode information about both space and time. The simplest case to consider is an observer who does not move trying to perceive an object that does.

As an object moves across an observer's stationary visual field, it first stimulates one location on the retina, and then a little later it stimulates another location on the retina. Neural circuits in the brain can detect this change in position over time and respond to specific speeds and directions of motion (Emerson, Bergen, & Adelson, 1992). A region in the middle of the temporal lobe referred to as *MT* is specialized for the visual perception of motion (Born & Bradley, 2005; Newsome & Paré, 1988), and brain damage in this area leads to a deficit in normal motion perception (Zihl, von Cramon, & Mai, 1983).

Of course, in the real world, rarely are you a stationary observer. As you move around, your head and eyes move all the time, and motion perception is not as simple. The motion-perception system must take into account the position and movement of your eyes, and ultimately of your head and body, in order to perceive the motions of objects correctly and allow you to approach or avoid them. The brain accomplishes this by monitoring your eye and head movements and "subtracting" them from the motion in the retinal image.

**apparent motion** The perception of movement as a result of alternating signals appearing in rapid succession in different locations.


(a)


(b)

PHIL SCHERMEISTER/CORBIS

**FIGURE 4.18**
**The Amazing Ames Room** *(a) A diagram showing the actual proportions of the Ames room reveals its secrets. The sides of the room form a trapezoid with parallel sides but a back wall that's way off square. The uneven floor makes the room's height in the far back corner shorter than the other. Add misleading cues such as specially designed windows and flooring and position the room's occupants in each far corner, and you're ready to lure an unsuspecting observer. (b) Looking into the Ames room through the viewing port with only one eye, the observer infers a normal size-distance relationship—that both girls are the same distance away. But the different image sizes they project on the retina leads the viewer to conclude, based on the monocular cue of familiar size, that one girl is very small and the other very large.*

Motion perception, like color perception, is subject to sensory adaptation. A motion aftereffect called the *waterfall illusion* is analogous to color aftereffects. If you stare at the downward rush of a waterfall for several seconds, you'll experience an upward motion aftereffect when you then look at stationary objects near the waterfall such as trees or rocks. What's going on here?

The process is similar to seeing green after staring at a patch of red. Motion-sensitive neurons are connected to motion detector cells in the brain that encode motion in opposite directions. A sense of motion comes from the difference in the strength of these two opposing sensors. If one set of motion detector cells is fatigued through adaptation to motion in one direction, then the opposing sensor will take over. The net result is that motion is perceived in the opposite direction. Evidence from fMRI indicates that when people experience the waterfall illusion while viewing a stationary stimulus, there is increased activity in region MT, which plays a key role in motion perception (Tootell et al., 1995).

**How can flashing lights on a casino sign give the impression of movement?**

The movement of objects in the world is not the only event that can evoke the perception of motion. The successively flashing lights of a Las Vegas casino sign can evoke a strong sense of motion, exactly the sort of illusion that inspired Max Wertheimer to investigate the *phi phenomenon,* discussed in Chapter 1. Recall, too, the Gestalt grouping rule of *common fate:* People perceive a series of flashing lights as a whole, moving object (see **FIGURE 4.13f** on page 105). This *perception of movement is a result of alternating signals appearing in rapid succession in different locations* is called **apparent motion.**

Video technology and animation depend on apparent motion. A sequence of still images sample the continuous motion in the original scene. In the case of motion pictures, the sampling rate is 24 frames per second (fps). A slower sampling rate would produce a much choppier sense of motion; a faster sampling rate would be a waste of resources because we would not perceive the motion as any smoother than it appears at 24 fps.


VISIONS OF AMERICA/JOE SOHM/GETTY IMAGES

*Want a powerful demonstration of apparent motion? Take a stroll down the Las Vegas strip.*

## summary quiz [4.2]

**5.** Which is the correct sequence of eye parts that light passes through on its way to the brain?
- a. pupil, lens, cornea, retina
- b. cornea, pupil, lens, retina
- c. iris, lens, pupil, cornea
- d. lens, pupil, cornea, retina

**6.** Objects in your peripheral vision are less clear because light reflecting from these objects has a hard time landing in
- a. the retinal ganglion cell layer.
- b. the lens.
- c. the pupil.
- d. the fovea.

**7.** Color deficiency (also called color blindness) is a result of a disorder in which
- a. one type of rod is missing.
- b. one type of cone is missing.
- c. the blind spot is larger than normal.
- d. the individual has synesthesia.

**8.** The hypothesis that specialized brain areas detect and represent various object categories is called
- a. the perceptual constancy view.
- b. signal detection theory.
- c. the distributed representation view.
- d. the modular view.

**9.** "When confronted with two or more possible interpretations of an object's shape, we tend to select the most likely interpretation." This is a statement of which rule?
- a. closure
- b. continuity
- c. simplicity
- d. similarity

**10.** You are at Niagara Falls, staring at the downward rush of the water for several seconds. When you then look at the nearby trees and rocks, they seem to be moving upward. You are experiencing
- a. the phi phenomenon.
- b. apparent motion.
- c. motion parallax.
- d. the waterfall illusion.

# Audition: More Than Meets the Ear

Vision is based on the spatial pattern of light waves on the retina. The sense of hearing, by contrast, is all about *sound waves*—changes in air pressure unfolding over time. Plenty of things produce sound waves: the collision of a tree hitting the forest floor, the impact of two hands clapping, the vibration of vocal cords during a stirring speech, the resonance of a bass guitar string during a thrash metal concert. Except for synesthetes who "hear colors," understanding most people's auditory experience requires understanding how we transform changes in air pressure into perceived sounds.

*"The ringing in your ears—I think I can help."*



## Sensing Sound

Striking a tuning fork produces a *pure tone,* a simple sound wave that first increases air pressure and then creates a relative vacuum. This cycle repeats hundreds or thousands of times per second as sound waves propagate outward in all directions from the source.

Just as there are three dimensions of light waves corresponding to three dimensions of visual perception, so too there are three physical dimensions

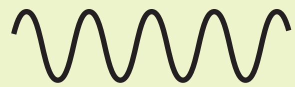
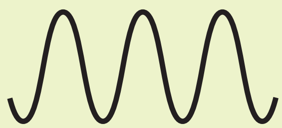
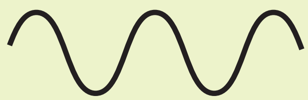
**pitch** How high or low a sound is.

**loudness** A sound's intensity.

**timbre** A listener's experience of sound quality or resonance.

**TABLE 4.3**

**Properties of Sound Waves**

| | | |
|---|---|---|
| **Frequency** Corresponds to our perception of pitch. |  Low frequency (low-pitched sound) |  High frequency (high-pitched sound) |
| **Amplitude** Corresponds to our perception of loudness. |  High amplitude (loud sound) |  Low amplitude (soft sound) |
| **Complexity** Corresponds to our perception of timbre. |  Simple (pure tone) |  Complex (mix of frequencies) |

of a sound wave. Frequency, amplitude, and complexity determine what we hear as the pitch, loudness, and quality of a sound (see **TABLE 4.3** above).

The *frequency* of the sound wave, or its wavelength, depends on how often the peak in air pressure passes the ear or a microphone, measured in cycles per second, or hertz (abbreviated Hz). Changes in the physical frequency of a sound wave are perceived by humans as changes in **pitch**, *how high or low a sound is*.

The *amplitude* of a sound wave refers to its height, relative to the threshold for human hearing (which is set at zero decibels, or dBs). Amplitude corresponds to **loudness**, or *a sound's intensity*. To give you an idea of amplitude and intensity, the rustling of leaves in a soft breeze is about 20 dB, normal conversation is measured at about 40 dB, shouting produces 70 dB, a Slayer concert is about 130 decibels, and the sound of the space shuttle taking off one mile away registers at 160 dB or more. That's loud enough to cause permanent damage to the auditory system and is well above the pain threshold; in fact, any sounds above 85 decibels can be enough to cause hearing damage, depending on the length and type of exposure.

**Why does one note sound so different on a flute and a trumpet?**

Differences in the *complexity* of sound waves, or their mix of frequencies, correspond to **timbre**, *a listener's experience of sound quality or resonance*. Timbre (pronounced "TAM-ber") offers us information about the nature of sound. The same note played at the same loudness produces a perceptually different experience depending on whether it was played on a flute versus a trumpet, a phenomenon due entirely to timbre. Many "natural" sounds also illustrate the complexity of wavelengths, such as the sound of bees buzzing, the tonalities of speech, or the babbling of a brook. Unlike the purity of a tuning fork's hum, the drone of cicadas is a clamor of overlapping sound frequencies.

JEWEL SAMAD/AFP/GETTY IMAGES

*Foo Fighters star Dave Grohl has revealed that his deafness is causing problems in his marriage. "I'm virtually deaf . . . my wife asks me where we should go for dinner, and it sounds like the schoolteacher from the TV show Charlie Brown!"*

**cochlea** A fluid-filled tube that is the organ of auditory transduction.

**basilar membrane** A structure in the inner ear that undulates when vibrations from the ossicles reach the cochlear fluid.

**hair cells** Specialized auditory receptor neurons embedded in the basilar membrane.

**area A1** A portion of the temporal lobe that contains the primary auditory cortex.

Of the three dimensions of sound waves, frequency provides most of the information we need to identify sounds. Amplitude and complexity contribute texture to our auditory perceptions, but it is frequency that carries their meaning. Sound-wave frequencies blend together to create countless sounds, just as different wavelengths of light blend to create the richly colored world we see. Changes in frequency over time allow us to identify the location of sounds, an ability that can be crucial to survival and also allow us to understand speech and appreciate music, skills that are valuable to our cultural survival. The focus in our discussion of hearing, then, is on how the auditory system encodes and represents sound-wave frequency (Kubovy, 1981).

## The Human Ear

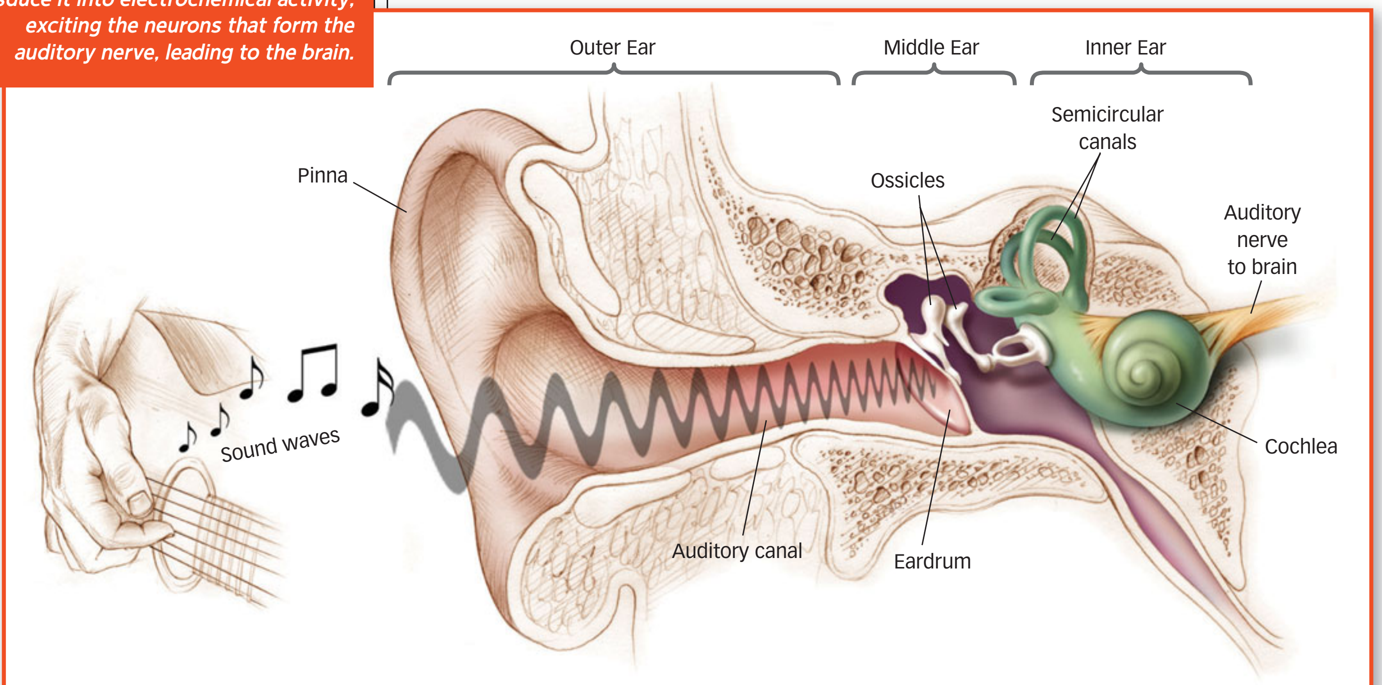
How does the auditory system convert sound waves into neural signals? The process is very different from the visual system, which is not surprising, given that light is a form of electromagnetic radiation, whereas sound is a physical change in air pressure over time. Different forms of energy suggest different processes of transduction. The human ear is divided into three distinct parts, as shown in FIGURE 4.19 (below). The *outer ear* collects sound waves and funnels them toward the *middle ear,* which transmits the vibrations to the *inner ear,* embedded in the skull, where they are transduced into neural impulses.

The outer ear consists of the visible part on the outside of the head (called the *pinna*); the auditory canal; and the eardrum, an airtight flap of skin that vibrates in response to sound waves gathered by the pinna and channeled into the canal. The middle ear, a tiny, air-filled chamber behind the eardrum, contains the three smallest bones in the body, called *ossicles*. Named for their appearance as hammer, anvil, and stirrup, the ossicles fit together into a lever that mechanically transmits and intensifies vibrations from the eardrum to the inner ear.

**How do hair cells in the ear enable us to hear?**

The inner ear contains the spiral-shaped **cochlea** (Latin for "snail"), *a fluid-filled tube that is the organ of auditory transduction.* The cochlea is divided along its length by the **basilar membrane,** *a structure in the inner ear that undulates when vibrations from the ossicles reach the cochlear fluid* (see FIGURE 4.20). Its wavelike movement stimulates thousands of tiny **hair cells,** *specialized auditory receptor neurons embedded in the basilar membrane.* The hair cells then release neurotransmitter molecules, initiating a neural signal in the auditory

FIGURE 4.19 **Anatomy of the Human Ear** *The pinna funnels sound waves into the auditory canal to vibrate the eardrum at a rate that corresponds to the sound's frequency. In the middle ear, the ossicles pick up the eardrum vibrations, amplify them, and pass them along by vibrating a membrane at the surface of the fluid-filled cochlea in the inner ear. Here fluid carries the wave energy to the auditory receptors that transduce it into electrochemical activity, exciting the neurons that form the auditory nerve, leading to the brain.*



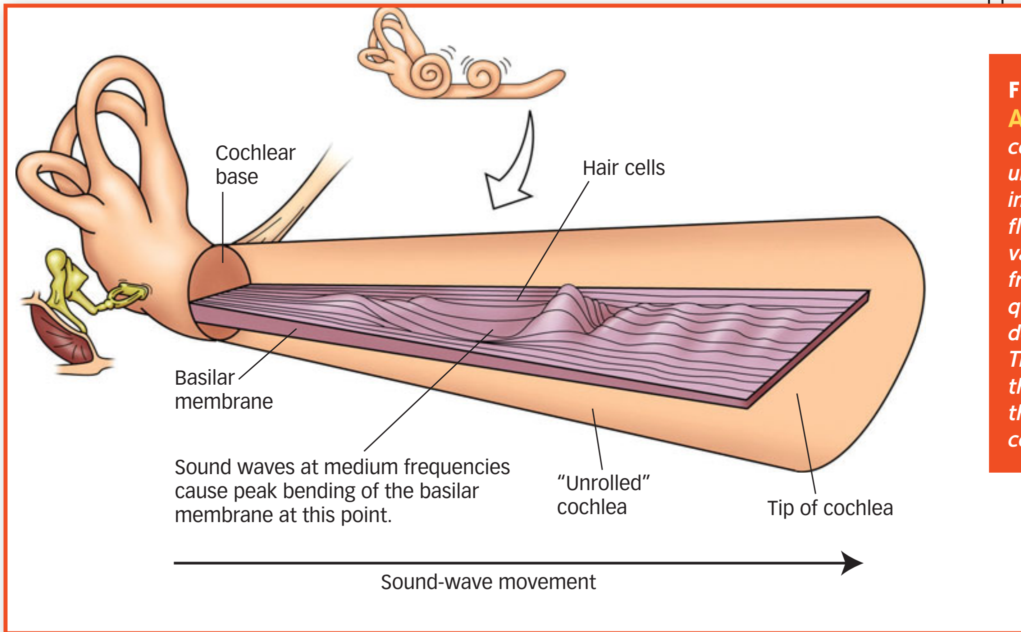



**FIGURE 4.20** **Auditory Transduction** *Inside the cochlea, shown here as though it were uncoiled, the basilar membrane undulates in response to wave energy in the cochlear fluid. Waves of differing frequencies ripple varying locations along the membrane, from low frequencies at its tip to high frequencies at the base, and bend the embedded hair cell receptors at those locations. The hair-cell motion generates impulses in the auditory neurons, whose axons form the auditory nerve that emerges from the cochlea .*

nerve that travels to the brain. You might not want to think that the whispered "I love you" that sends chills up your spine got a kick start from lots of little hair cells wiggling around, but the mechanics of hearing are what they are!

## Perceiving Pitch

From the inner ear, action potentials in the auditory nerve travel to the thalamus and ultimately to the contralateral ("opposite side"; see Chapter 3) hemisphere of the cerebral cortex. This is called **area A1**, *a portion of the temporal lobe that contains the primary auditory cortex* (see **FIGURE 4.21**, below). For most of us, the auditory areas in the left hemisphere analyze sounds related to language and those in the right hemisphere specialize in rhythmic sounds and music.

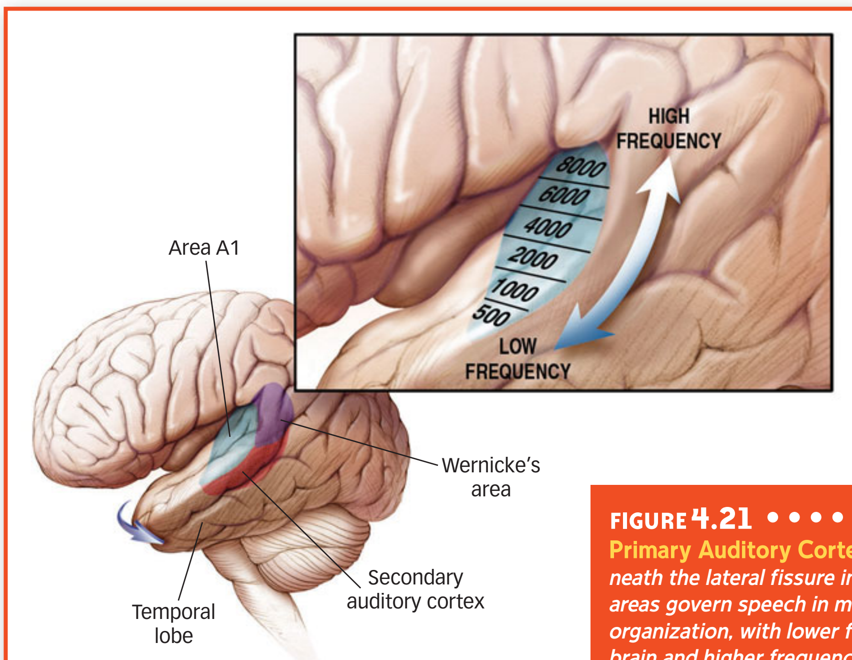



**FIGURE 4.21** **Primary Auditory Cortex** *Area A1 is folded into the temporal lobe beneath the lateral fissure in each hemisphere. The left hemisphere auditory areas govern speech in most people. (inset) A1 cortex has a topographic organization, with lower frequencies mapping toward the front of the brain and higher frequencies toward the back, mirroring the organization of the basilar membrane along the cochlea (see Figure 4.20).*

**place code** The cochlea encodes different frequencies at different locations along the basilar membrane.

**temporal code** The cochlea registers low frequencies via the firing rate of action potentials entering the auditory nerve.

**haptic perception** The active exploration of the environment by touching and grasping objects with our hands.

Neurons in area A1 respond to simple tones, and successive auditory areas in the brain process sounds of increasing complexity (Schreiner, Read, & Sutter, 2000). Like area V1 in the visual cortex, area A1 has a topographic organization: Similar frequencies activate neurons in adjacent locations (see **FIGURE 4.21**, inset, on page 113). A young adult with normal hearing ideally can detect sounds between about 20 and 20,000 Hz, although the ability to hear at the upper range decreases with age. The human ear is most sensitive to frequencies around 1,000 to 3,500 Hz. But how is the frequency of a sound wave encoded in a neural signal?

Our ears have evolved two mechanisms to encode sound-wave frequency, one for high frequencies and one for low frequencies. The **place code**, used mainly for high frequencies, is active when *the cochlea encodes different frequencies at different locations along the basilar membrane*. When the frequency is low, the wide end (*apex*) of the basilar membrane moves the most; when the frequency is high, the narrow end (*base*) of the membrane moves the most. The movement of the basilar membrane causes hair cells to bend, initiating a neural signal in the auditory nerve. The place code works best for relatively high frequencies that resonate at the basilar membrane's base and less well for low frequencies that resonate at the apex.

● How does the frequency of a sound wave relate to what we hear?

A complementary process handles lower frequencies. A **temporal code** *registers low frequencies via the firing rate of action potentials entering the auditory nerve*. Action potentials from the hair cells are synchronized in time with the peaks of the incoming sound waves (Johnson, 1980). If you imagine the rhythmic *boom-boom-boom* of a bass drum, you can probably also imagine the *fire-fire-fire* of action potentials corresponding to the beats. This process provides the brain with very precise information about pitch that supplements the information provided by the place code.

However, individual neurons can produce action potentials at a maximum rate of only about 1,000 spikes per second, so the temporal code does not work as well as the place code for high frequencies. (Imagine if the action potential has to fire in time with the *rat-a-tat-a-tat-a-tat* of a snare drum roll!) Like the cones in color processing, the place code and the temporal code work together to cover the entire range of pitches that people can hear.

## Localizing Sound Sources

Just as the differing positions of our eyes give us stereoscopic vision, the placement of our ears on opposite sides of the head give us stereophonic hearing. The sound arriving at the ear closer to the sound source is louder than the sound in the farther ear, mainly because the listener's head partially blocks sound energy. This loudness difference decreases as the sound source moves from a position directly to one side (maximal difference) to straight ahead (no difference).

Another cue to a sound's location arises from timing: Sound waves arrive a little sooner at the near ear than at the far ear. The timing difference can be as brief as a few microseconds, but together with the intensity difference, it is sufficient to allow us to perceive the location of a sound. When the sound source is ambiguous, you may find yourself turning your head from side to side to localize it. By doing this, you are changing the relative intensity and timing of sound waves arriving in your ears and collecting better information about the likely source of the sound.

### summary quiz [4.3]

**11.** As the number of cycles per second of a sound wave increases, we experience a _____ sound.

a. higher
b. lower
c. louder
d. softer

**12.** The fluid filled tube that is the organ of auditory transduction is the
a. cochlea. c. auditory canal.
b. basilar membrane. d. eardrum.

**13.** The place code works best for encoding
a. high intensities. c. low frequencies.
b. medium frequencies. d. high frequencies.

## The Body Senses: More Than Skin Deep

Vision and audition provide information about the world at a distance. By responding to light and sound energy in the environment, these "distance" senses allow us to identify and locate the objects and people around us. In comparison, the body senses, also called *somatosenses* (*soma* from the Greek for "body"), are up close and personal. **Haptic perception** results from our *active exploration of the environment by touching and grasping objects with our hands*. We use sensory receptors in our muscles, tendons, and joints as well as a variety of receptors in our skin to get a feel for the world around us.

### Touch

Four types of receptors located under the skin's surface enable us to sense pressure, texture, pattern, or vibration against the skin (see **FIGURE 4.22**, below). The receptive fields of these specialized cells work together to provide a rich tactile (from Latin, "to touch") experience when you explore an object by feeling it or attempt to grasp it. In addition, *thermoreceptors,* nerve fibers that sense cold and warmth, respond when your skin temperature changes. All these sensations blend seamlessly together in perception, of course, but detailed physiological studies have successfully isolated the parts of the touch system (Johnson, 2002).

Touch begins with the transduction of skin sensations into neural signals. Like cells in the retina of each eye, touch receptors have receptive fields that, when stimulated, cause that cell's response to change. The representation of touch in the brain follows a topographic scheme, much as vision and hearing do. Think back to the homunculus

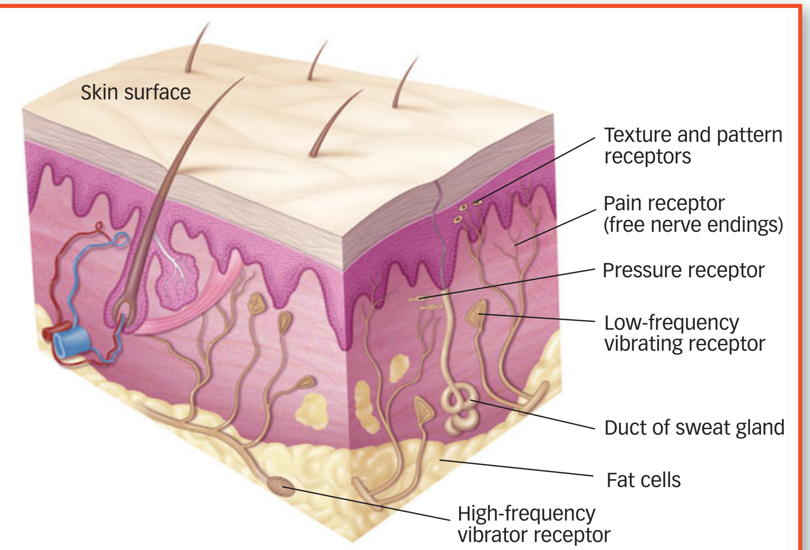



**FIGURE 4.22** **Touch Receptors** *Specialized sensory neurons form distinct groups of haptic receptors that detect pressure, temperature, and vibrations against the skin. Touch receptors respond to stimulation within their receptive fields, and their long axons enter the brain via the spinal or cranial nerves. Pain receptors populate all body tissues that feel pain: They are distributed around bones and within muscles and internal organs as well as under the skin surface. Both types of pain receptors—the fibers that transmit immediate, sharp pain sensations quickly and those that signal slow, dull pain that lasts and lasts—are free nerve endings.*

you read about in Chapter 3; you'll recall that different locations on the body project sensory signals to different locations in the somatosensory cortex in the parietal lobe.

Two important principles describe the neural representation of the body's surface. First, there is contralateral organization: The left half of the body is represented in the right half of the brain and vice versa. Second, more of the tactile brain is devoted to parts of the skin surface that have greater spatial resolution. Regions such as the fingertips and lips are very good at discriminating fine spatial detail, whereas areas such as the lower back are quite poor at that task. These perceptual abilities are a natural consequence of the fact that the fingertips and lips have a relatively dense arrangement of touch receptors and a large topographical representation in the somatosensory cortex; comparatively, the lower back, hips, and calves have a relatively small representation (Penfield & Rasmussen, 1950).

● **Why might discriminating spatial detail be important for fingertips and lips?**

## Pain

Although pain is arguably the least pleasant of sensations, this aspect of touch is among the most important for survival. Pain indicates damage or potential damage to the body. The possibility of a life free from pain might seem appealing, but without the ability to feel pain, we might ignore infections, broken bones, or serious burns. Congenital insensitivity to pain, a rare inherited disorder that specifically impairs pain perception, is more of a curse than a blessing: Children who experience this disorder often mutilate themselves (biting into their tongues, for example, or gouging their skin while scratching) and are at increased risk of dying during childhood (Nagasako, Oaklander, & Dworkin, 2003).

Tissue damage is transduced by pain receptors, the free nerve endings shown in FIGURE 4.22, on page 115. Researchers have distinguished between fast-acting *A-delta fibers,* which transmit the initial sharp pain one might feel right away from a sudden injury, and slower *C fibers,* which transmit the longer-lasting, duller pain that persists after the initial injury. If you were running barefoot outside and stubbed your toe against a rock, you would first feel a sudden stinging pain transmitted by A-delta fibers that would die down quickly, only to be replaced by the throbbing but longer-lasting pain carried by C fibers. Both the A-delta and C fibers are impaired in cases of congenital insensitivity to pain, which is one reason why the disorder can be life threatening.

As you'll remember from Chapter 3, the pain withdrawal reflex is coordinated by the spinal cord. No brainpower is required when you touch a hot stove; you retract your hand almost instantaneously. But neural signals for pain—such as wrenching your elbow as you brace yourself from falling—travel to two distinct areas in the brain and evoke two distinct psychological experiences (Treede et al., 1999). One pain pathway sends signals to the somatosensory cortex, identifying where the pain is occurring and what sort of pain it is (sharp, burning, dull). The second pain pathway sends signals to the motivational and emotional centers of the brain, such as the hypothalamus and amygdala, and to the frontal lobe. This is the aspect of pain that is unpleasant and motivates us to escape from or relieve the pain.

Pain typically feels as if it comes from the site of the tissue damage that caused it. If you burn your finger, you will perceive the pain as originating there. But we have pain receptors in many areas besides the skin—around bones and within muscles and internal organs as well. When pain originates internally, in a body organ, for example, we actually feel it on the surface of the body. This kind of **referred pain** occurs when *sensory information from internal and external areas converge on the same nerve cells in the spinal cord.* One common example is

● *Injuries are a part of football, but knowing that doesn't make them any less painful.*

AP PHOTO/THE DECATUR DAILY/DAN HENRY

a heart attack: Victims often feel pain radiating from the left arm rather than from inside the chest.

Pain intensity cannot always be predicted solely from the extent of the injury that causes the pain (Keefe, Abernathy, & Campbell, 2005). For example, *turf toe* sounds like the mildest of ailments; it is pain at the base of the big toe as a result of bending or pushing off repeatedly, as a runner or football player might do during a sporting event. This small-sounding injury in a small area of the body can nonetheless sideline an athlete for a month with considerable pain. At the same time, you've probably heard a story or two about someone treading bone-chilling water for hours on end, or dragging their shattered legs a mile down a country road to seek help after a tractor accident, or performing some other incredible feat despite searing pain and extensive tissue damage. Pain type and pain intensity show a less-than-perfect correlation, a fact that has researchers intrigued.

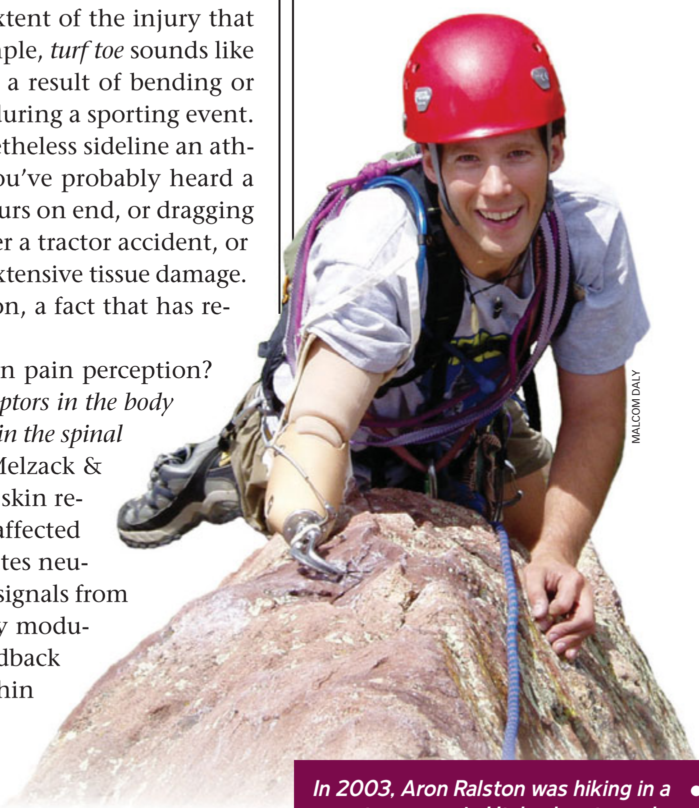
How do psychologists account for this puzzling variability in pain perception? According to **gate-control theory**, *signals arriving from pain receptors in the body can be stopped, or gated, by interneurons in the spinal cord via feedback from two directions* (Melzack & Wall, 1965). Pain can be gated by the skin receptors, for example, by rubbing the affected area. Rubbing your stubbed toe activates neurons that "close the gate" to stop pain signals from traveling to the brain. Pain can also be gated from the brain by modulating the activity of pain-transmission neurons. This neural feedback is elicited not by the pain itself, but rather by activity deep within the thalamus.

● Why does rubbing an injured area sometimes help alleviate pain?

The neural feedback comes from a region in the midbrain called the *periaqueductal gray* (PAG). Under extreme conditions, such as high stress, naturally occurring endorphins can activate the PAG to send inhibitory signals to neurons in the spinal cord that then suppress pain signals to the brain, thereby modulating the experience of pain. The PAG is also activated through the action of opiate drugs, such as morphine.

A different kind of feedback signal can *increase* the sensation of pain. This system is activated by events such as infection and learned danger signals. When we are quite ill, what might otherwise be experienced as mild discomfort can feel quite painful. This pain facilitation signal presumably evolved to motivate people who are ill to rest and avoid strenuous activity, allowing their energy to be devoted to healing.

Gate-control theory offers strong evidence that perception is a two-way street. The senses feed information, such as pain sensations, to the brain, a pattern termed *bottom-up control* by perceptual psychologists. The brain processes this sensory data into perceptual information at successive levels to support movement, object recognition, and eventually more complex cognitive tasks, such as memory and planning. But there is ample evidence that the brain exerts plenty of control over what we sense as well. Visual illusions and the Gestalt principles of filling in, shaping up, and rounding out what isn't really there provide some examples. This kind of *top-down control* also explains the descending pain pathway initiated in the midbrain.



MALCOM DALY

*In 2003, Aron Ralston was hiking in a remote canyon in Utah when tragedy struck. A 1,000-pound boulder pinned him in a three-foot-wide space for five days, eventually leaving him no choice but to amputate his own arm with a pocketknife. He then applied a tourniquet, rappelled down the canyon, and hiked out to safety. These and similar stories illustrate that the extent of an injury is not perfectly correlated with the amount of pain felt. Although self-amputation is undoubtedly excruciating, luckily in this case it was not debilitating.*

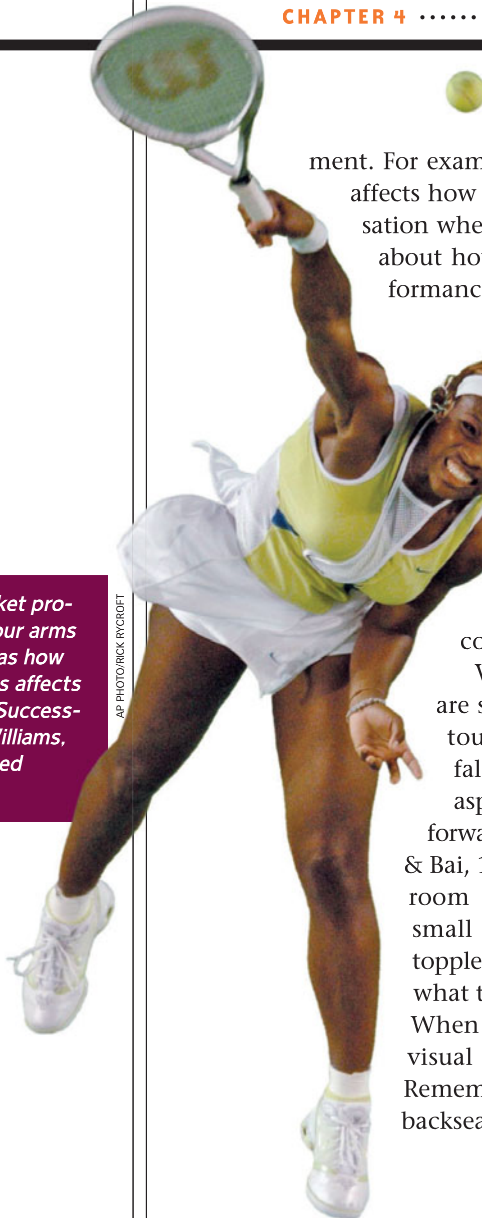
## Body Position, Movement, and Balance

It may sound odd, but one aspect of sensation and perception is knowing where parts of your body are at any given moment. Your body needs some way to sense its position in physical space other than moving your eyes to constantly visually check the location of your limbs. Sensations related to position, movement, and balance depend on stimulation produced within our bodies.

Sensory receptors in the muscles, tendons, and joints signal the position of the body in space, providing the information we need to perceive the position and movement of our limbs, head, and body. These receptors also provide feedback about whether we are

**referred pain** The feeling of pain when sensory information from internal and external areas converge on the same nerve cells in the spinal cord.

**gate-control theory** A theory of pain perception based on the idea that signals arriving from pain receptors in the body can be stopped, or *gated*, by interneurons in the spinal cord via feedback from two directions.



AP PHOTO/RICK RYCROFT

*Hitting a ball with a bat or racket provides feedback as to where your arms and body are in space as well as how the resistance of these objects affects your movement and balance. Successful athletes, such as Serena Williams, have particularly well-developed body senses.*

performing a desired movement correctly and how resistance from held objects may be influencing the movement. For example, when you swing a baseball bat, the weight of the bat affects how your muscles move your arm as well as the change in sensation when the bat hits the ball. Muscle, joint, and tendon feedback about how your arms actually moved can be used to improve performance through learning.

Maintaining balance depends primarily on the **vestibular system**, *the three fluid-filled semicircular canals and adjacent organs located next to the cochlea in each inner ear* (see **FIGURE 4.19** on page 112). The semicircular canals are arranged in three perpendicular orientations and studded with hair cells that detect movement of the fluid when the head moves or accelerates. This detected motion enables us to maintain our balance, or the position of our bodies relative to gravity. The movements of the hair cells encode these somatic sensations (Lackner & DiZio, 2005).

Vision also helps us keep our balance. If you see that you are swaying relative to a vertical orientation, such as the contours of a room, you move your legs and feet to keep from falling over. Psychologists have experimented with this visual aspect of balance by placing people in rooms that can be tilted forward and backward (Bertenthal, Rose, & Bai, 1997; Lee & Aronson, 1974). If the room tilts enough—particularly when small children are tested—people will topple over as they try to compensate for what their visual system is telling them. When a mismatch occurs between the information provided by visual cues and vestibular feedback, motion sickness can result. Remember this discrepancy the next time you try reading in the backseat of a moving car!

**Why is it so hard to stand on one foot with your eyes closed?**

## summary quiz [4.4]

**14.** Which part of the body occupies the greatest area in the somatosensory cortex?
a. calves
b. lips
c. lower back
d. hips

**15.** Which is an example of referred pain?
a. A football player develops pain at the base of the big toe from pushing off repeatedly.
b. You stub your toe on a rock and feel a sudden, stinging pain.
c. You touch a hot stove and retract your hand immediately.
d. A heart attack victim feels pain radiating from the left arm.

**16.** A mismatch between the information processed by visual feedback and vestibular cues can cause
a. referred pain.
b. motion sickness.
c. turf toe.
d. visual-form agnosis.

**vestibular system** The three fluid-filled semicircular canals and adjacent organs located next to the cochlea in each inner ear.

**olfactory receptor neurons (ORNs)** Receptor cells that initiate the sense of smell.

# The Chemical Senses: Adding Flavor

Somatosensation is all about physical changes in or on the body. Vision and audition sense energetic states of the world—light and sound waves—and touch is activated by physical changes in or on the body surface. The last set of senses we'll consider shares a chemical basis to combine aspects of distance and proximity. The chemical senses of *olfaction* (smell) and *gustation* (taste) respond to the molecular structure of substances floating into the nasal cavity as you inhale or dissolving in saliva. Smell and taste combine to produce the perceptual experience we call *flavor.*

## Smell

Olfaction is the least understood sense and the only one directly connected to the forebrain, with pathways into the frontal lobe, amygdala, and other forebrain structures (recall from Chapter 3 that the other senses connect first to the thalamus). This mapping indicates that smell has a close relationship with areas involved in emotional and social behavior. Smell seems to have evolved in animals as a signaling sense for the familiar—a friendly creature, an edible food, or a sexually receptive mate.

● How many scents can humans smell?

Countless substances release odors into the air, and some of their *odorant molecules* make their way into our noses, drifting in on the air we breathe. Situated along the top of the nasal cavity, shown in **FIGURE 4.23**, is a mucous membrane called the *olfactory epithelium,* which contains about 10 million **olfactory receptor neurons (ORNs)**, *receptor cells that initiate the sense of smell.* Odorant molecules

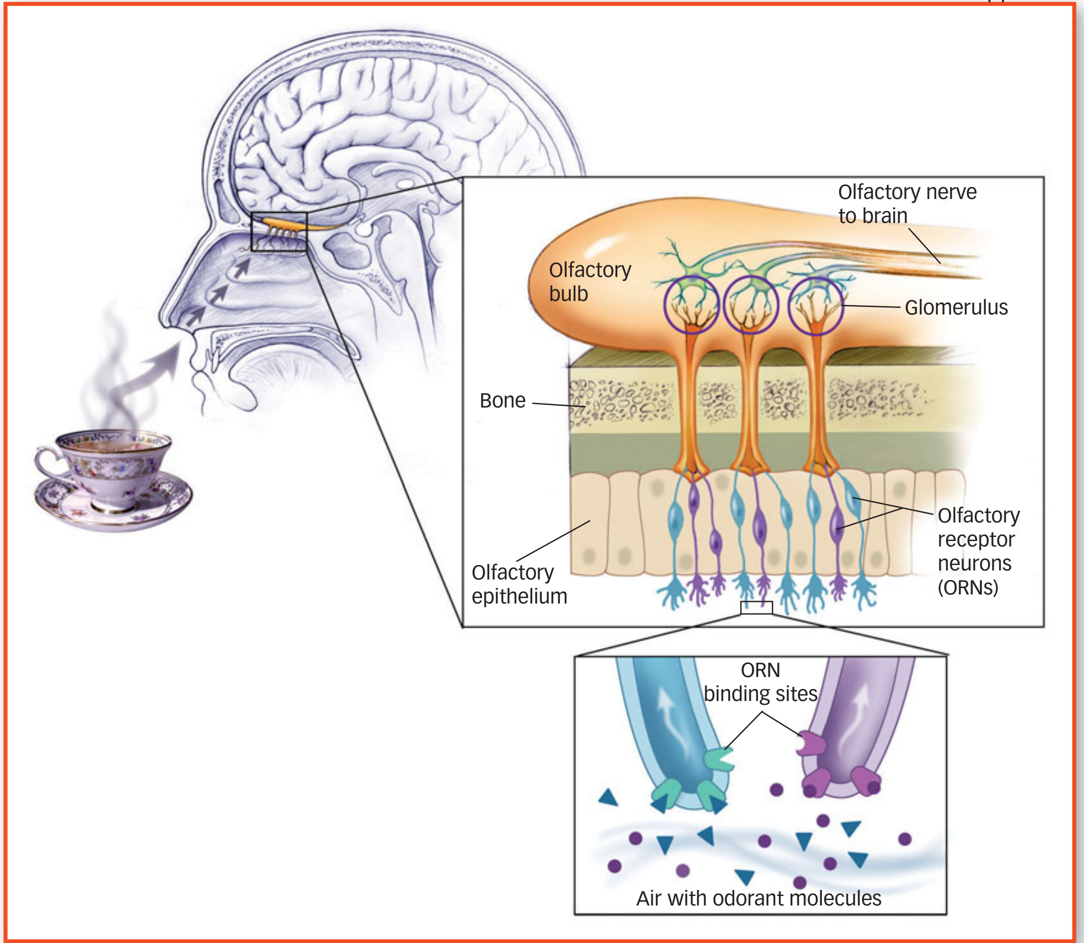



**FIGURE 4.23** **Anatomy of Smell** *Along the roof of the nasal cavity, odorant molecules dissolve in the mucous membrane that forms the olfactory epithelium. Odorants may then bind to olfactory receptor neurons (ORNs) embedded in the epithelium. ORNs respond to a range of odors and, once activated, relay action potentials to their associated glomeruli in the olfactory bulb, located just beneath the frontal lobes. The glomeruli synapse on neurons whose axons form the olfactory nerve, which projects directly into the forebrain.*

**olfactory bulb** A brain structure located above the nasal cavity beneath the frontal lobes.

**pheromones** Biochemical odorants emitted by other members of their species that can affect an animal's behavior or physiology.

**taste buds** The organ of taste transduction.

bind to sites on these specialized receptors, and if enough bindings occur, the ORNs send action potentials into the olfactory nerve (Dalton, 2003).

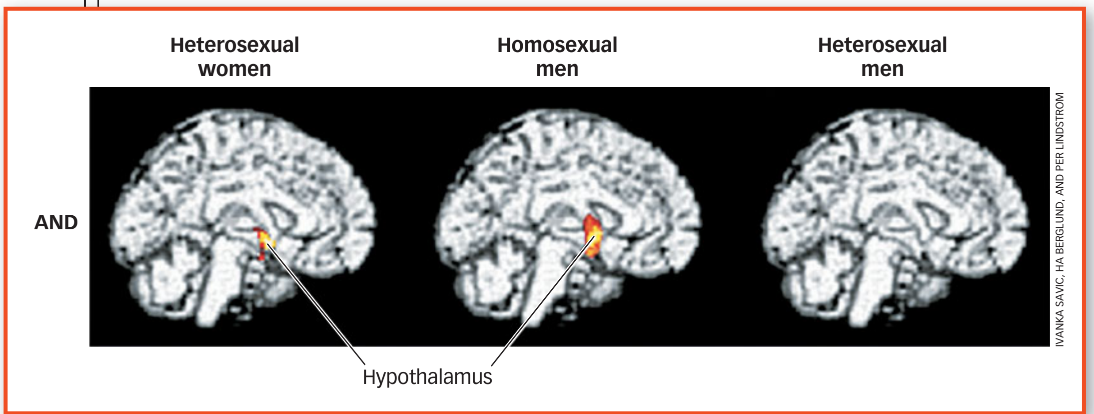
Each olfactory neuron has receptors that bind to some odorants but not to others, as if the receptor is a lock and the odorant is the key (see FIGURE 4.23 on page 119). Groups of ORNs send their axons from the olfactory epithelium into the **olfactory bulb**, *a brain structure located above the nasal cavity beneath the frontal lobes*. Humans possess about 350 different ORN types that permit us to discriminate among some 10,000 different odorants through the unique patterns of neural activity each odorant evokes. This setup is similar to our ability to see a vast range of colors based on only a small number of retinal cell types or to feel a range of skin sensations based on only a handful of touch receptor cell types.

The olfactory bulb sends outputs to various centers in the brain, including the parts that are responsible for controlling basic drives, emotions, and memories. This explains why smells can have immediate strongly positive or negative effects on us. If the slightest whiff of an apple pie baking brings back fond memories of childhood or the unexpected sniff of vomit mentally returns you to a particularly bad party you once attended, you've got the idea. Thankfully, sensory adaptation is at work when it comes to smell, just as it is with the other senses. Whether the associations are good or bad, after just a few minutes the smell fades. Smell adaptation makes sense: It allows us to detect new odors that may require us to act, but after that initial evaluation has occurred, it may be best to reduce our sensitivity to allow us to detect other smells. Evidence from research using fMRI indicates that experience with a smell can modify odor perception by changing how specific parts of the brain involved in olfaction respond to that smell (Li et al., 2006).

Smell may also play a role in social behavior. Humans and other animals can detect odors from **pheromones**, *biochemical odorants emitted by other members of their species that can affect the animal's behavior or physiology*. Parents can distinguish the smell of their own children from other people's children. An infant can identify the smell of its mother's breast from the smell of other mothers. Pheromones also play a role in reproductive behavior in insects and in several mammalian species, including mice, dogs, and primates (Brennan & Zufall, 2006). Can the same thing be said of human reproductive behavior?

Studies of people's preference for the odors of individuals of the opposite sex have produced mixed results, with no consistent tendency for people to prefer them over other pleasant odors. Recent research, however, has provided a link between sexual orientation and responses to odors that may constitute human pheromones (FIGURE 4.24). Researchers used positron emission tomography (PET) scans to study the brain's response to two odors, one related to testosterone, which is produced in men's sweat, and the other related to estrogen, which is found in women's

**FIGURE 4.24**
**Smell and Social Behavior** *In a PET study, heterosexual women, homosexual men, and heterosexual men were scanned as they were presented with each of several odors. During the presentation of a testosterone-based odor (referred to in the figure as AND), there was significant activation in the hypothalamus for heterosexual women (left) and homosexual men (center) but not for heterosexual men (right) (Savic et al., 2005).*



urine. The testosterone-based odor activated the hypothalamus (a part of the brain that controls sexual behavior; see Chapter 3) in heterosexual women but not heterosexual men, whereas the estrogen-based odor activated the hypothalamus in heterosexual men but not women. Strikingly, homosexual men responded to the two chemicals in the same way as women did (Savic, Berglund, & Lindstrom, 2005). Other common odors unrelated to sexual arousal were processed similarly by all three groups. A follow-up study with lesbian women showed that their responses to the testosterone- and estrogen-based odors were largely similar to those of heterosexual men (Berglund, Lindstrom, & Savic, 2006). Taken together, the two studies suggest that some human pheromones are related to sexual orientation.

## Taste

One of the primary responsibilities of the chemical sense of taste is identifying things that are bad for you—as in "poisonous and lethal." Many poisons are bitter, and we avoid eating things that nauseate us for good reason, so taste aversions have a clear adaptive significance. Some aspects of taste perception are genetic, such as an aversion to extreme bitterness, and some are learned, such as an aversion to a particular food that once caused nausea. In either case, the direct contact between a tongue and possible foods allows us to anticipate whether something will be harmful or palatable.

● Why is the sense of taste an evolutionary advantage?

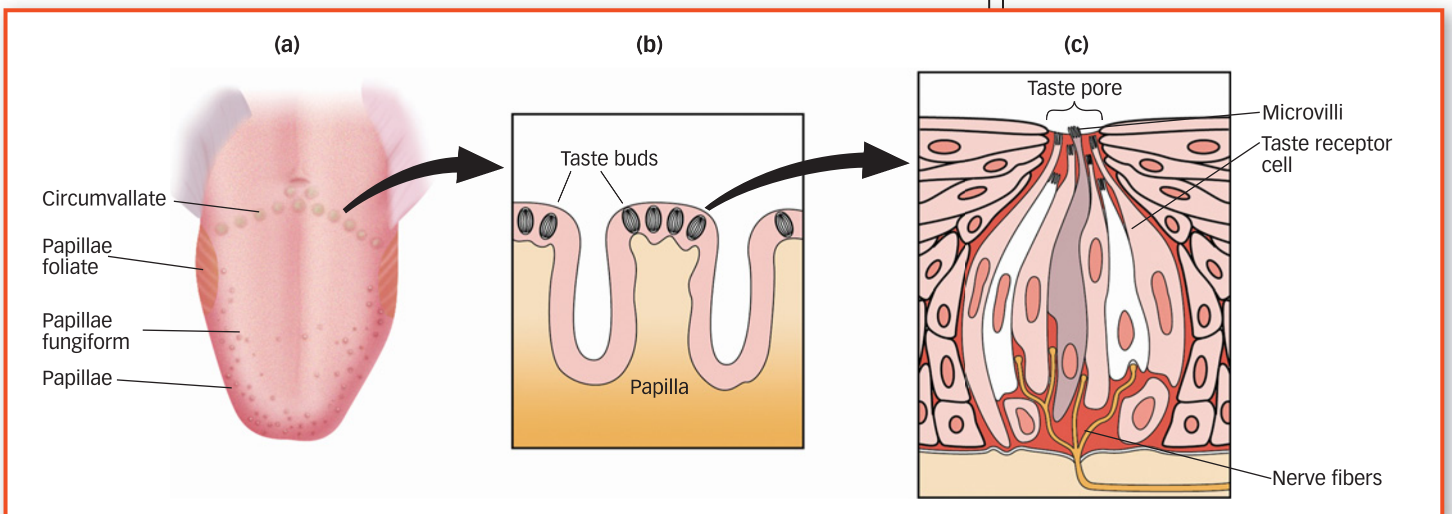
The tongue is covered with thousands of small bumps, called *papillae,* which are easily visible to the naked eye. Within each papilla are hundreds of **taste buds,** *the organ of taste transduction* (see **FIGURE 4.25**, below). Most human mouths contain between 5,000 and 10,000 taste buds fairly evenly distributed over the tongue, roof of the mouth, and upper throat (Bartoshuk & Beauchamp, 1994; Halpern, 2002). Each taste bud contains 50 to 100 taste receptor cells. Taste perception fades with age: On average, people lose half their taste receptors by the time they turn 20. This may help explain why young children seem to be "fussy eaters," because their greater number of taste buds brings with it a greater range of taste sensations.

The human eye contains millions of rods and cones, the human nose contains some 350 different types of olfactory receptors, but the taste system contains just five main types of taste receptors, corresponding to five primary taste sensations: salt, sour, bitter, sweet, and umami (savory). The first four are quite familiar, but *umami* may

**ONLY HUMAN**

**I LOVE THE TASTE OF ASPHALT IN THE MORNING** In April 2006, Jim Werych of the Wednesday Night Classics car club in Brookfield, Wisconsin, ritually dragged his tongue, in a deep lick, across Lisbon Road (with traffic stopped in both directions) to verify and proclaim that the streets were free of winter salt and thus safe for the club's delicate classics.

**FIGURE 4.25**
**A Taste Bud** *(a) Taste buds stud the bumps (papillae) on your tongue, shown here, as well as the back, sides, and roof of the mouth. (b) Each taste bud contains a range of receptor cells that respond to varying chemical components of foods called tastants. Tastant molecules dissolve in saliva and stimulate the microvilli that form the tips of the taste receptor cells. (c) Each taste bud contacts the branch of a cranial nerve at its base.*



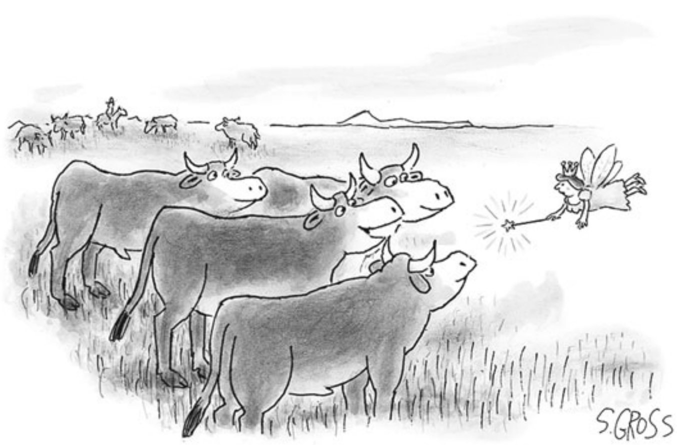
A top chef knows how to activate our various taste receptor cells in a way that puts a smile on our face.


STEPHEN LOVEKIN/GETTY IMAGES

not be. In fact, perception researchers are still debating its existence. The umami receptor was discovered by Japanese scientists who attributed it to the tastes evoked by foods containing a high concentration of protein, such as meats and cheeses (Yamaguchi, 1998). If you're a meat eater and you savor the feel of a steak topped with butter or a cheeseburger as it sits in your mouth, you've got an idea of the umami sensation.

Each taste bud contains several types of taste receptor cells whose tips, called *microvilli,* react with *tastant molecules* in food. Salt taste receptors are most strongly activated by sodium chloride—table salt. Sour receptor cells respond to acids, such as vinegar or lime juice. Bitter and sweet taste receptors are more complex. Some 50 to 80 distinct binding sites in bitter receptors are activated by an equal number of different bitter-tasting chemicals. Sweet receptor cells likewise can be activated by a wide range of substances in addition to sugars.

Although umami receptor cells are the least well understood, researchers are honing in on their key features (Chandrashekar et al., 2006). They respond most strongly to glutamate, an amino acid in many protein-containing foods. Recall from Chapter 3, glutamate acts as a neurotransmitter; in fact, it's a major excitatory neurotransmitter.




*"We would like to be genetically modified to taste like Brussels sprouts."*

The food additive *monosodium glutamate* (MSG), which is often used to flavor Asian foods, particularly activates umami receptors. Some people develop headaches or allergic reactions after eating MSG.

Of course, the variety of taste experiences greatly exceeds the five basic receptors discussed here. Any food molecules dissolved in saliva evoke specific, combined patterns of activity in the five taste receptor types. Although we often think of taste as the primary source for flavor, in fact, taste and smell collaborate to produce this complex perception.

You can easily demonstrate the contribution of smell to flavor by tasting a few different foods while holding your nose, preventing the olfactory system from detecting their odors. If you have a head cold, you probably already know how this turns out. Your favorite spicy burrito or zesty pasta probably tastes as bland as can be.

ALUMA IMAGES/MASTERFILE/RADIUS IMAGES

*Together, taste and smell produce what we perceive as flavor. This is why smelling the "bouquet" of a wine is an essential part of the wine-tasting ritual. Without smell, it would be difficult to taste subtle differences between wines.*

## summary quiz [4.5]

**17.** Which is the correct sequence of transmission for the sense of smell?
a. olfactory receptor neurons; olfactory bulb; olfactory nerve
b. olfactory nerve; olfactory bulb; olfactory reception neurons
c. olfactory bulb; olfactory receptor neurons; olfactory nerve
d. olfactory receptor neurons; olfactory nerve; olfactory bulb

**18.** An infant can identify the smell of its mother's breast from the smell of other mothers. This is likely due to the influence of
a. taste transduction.
b. pheromones.
c. subliminal visual cues.
d. somatosensory cues.

**19.** People lose about half their taste buds by the time they turn
a. 20.
b. 40.
c. 60.
d. 80.

## WhereDoYouStand?

### Perception and Persuasion

In the 1950s, movie theater owners experimented with a new and controversial marketing technique: subliminal advertising. They screened films into which studios had spliced single frames containing photographs of popcorn and soda or word images such as *I'm thirsty*. At normal projection speed, these images were too brief for moviegoers to perceive consciously, but theater owners hoped that projecting the messages would register with viewers and thus increase concession sales during intermissions. However, scientific evidence for this kind of subliminal persuasion has been mixed at best.

These days, marketers advocate a more subtle form of advertising known as *sensory branding* (Lindstrom, 2005). The idea is to exploit all the senses to promote a product or a brand. We're used to seeing advertisements that feature exciting, provocative, or sexual images to sell products. In television commercials, these images are accompanied by popular music that advertisers hope will evoke an overall mood favorable to the product. The notion is that the sight and sound of exciting things will become associated with what might be an otherwise drab product.

But sensory branding goes beyond sight and sound by enlisting smell, taste, and touch as well as vision and hearing. That new-car smell you anticipate while you take a test drive? Actually, it's a manufactured fragrance sprayed into the car, carefully tested to evoke positive feelings among potential buyers. Singapore Airlines, which has consistently been rated "the world's best airline," has actually patented the smell of its airplane cabins (it's called Stefan Floridian Waters).

Is there any harm in marketing that bombards the senses or even sneaks through to perception undetected? On the one hand, advertising is a business, and like any business it is fueled by innovation in search of a profit. Perhaps these recent trends are simply the next clever step to get potential buyers to pay attention to a product message. On the other hand, is there a point when "enough is enough"? Do you want to live in a world where every sensory event is trademarked, patented, or test-marketed before reaching your perceptual system? Where do you stand?

# CHAPTER REVIEW

## Summary

### The Doorway to Psychology

- Sensation is the awareness that results from stimulation of a sense organ; perception organizes, identifies, and interprets sensation at the level of the brain.
- Psychophysics is an approach to measuring the strength of a stimulus and an observer's sensitivity to that stimulus.
- An observer's absolute threshold is the smallest intensity needed to detect a stimulus; the just noticeable difference (JND) is the smallest change in a stimulus that can be detected.
- Signal detection theory allows researchers to distinguish between an observer's perceptual sensitivity to a stimulus and criteria for making decisions about the stimulus.
- Sensory adaptation occurs because sensitivity to stimulation tends to decline over time.

### Vision: More Than Meets the Eye

- Light passes through several layers in the eye, where two types of photoreceptor cells in the retina transduce light into neural impulses: cones, which operate under normal daylight conditions and sense color, and rods, which are active under low-light conditions for night vision.
- The outermost layer of the retina consists of retinal ganglion cells (RGCs) that collect and send signals to the brain.
- Cones are specialized to respond to short-wavelength (bluish) light, medium-wavelength (greenish) light, and long-wavelength (reddish) light; the overall pattern of response across the three cone types results in a unique code for each color.
- The outermost layer of the retina collects and sends signals along the optic nerve to the lateral geniculate nucleus in the thalamus, and then to primary visual cortex (area V1) in the occipital lobe of the brain.
- Some regions in the occipital and temporal lobes respond selectively to specific object categories; some neurons in the temporal lobe respond to specific objects when viewed from different angles or to specific objects whether presented as photos or words.
- Gestalt principles of perceptual grouping govern how the features and regions of things fit together.
- Depth perception depends on monocular cues and binocular cues.
- We experience a sense of motion through the differences in strengths of output from motion-sensitive neurons.

### Audition: More Than Meets the Ear

- The frequency of a sound wave determines pitch; the amplitude determines loudness; and differences in complexity, or mix, of frequencies determine the sound quality or timbre.
- Auditory perception begins in the outer ear, which funnels sound waves toward the middle ear, which in turn sends the vibrations to the inner ear, which contains the cochlea.
- Action potentials from the inner ear travel along an auditory pathway through the thalamus to the contralateral primary auditory cortex (area A1) in the temporal lobe.
- Auditory perception depends on both a place code and a temporal code, which together cover the full range of pitches that people can hear.
- Our ability to localize sound sources depends critically on the placement of our ears on opposite sides of the head.

### The Body Senses: More Than Skin Deep

- Touch is represented in the brain according to a topographic scheme in which locations on the body project sensory signals to locations in the somatosensory cortex in the parietal lobe.
- The experience of pain depends on signals that travel along two distinct pathways: one sends signals to the somatosensory cortex to indicate the location and type of pain; the other sends signals to the emotional centers of the brain, resulting in unpleasant feelings that we wish to escape.
- Balance and acceleration depend primarily on the vestibular system but are also influenced by vision.

### The Chemical Senses: Adding Flavor

- Our experience of smell, or olfaction, occurs when odorant molecules bind to sites on specialized olfactory receptors, which converge at the olfactory bulb. The olfactory bulb in turn sends signals to parts of the brain that control drives, emotions, and memories.
- Sensations of taste depend on taste buds, which are distributed across the tongue, roof of the mouth, and upper throat. Taste buds contain taste receptors that correspond to the five primary taste sensations of salt, sour, bitter, sweet, and umami.

## Key Terms

sensation (p. 90)
perception (p. 90)
transduction (p. 91)
psychophysics (p. 92)
absolute threshold (p. 92)
just noticeable difference (JND) (p. 93)
Weber's law (p. 93)
signal detection theory (p. 93)
sensory adaptation (p. 94)
visual acuity (p. 96)
retina (p. 97)
cones (p. 98)
rods (p. 98)
fovea (p. 98)
blind spot (p. 99)
receptive field (p. 100)
area V1 (p. 102)
perceptual constancy (p. 104)
monocular depth cues (p. 106)

binocular disparity (p. 107)
apparent motion (p. 109)
pitch (p. 111)
loudness (p. 111)
timbre (p. 111)
cochlea (p. 112)
basilar membrane (p. 112)
hair cells (p. 112)
area A1 (p. 113)
place code (p. 114)
temporal code (p. 114)
haptic perception (p. 115)
referred pain (p. 116)
gate-control theory (p. 117)
vestibular system (p. 118)
olfactory receptor neurons (ORNs) (p. 119)
olfactory bulb (p. 120)
pheromones (p. 120)
taste buds (p. 121)

## Critical Thinking Questions

1. Sensory adaptation refers to the fact that sensitivity to prolonged stimulation tends to decline over time. According to the theory of natural selection, inherited characteristics that provide a survival advantage tend to spread throughout the population across generations.

   Why might sensory adaptation have evolved? What survival benefits might it confer to a small animal trying to avoid predators? To a predator trying to hunt prey?
2. When visual light (light waves with particular length, amplitude, and purity) reaches the retina, it is transduced by rods and cones into visual signals, interpreted by the brain as color, brightness and saturation.

   Many people (including about 5% of all males) inherit a common type of color blindness, in which the cones that normally process green light are mildly deficient; these people have difficulty distinguishing red from green. Unfortunately, in the United States, traffic signals use red and green lights to indicate whether cars should stop or go through an intersection. Why do drivers with red-green color blindness not risk auto accidents every time they approach an intersection?
3. Color perception and motion perception both rely partially on opponent processing, which is why we fall prey to illusions such as color aftereffects and the waterfall illusion.

   How might the concept of aftereffects account for "sea legs," in which a person who has been on a small boat for a few hours has trouble walking on land—because the ground seems to be rising and falling as if the person were still on the boat?

## Answers to Summary Quizzes

### Summary Quiz 4.1
1. c; 2. c; 3. c; 4. c

### Summary Quiz 4.2
5. b; 6. d; 7. b; 8. d; 9. c; 10. d

### Summary Quiz 4.3
11. a; 12. a; 13, d

### Summary Quiz 4.4
14. b; 15. d; 16. b

### Summary Quiz 4.5
17. a; 18. b; 19. a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