

The Senses

Jennifer Carbrey, PhD

The underlined headings correspond to the three Senses videos.

1. Introduction and vision

Sensory systems consist of sensory cells that respond to changes in the external or internal environment of our bodies and relay that information to the central nervous system. We are unaware of most of the sensory information collected by sensory cells. The sensation tells us what the stimulus is, where it is in relation to our body, and the strength of the stimulus. Sensory systems also have the ability to adapt to constant stimulation by decreasing in sensitivity. **Adaptation** leads to decreased action potential frequency after exposure to the same stimulus repeatedly. Interpretation of a sensation by the central nervous system leads to our **perception** of the stimulus. How the central nervous system is able to convert sensations into perceptions is not well understood in most cases.

Peripheral Nervous System Input

In general, there are two different ways that sensory information is conveyed to the central nervous system. In some cases, such as the odorant receptor cells of the nose, an afferent neuron has a specialized ending that produces graded potentials which can lead to action potentials in response to a stimulus. In other systems such as vision, taste, and hearing, a specialized receptor cell produces graded potentials that can trigger an action potential in an afferent neuron. Each afferent neuron receives signals from a single type of stimulus.

Somatosensation

The skin, muscles, and joints have receptors that can sense touch, pressure, temperature, pain, or the position of the body. The information gathered by these receptors leads to sensations referred to as **somatosensations**.

Each receptor type responds primarily to only one type of stimulus. **Mechanoreceptors** are nerve endings that are encapsulated by connective tissue that sense touch and pressure. There are different types of encapsulated nerve endings that have different morphologies which allow them to respond to a specific kind of touch. Stretching of the connective tissue fibers of the encapsulated endings activates ion channels which can produce action potentials that signal to the central nervous system.

Posture and movement of body parts are sensed by muscle stretch mechanoreceptors, as well as mechanoreceptors present in skin, joints, tendons, and ligaments. Together they sense the amount of muscle stretch as well as the rate of muscle stretch. Vision and balance also play a role in the perception of where the body is in space, or **proprioception**.

Temperature is sensed in the skin using different types of **thermoreceptors**. Free nerve endings, which are processes of neurons, sense temperature using ion channels that are activated only at certain temperatures. A single sensory neuron only expresses a single kind of thermoreceptor. Thermoreceptors can also detect certain chemicals. For instance, cold-sensing thermoreceptors respond to menthol, while heat-sensing thermoreceptors respond to capsaicin (from chili peppers) and ethanol.

Pain is sensed by free nerve endings expressing **nociceptors**, which are receptors that sense extreme mechanical deformation, high temperatures, as well as chemicals released by damaged cells or immune cells.

Vision

Overview. The visual system detects light to allow us to perceive the shape and color of objects as well as their movement. The light sensing portion of the eye, the **retina**, lines the inside of the back of the eye. It consists of **photoreceptor** cells and their afferent neurons. Before coming in contact with the retina, light passes through the **cornea**, a clear epithelium, and the **lens** of the eye. Between the cornea and lens, the anterior chamber is filled with fluid, called aqueous humor. The posterior chamber is between the lens and the retina. It contains a gel called vitreous humor.

In vision, light is reflected by objects and enters the eye. The **pupil** controls the amount of light entering the eye. The light is focused by the lens on to the retina. The photoreceptor cells convert energy from the light into an electrical signal that is processed by the brain and transformed into a perceived image.

Refraction and Focusing of light. Only photons with certain wavelengths can be detected by the retina. Different wavelengths of light within the visible range are perceived by the central nervous system as different colors. When light hits the cornea, it is bent, or refracted as it passes from air into the tissue. This is the largest source of refraction and focusing by the eye. The light continues through the aqueous humor and is refracted as it travels through the lens, which can adjust to focus on objects a certain distance away. Ciliary muscles encircle the perimeter of the lens and flatten the lens when the muscles relax or make the lens more round when the muscles contract. A lens that is more round allows the eye to focus on closer objects. Due to the refraction of light by the cornea, the image on the retina appears upside down and backwards. The pupil plays a role in focusing light by restricting bright light to the center of the retina for clearer vision.

Retina. The retina contains two types of photoreceptor cells, the **rods** and **cones**. Because the light-sensing portion of the photoreceptor cells faces the back of the retina, the light must travel through several layers of cells before it is detected. **Photopigment** proteins in the plasma membrane of the photoreceptors contain **retinal**, a derivative of vitamin A that changes its conformation in response to a photon of light. The change in conformation of retinal affects the conformation of the photopigment protein which starts a signal transduction cascade. The signal transduction cascade causes a ligand-gated cation channel to close which hyperpolarizes the photoreceptor cell and eventually results in signaling to the central nervous system.

Rods. Photoreceptor rod cells express **rhodopsin** photopigment protein and are very sensitive to light. As a result, they are used in night vision. Many rod photoreceptor cells bind a single **bipolar cell**. This convergence of signals translates into low resolution vision during conditions of low illumination.

Cones. Photoreceptor cone cells express one of three different photopigment proteins called **opsins**. Cones are less sensitive to light and so are used in conditions of high levels of illumination. Bipolar cells bind only one cone cell so there is high resolution vision with cones. The three different opsins that are expressed by the three types of cones bind retinal in unique ways which leads to absorption of light at different wavelengths. The three opsins are sensitive to red, blue or green wavelengths of light. For instance, red light from a red object hyperpolarizes cones expressing red-sensitive opsin only. This activates red bipolar cells and ganglion cells. Colors other than red, blue, or green are perceived when combinations of different cones are stimulated. For instance, we perceive yellow when the red and green cones are stimulated to the same extent.

2. Hearing and the vestibular system

Sound. Sound waves cause vibration of air molecules so that the molecules alternate between being compressed and expanding. The amplitude of the difference between the high and low pressure of air molecules determines the volume of the sound (measured as decibels, dB). The frequency of the changes between high and low pressure determines the pitch of the sound (measured as Hertz, cycles per second).

Sound transmission. The outer ear, which consists of the pinna and external auditory canal, amplify and direct the sound to the **middle ear**. The middle ear is an air filled cavity with three bones, the malleus, incus, and stapes. The sound hits and deforms the **tympanic membrane** between the outer and middle ear. The three bones of the middle ear respond to the deformation of the tympanic membrane and amplify the vibration to the **oval window** on the **cochlea** of the inner ear. Because the oval window is much smaller than the tympanic membrane, the vibrations are amplified. This is important because in the inner ear, fluid is used to transmit the sound.

Cochlea. The cochlea contains the receptor cells for sound which are located in a central fluid-filled cavity called the **cochlear duct**. The cochlear duct is bordered by two additional fluid-filled cavities that vibrate in response to deformation of the oval window. Sound travels down the **scala vestibuli** after deformation of the oval window and then travels down the **scala tympani** and ends at the **round window**. During this process the **basilar membrane** of the cochlear duct vibrates.

Organ of Corti. Within the cochlear duct, sitting on the basilar membrane is the organ of Corti, which contains the hair cells that serve as the receptor cells for sound. **Stereocilia** of the hair cells are embedded in a **tectorial membrane**. As the basilar membrane bounces up and down, the stereocilia bend. Bending the stereocilia on the hair cells opens stretch-sensitive K+ channels and K+ enters the cells due to the composition of the surrounding fluid. K+ entry *depolarizes* the hair cell and neurotransmitter is released. Bending in the other direction hyperpolarizes the cell and inhibits neurotransmitter release. After a hair cell activates the afferent neuron, axons from these neurons join to form the cochlear nerve. The region of the basilar membrane along the length of the cochlea that vibrates the most correlates with the frequency of the sound. As a result, the sensation of pitch is determined by which portion of the basilar membrane is activated. The louder the sound, the more vibration and the greater frequency of action potentials produced in the afferent neurons.

Balance

The portions of the inner ear that sense movement of the head are called the **vestibular system**. The **semicircular canals** detect rotation of the head while the **otolith organs** detect linear movement of the head.

Semicircular canals. There are three semicircular canals in the inner ear that allow detection of head rotation along three perpendicular axes – nodding the head, shaking the head, and tipping the ear towards the shoulder. Each canal contains hair cells that move with the head as it rotates around a certain axis. Because the fluid in the canals remains stationary, it bends the steriocilia of the hair cells which causes release of neurotransmitter similar to hair cells of the auditory system.

Otolith organs. The otolith organs contain sheets of hair cells that have calcium carbonate crystals, called **otoliths**, embedded in gel that surrounds the stereocilia of the hair cells. Since the otoliths are heavier than the fluid around the hair cells, they remain stationary and pull on the stereocilia during linear movements. The **utricle** contains hair cells that point straight up in a standing position and respond to horizontal linear acceleration. The **saccule** contains hair cells that are oriented at a 90 degree angle compared to those of the utricle. This allows them to detect up and down motions.

3. Chemical senses

Chemoreceptors all bind chemicals but they differ in their specificity. Taste buds in the tongue and odor receptors in the nose bind chemicals in food and air, respectively. There are other chemoreceptors such as those in the carotid arteries that sense the levels of blood gases and neurons in the brain that sense the osmolarity of blood.

Taste

Taste ligands dissolved in saliva bind to chemoreceptors on taste buds. Receptor binding raises intracellular Ca++ causing the release of neurotransmitters and producing graded potentials. This leads to the initiation of action potentials in the postsynaptic neuron. Taste buds can detect chemicals that can be categorized into five different flavors: sweet, sour, salty, bitter, and umami. Each type of chemical is detected by different receptors. Each taste bud responds primarily to one flavor at low concentrations and two or three at higher concentrations.

Smell

Odors in the air are detected by chemoreceptors of olfactory neurons. The olfactory neuron serves as the receptor cell as well as the afferent neuron. Binding of an odorant receptor leads to activation of signal transduction pathways that open cation channels and lead to graded potentials. Each odorant binds a combination of odorant receptors that are specific for different parts of the molecule. It is the combination of activated receptors that leads to our perception of a smell of a particular substance.