Color Vision

7-4 How do the trichromatic theory and opponent-process theory contribute to our understanding of color vision?

Our visual system is so good at detecting minor variations in color that we can detect *a million* separate hues.[5] The richness this ability adds to our visual world is apparent in the array of color chips available at the paint store and the variety of lipstick colors at the cosmetics counter.

Color, as we know, is a function of the cones. According to a theory first proposed in the nineteenth century and based on the work of Hermann von Helmholtz and Thomas Young, cones are sensitive to three wavelengths of light, which produce red, green, and blue. According to this **trichromatic (three-color) theory,** these three colors combine to create a million color combinations. The trichromatic system is similar to the design used to enable color on TV screens, video projectors, and computer monitors. These screens produce different intensities of red, green, and blue, and all the colors you see on the screen are mixtures of these three basic colors. The cones in the retina operate the same way.

trichromatic theory A theory of color vision that says cones are sensitive to red, green, or blue light—the three colors that combine to create millions of color combinations.

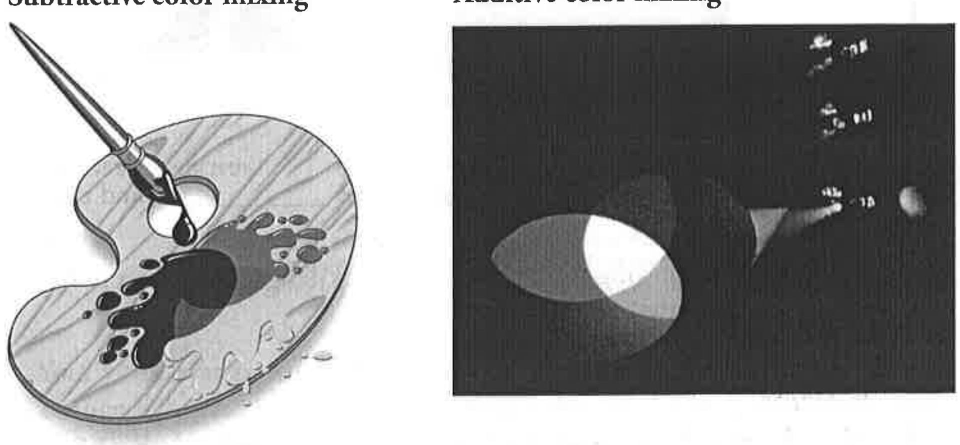
If you've studied art, you may have learned that the primary colors are red, blue, and yellow and wonder why cones aren't tuned to these three colors. You'll find the answer in **Figure 7.9**. Painting produces color by a *subtractive* process: Each paint pigment subtracts—absorbs or soaks up—different wavelengths of light. Red paint, for example, absorbs all wavelengths except red, which is reflected back to the eye. If you mix red, blue, and yellow paint together, you end up with black; together, those three pigments subtract all wavelengths of light.

Vision, however, operates on an *additive* process, with each wavelength of light adding a new color to the mix. If you mix red, green, and blue lights, you end up with white, not black. Those three lights are primary because they produce white light, which combines all wavelengths.

Color-blind people generally lack one of the three types of cones. A more accurate term is *color deficient* because people with this condition are not blind to color but are just limited in the number of colors they can see. Usually they

FIGURE 7.9 What Are the Primary Colors? That depends on whether you're mixing paints or lights. Mixing paints is a subtractive process—each new pigment soaks up another wavelength of reflected light. All wavelengths are subtracted with a mixture of red, blue, and yellow (the result is black), so they are primary. Mixing colored lights is an additive process—each new color adds another wavelength. In this case, the fewest colors that can be mixed to produce white light (representing all wavelengths) are red, green, and blue, so they are primary for this additive process.

Subtractive color mixing **Additive color mixing**



Fritz Goro/The LIFE Picture Collection/Getty Images lack either the red cones or the green cones and have trouble telling the difference between the two.[6] This inherited condition is more common among males than females. Many times, the person with the color deficiency does not even realize a problem exists.

There are some things trichromatic theory does not explain. One of the most fascinating is why we see color afterimages. If you have normal color vision, try this for yourself with **Figure 7.10** by turning the odd green, black, and yellow American flag into the more familiar red, white, and blue version of the Stars and Stripes. Ewald Hering proposed an **opponent-process theory** of color to explain such images. Hering's theory argues that color is processed in opponent pairs (red–green, yellow–blue, and black–white). Light that stimulates one half of the pair inhibits or blocks the other half. For example, stimulation that turns *on* a green-processing neuron ensures that a red-processing neuron will be *off*.[7] Thus, you can see red *or* green at any one spot at a given time but not both simultaneously. Many color pairs combine easily (red and blue, for example, combine to form violet), but there is no greenish-red color.

When you stared at the flag in Figure 7.10, you did so long enough to fatigue your green-detection neurons. Then, when you looked at the white space, your red-detection neurons, which were not tired, produced a red aftereffect that lasted until the green cells recovered.

So, we have two entirely different theories of color vision: the Young-Helmholtz trichromatic theory and the Hering opponent-process theory. Which one is right? *Both* are. Substantial experimental evidence indicates that both systems function to let you see color, and we have no reason to suspect that the existence of one makes the other impossible. Color is clearly important to us.

Luis Santos/Shutterstock

Stop on Red, Go on Blue?
Isn't it interesting that traffic lights use red and green—the two colors most likely to be confused by a person with color vision deficiencies—as the means of conveying the important information of whether to stop or proceed? If you check, you'll notice that newer traffic signals now have a lot of blue in the green light; now it's more of a teal light. This slight change helps people with color-deficient vision tell the difference between stop and go. It also helps, of course, that red and green occupy different positions in the box that houses the lights.

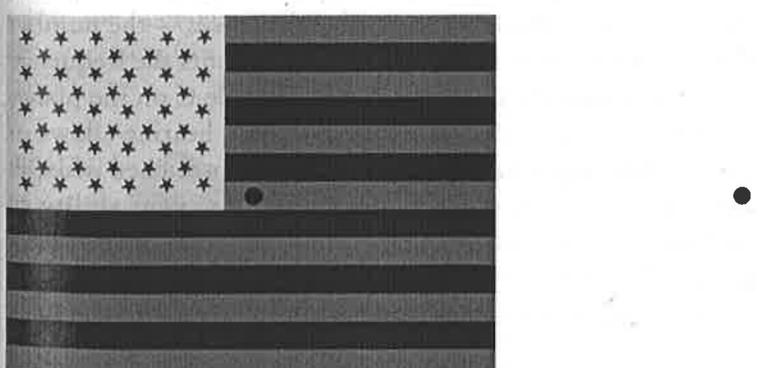


FIGURE 7.10
Color Afterimages
Look at the center dot of the flag for about a minute; then shift your gaze to the dot beside it. An afterimage will develop, but it will be in red, white, and blue. The opponent-process theory of color vision can explain this, but the trichromatic theory cannot.

MAKE IT STICK!

1. Why is *color deficient* generally a more accurate term than *color blind* to describe people who have trouble seeing the world in normal color?
2. Reversed-color afterimage effects can be explained with the ________ theory of color vision.
3. The trichromatic theory of color visions says that
   a. color is processed as light travels through the three layers of the lens.
   b. rods, cones, and bipolar cells all play a role in color vision.
   c. three different kinds of cones detect three different colors.
   d. there are three color reversals in color afterimage drawings.

opponent-process theory
A theory of color vision that says color is processed by cones organized in opponent pairs (red–green, yellow–blue, and black–white); light that stimulates one half of the pair inhibits the other half.

Hearing

7-5 What are the structures of the ear? How do they work to detect sound waves and change them into neural impulses?

Silence may be golden, but sound enriches our experience of the world. In this section, we explore what sound is and how we process it into a form we can understand.

The Nature of Sound

Sound Enriches Our World Sound can annoy—think of fingernails on a chalkboard. But it can also elate. This girl is clearly lost in a world of music.

proxyminder/istockphoto

Light enters the eye as waves of electromagnetic energy. Sound comes in waves, too (see Figure 7.4), but in this case the waves are produced by vibration. Sound *is* vibration. You can feel your vocal cords vibrate if you touch your neck while singing or talking. Musical instruments all produce vibrations—of strings in the case of guitars and pianos, of reeds in the case of saxophones, of drum skins in the case of kettledrums. But you won't hear any of these sounds unless the vibration is carried from its source to your ear. Typically, the vibration travels in pulses of air molecules. But other substances can carry sound waves, too, such as the bones of our skull transmitting the sound of a fast-beating heart to our ears or the water in a pool transmitting the sound of music to the ears of synchronized swimmers. In the case of light, the length of the wave produces hue, and the amplitude (height) of the wave produces brightness. For sound, the length of the wave (frequency) determines **pitch,** the sound's highness or lowness. Pitch is expressed as *hertz (Hz)*—the number of sound waves that reach the ear per second. Hertz represents the frequency of a sound wave and determines the pitch of a sound. Middle C on the piano, for instance, represents a sound of 256 Hz. Normal human hearing allows us to hear deep, rumbling bass sounds as low as 20 Hz or high-pitched whistles of 20,000 Hz, although as you get older you gradually lose your ability to hear higher-pitched sounds. This is why the so-called mosquito or teen buzz ringtone (you can find examples on the internet if you have not listened to it) can be heard by most teenagers but not by most adults. This sound is a little above 17,000 Hz.

pitch A sound's highness or lowness, which depends on the frequency of the sound wave.

The height, or amplitude, of the sound wave determines *loudness,* which is usually measured in *decibels (dB),* named after Alexander Graham Bell. The absolute threshold for hearing is 0 dB. You can see a rough approximation of the decibel level of some common sounds in **Figure 7.11**. Notice that any prolonged sound exceeding 85 dB can produce hearing loss. Sound at the 85 dB level is not painful, and many people play music through headphones at volume levels above 85 dB. This is not a good idea. The hearing loss will not be noticeable on a day-to-day basis, but exposure to any loud, prolonged noise (including good music!) will produce gradual, irreversible hearing loss. Many aging rockers from the 1960s—including Pete Townshend of The Who and Stephen Stills of Crosby, Stills, and Nash—are now dealing with hearing loss caused by exposure to loud amps at countless concerts. Listen up, music fans, and turn down the volume on your speakers and earbuds.

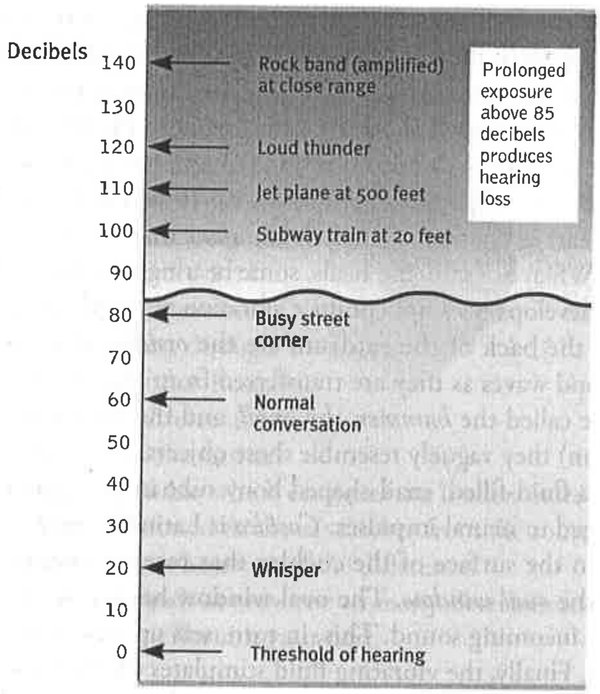
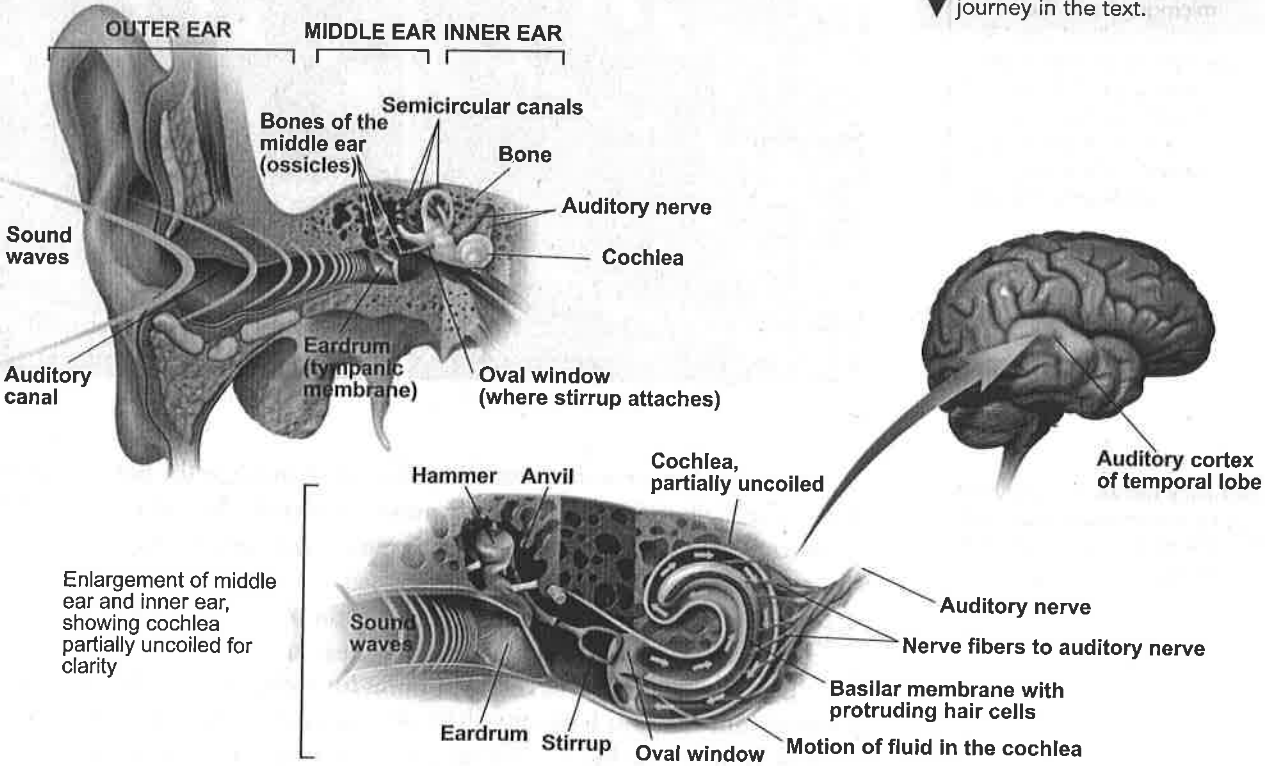


FIGURE 7.11
How Loud Is Loud?
The loudness of sound is measured in decibel (dB) units. Every 10 dB increase represents a *tenfold* increase in loudness (a 20 dB increase is 100 times louder, and a 30 dB increase is 1000 times louder). Prolonged exposure to sounds of 85 dB or more can cause hearing loss.

The Structure of the Auditory System

When your best friend shouts your name across the cafeteria at school, what happens? First, the vocal cord vibrations that constitute the sound must travel through the air from your friend's mouth to your ear. When the sound waves reach your ear, they are funneled by the tissue of your outer ear and travel down the *auditory canal,* the opening through which sound waves travel as they move into the ear for processing (see **Figure 7.12**). At the end of the auditory canal, the sound waves

FIGURE 7.12
The Amazing Journey of a Sound
Sound waves must travel through air, tissue, bone, and fluid before the receptor cells for hearing, the hair cells in the cochlea, generate nerve impulses that the brain can interpret. Use this diagram to follow the path of sound as you read about its journey in the text.



reach a piece of tissue that seals the inner workings of the ear from the dirt, Q-tips, and small Lego pieces of the outside world. This tissue is called the *eardrum* (more formally known as the *tympanic membrane*). The eardrum transfers sound vibration from the air (your friend shouting your name) to the three tiny bones of the middle ear. The tissue of the eardrum is quite tough, but it can be damaged, either by direct contact with objects inserted in the ear (this is why you shouldn't insert objects in your ear) or by exceptionally loud noises that can literally cause the eardrum to burst. When the eardrum heals, some hearing loss will remain because the scar tissue that develops does not conduct vibration as readily as the original tissue.

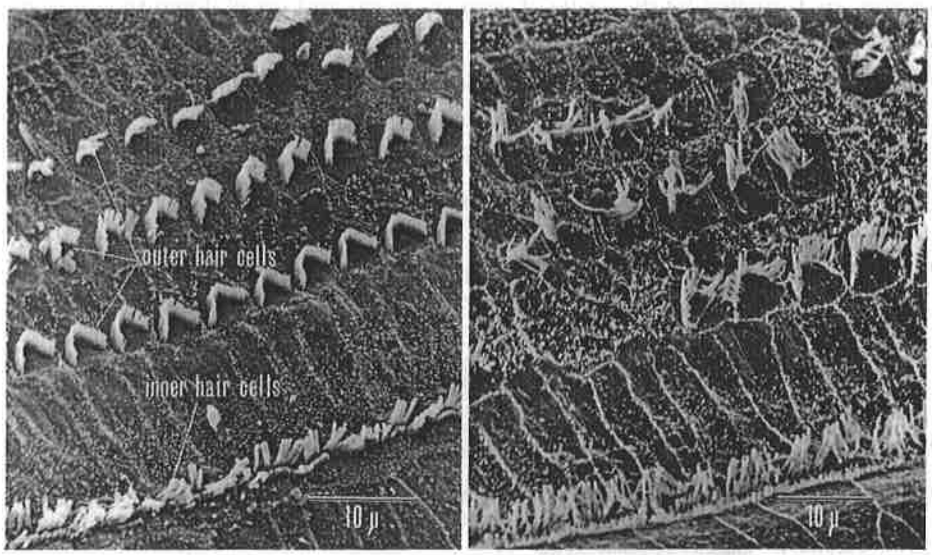
Attached to the back of the eardrum are the *ossicles,* three small bones that amplify the sound waves as they are transferred from the eardrum to the cochlea. These bones are called the *hammer,* the *anvil,* and the *stirrup* because (if you use your imagination) they vaguely resemble these objects. The main organ of hearing is the **cochlea,** a fluid-filled, snail-shaped bony tube in the inner ear where sound waves are changed to neural impulses. *Cochlea* is Latin for *snail.*

cochlea [KOHK-lee-uh] The major organ of hearing; a snail-shaped, bony, fluid-filled structure in the inner ear where sound waves are changed to neural impulses.

hair cells The receptor cells for hearing; these are located in the cochlea and are responsible for changing sound vibrations into neural impulses.

The point on the surface of the cochlea that receives sound vibrations from the ossicles is the *oval window.* The oval window begins to vibrate at the same frequency as an incoming sound. This, in turn, sets up vibrations in the fluid that fills the cochlea. Finally, the vibrating fluid stimulates thousands of **hair cells,** tiny projections in the cochlea that are the receptor cells for hearing. When vibration causes the tips of these hair cells to move even the width of an atom, the vibrations cause the hair cells to generate neural impulses that your brain can process.[8] But prolonged exposure to loud noise will damage these vitally important cells. The two photos in **Figure 7.13** show hair cells before and after such damage.

FIGURE 7.13 Warning: Rock Concerts Can Be Dangerous to Your Guinea Pig (and You) These scanning electron micrographs of the inner ear hair cells of a guinea pig (a) before and (b) after exposure to 24 hours of loud noise (comparable to that of a loud rock concert) testify to noise's destructive effects.



(a) (b)

Robert Preston & Joseph E. Hawkins, Kresge Hearing Research Institute, University of Michigan

auditory nerve The nerve that carries sound information from the ears to the temporal lobes of the brain.

The neural impulses are collected by fibers that attach to the base of each hair cell. These fibers join to form the **auditory nerve,** which exits the cochlea and carries sound information to the temporal lobes of the brain, where auditory processing occurs.

Sound Localization

If you are a hearing person, close your eyes for a moment and listen to the sounds around you. Do you have any difficulty knowing where a particular sound is coming from—whether it's behind you or in front, to your left or to your right?

Localizing sounds is something we are good at, and it's important that we are. Sounds often signify important environmental events, including the presence of danger. We'd *better* be able to locate the source quickly. How do we do it?

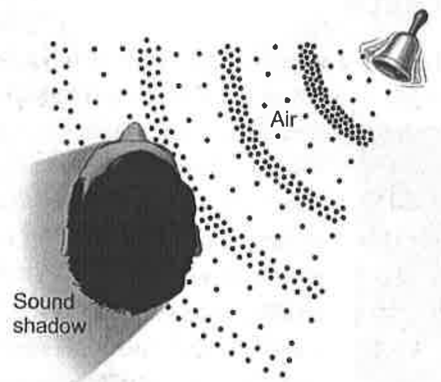


FIGURE 7.14
How Do You Know Where a Sound Is Coming From?
When a sound originates from your right, as in this figure, it reaches your right ear slightly faster and slightly louder than it reaches your left ear. Your brain calculates the differences to locate the source of the sound. Sometimes it is difficult to tell if a sound is coming from directly ahead of you or directly behind you because sounds in this plane reach both ears at the same time and with equal intensity.

We rely on two important cues to locate sound sources (see **Figure 7.14**). Step one is to determine which ear hears the sound first. Sound traveling through air moves about 750 miles per hour. That's fast, but there is still a detectable time lag before sound reaches the farther ear.[9, 10] In step two, we determine which ear hears the louder, more intense sound. By the time a sound moves around to the ear farther from the source, the sound is muted enough for your brain to be aware of the difference.

Locating the source of sounds is only one of many determinations your brain makes without any conscious effort on your part.

MAKE IT STICK!

1. Which two structures can be most easily damaged by loud sounds?
   a. the oval window and the auditory nerve
   b. the auditory canal and the stirrup
   c. the tympanic membrane and the hair cells
   d. the hammer and the anvil

2. The snail-shaped organ of hearing is the ________.

3. The amplitude of sound waves determines
   a. loudness.
   b. Hertz value.
   c. pitch.
   d. sound localization.

Other Senses

7-6 How are tastes, smells, and touch sensations processed?

We have spent considerable time on vision and hearing, which no doubt are vital senses. They also are the best-understood sensory systems and the ones that first come to mind when the topic of sensation comes up. But think about what life would be like with no ability to taste or smell. Without the ability to savor the taste and smell of food, would you still be willing to put effort into preparing meals and eating them? And what would life be like with no sense of touch? You would lose not only good touch, like the satisfaction of a hug or kiss from someone you care about deeply, but also the ability to detect pain. This loss may sound like an improvement, but it wouldn't be. Pain is one of the most effective mechanisms we have to protect ourselves from environmental dangers. Without pain, we wouldn't realize that we had placed our hand on a red-hot stove burner until we smelled our flesh burning—far too late to minimize the seriousness of the injury. Finally, what about your sense of balance and your ability to judge the position of your body parts? Walking would be incredibly difficult if you didn't have a sense of what your legs were doing at each step (excuse the pun) of the process.

Let's take a brief look at some of our remaining senses.

Taste

Taste is a chemical sense. You have receptor cells on the surface of the tongue (and, to a lesser degree, elsewhere in the mouth) that respond to the chemical structure of the foods you eat. These receptor cells can detect five tastes. We have known about salty, sweet, sour, and bitter for a long time.[11] Most recently, researchers discovered a fifth taste receptor for the savory, meaty, cheesy taste called *umami*.[12] It's possible there are other tastes still waiting to be discovered. Newborn babies have a natural attraction to salty and sweet tastes, a biological predisposition that ensures that they will seek mother's milk (which is sweet) and salt (which is necessary for survival). Babies also have natural dislikes—of sour and bitter tastes—which protect them from substances that are more likely to be poisonous.

Bob Krist/Getty Images

Flavor, a Sensory Interaction
We often speak of taste when we really mean flavor. Taste can detect only sweet, sour, salty, bitter, and umami. The flavors shown here on these sumptuous plates also involve their smell, texture, temperature, and appearance.

Taste receptor cells can be damaged by heat, as you no doubt know if you've ever burned your mouth on hot food you couldn't wait to eat. Tobacco smoke also harms these cells. Fortunately, taste cells do replace themselves within a few days. An added benefit of kicking the cigarette habit is that food starts to taste better as the taste cells regenerate.

One interesting fact about taste is that we don't all have the same sensitivity to taste. About a quarter of the population, dubbed supertasters by researcher **Linda Bartoshuk** and her colleagues,[13] have an abundance of taste receptors that allow them to experience tastes, especially bitter tastes, more intensely than most of us do. Bartoshuk theorizes that these individuals were the poison detectors of ancient civilization. If they avoided a food, it was likely to be dangerous and others would avoid it as well. Even today, supertasters, with their enhanced sensitivity to alcohol's bitter taste, are less likely to become dependent on alcohol than are those who don't share this trait.

Courtesy University of Florida Health

LINDA BARTOSHUK (1938–)
Renowned researcher on the role of genetics and the treatment of disorders in the chemical senses of taste and smell.

Another quarter of the population are nontasters. They do taste, of course, but with much less intensity than people with more taste cells. These individuals tend to do well in times of food scarcity because they are willing to eat anything, no matter how bad it tastes. In times of plenty, this tendency can be dangerous, but it just might allow survival in famine. Most of us, about half the population, fall in the middle as medium tasters.

Smell

Smell, like taste, is a chemical sense. Molecules given off by many substances circulate in the air (see **Figure 7.15**). When these molecules reach the upper nasal passages, *olfactory cells* that project from the brain can process these smells. In some ways, smell is more complicated than taste. By triggering various combinations of receptors on the olfactory cells, over a trillion odors can potentially be detected.[14]

LIFE MATTERS

Unlike our other senses, our sense of smell travels through the limbic system, where our memories are processed and emotions are regulated. It's no wonder why a simple whiff of an ex's cologne or perfume can instantly bring you back to a memory of your first kiss or to the heartache you felt when you were dumped.

Taste and smell interact to produce flavor. Perhaps you've noticed that flavor is greatly diminished when you have a head cold with lots of congestion. Odors that normally travel up to the nasal passages from the back of the throat are blocked when you have a head cold, and you are left with taste alone. Try plugging your nose and closing your lips tightly the next time you eat a fruit-flavored jelly bean or Starburst candy. You can detect sour (from the citrus) and sweet (from the sugar), but you cannot tell the flavor (cherry, lemon, and so on). As soon as you unplug your nose, however, the flavor becomes instantly apparent! Actually, flavor

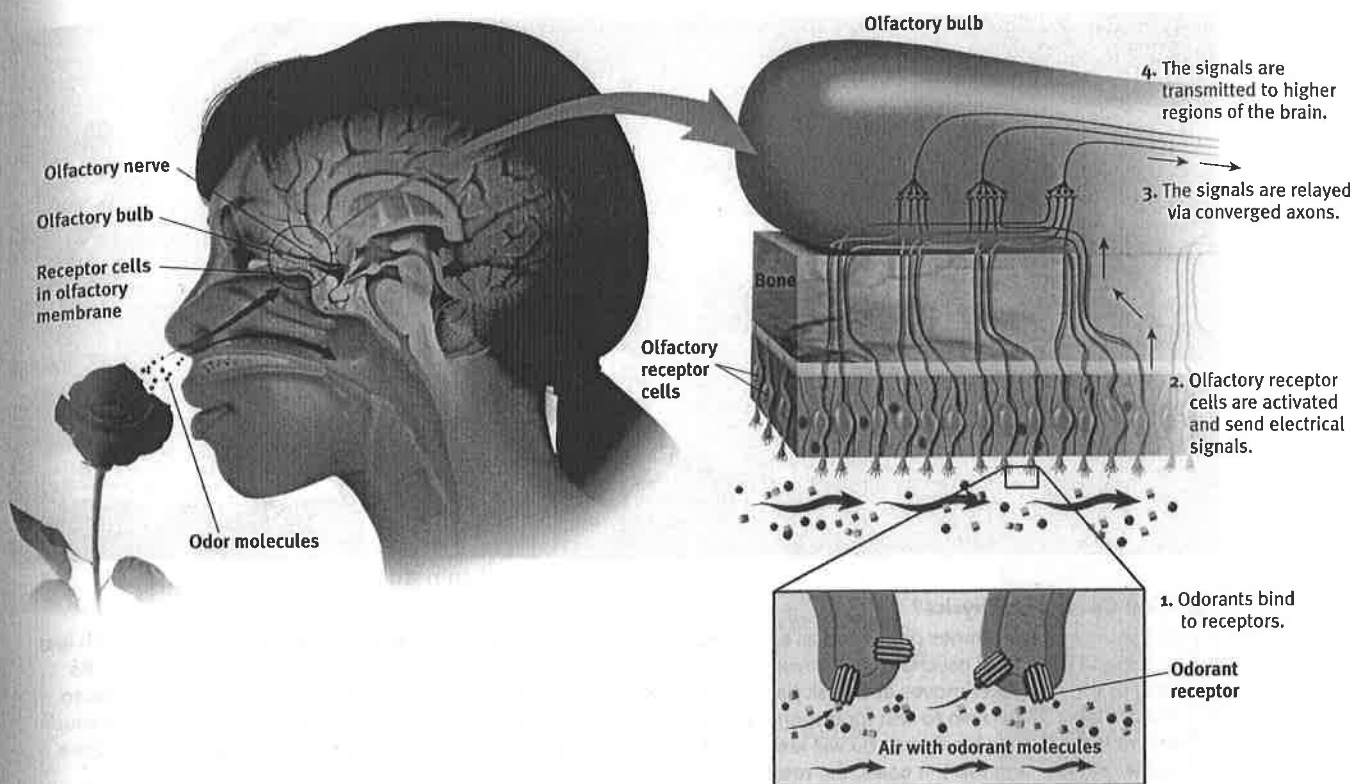


FIGURE 7.15
The Sense of Smell
We are sometimes advised to stop and smell the roses. This is not as easy as it seems!

is an interaction of more than just taste and smell. Appearance is important (how much appeal would blue milk have?), which is why fine restaurants spend so much effort on the visual presentation of their food. Feel or texture is also important (imagine soggy potato chips!), as is temperature (how does a steaming-hot cup of Coca-Cola sound?).

Touch

Touch is your physical connection with the outside world. Your skin is embedded with receptors that respond to various kinds of stimulation. The basic skin senses are pain, warmth, cold, and pressure. Your experience of other skin sensations flows from various combinations of these four basic skin senses. An itch, for example, results from gentle stimulation of pain receptors, hot from simultaneous stimulation of warm and cold (see **Figure 7.16**), and wetness from simultaneous stimulation of cold and pressure.

To explain pain, researchers Ronald Melzack and Patrick Wall have proposed a gate-control theory.[15] According to this gate-control theory, pain messages from the body travel on one set of nerve fibers in the spinal cord, while other kinds of sensory information travel on another set of fibers. The fibers carrying pain messages contain pain gates, which are open when we experience pain. Under some conditions, the nonpain fibers can actually close the pain gates.[16] This is why other touch sensations (rubbing the area that hurts or icing it, for example) can partially block the sensation of pain.

These incoming pain messages involve bottom-up processing. But pain also involves top-down processing. That is, your brain significantly affects whether and how you perceive pain. Athletes in competition may not be fully aware of a painful injury until after their competition is completed. Their level of focus blocks the pain messages from conscious awareness. You've witnessed another example of the top-down processing of pain if you've ever been taking care of a toddler who

FIGURE 7.16
When Is Hot Not?
When cold and warm receptors are stimulated at the same time, the result is an eerie sensation of hot.

Wally Santana/AP Images

Wally Santana/AP Images

Mind Control or Physics?
Fire walking is sometimes presented as an example of mental discipline, or mind over matter. In fact, it has much less to do with supposed psychological powers than with basic physics. Burning coals are poor conductors of heat. As long as the firewalker moves at a brisk pace, he is unlikely to burn himself. It's the same principle that allows you to touch a cake in an oven to test for doneness without burning yourself. Cake is a poor conductor of heat. If you touch the metal cake pan, however, you will learn that it conducts heat much more effectively! And if you walked across a metal grid placed atop the coals, the result would be severe burns.

stumbled and scraped a knee. If you point to the reddened knee and say, "Look!" you'll probably initiate tears and crying. But if you distract the child by handing her a new toy to play with, chances are there will be no crying.

Body Senses

When people speak of the five senses, they are referring to sight, hearing, taste, smell, and touch, but two additional body senses are critically important to our functioning—the kinesthetic sense and the vestibular sense.

kinesthetic sense The system for sensing the position and movement of individual body parts.

Your **kinesthetic sense** is the system that senses the position and movement of your individual body parts. It relies on receptor cells located throughout your muscles and joints. I experienced a disruption of this sense when I had surgery to repair a tendon in the pinky finger of my right hand. I was fully conscious during the surgery, and the anesthetic was administered by an injection in my armpit—which sounds worse than it was—while I held my hand behind my head. I temporarily lost all sensation in my arm after this injection. The odd thing was that I felt totally dissociated from that arm. After the injection, my arm was stretched straight out to my side for the operation, but my brain remembered it as being in the last place it had provided kinesthetic information. In other words, it felt like my hand was still behind my head even though I could see that my arm

Ian MacNicol/Getty Images

A Balancing Act
Your ability to balance results from the vestibular sense that gets its information from the semicircular canals in the inner ear. Gymnasts like Simone Biles use this system to stay oriented no matter what position the body is in.

was straight. A more common disruption of the kinesthetic sense happens when your leg falls asleep. This occurs when you've held your leg in the same position for so long that the nerve temporarily stops transmitting kinesthetic information. It is almost impossible to walk smoothly until the link is reestablished.

A second body sense, the **vestibular sense,** is the system for sensing body orientation and balance. The vestibular sense is located in your inner ear, and it relies on the fluid-filled semicircular canals perched on top of the cochlea, which are visible in Figure 7.12. The easiest way to disrupt your vestibular sense is to spin in circles until you become dizzy. After you stop spinning, the fluid in the vestibular system continues to spin, much as water continues to swirl in a beaker after you've stopped moving the container. You won't know which way is up until the fluid settles down.

vestibular sense The system for sensing body orientation and balance, which is located in the semicircular canals of the inner ear.

MAKE IT STICK!

1. How are taste and smell different from the other senses?
   a. Taste and smell have higher difference thresholds than other senses.
   b. Taste and smell rely on chemical stimuli rather than some other form of energy.
   c. Taste and smell are the only senses that are part of the vestibular system.
   d. Taste and smell are top-down rather than bottom-up senses.
2. The ____________ theory of pain describes how pain information travels up and down the spinal cord.
3. The ____________ sense is located in the inner ear.

LIFE MATTERS

Have you ever gotten motion sickness from hilly backroads while riding in a bus or car? The nausea, dizziness and vomiting experienced with motion sickness are caused by the repeated movement of the vehicle, which overstimulates the semicircular canals in your inner ears.

Your senses are your windows to the world, sources of the raw information you need to guide your thoughts and behaviors. Now that you know a little about how they operate, surely you'll agree that they're *sensational*!

Module 7 Summary and Assessment

Sensation

7-1 What's a possible real-life application of thresholds, signal detection, sensory adaptation, and selective attention?

- A difference threshold allows us to tell that the heating system needs to be repaired because the room is very gradually becoming cooler than it was.
- Signal detection theory helps us know under what circumstances we will be able to successfully tell that there is a gas leak from the water heater.
- Sensory adaptation is useful because it helps us grow accustomed to and filter out an annoying constant hum from an air conditioner.
- Selective attention makes it possible to focus on a movie despite being able to hear the conversations of other people in the theater.