CAMPBELL
BIOLOGY
TENTH EDITION

Reece • Urry • Cain • Wasserman • Minorsky • Jackson

# 50 Sensory and Motor Mechanisms

Lecture Presentation by
Nicole Tunbridge and
Kathleen Fitzpatrick



## Sense and Sensibility

- The star-nosed mole can catch insect prey in near total darkness in as little as 120 milliseconds
- It uses the 11 pairs of appendages protruding from its nose to locate and capture prey
- Sensory processes convey information about an animal's environment to its brain, and muscles and skeletons carry out movements as instructed by the brain




Figure 50.1

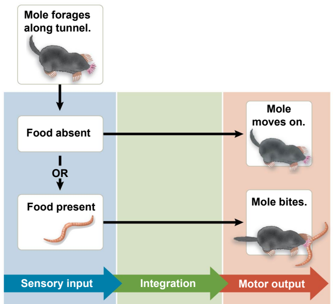



## Concept 50.1: Sensory receptors transduce stimulus energy and transmit signals to the central nervous system

- All stimuli represent forms of energy
- Sensation involves converting energy into a change in the membrane potential of sensory receptors
- When a stimulus's input to the nervous system is processed a motor response may be generated
- This may involve a simple reflex or more elaborate processing




Figure 50.2







- Sensory pathways have four basic functions in common
  - Sensory reception
  - Transduction
  - Transmission
  - Integration

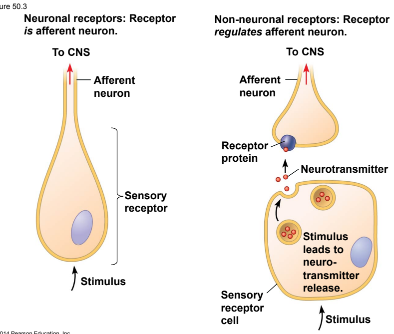



## Sensory Reception and Transduction

- Sensations and perceptions begin with **sensory reception**, detection of stimuli by sensory receptors
- **Sensory receptors** interact directly with stimuli, both inside and outside the body




Figure 50.3







- **Sensory transduction** is the conversion of stimulus energy into a change in the membrane potential of a sensory receptor
- This change in membrane potential is called a **receptor potential**
- Receptor potentials are graded potentials; their magnitude varies with the strength of the stimulus

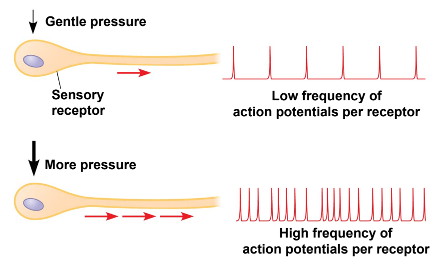



## Transmission

- For many sensory receptors, transducing the energy in a stimulus into a receptor potential initiates action potentials that are transmitted to the CNS
- Some sensory receptors are specialized neurons while others are specialized cells that regulate neurons




Figure 50.4







- The response of a sensory receptor varies with intensity of stimuli
- If the receptor is a neuron, a larger receptor potential results in more frequent action potentials
- If the receptor is not a neuron, a larger receptor potential causes more neurotransmitters to be released




- Processing of sensory information can occur before, during, and after transmission of action potentials to the CNS
- Usually, integration of sensory information begins as soon as the information is received




## Perception

- **Perceptions** are the brain's construction of stimuli
- Stimuli from different sensory receptors travel as action potentials along dedicated neural pathways
- The brain distinguishes stimuli from different receptors based on the area in the brain where the action potentials arrive




## Amplification and Adaptation

- **Amplification** is the strengthening of a sensory signal during transduction
- **Sensory adaptation** is a decrease in responsiveness to continued stimulation




## Types of Sensory Receptors

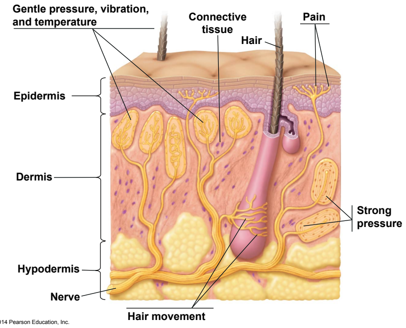
- Based on energy transduced, sensory receptors fall into five categories
  - Mechanoreceptors
  - Chemoreceptors
  - Electromagnetic receptors
  - Thermoreceptors
  - Pain receptors

## *Mechanoreceptors*

- **Mechanoreceptors** sense physical deformation caused by stimuli such as pressure, stretch, motion, and sound
- The knee-jerk response is triggered by the vertebrate stretch receptor, a mechanoreceptor that detects muscle movement
- The mammalian sense of touch relies on mechanoreceptors that are dendrites of sensory neurons




Figure 50.5







## *Chemoreceptors*

- General **chemoreceptors** transmit information about the total solute concentration of a solution
- Specific chemoreceptors respond to individual kinds of molecules
- When a stimulus molecule binds to a chemoreceptor, the chemoreceptor becomes more or less permeable to ions
- The antennae of the male silkworm moth have very sensitive specific chemoreceptors




Figure 50.6

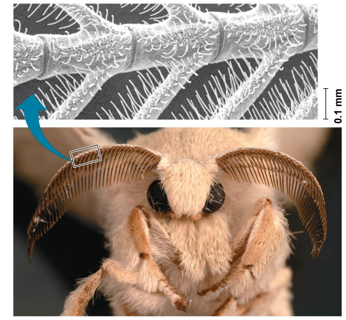






Figure 50.6a

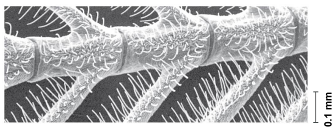






Figure 50.6b




## *Electromagnetic Receptors*

- **Electromagnetic receptors** detect electromagnetic energy such as light, electricity, and magnetism
- Some snakes have very sensitive infrared receptors that detect body heat of prey against a colder background
- Many animals apparently migrate using Earth's magnetic field to orient themselves




Figure 50.7


(a) Beluga whales

(b) Rattlesnake

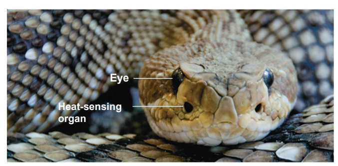



Figure 50.7a

(a) Beluga whales




Figure 50.7b




(b) Rattlesnake




## *Thermoreceptors*

- **Thermoreceptors**, which respond to heat or cold, help regulate body temperature by signaling both surface and body core temperature
- Mammals have a variety of thermoreceptors, each specific for a particular temperature range




## *Pain Receptors*

- In humans, **pain receptors**, or **nociceptors**, detect stimuli that reflect harmful conditions
- They respond to excess heat, pressure, or chemicals released from damaged or inflamed tissues




## Concept 50.2: The mechanoreceptors responsible for hearing and equilibrium detect moving fluid or settling particles

- Hearing and perception of body equilibrium are related in most animals
- For both senses, settling particles or moving fluid is detected by mechanoreceptors

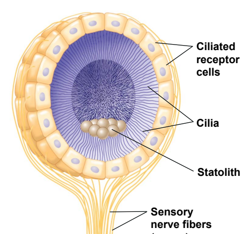



## Sensing Gravity and Sound in Invertebrates

- Most invertebrates maintain equilibrium using mechanoreceptors located in organs called **statocysts**
- Statocysts contain mechanoreceptors that detect the movement of granules called **statoliths**




Figure 50.8







- Many arthropods sense sounds with body hairs that vibrate or with localized "ears" consisting of a tympanic membrane stretched over an internal air chamber

Figure 50.9

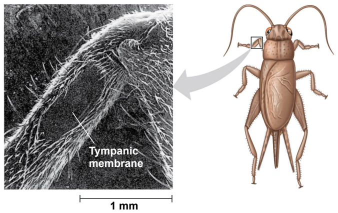
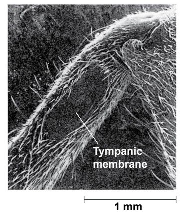






Figure 50.9a







## Hearing and Equilibrium in Mammals

- In most terrestrial vertebrates, sensory organs for hearing and equilibrium are closely associated in the ear




Figure 50.10

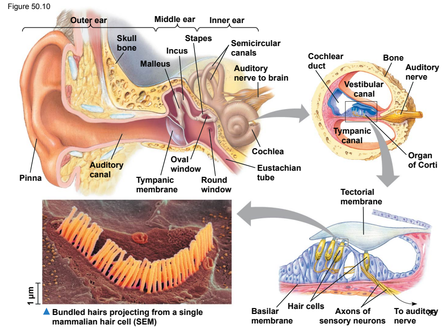





Figure 50.10a

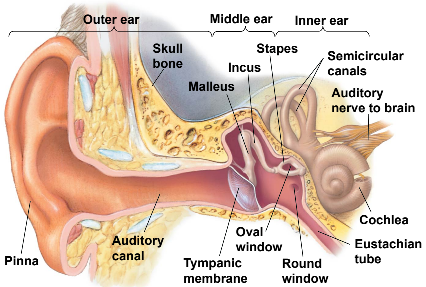






Figure 50.10b

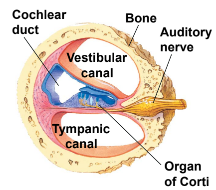






Figure 50.10c

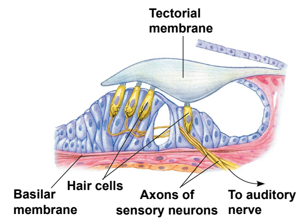






Figure 50.10d


Bundled hairs projecting from a single mammalian hair cell (SEM)




## *Hearing*

- Vibrating objects create percussion waves in the air that cause the tympanic membrane to vibrate
- The three bones of the middle ear transmit the vibrations of moving air to the oval window on the cochlea
- These vibrations create pressure waves in the fluid in the cochlea that travel through the vestibular canal




- Pressure waves in the canal cause the basilar membrane to vibrate, bending its **hair cells**
- This bending of hair cells depolarizes the membranes of mechanoreceptors and sends action potentials to the brain via the auditory nerve




Figure 50.11

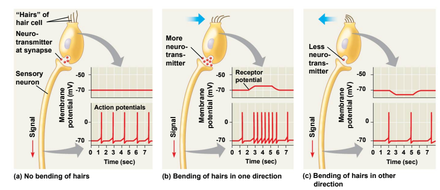
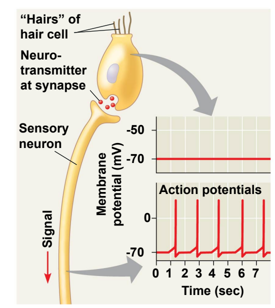






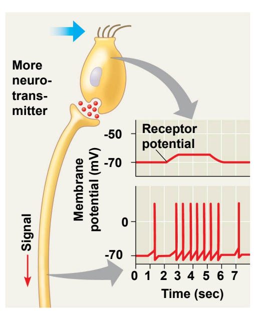
Figure 50.11a




(a) No bending of hairs



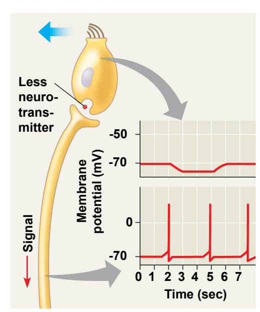

Figure 50.11b




(b) Bending of hairs in one direction




Figure 50.11c




(c) Bending of hairs in one direction




- The fluid waves dissipate when they strike the **round window** at the end of the tympanic canal




- The ear conveys information about
  - *Volume*, the amplitude of the sound wave
  - *Pitch*, the frequency of the sound wave
- The cochlea can distinguish pitch because the basilar membrane is not uniform along its length
- Each region of the basilar membrane is tuned to a particular vibration frequency

Figure 50.12

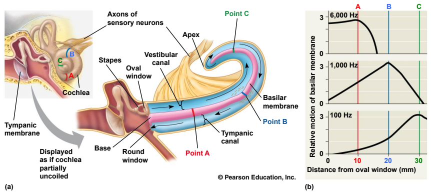







Figure 50.12a

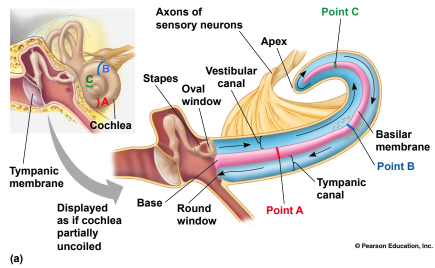
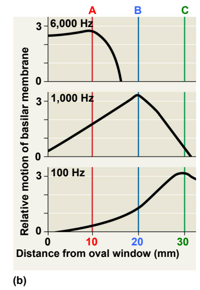







Figure 50.12b







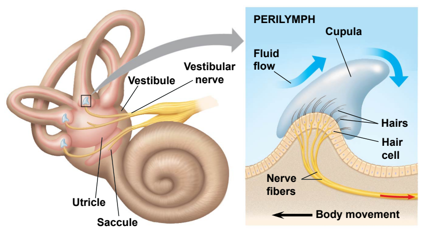

## *Equilibrium*

- Several organs of the inner ear detect body movement, position, and balance
  - The **utricle** and **saccule** contain granules called otoliths that allow us to perceive position relative to gravity or linear movement
  - Three semicircular canals contain fluid and can detect angular movement in any direction





Figure 50.13








## Hearing and Equilibrium in Other Vertebrates

- Unlike mammals, fishes have only a pair of inner ears near the brain
- Most fishes and aquatic amphibians also have a **lateral line system** along both sides of their body
- The lateral line system contains mechanoreceptors with hair cells that detect and respond to water movement





Figure 50.14

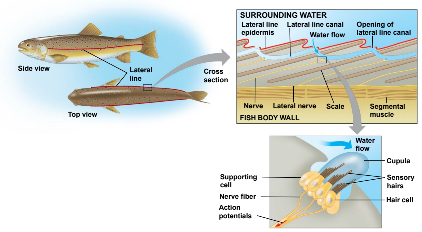







Figure 50.14a

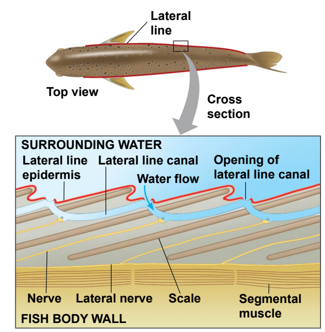
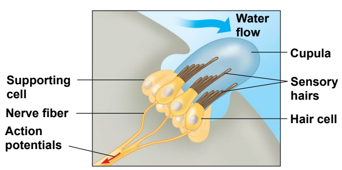







Figure 50.14b








## Concept 50.3: The diverse visual receptors of animals depend on light-absorbing pigments

- Animals use a diverse set of organs for vision, but the underlying mechanism for capturing light is the same, suggesting a common evolutionary origin





## Evolution of Visual Perception

- Light detectors in the animal kingdom range from simple clusters of cells that detect direction and intensity of light to complex organs that form images
- Light detectors all contain **photoreceptors**, cells that contain light-absorbing pigment molecules





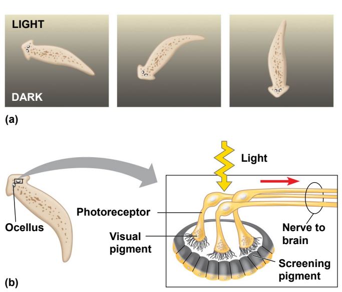
## *Light-Detecting Organs*

- Most invertebrates have a light-detecting organ
- One of the simplest light-detecting organs is that of planarians
- A pair of ocelli called eyespots are located near the head
- These allow planarians to move away from light and seek shaded locations





Figure 50.15








## *Compound Eyes*

- Insects and crustaceans have **compound eyes**, which consist of up to several thousand light detectors called **ommatidia**
- Compound eyes are very effective at detecting movement
- Insects have excellent color vision, and some can see into the ultraviolet range





Figure 50.16

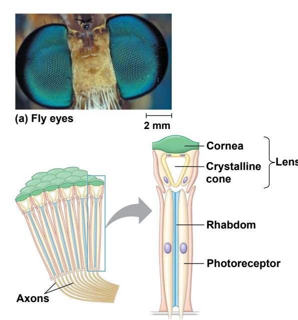
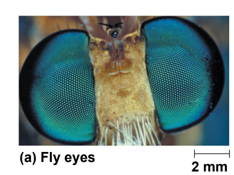







Figure 50.16a



## *Single-Lens Eyes*

- Among invertebrates, **single-lens eyes** are found in some jellies, polychaetes, spiders, and many molluscs
- They work on a camera-like principle: the **iris** changes the diameter of the **pupil** to control how much light enters
- The eyes of all vertebrates have a single lens





## The Vertebrate Visual System

- In vertebrates the eye detects color and light, but the brain assembles the information and perceives the image





Figure 50.17a

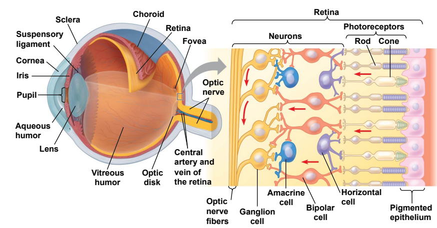







Figure 50.17aa

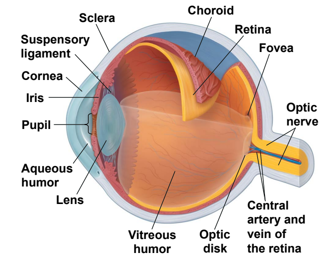







Figure 50.17ab

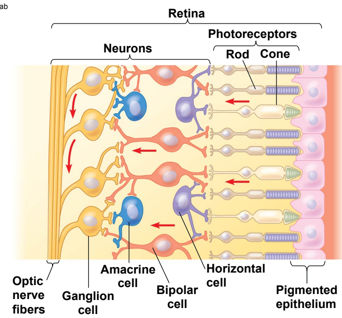







Figure 50.17b

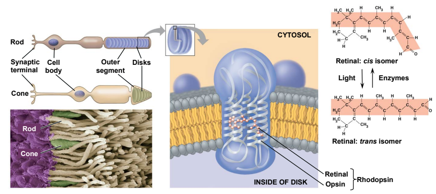







Figure 50.17ba

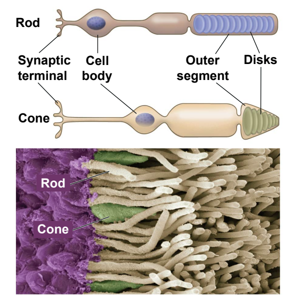







Figure 50.17bb

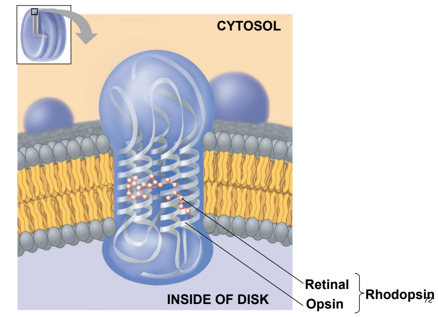







Figure 50.17bc

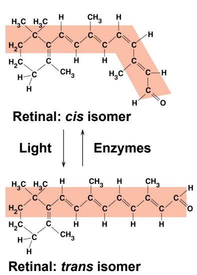
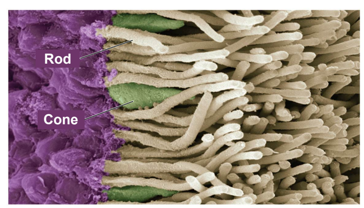







Figure 50.17bd








## *Sensory Transduction in the Eye*

- Transduction of visual information to the nervous system begins when light induces the conversion of *cis*-retinal to *trans*-retinal
- *Trans*-retinal activates rhodopsin, which activates a G protein, eventually leading to hydrolysis of cyclic GMP



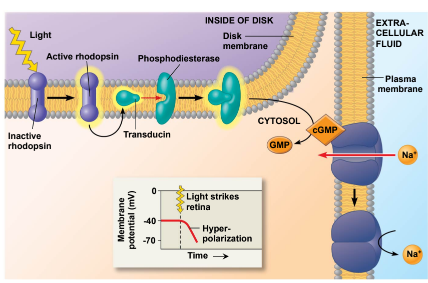


- When cyclic GMP breaks down, $Na^+$ channels close
- This hyperpolarizes the cell
- The signal transduction pathway usually shuts off again as enzymes convert retinal back to the *cis* form





Figure 50.18








## *Processing of Visual Information in the Retina*

- Processing of visual information begins in the retina
- In the dark, rods and cones continually release the neurotransmitter glutamate into synapses with neurons called bipolar cells
- Some bipolar cells are hyperpolarized in response to glutamate while others are depolarized



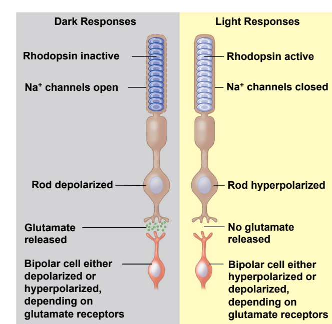


- In the light, rods and cones hyperpolarize, shutting off release of glutamate
- The bipolar cells are then either depolarized or hyperpolarized





Figure 50.19



- Horizontal cells, stimulated by illuminated rods and cones, enhance contrast of the image, a process called lateral inhibition
- Amacrine cells distribute information from one bipolar cell to several ganglion cells
- Lateral inhibition is repeated by the interaction of amacrine and ganglion cells and occurs at all levels of visual processing in the brain
- Rods and cones that feed information to one ganglion cell define a receptive field




## *Processing of Visual Information in the Brain*

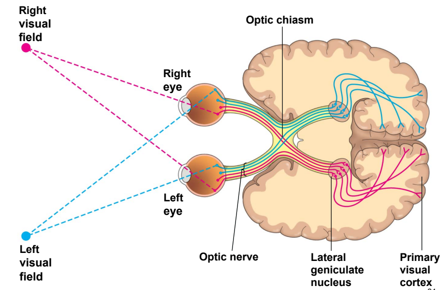
- The optic nerves meet at the optic chiasm near the cerebral cortex
- Sensations from the left visual field of both eyes are transmitted to the right side of the brain
- Sensations from the right visual field of both eyes are transmitted to the left side of the brain




- Most ganglion cell axons lead to the lateral geniculate nuclei
- The lateral geniculate nuclei relay information to the primary visual cortex in the cerebrum
- At least 30% of the cerebral cortex, in dozens of integrating centers, is active in creating visual perceptions




Figure 50.20







## *Color Vision*

- Among vertebrates, most fish, amphibians, and reptiles, including birds, have very good color vision
- Humans and other primates are among the minority of mammals with the ability to see color well
- Mammals that are nocturnal usually have a high proportion of rods in the retina



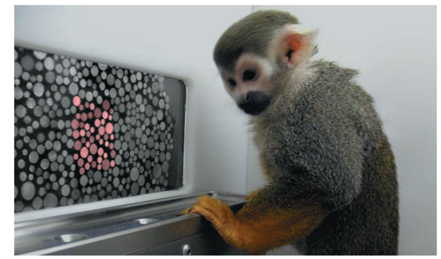

- In humans, perception of color is based on three types of cones, each with a different visual pigment: red, green, or blue
- These pigments are called photopsins and are formed when retinal binds to three distinct opsin proteins




- Abnormal color vision results from alterations in the genes for one or more photopsin proteins
- In 2009, researchers studying color blindness in squirrel monkeys made a breakthrough in gene therapy




Figure 50.21






## *The Visual Field*

- The brain processes visual information and controls what information is captured
- Focusing occurs by changing the shape of the lens
- The **fovea** is the center of the visual field and contains no rods, but a high density of cones




Figure 50.22

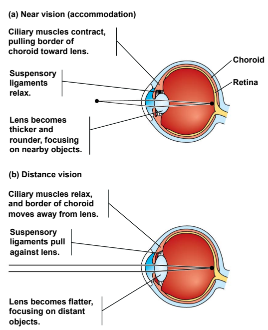






Figure 50.22a

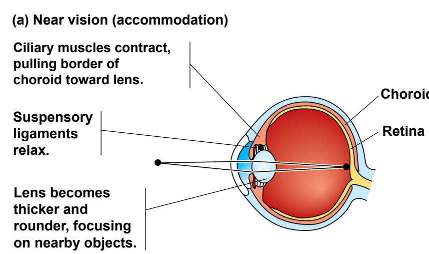
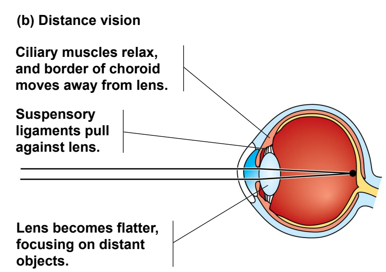






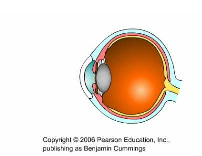
Figure 50.22b







## Animation: Near and Distance Vision







## Concept 50.4: The senses of taste and smell rely on similar sets of sensory receptors

- In terrestrial animals
  - **Gustation** (taste) is dependent on the detection of chemicals called **tastants**
  - **Olfaction** (smell) is dependent on the detection of **odorant** molecules
- In aquatic animals there is no distinction between taste and smell
- Taste receptors of insects are in sensory hairs located on feet and in mouth parts



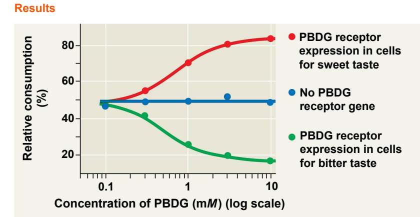

## Taste in Mammals

- In humans and other mammals, there are five taste perceptions: sweet, sour, salty, bitter, and umami (elicited by glutamate)
- Researchers have identified receptors for all five tastes
- Researchers believe that an individual taste cell expresses one receptor type and detects one of the five tastes




Figure 50.23

Results




Relative consumption = (Fluid intake from bottle containing PBDG ÷ Total fluid intake) × 100%

- Receptor cells for taste in mammals are modified epithelial cells organized into **taste buds**, located in several areas of the tongue and mouth
- Most taste buds are associated with projections called papillae
- Any region with taste buds can detect any of the five types of taste





Figure 50.24

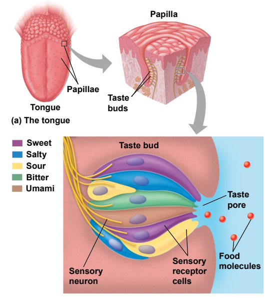







Figure 50.24a

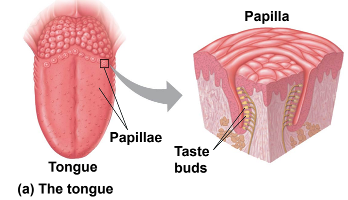
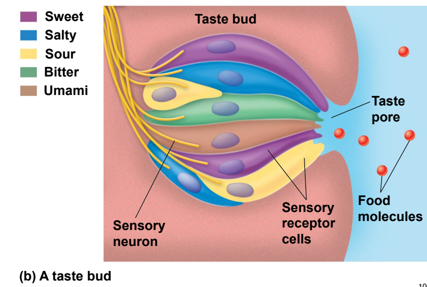







Figure 50.24b








- Taste receptors are of three types
  - The sensations of sweet, umami, and bitter require specific G protein-coupled receptors (GPCRs)
  - The receptor for sour belongs to the TRP family and is similar to the capsaicin and other thermoreceptor proteins
  - The taste receptor for salt is a sodium channel





## Smell in Humans

- Olfactory receptor cells are neurons that line the upper portion of the nasal cavity
- Binding of odorant molecules to receptors triggers a signal transduction pathway, sending action potentials to the brain
- Humans can distinguish thousands of different odors
- Although receptors and brain pathways for taste and smell are independent, the two senses do interact





Figure 50.25

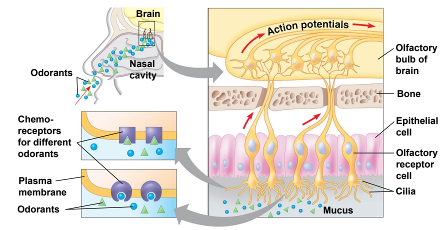







Figure 50.25a

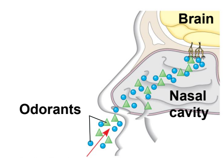







Figure 50.25b

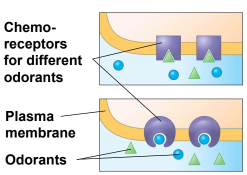
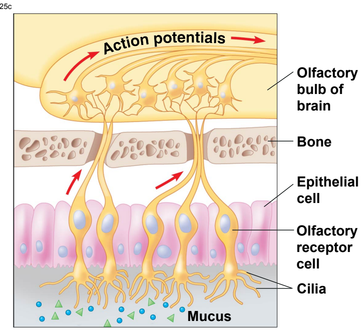







Figure 50.25c








## Concept 50.5: The physical interaction of protein filaments is required for muscle function

- Muscle activity is a response to input from the nervous system
- Muscle cell contraction relies on the interaction between **thin filaments**, composed mainly of actin, and **thick filaments**, staggered arrays of myosin





## Vertebrate Skeletal Muscle

- Vertebrate **skeletal muscle** moves bones and the body and is characterized by a hierarchy of smaller and smaller units
- A skeletal muscle consists of a bundle of long fibers, each a single cell, running parallel to the length of the muscle
- Each muscle fiber is itself a bundle of smaller **myofibrils** arranged longitudinally





- Skeletal muscle is also called striated muscle because the regular arrangement of myofilaments creates a pattern of light and dark bands
- The functional unit of a muscle is called a **sarcomere** and is bordered by Z lines, where thin filaments attach





Figure 50.26

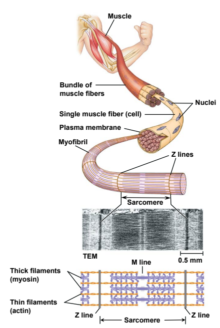







Figure 50.26a

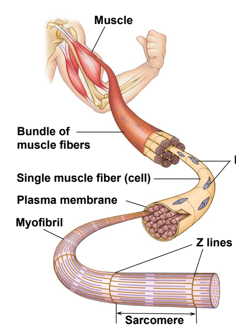







Figure 50.26b

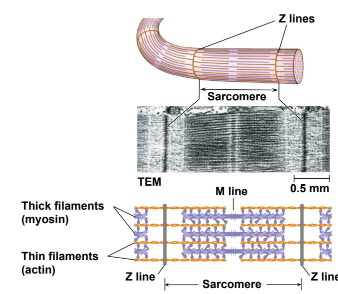
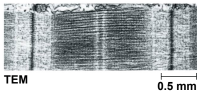


Figure 50.26c







## *The Sliding-Filament Model of Muscle Contraction*

- According to the **sliding-filament model**, thin and thick filaments slide past each other longitudinally, powered by the myosin molecules




Figure 50.27

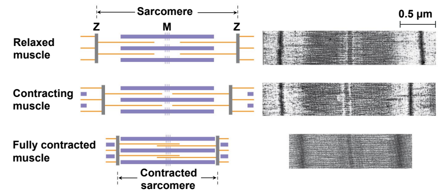






Figure 50.27a





Figure 50.27b

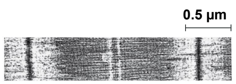




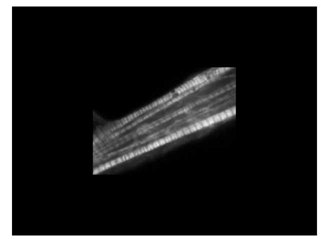


Figure 50.27c





## Video: Cardiac Muscle Contraction






- The sliding of filaments relies on interaction between actin and myosin
- The "head" of a myosin molecule binds to an actin filament, forming a cross-bridge and pulling the thin filament toward the center of the sarcomere
- Muscle contraction requires repeated cycles of binding and release




- Glycolysis and aerobic respiration generate the ATP needed to sustain muscle contraction




Figure 50.28

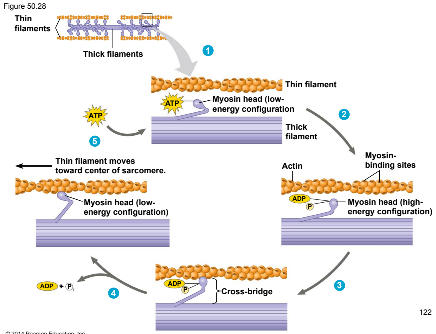






Figure 50.28a-1

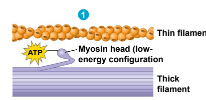






Figure 50.28a-2

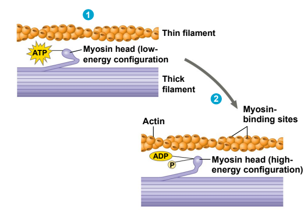






Figure 50.28a-3

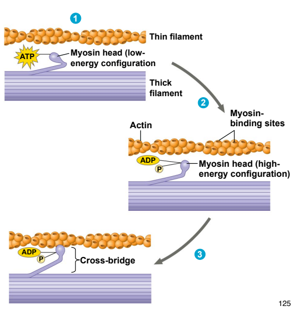






Figure 50.28a-4

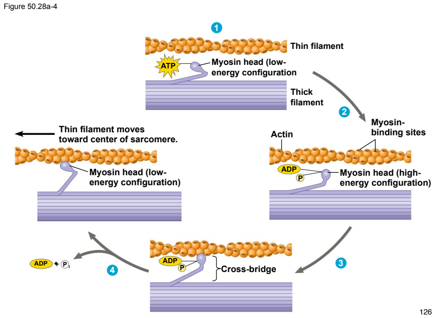
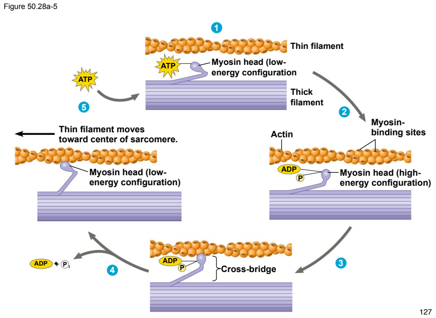






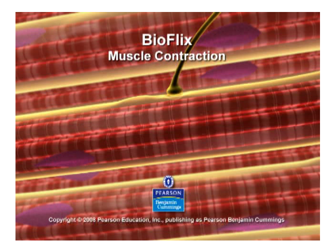
Figure 50.28a-5



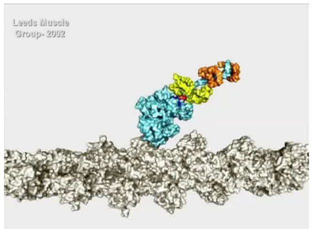




## BioFlix: Muscle Contraction



## Video: Mysoin-actin Interaction








## *The Role of Calcium and Regulatory Proteins*

- The regulatory protein **tropomyosin** and the **troponin complex**, a set of additional proteins, bind to actin strands on thin filaments when a muscle fiber is at rest
- This prevents actin and myosin from interacting



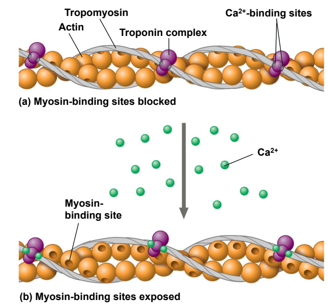


- For a muscle fiber to contract, myosin-binding sites must be uncovered
- This occurs when calcium ions ($Ca^{2+}$) bind to the troponin complex and expose the myosin-binding sites
- Contraction occurs when the concentration of $Ca^{2+}$ is high; muscle fiber contraction stops when the concentration of $Ca^{2+}$ is low





Figure 50.29








- The stimulus leading to contraction of a muscle fiber is an action potential in a motor neuron that makes a synapse with the muscle fiber
- The synaptic terminal of the motor neuron releases the neurotransmitter acetylcholine
- Acetylcholine depolarizes the muscle, causing it to produce an action potential





- Action potentials travel to the interior of the muscle fiber along **transverse (T) tubules**
- The action potential along T tubules causes the **sarcoplasmic reticulum (SR)** to release $Ca^{2+}$
- The $Ca^{2+}$ binds to the troponin complex on the thin filaments
- This binding exposes myosin-binding sites and allows the cross-bridge cycle to proceed





- When motor neuron input stops, the muscle cell relaxes
- Transport proteins in the SR pump $Ca^{2+}$ out of the cytosol
- Regulatory proteins bound to thin filaments shift back to the myosin-binding sites





Figure 50.30

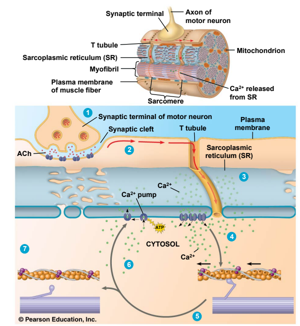







Figure 50.30a

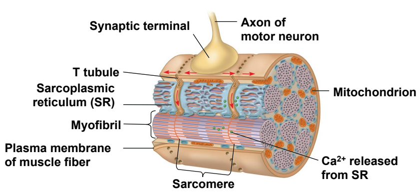
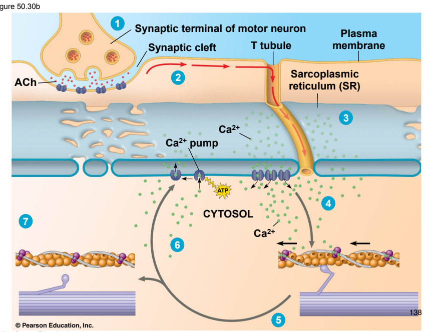







Figure 50.30b








- Amyotrophic lateral sclerosis (ALS), formerly called Lou Gehrig's disease, interferes with the excitation of skeletal muscle fibers; this disease is usually fatal
- Myasthenia gravis is an autoimmune disease that attacks acetylcholine receptors on muscle fibers; treatments exist for this disease





## *Nervous Control of Muscle Tension*

- Contraction of a whole muscle is graded, which means that the extent and strength of its contraction can be voluntarily altered
- There are two basic mechanisms by which the nervous system produces graded contractions
  - Varying the number of fibers that contract
  - Varying the rate at which fibers are stimulated



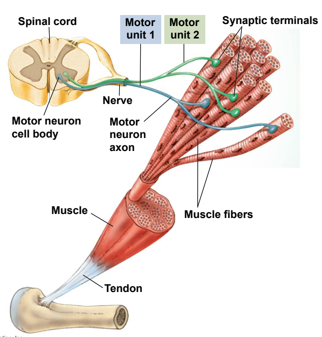


- In vertebrates, each motor neuron may synapse with multiple muscle fibers, although each fiber is controlled by only one motor neuron
- A **motor unit** consists of a single motor neuron and all the muscle fibers it controls





Figure 50.31





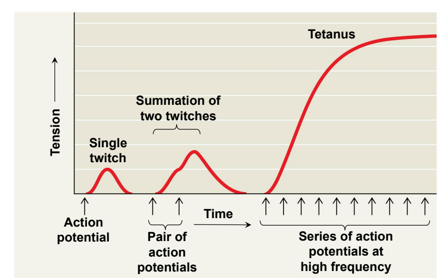



- Recruitment of multiple motor neurons results in stronger contractions
- A twitch results from a single action potential in a motor neuron
- More rapidly delivered action potentials produce a graded contraction by summation





Figure 50.32



- **Tetanus** is a state of smooth and sustained contraction produced when motor neurons deliver a volley of action potentials





## *Types of Skeletal Muscle Fibers*

- There are several distinct types of skeletal muscles, each of which is adapted to a particular function
- They are classified by the source of ATP powering the muscle activity or by the speed of muscle contraction





Table 50.1

**Table 50.1** Types of Skeletal Muscle Fibers

| | Slow Oxidative | Fast Oxidative | Fast Glycolytic |
|---|---|---|---|
| Contraction speed | Slow | Fast | Fast |
| Major ATP source | Aerobic respiration | Aerobic respiration | Glycolysis |
| Rate of fatigue | Slow | Intermediate | Fast |
| Mitochondria | Many | Many | Few |
| Myoglobin content | High (red muscle) | High (red muscle) | Low (white muscle) |





### Oxidative and Glycolytic Fibers

- Oxidative fibers rely mostly on aerobic respiration to generate ATP
- These fibers have many mitochondria, a rich blood supply, and a large amount of **myoglobin**
- Myoglobin is a protein that binds oxygen more tightly than hemoglobin does





- Glycolytic fibers use glycolysis as their primary source of ATP
- Glycolytic fibers have less myoglobin than oxidative fibers and tire more easily
- In poultry and fish, light meat is composed of glycolytic fibers, while dark meat is composed of oxidative fibers





### Fast-Twitch and Slow-Twitch Fibers

- **Slow-twitch fibers** contract more slowly but sustain longer contractions
- All slow-twitch fibers are oxidative
- **Fast-twitch fibers** contract more rapidly but sustain shorter contractions
- Fast-twitch fibers can be either glycolytic or oxidative





- Most skeletal muscles contain both slow-twitch and fast-twitch fibers in varying ratios
- Some vertebrates have muscles that twitch at rates much faster than human muscles
- In producing its characteristic mating call, the male toadfish can contract and relax certain muscles more than 200 times per second





Figure 50.33





## Other Types of Muscle

- In addition to skeletal muscle, vertebrates have cardiac muscle and smooth muscle
- **Cardiac muscle**, found only in the heart, consists of striated cells electrically connected by **intercalated disks**
- Cardiac muscle can generate action potentials without neural input





- In **smooth muscle**, found mainly in walls of hollow organs such as those of the digestive tract, contractions are relatively slow and may be initiated by the muscles themselves
- Contractions may also be caused by stimulation from neurons in the autonomic nervous system





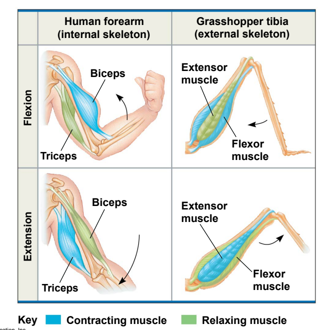
## Concept 50.6: Skeletal systems transform muscle contraction into locomotion

- Skeletal muscles are attached in antagonistic pairs, the actions of which are coordinated by the nervous system
- The skeleton provides a rigid structure to which muscles attach
- Skeletons function in support, protection, and movement





Figure 50.34








## Types of Skeletal Systems

- The three main types of skeletons are
  - Hydrostatic skeletons (lack hard parts)
  - Exoskeletons (external hard parts)
  - Endoskeletons (internal hard parts)





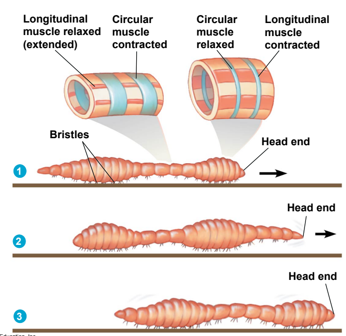
## *Hydrostatic Skeletons*

- A **hydrostatic skeleton** consists of fluid held under pressure in a closed body compartment
- This is the main type of skeleton in most cnidarians, flatworms, nematodes, and annelids
- Annelids use their hydrostatic skeleton for **peristalsis**, a type of movement produced by rhythmic waves of muscle contractions from front to back





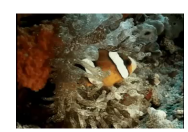
Figure 50.35








## Video: Clownfish and Anemone



## Video: Coral Reef



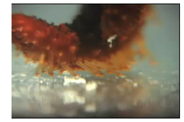


## Video: Earthworm Locomotion





## Video: Echinoderm Tube Feet







## Video: Jelly Swimming





## Video: Thimble Jellies





## *Exoskeletons*

- An **exoskeleton** is a hard encasement deposited on the surface of an animal
- Exoskeletons are found in most molluscs and arthropods
- Arthropods have a jointed exoskeleton called a cuticle, which can be both strong and flexible
- The polysaccharide **chitin** is often found in arthropod cuticle





## *Endoskeletons*

- An **endoskeleton** consists of a hard internal skeleton, buried in soft tissue
- Endoskeletons are found in organisms ranging from sponges to mammals
- A mammalian skeleton has more than 200 bones
- Some bones are fused; others are connected at joints by ligaments that allow freedom of movement





Figure 50.36

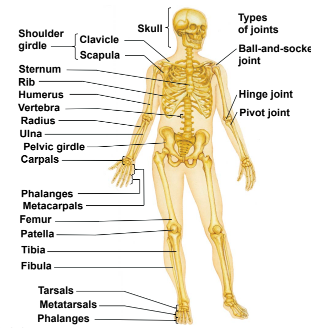
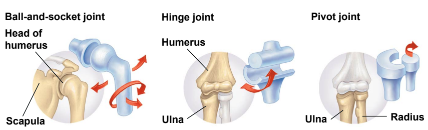







Figure 50.37








- The skeletons of small and large animals have different proportions
- In mammals and birds, the position of legs relative to the body is very important in determining how much weight the legs can bear





## Types of Locomotion

- Most animals are capable of **locomotion**, or active travel from place to place
- In locomotion, energy is expended to overcome friction and gravity





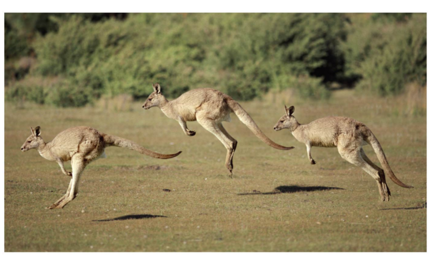
## *Locomotion on Land*

- Walking, running, hopping, or crawling on land requires an animal to support itself and move against gravity
- Diverse adaptations for locomotion on land have evolved in vertebrates





Figure 50.38







- Air poses relatively little resistance for land locomotion
- Maintaining balance is a prerequisite to walking, running, or hopping
- Crawling poses a different challenge; a crawling animal must exert energy to overcome friction





## *Swimming*

- In water, friction is a bigger problem than gravity
- Fast swimmers usually have a sleek, torpedo-like shape to minimize friction
- Animals swim in diverse ways
  - Paddling with their legs as oars
  - Jet propulsion
  - Undulating their body and tail from side to side, or up and down





## *Flying*

- Active flight requires that wings develop enough lift to overcome the downward force of gravity
- Many flying animals have adaptations that reduce body mass
  - For example, birds have no urinary bladder or teeth and have relatively large bones with air-filled regions

Figure 50.UN01a

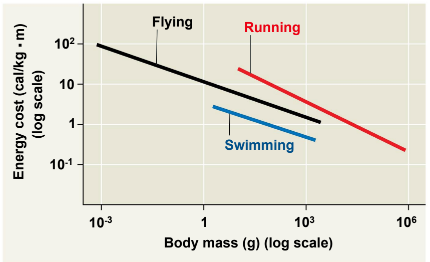







Figure 50.UN01b

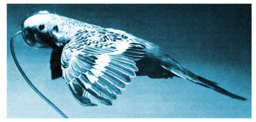






Figure 50.UN02

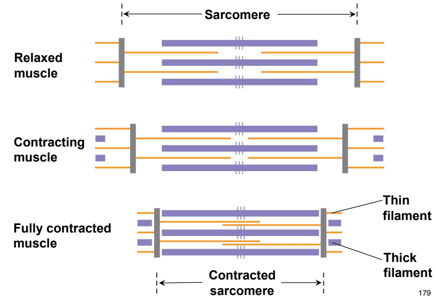







Figure 50.UN03

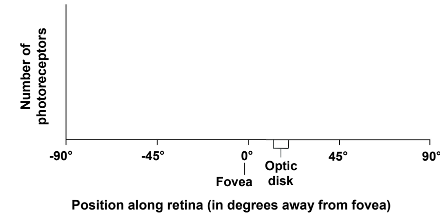







Figure 50.UN04