CHAPTER 29

The Senses

Objectives

Introduction Explain how salmon navigate from streams and back again during their life cycle.

29.1 Define and compare sensations and perceptions.

Sensory Reception

29.2 Define sensory transduction, a receptor potential, and sensory adaptation. Illustrate each with examples.

29.3 Describe the five general categories of sensory receptors found in animals. Note examples of each.

Vision

29.4 Describe and compare the three main types of photoreceptors found in animals.

29.5 Describe the parts of the human eye and their functions.

29.6 Compare the mechanisms used to focus the eyes of a squid and a human.

29.7 Explain the causes and symptoms of hyperopia, myopia, presbyopia, and astigmatism.

29.8 Compare the structures, functions, distributions, and densities of rods and cones.

Hearing and Balance

29.9 List in order the structures of the ear involved in hearing. Describe the possible causes of hearing loss.

29.10 Explain how the body position and movement are sensed in the inner ear.

29.11 Explain what causes motion sickness and what can be done to prevent it.

Taste and Smell

29.12 Explain how odor and taste receptors help contribute to the senses of smell and taste.

29.13 Explain the role of the central nervous system in sensory perception.

Key Terms

sensation
perception
sensory transduction
receptor potential
sensory adaptation
pain receptor
thermoreceptor
mechanoreceptor
stretch receptor
hair cell
chemoreceptor
electromagnetic receptor
photoreceptor
eye cup
compound eye
ommatidium
single-lens eye
sclera
cornea
choroid
iris
pupil
lens
retina
fovea
blind spot
vitreous humor
aqueous humor
conjunctiva
accommodation

visual acuity
nearsightedness
farsightedness
astigmatism
cone
rod
rhodopsin
photopsin
outer ear
pinna
auditory canal
eardrum
middle ear
oval window
Eustachian tube
inner ear
cochlea
organ of Corti
basilar membrane
semicircular canal
utricle
saccule

Word Roots

aqua- = water (*aqueous humor:* the clear, watery substance that fills the anterior cavity of the eye)

chemo- = chemical (*chemoreceptor:* a receptor that transmits information about the total solute concentration in a solution or about individual kinds of molecules)

electro- = electricity (*electromagnetic receptor:* receptors of electromagnetic energy, such as visible light, electricity, and magnetism)

fovea- = a pit (*fovea:* the center of the visual field of the eye)

mechano- = an instrument (*mechanoreceptor:* a sensory receptor that detects physical deformations in the body's environment associated with pressure, touch, stretch, motion, and sound)

omma- = the eye (*ommatidia:* the facets of the compound eye of arthropods and some polychaete worms)

photo- = light (*photoreceptor:* receptors of light)

rhodo- = red (*rhodopsin:* a visual pigment consisting of retinal and opsin)

sacc- = a sack (*saccule:* a chamber in the vestibule behind the oval window that participates in the sense of balance)

thermo- = heat (*thermoreceptor:* an interoreceptor stimulated by either heat or cold)

utric- = a leather bag (*utricle:* a chamber behind the oval window that opens into the three semicircular canals)

vitre- = glass (*vitreous humor:* the jellylike material that fills the posterior cavity of the vertebrate eye)

Lecture Outline

Introduction *An Animal's Senses Guide Its Movements*

A. Sensory information gathered by sensory receptors guides animals in their activities (chapter-opening photo).
   1. Bears learn as cubs to feed at certain streams. They find the same streams year after year, using their well-tuned sense of smell. Their sense of smell and very fast reflexes make up for poor eyesight to aid in the capture of food.
      NOTE: The relatively large size of the nasal area of a bear's head.
   2. Salmon form a memory of the chemical "scent" of the river where they hatch. After migrating downstream and spending several years feeding and growing in the open ocean, they use a variety of senses to return to their home spawning grounds. They use sight of the sun's angle (and perhaps a sense of Earth's changing magnetism) to

find the river's ocean mouth. Once in the river, they use smell to follow the increasing concentration of the spawning ground's scent as they make the correct turns up the stream's branches.

Module 29.1 Sensory inputs become sensations and perceptions in the brain.

A. Receptor cells detect stimuli such as chemicals, light, muscle tension, sounds, electricity, cold, heat, and touch. They trigger action potentials that travel to the central nervous system.

B. **Sensation** is the awareness of a sensory stimulus.

C. **Perception** is the integration of a sensation with other information, including other sensations and memories. For instance, the perception of a fragrant rose results from the sum total of interconnected neurons in the visual and odor centers, and their associated memory areas in the brain.

D. The visual demonstration provided may first be sensed as just splotches and later integrated into the perception of a person riding a horse (Figure 29.1).

I. Sensory Reception

Module 29.2 Sensory receptor cells convert stimuli into electrical energy.

A. This conversion, known as **sensory transduction,** occurs in the plasma membrane of the receptor cell. For example, in a taste bud sensing sugar, the sugar molecules enter the region of the sensory receptor cells, bind to specific proteins in the cell's membrane, cause ion channels to open, and induce a rise in membrane potential. The result is a receptor potential produced as a result of signal transduction (Figure 29.2A).
Review: Signal transduction (Module 11.13).

B. Unlike action potentials, the stronger the stimulus, the larger the **receptor potential.**

C. Receptors synapse with sensory neurons and generate receptor potentials by increasing their release of neurotransmitter.
Review: Synapses and neurotransmitters (Modules 28.6–28.8).

D. A receptor normally secretes neurotransmitter at a constant, low rate. The stimulus results in some higher rate. In the brain, the stimulus is sensed as a change in the frequency of action potentials arriving on the sensory neuron. The strength of the stimulus is also interpreted from how many sensory neurons send a signal of it (Figure 29.2B).

E. Signals from different sensory receptors are perceived as different (sweet versus salty) depending on which interneurons in which region of the brain are stimulated.
NOTE: Distinguishing stimulus types depends both on genetically determined, "hard-wired" neuronal connections between association centers and on comparison with learned memories of other similar stimuli.

F. **Sensory adaptation** is the tendency of receptor cells to become less sensitive to constant stimulation, because stimuli are perceived as changes in rate. This keeps the body from becoming overloaded with background stimuli.

Module 29.3 Specialized sensory receptors detect five categories of stimuli.

A. There are five general categories of sensory receptors: **pain receptors, thermoreceptors, mechanoreceptors, chemoreceptors,** and **electromagnetic receptors.**

B. Skin contains receptors falling into three of these categories: pain receptors, thermoreceptors, and mechanoreceptors. In this case, each receptor is also the sensory neuron delivering the stimulus to the brain (Figure 29.3A).

C. Pain receptors indicate the presence of danger and often elicit withdrawal to safety. With the exception of the brain, all parts of the human body have pain receptors. Pain receptors may respond to excessive heat and pressure. Inflamed tissues release histamines and prostaglandins (PG) that trigger pain receptors. Aspirin and ibuprofen inhibit PG synthesis, thus reducing pain.

D. Thermoreceptors detect either heat or cold and also monitor blood temperature deep in the body. The hypothalamus (Module 28.15) sets and monitors body temperature. *Review:* Thermoregulation as a homeostatic mechanism is discussed in Module 20.13; also see Module 25.2.

E. Mechanoreceptors are diverse and respond to touch, pressure (including blood pressure), stretching of muscles **(stretch receptors),** motion, and sound. **Hair cells** detect movement of cilia or special projections of the cell membrane when exposed to stimuli from sound waves and other forms of movement. In one direction, more neurotransmitter molecules are released, and in the other, fewer (Figure 29.3B).

F. Chemoreceptors include sensory receptors in the nose and mouth, and internal receptors that monitor blood levels of chemicals. Chemoreceptors of insects can be extremely sensitive to just a few molecules (Figure 29.3C).

G. Electromagnetic receptors are sensitive to energy of various wavelengths, including electricity, magnetism, and light **(photoreceptors).** Some fishes are sensitive to changes in electrical fields caused by environmental interaction with electrical currents the fish produce. The heads of a number of animals contain magnetite that they may use to sense changes in magnetic fields. Photoreceptors are sensitive to humanly visible wavelengths and to infrared (in invertebrates such as mosquitoes and in vertebrates such as snakes; Figure 29.3D; Figure 7.6A) and ultraviolet (in many pollinating insects) wavelengths.

H. Photoreceptors are genetically ancient, based on molecular evidence and similarities in pigment structure and function.

II. Vision

Module 29.4 Three different types of eyes have evolved among invertebrates.

A. **Eye cups** (in planarian flatworms and other invertebrates) are composed of rounded shields of dark-colored cells that shade photoreceptor cells from one side. They do not form images, but allow the animal to sense the intensity and direction of light. When the intensity and direction have equalized the planarian moves in the opposite direction, maintaining the equilibrium, thus moving in the direction exactly opposite the light. The animal can then escape to shady hiding places (Figure 29.4A).

B. **Compound eyes** (found in insects and other arthropods) are composed of many tiny light detectors **(ommatidia),** each with its own covering (cornea) and lens, that focuses light onto a cluster of photoreceptor cells. Each ommatidium responds to light from a portion of a field of view. The brain then integrates this information into a visual image. Compound eyes are extremely acute motion detectors and most provide color vision (Figure 29.4B).

C. **Single-lens eyes** (e.g., squid) function like cameras. Light rays reflected from an object enter through a small pupil and are focused into an image on the photoreceptor surface of the retina. This produces a fine-grained, integrated image in the brain (Figure 29.4C).

Module 29.5 Vertebrates have single-lens eyes.

A. The vertebrate eye evolved independently of the single-lens eye of invertebrates and differs in many details.

NOTE: Humans have two eyes that both face forward to focus on the same object. This is known as convergence and allows for depth perception.

B. The outermost layer of the eyeball is the **sclera.** The sclera forms the white of the eyeball, and in front, the transparent **cornea.** The **conjunctiva** is a thin mucous membrane that lines the eyelids and the front of the eyeball, except the cornea. The conjunctiva helps keep the eye moist. The glands that keep the conjunctiva moist respond to eye irritations and emotional distress.
NOTE: When the blood vessels of the conjunctiva are dilated, the eyes appear to be bloodshot.

C. The sclera surrounds a thin pigmented layer, the **choroid.** The **iris,** which gives the eye its color, is formed from the choroid. Muscles in the iris regulate the size of the **pupil,** the opening that lets light into the eye's interior.
NOTE: The pigmented choroid absorbs light rays and prevents them from reflecting within the eyeball and blurring vision.

D. After going through the pupil, light passes through a transparent **lens** that focuses images on the **retina,** the layer of photoreceptors that lies on the inner surface of the choroid (Figure 29.5).
NOTE: Although transparent, the lens is composed of hundreds of cells arranged in layers like the scales of an onion.

E. The photoreceptor cells of the retina are most highly concentrated in a region called the **fovea.**

F. The photoreceptor cells of the retina transduce light energy into action potentials, the nerve impulses then travel along the optic nerve to the visual areas of the brain.

G. Since there are no photoreceptors located where the optic nerve attaches to the eye this region of the retina is a **blind spot.**

H. The chamber in front of the lens is filled with **aqueous humor,** a liquid similar to blood plasma that nurtures the lens. The chamber behind the lens is filled with **vitreous humor,** a jellylike fluid. Fluid in both chambers maintains the shape of the eyeball. Excess aqueous humor is caused by glaucoma and can lead to blindness by causing excess pressure on the retina.

Module 29.6 To focus, a lens changes position or shape.

A. In fish, the lens moves back and forth (relative to the retina), moving the fixed point of focus.

B. In mammals, the lens changes shape, thereby changing the distance at which images are focused. This process is called **accommodation.** Muscles attached to the choroid contract, reducing tension on the ligaments that support the lens, thus allowing it to take a more rounded shape and focus images of nearby objects on the retina. When the muscles relax, the lens is stretched into a more elongated shape to focus images of distant objects (Figure 29.6).
NOTE: The pupil also accommodates to near and far vision. For near vision, the iris decreases the size of the pupil so as to eliminate peripheral light rays.

Module 29.7 Connection: Artificial lenses or surgery can correct focusing problems.

A. **Visual acuity** is the ability to distinguish fine detail. So-called normal vision, or 20/20 acuity, indicates that at 20 feet, the eye can read letters on a chart normally readable at 20 feet. Acuity of 20/10 is better than normal; at 20 feet, the eye can read letters normally readable at 10 feet. And acuity of 20/50 is worse than normal; at 20 feet, the eye can read letters normally readable at 50 feet.

B. Nearsighted (myopic) people cannot focus on far objects because their eyeballs are too elongated and the lens cannot accommodate. Corrective lenses that are thinner in the middle correct **nearsightedness** (Figure 29.7A).

C. Farsighted (hyperopic) people cannot focus on near objects because their eyeballs are too short and the lens cannot accommodate. As the lenses age they become less elastic and hyperopia becomes worse (called presbyopia; Greek for "old eyes"). Corrective lenses that are thicker in the middle correct **farsightedness** (Figure 29.7B).

D. **Astigmatism** is blurred vision caused by lenses or corneas that are misshapen. Asymmetrical lenses are used to correct the problem.

Module 29.8 Our photoreceptor cells are rods and cones.

A. The human eye contains about 130 million photoreceptors (Figure 29.8A).

B. **Rods** are most sensitive to dim light and distinguish shades of gray, not color, using the light-absorbing pigment **rhodopsin.** They are most common in the outer margins of the retina and completely absent from the eye's center of focus (fovea). The best night vision is thus achieved by looking at things out of the "corner of your eye."

C. **Cones** are sensitive to bright light, and they distinguish color. Three types of cones can distinguish three predominant wavelengths using three kinds of the light-absorbing pigment **photopsin.** Groups of cones can distinguish thousands of different tints. Cones are less numerous in the retina's margins and are densest in the fovea. The best color vision and most acute vision are achieved by looking right at an object in bright light.
NOTE: Rods are more sensitive to light than are cones. This is why we do not see color when there is little light available.

D. Photoreceptors detect light when light is absorbed by a pigment that changes it chemically, triggering signal transduction pathways that alter membrane permeability and result in a receptor potential. Integration of the stimuli first occurs among interneurons that interconnect the output of several neighboring rods and cones. Many such integrated signals occur in a layer of neurons (on the surface of the retina), combining to leave the eyeball via the optic nerve (Figure 29.8B).
NOTE: Isn't it odd that light must pass through several layers of neurons before reaching the photoreceptors?

III. Hearing and Balance

Module 29.9 The ear converts air pressure waves into action potentials that are perceived as sound.

A. The **outer ear** (aka **pinna**) collects sound waves and channels them through the **auditory canal** to the **eardrum.** The **middle ear** relays the sound wave vibrations from the eardrum through three small bones—the hammer, anvil, and stirrup—to the **oval window,** a membrane that separates the middle and inner ears. Air pressure in the middle ear and outer ear is equalized by the **Eustachian tube.** The **inner ear** houses the hearing organ, which is composed of several channels of fluid wrapped in a spiral (the **cochlea**) and encased in bones of the skull. Vibrations of the oval window produce pressure waves in the fluid (Figure 29.9A–C).

B. The pressure waves travel through the upper canal to the tip of the cochlea, then enter the lower canal and gradually fade away. Pressure waves in the upper canal push down on the middle canal, causing the **basilar membrane** below this canal to vibrate. The vibrations stimulate the hair cells attached to the membrane by bending them up against the overlying shelf of tissue (this whole structure is the **organ of Corti**). The hair cells develop receptor potentials when bent and release neurotransmitter molecules, thereby inducing action potentials in auditory neurons (grouped together as the auditory nerve). Each region of the cochlea vibrates best at a given pitch (Figure 29.9D).

C. Young people are sensitive to pitches between 20 and 20,000 Hz. Dogs can hear to 40,000 Hz, and bats echolocate with sounds as high pitched as 75,000 Hz.
NOTE: Bats can use their ears much as we use our eyes. Bats can hear the patterns formed by sounds bouncing off their environment and prey. A fishing bat can hear, in three dimensions, the ripples on the surface of water, indicating the movement of a fish below the surface.

D. The organ of Corti is sensitive to a considerable range of sound amplitudes without perceiving pain, from about 0 to 120 dB. Exposure to sounds of 90 dB (modestly amplified rock music or occupation-related noise) for long periods can cause hearing loss (Figure 29.9C). Ear protection is recommended when listening to loud music and is a must for employees exposed to occupational noise.

Module 29.10 The inner ear houses our organs of balance.

A. These organs lie next to the cochlea.

B. Three **semicircular canals** detect changes in the head's rate of movement. Because they are arranged in three perpendicular planes, they detect movement in all directions. Receptor potentials are triggered when a jellylike mass of tissue (the cupula) suspended in the thick fluid in a canal moves against hair cells (Figure 29.10).

C. The **utricle** and **saccule** detect the position of the head relative to the force of gravity. Within these chambers, calcium carbonate particles are pulled by gravity in different directions (depending on the head's orientation) against hair cells.

Module 29.11 Connection: What causes motion sickness?

A. Motion sickness seems to stem from the brain's receiving mixed signals from equilibrium receptors of the inner ear and a different set of perceptions, usually visual. Sometimes the sick feeling can be relieved simply by closing the eyes.

B. People vary considerably in what it takes to produce motion sickness. As NASA has discovered, some people are able to consciously override the sick feelings stemming from the mixed messages.

IV. Taste and Smell

Module 29.12 Odor and taste receptors detect categories of chemicals.

A. Chemoreceptors in the nose detect airborne molecules, distinguishing about fifty general types of odor (Figure 29.12A). Humans have a relatively poor olfactory sense, particularly compared to other animals like dogs, cats, and bears. Olfactory chemoreceptors are in the upper portion of the nasal cavity and are covered with mucus secreted by neighboring cells. Molecules enter the nose, dissolve in the mucus, and bind to specific receptor molecules on the chemoreceptor cilia. The binding triggers receptor potentials.
Review: Olfaction is tied to the limbic system, which is why it is particularly good at evoking emotions and memories (Module 28.19).

B. Chemoreceptors localized in taste buds detect molecules in food (Figure 29.12A, B). There are four types of taste buds that detect sweet, sour, salty, and bitter. A broad range of molecules from each category stimulates each type of taste bud (Module 3.6). They are arranged in precise areas of the tongue. The perception of taste results from similar signal mechanisms as for smell.
NOTE: Our sense of taste is strongly influenced by associated smells. When a cold "clouds" our sense of smell, we lose much of our taste discrimination.

C. Many other animals have chemoreceptors in different locations. Flies taste with their feet (Figure 29.12C). Moths smell with their antennae (Figure 29.3C).

Module 29.13 *Review:* The central nervous system couples stimulus with response.

A. Sensory receptors enable an animal to avoid danger, communicate with others, find food and mates, and maintain homeostasis.

B. Tracing the information in the diagram: A flash of light stimulates the bear's photoreceptors. These cells transduce the light stimulus into action potentials that travel along sensory neurons to the brain. Additional perceptions (smell, sound, touch) are integrated, with memories, by the brain. The brain then sends action potentials along motor neurons to effector cells and muscles in the paws, neck, and jaws (Figure 29.13).

Class Activities

1. As the optic nerve runs from the eye to the brain, the fibers from the nasal half of each optic nerve cross over to the other side of the brain. The optic nerve fibers from the nasal (left) half of the right eye cross to the left side of the brain, and the optic nerve fibers from the nasal (right) half of the left eye cross to the right side of the brain. The place at which these fibers cross is the optic chiasma. This crossing of nerve fibers can be demonstrated by placing a tube (for example, a cardboard paper towel tube) in front of one eye and looking straight ahead out of both eyes. Put the palm of the hand on the same side as the eye that is not looking through the tube at arm's length and directly in front of that eye. Slowly move the palm closer to that eye, all the while continuing to look straight ahead out of both eyes. At a certain point, it will appear that there is a hole in the palm.
2. Having ears on either side of the head allows for the direction from which a sound arose to be localized. For example, if the sound reaches the right ear before reaching the left ear, the sound must be coming from the right. This can be demonstrated by having students, with their eyes closed, determine the location of a tuning fork that is vibrating on the right or left side of their head. If the tuning fork is placed directly above their head, they will be unable to determine where the sound is coming from.
3. There is evidence that the traditional taste map is wrong, and that there is a wider variety of taste receptors than previously thought. Using cotton swabs, see if your students can create a taste map of their tongues. Also, to demonstrate the importance of smell to that which is perceived as taste, have your students taste various foods while holding their nose. Of course, these demonstrations need to be done with the eyes closed.
4. Be careful when doing this one—demonstrate equilibrium by spinning a student in a chair and then having them walk. Ask how the resulting staggered walk relates to the structure of the ear.

Transparency Acetates

Figure 29.1	Sensation and perception
Figure 29.2A	Sensory transduction at a taste bud (Layer 1)
Figure 29.2A	Sensory transduction at a taste bud (Layer 2)
Figure 29.2A	Sensory transduction at a taste bud (Layer 3)
Figure 29.2A	Sensory transduction at a taste bud (Layer 4)
Figure 29.2B	How action potentials represent different taste sensations
Figure 29.3A	Sensory receptors in the human skin

Figure 29.3B	Mechanoreception by a hair cell
Figure 29.4A	The two eye cups of a planarian detect light direction, and the worm moves away from a light source
Figure 29.5	The single-lens eye of a vertebrate
Figure 29.6	How lenses focus light
Figure 29.7A	A nearsighted eye (eyeball too long)
Figure 29.7B	A farsighted eye (eyeball too short)
Figure 29.8A	Photoreceptor cells
Figure 29.8B	The vision pathway from light source to optic nerve
Figure 29.9A	An overview of the human ear
Figure 29.9B	The middle ear and the inner ear
Figure 29.9C	The organ of Corti, within the cochlea
Figure 29.9D	The route of sound waves through the ear
Figure 29.10	Equilibrium structures in the inner ear
Figure 29.12A	The mechanics of odor detection
Figure 29.12B	Taste in a fly
Figure 29.13	Coupling of stimuli to response by the nervous system

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 29A: *Structure and Function of the Eye*	29.6