

Brain Facts

SENSATION AND PERCEPTION

VISION. Our wonderful sense of sight allows us to perceive the world around us, from the genius of Michelangelo's Sistine Chapel ceiling to mist-filled vistas of a mountain range. Vision is one of our most delicate and complicated senses. It is also the most intensively studied. About one-fourth of the human brain is involved in visual processing, more than for any other sense. More is known about vision than any other vertebrate sensory system, with most of the information derived from studies of monkeys and cats.

Vision begins with light passing through the *cornea*, which does about three-quarters of the focusing, and then the *lens*, which adjusts the focus. Both combine to produce a clear image of the visual world on the sheet of *photoreceptors* in the *retina*. Photoreceptors absorb light and send electrical signals to nearby neurons lining the back of the eye.

As in a camera, the image on the retina is reversed: Objects to the right of center project images to the left part of the retina and vice versa; objects above the center project to the lower part and vice versa. The size of the pupil, which regulates how much light enters the eye, is controlled by the *iris*. The shape of the lens is altered by the muscles just behind the iris so that near or far objects can be brought into focus on the retina.

Photoreceptors, about 125 million in each human eye, are neurons specialized to turn light into electrical signals. They occur in two forms. *Rods* are most sensitive to dim light and do not convey color.

Cones work in bright light and are responsible for acute detail, black-and-white vision, and color vision. The human eye contains three types of cones, each sensitive to a different range of colors. Because their sensitivities overlap, cones work in combination to convey information about all visible colors. You might be surprised to know that we can see thousands of colors using only three types of cones, but computer monitors use a similar process to generate a spectrum of colors using only three kinds of phosphors: red, green, and blue.

Primates, including humans, have well-developed vision using two eyes, called binocular vision. Visual signals pass from each eye along the million or so fibers of the optic nerve to the optic chiasm, where some nerve fibers cross over, so both sides of the brain receive signals from both eyes. Consequently, the left halves of both retinas project to the left visual cortex and the right halves project to the right visual cortex.

The result is that the left half of the scene you are watching registers in your right hemisphere. Conversely, the right half of the

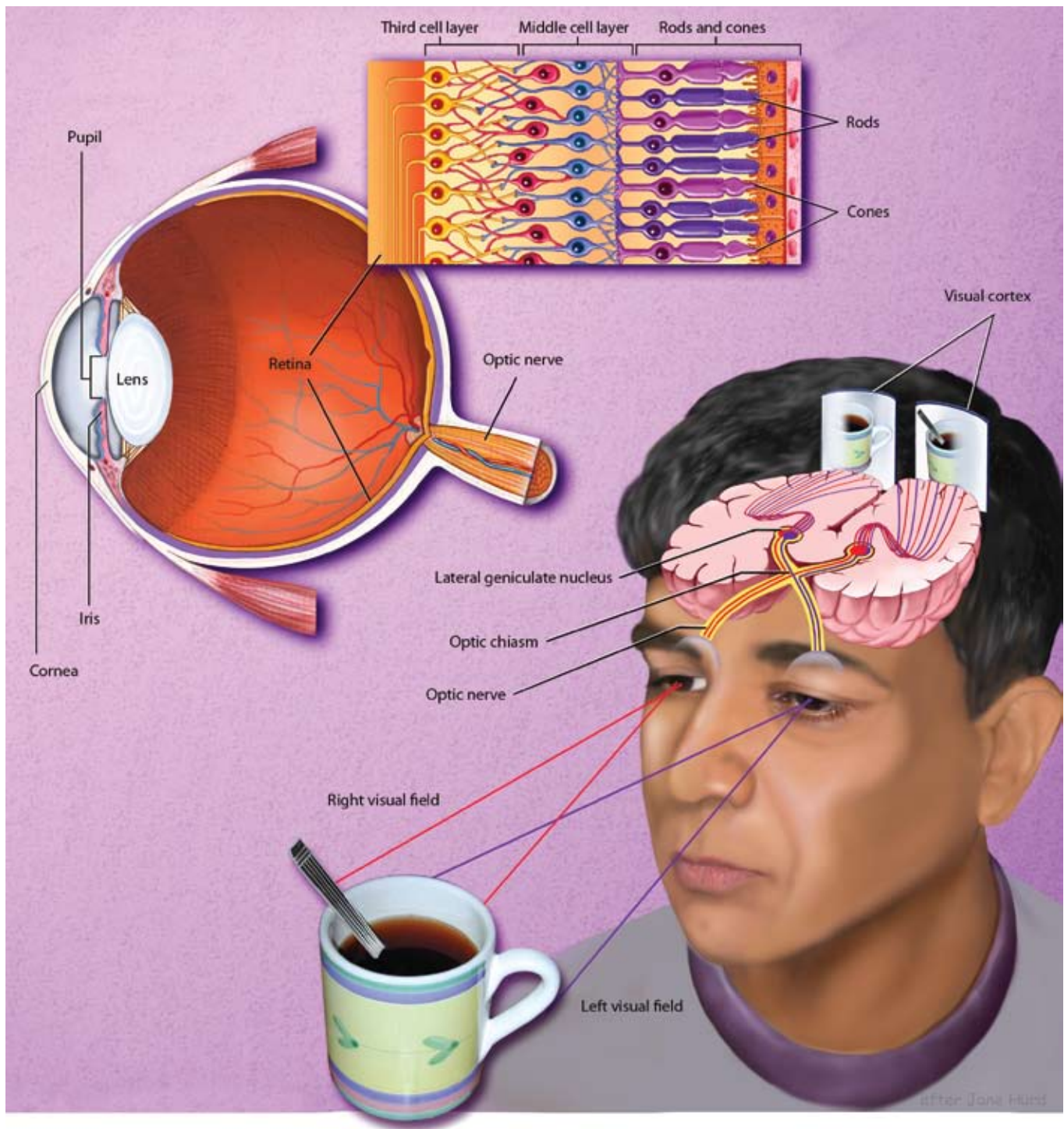
scene registers in your left hemisphere. A similar arrangement applies to movement and touch: Each half of the cerebrum is responsible for the opposite half of the body and external world.

Scientists know much about the way cells encode visual information in the retina, the *lateral geniculate nucleus* — an intermediate way station between the retina and visual cortex — and the visual cortex. These studies give us the best knowledge so far about how the brain analyzes and processes sensory information.

The retina contains three stages of neurons. The first, the layer of rods and cones, sends its signals to the middle layer, which relays signals to the third layer, which consists of the ganglion cells whose axons form the optic nerve. Each cell in the middle and third layer typically receives input from many cells in the previous layer, but the number of inputs varies widely across the retina. Near the center of the gaze, where visual acuity is highest, each cell in the third layer receives inputs — via the middle layer — from one cone or, at most, a few, allowing us to resolve very fine details. Near the margins of the retina, each cell in the third layer receives signals from a cluster of many rods and cones, explaining why we cannot see fine details off to either side. Whether large or small, the region of visual space providing input to a visual neuron is called its *receptive field*.

About 55 years ago, scientists discovered that the receptive field of a vision cell is activated when light hits a tiny region in its receptive field center and is inhibited when light hits the part of the receptive field surrounding the center. If light covers the entire receptive field, the cell responds weakly. Thus, the visual process begins by comparing the amount of light striking any small region of the retina with the amount of surrounding light.

Visual information from the retina is relayed through the lateral geniculate nucleus of the thalamus to the primary visual cortex — a thin sheet of tissue (less than one-tenth of an inch thick) a bit larger than a half-dollar that is located in the occipital lobe in the back of the brain. The primary visual cortex is densely packed with cells in many layers. In its middle layer, which receives messages from the lateral geniculate nucleus, scientists have found responses similar to those observed in the retina and in lateral geniculate cells. Cells above and below this layer respond differently. They prefer stimuli in the shape of bars or edges and those at a particular angle (orientation). Further studies have shown that different cells prefer edges at different angles or edges moving in a particular direction.



VISION. The cornea and lens help produce a clear image of the visual world on the retina, the sheet of photoreceptors and neurons lining the back of the eye. As in a camera, the image on the retina is reversed: Objects to the right of the center project images to the left part of the retina and vice versa. The eye's 125 million visual receptors — composed of rods and cones — turn light into electrical signals. Rods are most sensitive to dim light and do not convey the sense of color; cones work in bright light and are responsible for acute detail, black-and-white vision, and color vision. The human eye contains three types of cones that are sensitive to red, green, and blue but, in combination, convey information about all visible colors. Rods and cones connect with a middle cell layer and third cell layer (see inset, above). Light passes through these two layers before reaching the rods and cones. The two layers then receive signals from rods and cones before transmitting the signals onto the optic nerve, optic chiasm, lateral geniculate nucleus, and, finally, the visual cortex.

Although the process is not yet completely understood, recent findings suggest that visual signals are fed into at least three separate processing systems. One system appears to process information mainly about shape; a second, mainly about color; and a third, movement, location, and spatial organization. These findings of separate processing systems come from anatomical and physiological studies in monkeys. They are supported by human psychological studies showing that the perception of movement, depth, perspective, the relative size of objects, the relative movement of objects, shading, and gradations in texture all depend primarily on contrasts in light intensity rather than on color.

Why movement and depth perception should be emphasized by one processing system may be explained by a school of thought called Gestalt psychology. Perception requires various elements to be organized so that related ones are grouped together. This stems from the brain's ability to group the parts of an image together and also to separate images from one another and from their individual backgrounds.

How do all these systems combine to produce the vivid images of solid objects that we perceive? This involves extracting biologically relevant information at each stage and associating firing patterns of neuronal populations with past experience.

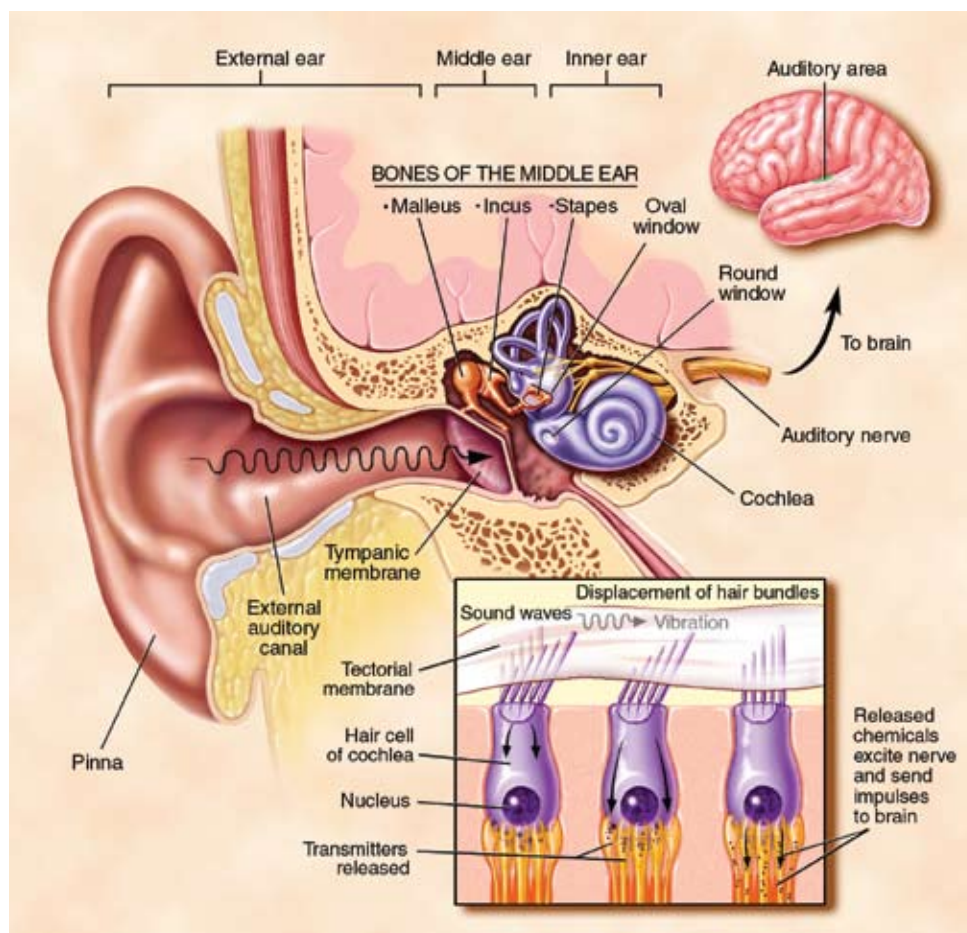
Vision studies also have led to better treatment for visual disorders. Information from research in cats and monkeys has improved the therapy for *strabismus*, or *squint*, a term for cross-eye or walleye. Children with strabismus initially have good vision in each eye. But because they cannot fuse the images in the two eyes, they tend to favor one eye and often lose useful vision in the other. Vision can be restored in such cases, but only during infancy or early childhood. Beyond the age of 6 or so, the blindness in one eye becomes permanent. Until a few decades ago, ophthalmologists waited until children reached the age of 4 before operating to align the eyes or prescribing exercises or an eye patch. Now strabismus is corrected very early in life — before age 4, when normal vision can still be restored.

Hearing

Often considered the most important sense for humans, hearing allows us to communicate with each other by receiving sounds and interpreting speech. It also gives us information vital to survival; for instance, by alerting us to an approaching car.

Like the visual system, our hearing system distinguishes several qualities in the signals it detects. Our hearing system, however,

HEARING. From the chirping of crickets to the roar of a rocket engine, sound waves are collected by the external ear — the pinna and the external auditory canal — and funneled to the tympanic membrane (eardrum) to make it vibrate. Attached to the tympanic membrane, the malleus (hammer) transmits the vibration to the incus (anvil), which passes vibration on to the stapes (stirrup). The stapes pushes on the oval window, which separates the air-filled middle ear from the fluid-filled inner ear, to produce pressure waves in the snail-shaped cochlea of the inner ear. Hair cells in the cochlea, riding on the vibrating basilar membrane, have “hair bundles” of microscopic stereocilia that are deflected by the overlying tectorial membrane. Hair cells convert the mechanical vibration to an electrical signal; they, in turn, release chemicals to excite the 30,000 fibers of the auditory nerve that carry the signals to the brainstem. Auditory information is analyzed by multiple brain centers as it flows to the temporal gyrus or auditory cortex, the part of the brain involved in perceiving sound.



does not blend different sounds, as the visual system does when two different wavelengths of light are mixed to produce color. Instead, it separates complex sounds into their component tones or frequencies so that we can follow different voices or instruments as we listen to conversations or to music.

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Hair cells in the cochlea, riding on the basilar membrane, have *hair bundles* of microscopic hairlike stereocilia that are deflected by the overlying tectorial membrane. Hair cells convert the mechanical vibration to an electrical signal; they in turn excite the 30,000 fibers of the auditory nerve that carry the signals to the brainstem. Because each hair cell rides on a different part of the basilar membrane, each is best excited by a different frequency, and so each nerve fiber carries information about a different frequency to the brain. Auditory information is analyzed by multiple brain centers as it flows to the temporal gyrus or auditory cortex, the part of the brain involved in perceiving sound.

In the auditory cortex, adjacent neurons tend to respond to tones of similar frequency. However, they specialize in different combinations of tones. Some respond to pure tones like a flute, and some to complex sounds like a violin. Some respond to long sounds and some to short, and some to sounds that rise or fall in frequency. Other neurons might combine information from these specialist neurons to recognize a word or an instrument.

Sound is processed in the auditory cortex on both sides of the brain. However the left side in most people is specialized for perceiving and producing speech. Damage to the left auditory cortex, such as from a stroke, can leave someone able to hear but unable to understand language.

Taste and smell

Although different, the two sensory experiences of taste and smell are intimately entwined. They are separate senses with their own receptor organs. However, these two senses act together to

allow us to distinguish thousands of different flavors. Alone, taste is a relatively focused sense concerned with distinguishing among sweet, salty, sour, bitter, and umami (Japanese for “savory”). The interaction between taste and smell explains why loss of the sense of smell causes a serious reduction in the overall taste experience, which we call flavor.

Taste is detected within *taste buds*, special structures embedded within *papillae*, or protuberances, located mainly on the tongue. Others are found in the back of the mouth and on the palate. Every

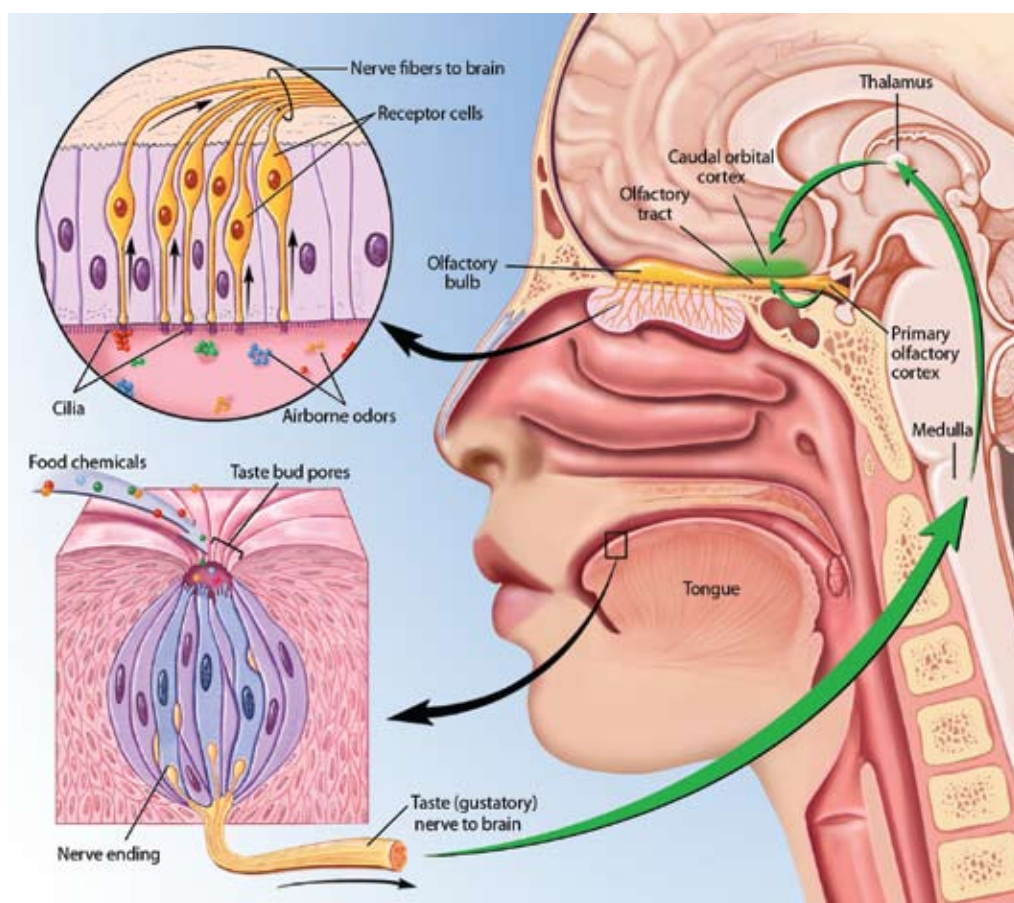
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person has between 5,000 and 10,000 taste buds. Taste substances stimulate specialized sensory cells, and each taste bud consists of 50 to 100 of these cells.

Taste signals in the sensory cells are transferred to the ends of nerve fibers, which send impulses along cranial nerves to taste regions in the brainstem. From here, the impulses are relayed to the thalamus and on to the cerebral cortex for conscious perception of taste.

Specialized olfactory receptor cells are located in a small patch of mucous membrane lining the roof of the nose. Axons of these sensory cells pass through perforations in the overlying bone and enter two elongated *olfactory bulbs* lying on top of the bone. The portion of the sensory cell that is exposed to odors possesses hairlike cilia. These cilia contain the receptor sites that are stimulated by airborne odor molecules. These molecules dissolve in the mucous lining in order to stimulate receptor proteins in the cilia to start the smell response. An odorant acts on many receptors to different degrees. Similarly, a receptor interacts with many different odorants to varying degrees.

The pattern of activity set up in the receptor cells is projected to the olfactory bulb, where neurons are activated to form a spatial



TASTE AND SMELL. Specialized receptors for smell are located in a patch of mucous membrane lining the roof of the nose. Each cell has several fine hairlike cilia containing receptor proteins, which are stimulated by odor molecules in the air, and a long fiber (axon), which passes through perforations in the overlying bone to enter the olfactory bulb. Stimulated cells give rise to impulses in the fibers, which set up patterns in the olfactory bulb that are relayed to the primary olfactory cortex at the back of the brain's frontal lobe to give rise to smell perception, and to the limbic system to elicit emotional responses. Tastes are detected by special structures, taste buds, of which every human has some 5,000 to 10,000. Taste buds are embedded within papillae (protuberances) mainly on the tongue, with a few located in the back of the mouth and on the palate. Each taste bud consists of about 100 receptors that respond to stimuli — sweet, salty, sour, bitter, and umami — from which all tastes are formed. A substance is tasted when chemicals in foods dissolve in saliva, enter the pores on the tongue, and come in contact with taste buds. Here they stimulate hairs projecting from the receptor cells and cause signals to be sent from the cells, via synapses, to cranial nerves and taste centers in the brain. Taste and smell information come together to form flavor in the caudal (back) part of the orbital cortex.

“image” of the odor. Impulses created by this stimulation pass to the primary olfactory cortex at the back of the underside (or orbital) part of the frontal lobe. Olfactory information then passes to adjacent parts of the orbital cortex where it is combined with taste information to form flavor.

Touch and pain

Touch is the sense by which we determine the characteristics of objects: size, shape, and texture. We do this through touch receptors in the skin. In hairy skin areas, some receptors consist of webs of sensory nerve cell endings wrapped around the base of hairs. The nerve endings are remarkably sensitive, being triggered by slight movement of the hairs.

Signals from touch receptors pass via sensory nerves to the spinal cord, where they synapse (make contact) with other nerve cells, which in turn send the information to the thalamus and sensory cortex. The transmission of this information is highly topographic, meaning that the body is represented in an orderly fashion at different levels of the nervous system. Larger areas of the cortex are devoted to sensations from the hands and lips; much smaller cortical regions represent less sensitive parts of the body.

Different parts of the body vary in their sensitivity to tactile and painful stimuli according to the number and distribution of receptors. The cornea is several hundred times more sensitive to painful stimuli than are the soles of the feet. The fingertips are good at touch discrimination, but the torso is not: You don't try to figure out what coin is in your pocket by rubbing it on your back.

Neurologists measure sensitivity by determining the patient's *two-point threshold*. This method involves touching the skin with calipers at two points. The two-point threshold is the distance between the two points that is necessary for the individual to distinguish two distinct stimuli from one. Not sur-

prisingly, acuity is greatest in the most densely nerve-packed areas of the body. The threshold is lowest on the fingers and lips.

Until recently, pain was thought to represent a simple message resulting from neurons sending electrical impulses from a site of injury directly to the brain. We now know that the process is far more complicated. Nerve impulses from sites of injury can persist for hours, days, or longer. Moreover, persistent injury can lead to changes in the nervous system that amplify and prolong the “pain” signal. The result is a state of hypersensitivity in which pain persists and can even be evoked by normally innocuous stimuli. Persistent pain is in many respects a disease of the nervous system, not merely a symptom of some other disease process.

The sensory fibers that respond to stimuli that damage tissue and can cause pain are called *nociceptors*. Different nociceptor

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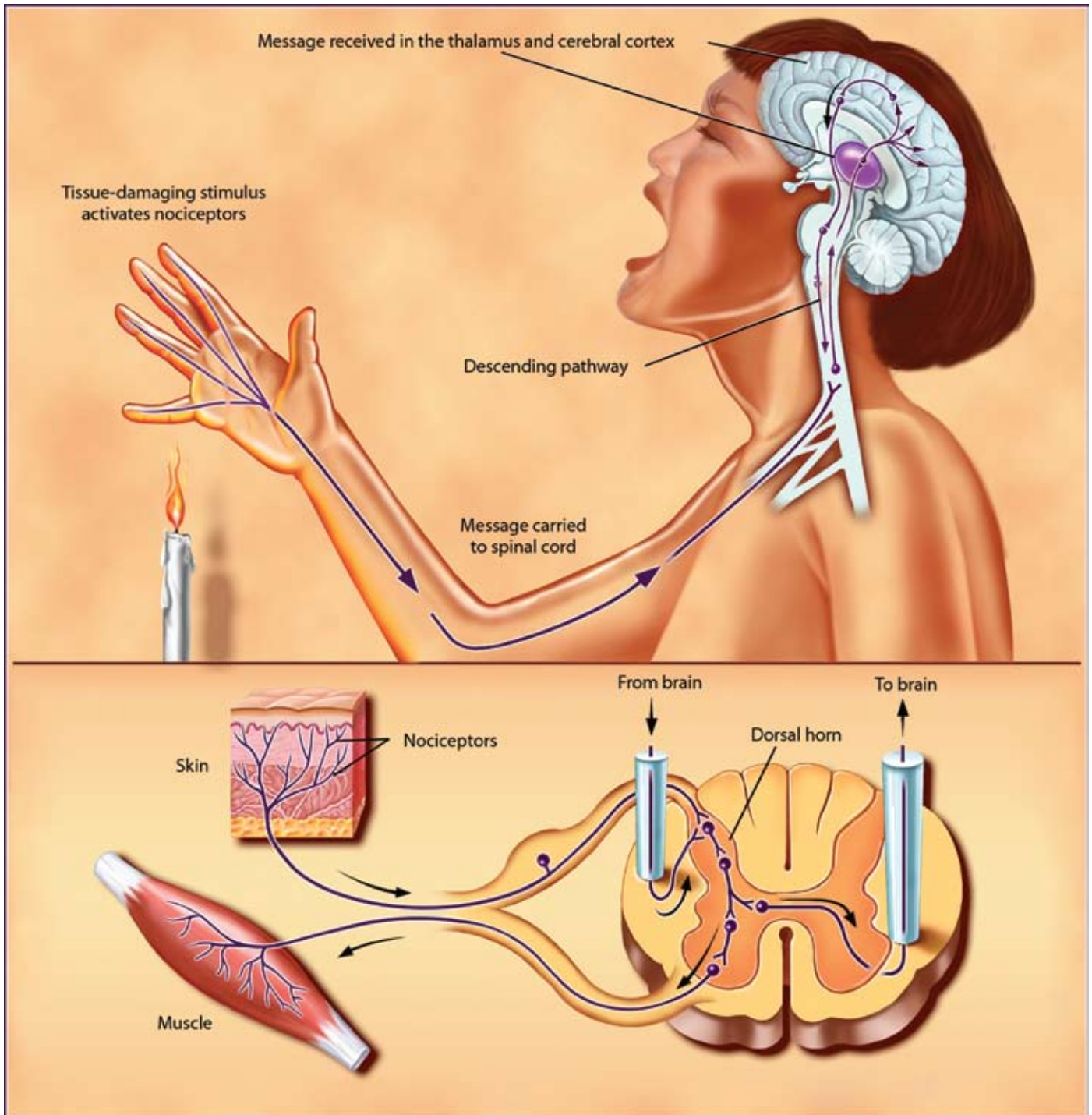
subsets express molecules that are responsible for the response to noxious (i.e., painful) thermal, mechanical, or chemical stimulation. Interestingly, these same molecules respond to plant-derived chemicals that can produce pain, such as capsaicin, garlic, and wasabi. Tissue injury also causes the release of numerous chemicals at the site of damage and inflammation. For example, *prostaglandins* enhance the sensitivity of receptors to tissue damage and ultimately can induce more intense pain sensations. Prostaglandins also contribute to the clinical condition of *allodynia*, in which innocuous stimuli can produce pain (as with sunburned skin).

Pain messages are transmitted to the spinal cord via small, myelinated fibers and C fibers — very small unmyelinated fibers. The small, myelinated, pain-sensitive nerve fibers probably evoke the sharp, fast pain that is produced by, for example, a pinprick. C fiber-induced pain, by contrast, is generally slower in onset, dull, and more diffuse.

In the *ascending system*, impulses are relayed from the spinal cord to several brain structures, including the thalamus and cerebral cortex, which is involved in the process by which pain messages become a conscious experience. The experience of pain is not just a function of the magnitude of the injury or even the intensity of the impulse activity generated by the injury. The setting in which the injury occurs (e.g., the pain of childbirth or that produced in a car accident) and the emotional component of the experience are also major contributors to the overall experience.

Pain messages can be suppressed by systems of neurons that originate within the gray matter in the brainstem. These *descending systems* suppress the transmission of pain signals from the dorsal horn of the spinal cord to higher brain centers. Some of these descending systems use naturally occurring chemicals, the endogenous opioids, or endorphins, which are functionally similar to morphine. The endorphins act at multiple opioid receptors in the brain and spinal cord, a discovery that has had important implications for pain therapy. For example, scientists began studying the spinal delivery of opioids when they discovered a dense distribution of opioid receptors in the spinal cord horn. Such treatments were begun in humans after the method was successfully used in animals; the technique is now common in treating pain after surgery.

Modern imaging tools are now used to monitor brain activity when pain is experienced. One finding is that no single area in the brain generates pain; rather, emotional and sensory components together constitute a mosaic of activity leading to pain. Interestingly, when people are hypnotized so that a painful stimulus is not experienced as unpleasant, activity in only some areas of the brain is suppressed. The stimulus is still experienced, but it doesn't hurt anymore. As such techniques for brain study improve, it should be possible to better monitor the changes in the brain that occur in people with persistent pain and to better evaluate the different painkilling drugs being developed.



PAIN. Messages about tissue damage are picked up by receptors and transmitted to the spinal cord via small myelinated fibers and very small unmyelinated fibers. From the spinal cord, the impulses are carried to the brainstem, thalamus, and cerebral cortex and ultimately perceived as pain. These messages can be suppressed by a system of neurons that originates in the gray matter of the midbrain. This descending pathway sends messages to the spinal cord where it suppresses the transmission of tissue damage signals to the higher brain centers. Some of these descending pathways use naturally occurring, opiatelike chemicals called endorphins.