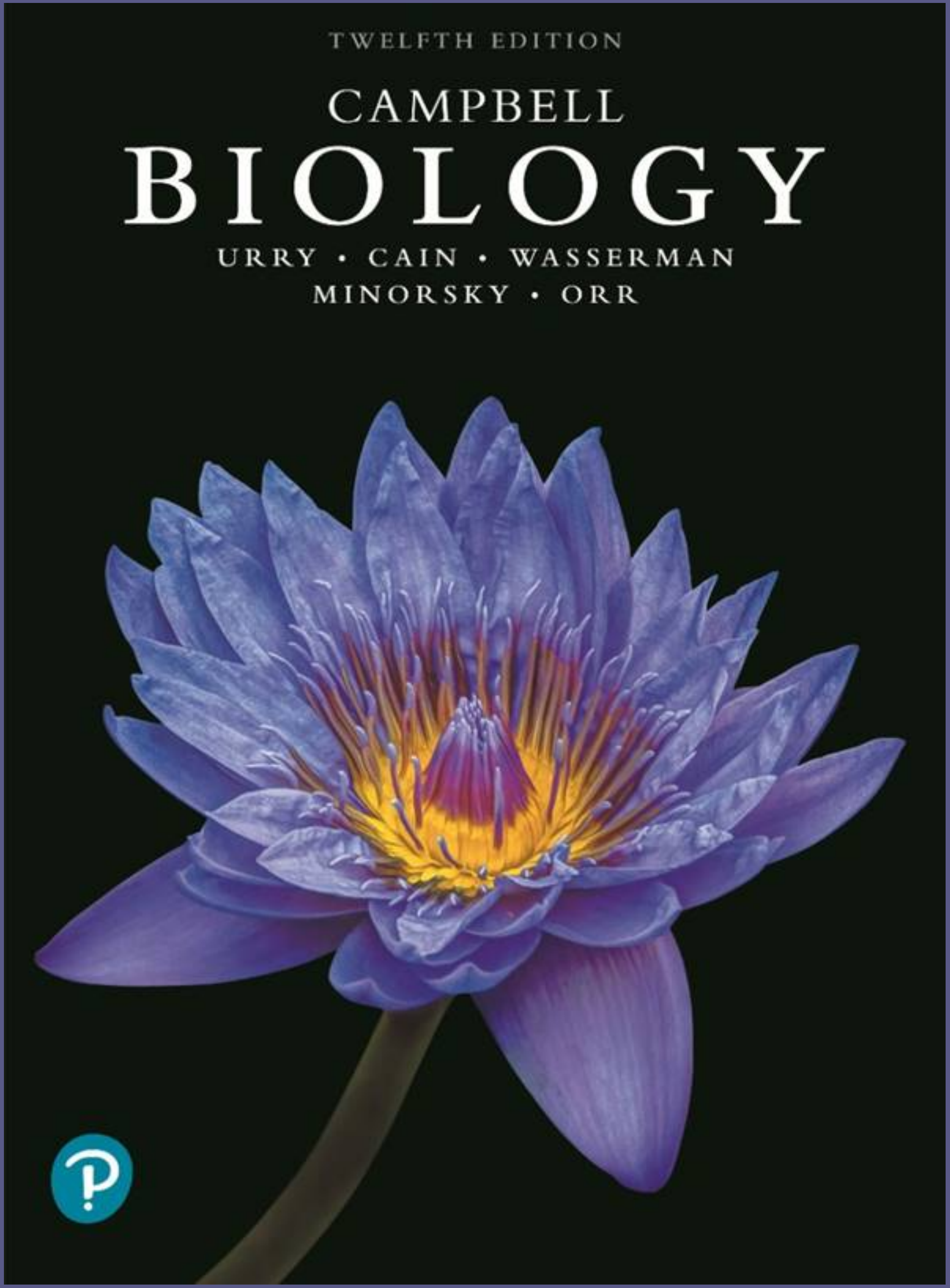


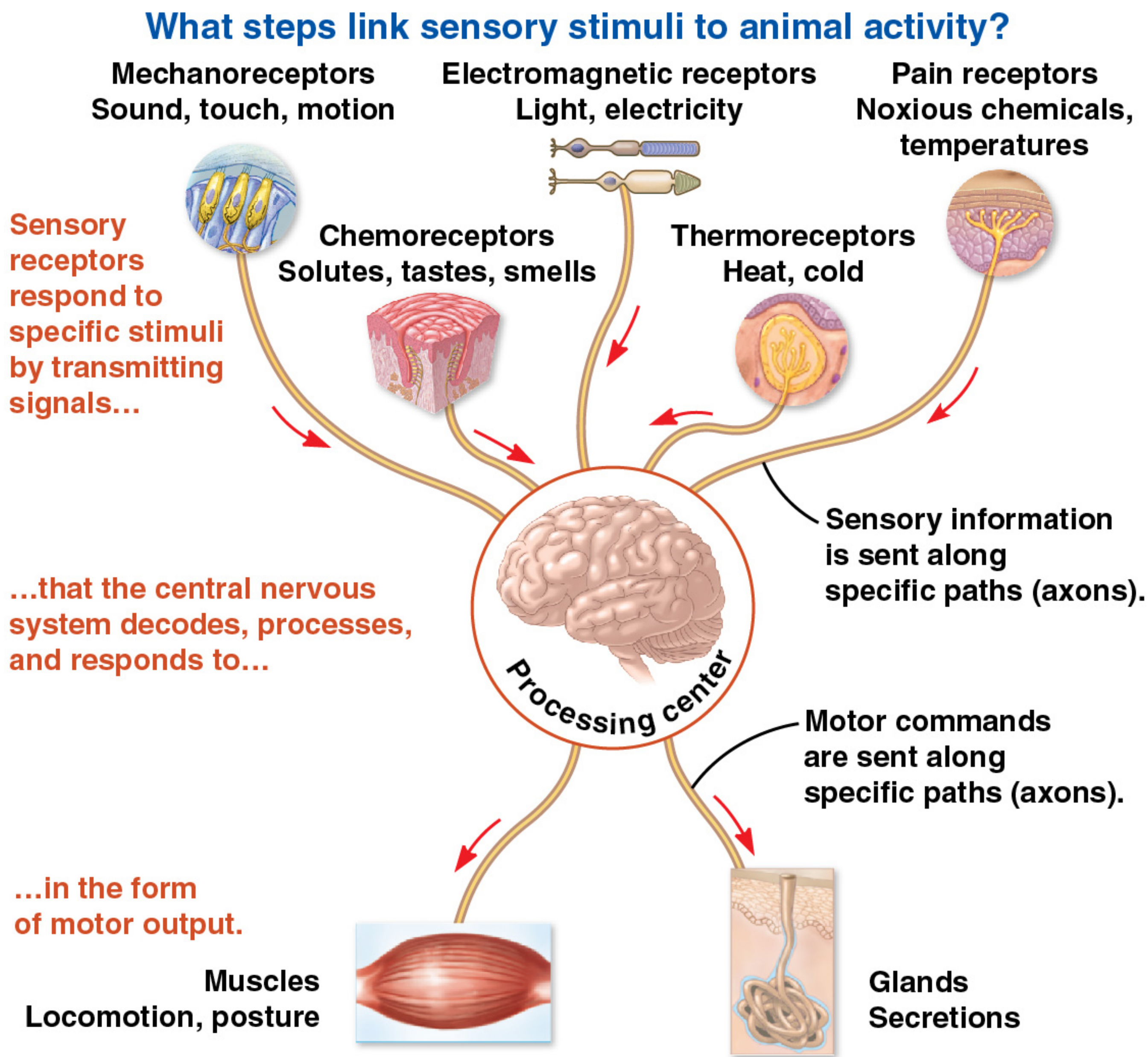
Chapter 50

Sensory and Motor Mechanisms

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 50.1a

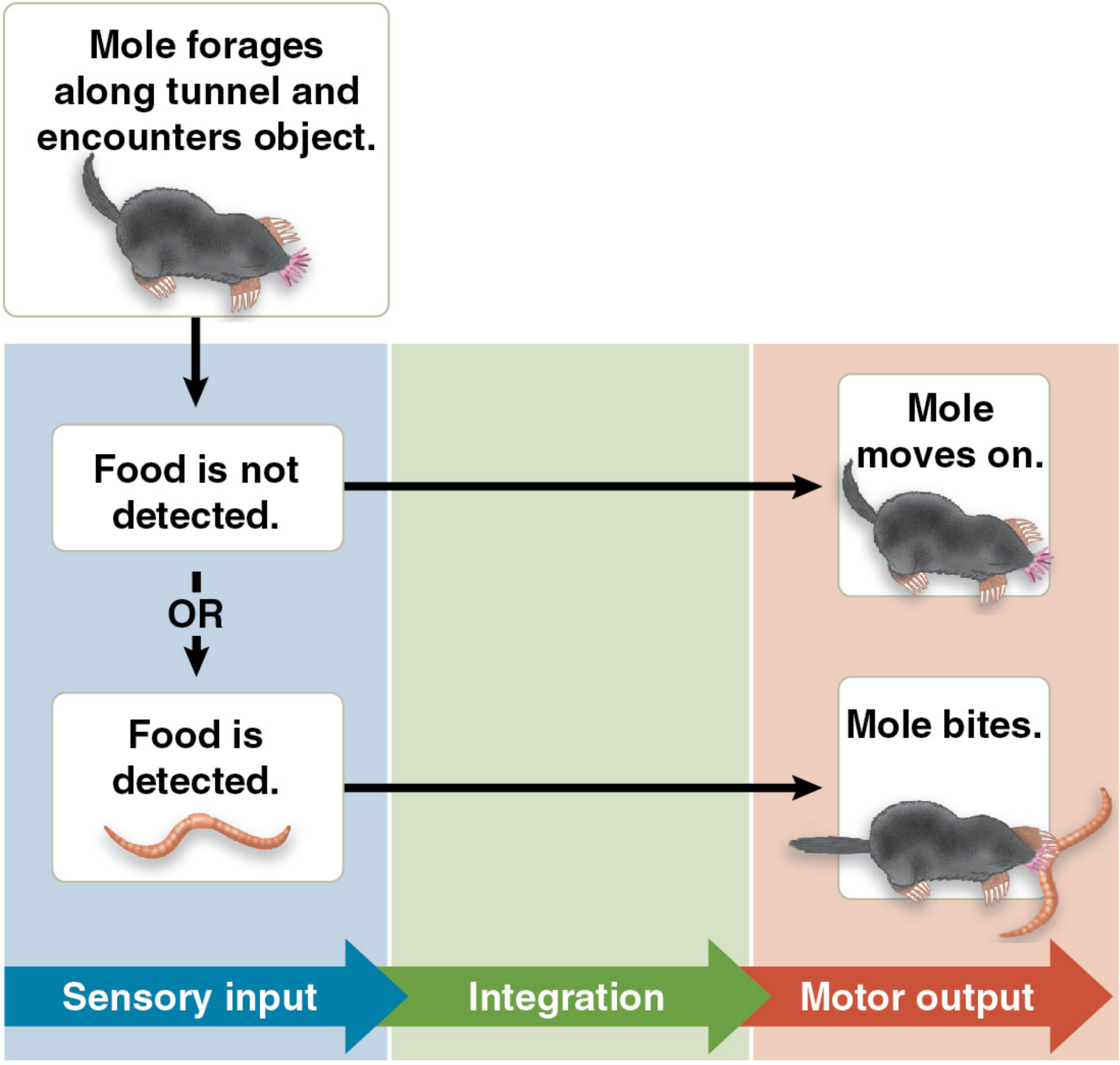
Figure 50.1b


What steps link sensory stimuli to animal activity?
Mechanoreceptors
Sound, touch, motion
Electromagnetic receptors
Light, electricity
Pain receptors
Noxious chemicals, temperatures
Sensory receptors respond to specific stimuli by transmitting signals…
Chemoreceptors
Solutes, tastes, smells
Thermoreceptors
Heat, cold
Sensory information is sent along specific paths (axons).
…that the central nervous system decodes, processes, and responds to…
Processing center
Motor commands are sent along specific paths (axons).
…in the form of motor output.
Muscles
Locomotion, posture
Glands
Secretions

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

- All stimuli represent forms of energy
- A sensory receptor converts stimulus energy into a change in the membrane potential
- When a stimulus is received and processed by the nervous system, a motor response may be generated
- This may involve a simple reflex or more elaborate processing

Figure 50.2



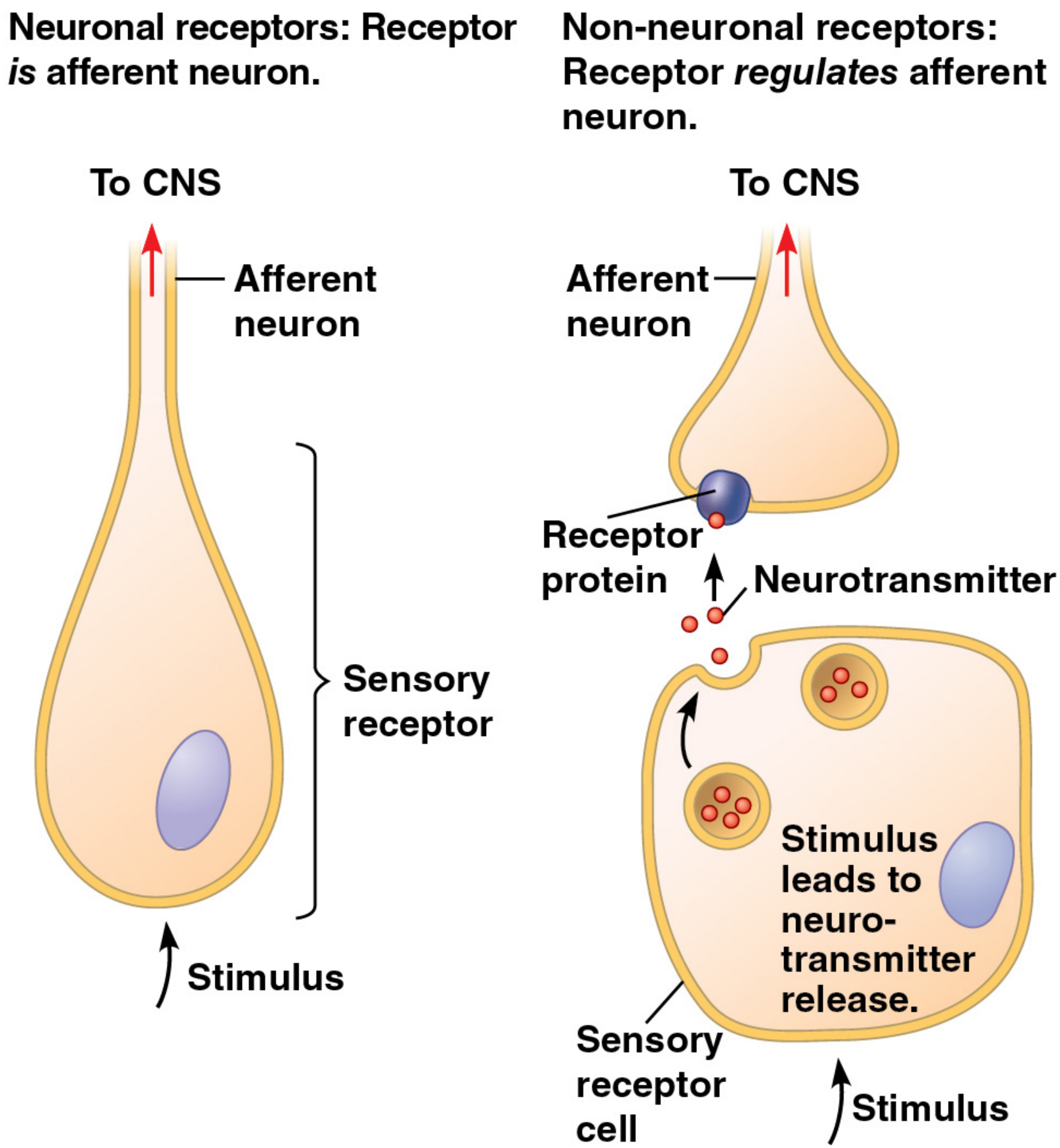
Mole forages along tunnel and encounters object.
Food is not detected.
OR
Food is detected.
Mole moves on.
Mole bites.
Sensory input
Integration
Motor output

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

Sensory Reception and Transduction

- A sensory pathway begins with **sensory reception**, detection of stimuli by sensory receptors
- **Sensory receptors** are sensory cells or organs
- They interact with stimuli, both inside and outside the body

Figure 50.3

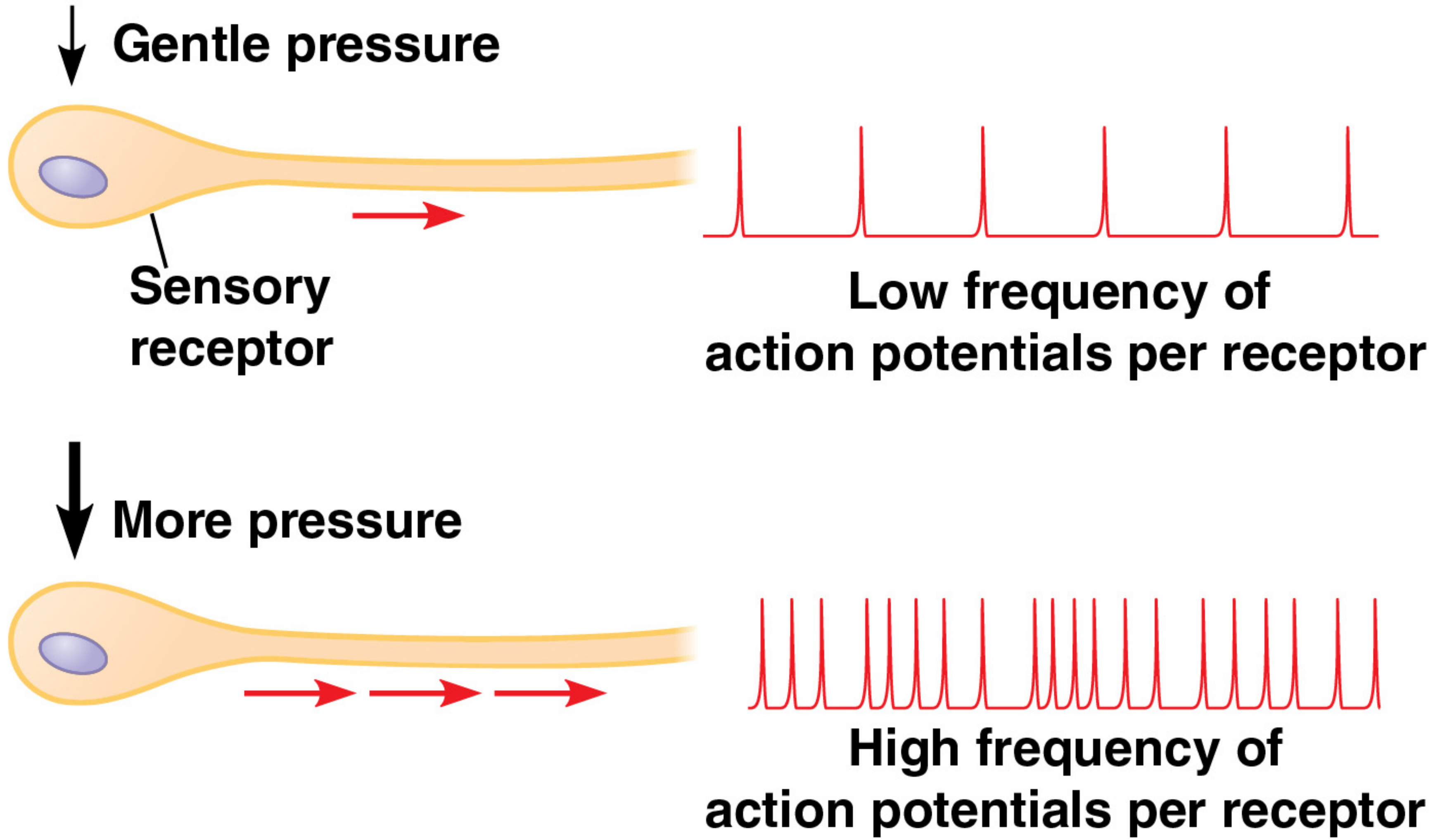

Neuronal receptors: Receptor *is* afferent neuron.
Non-neuronal receptors: Receptor *regulates* afferent neuron.
To CNS
Afferent neuron
Sensory receptor
Stimulus
To CNS
Afferent neuron
Receptor protein
Neurotransmitter
Stimulus leads to neuro-transmitter release.
Sensory receptor cell
Stimulus

- **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

- Sensory information travels through the nervous system as action potentials
- Sensory receptors may be neurons or non-neuronal receptors
- The size of a receptor potential increases with the intensity of the stimulus
- In sensory neurons that spontaneously generate action potentials at a low rate, a stimulus changes how often an action potential is produced

Figure 50.4


Gentle pressure
Sensory receptor
Low frequency of action potentials per receptor
More pressure
High frequency of action potentials per receptor

- Processing of sensory information can occur before, during, and after transmission of action potentials to the central nervous system (CNS)
- Integration often 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 path by which 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

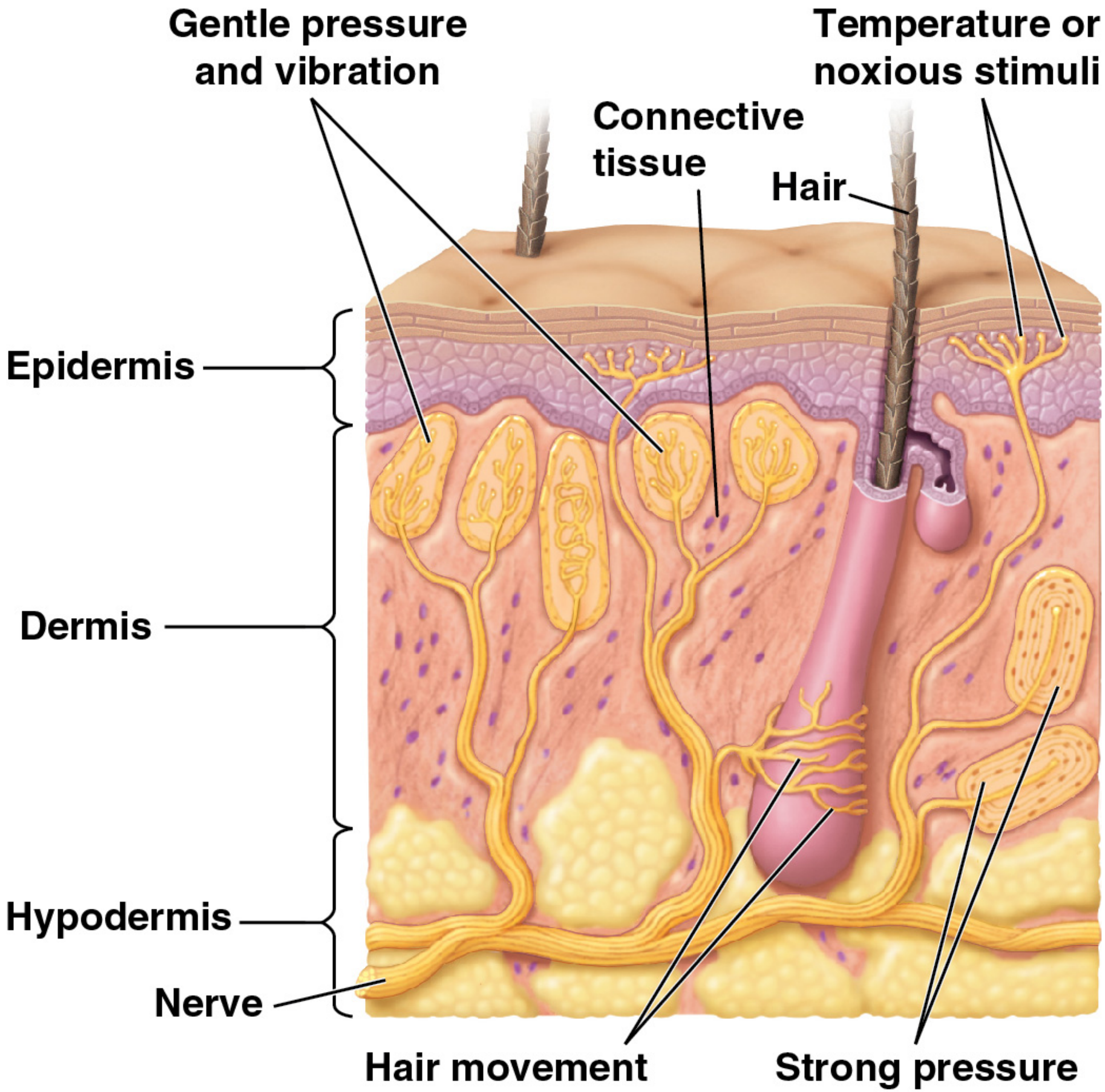
Types of Sensory Receptors

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

Mechanoreceptors

- **Mechanoreceptors** sense physical deformation caused by forms of mechanical energy
- They typically consist of ion channels linked to structures that end outside the cell, such as “hairs” (cilia)
- The mammalian sense of touch relies on mechanoreceptors that are dendrites of sensory neurons

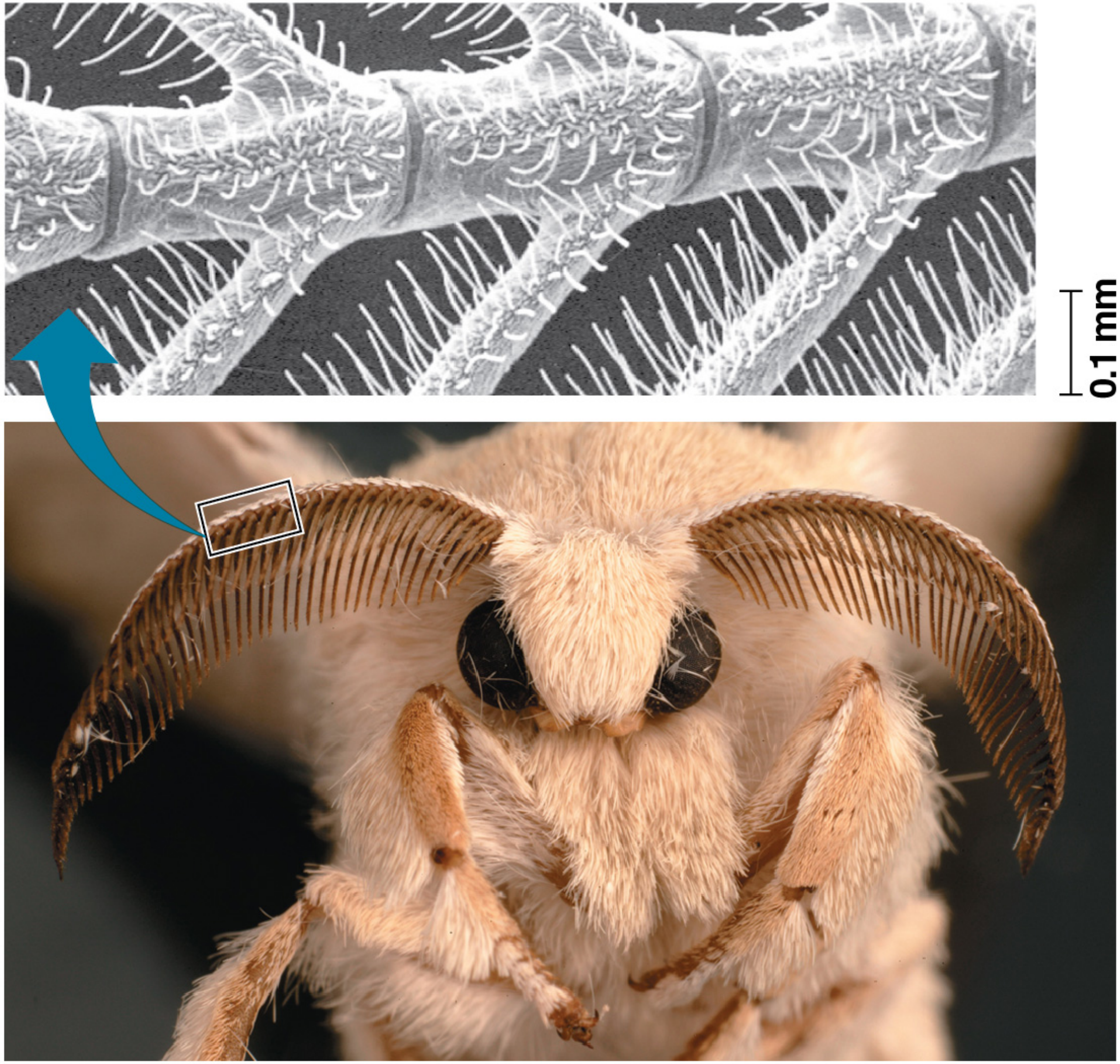
Figure 50.5


Gentle pressure
and vibration
Temperature or
noxious stimuli
Connective
tissue
Hair
Epidermis
Dermis
Hypodermis
Nerve
Hair movement
Strong pressure

Chemoreceptors

- Some **chemoreceptors** transmit information about the total solute concentration of a solution
- Others respond to specific molecules in body fluids
- 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



Electromagnetic Receptors

- **Electromagnetic receptors** detect electromagnetic energy such as light, electricity, and magnetism
- The platypus has electroreceptors on its bill that can detect the electric field generated by prey
- Many animals can migrate using Earth's magnetic field to orient themselves

(a) Beluga whales

(b) Rattlesnake

Thermoreceptors

- **Thermoreceptors** detect heat and cold
- Certain snakes rely on thermoreceptors to detect infrared radiation emitted by warm prey
- Jalapeno and cayenne peppers contain a substance called capsaicin
- Receptors that respond to capsaicin respond to high temperatures also, by opening a calcium channel
- 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 extreme pressure or temperature, or chemicals released from damaged or inflamed tissues
- Chemicals produced in an animal's body sometimes enhance the perception of pain

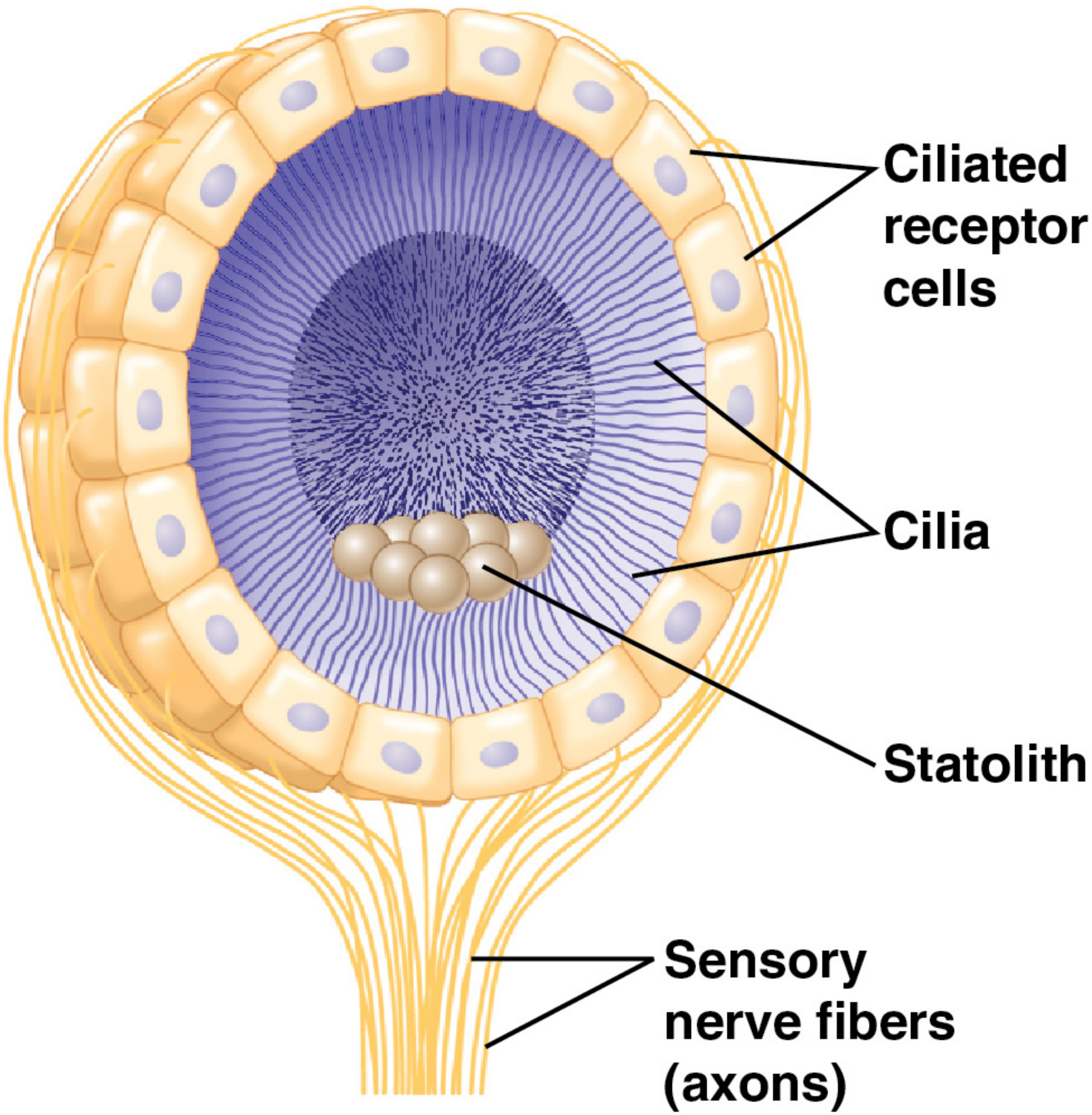
CONCEPT 50.2: In hearing and equilibrium, mechanoreceptors detect moving fluid or settling particles

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

Sensing of Gravity and Sound in Invertebrates

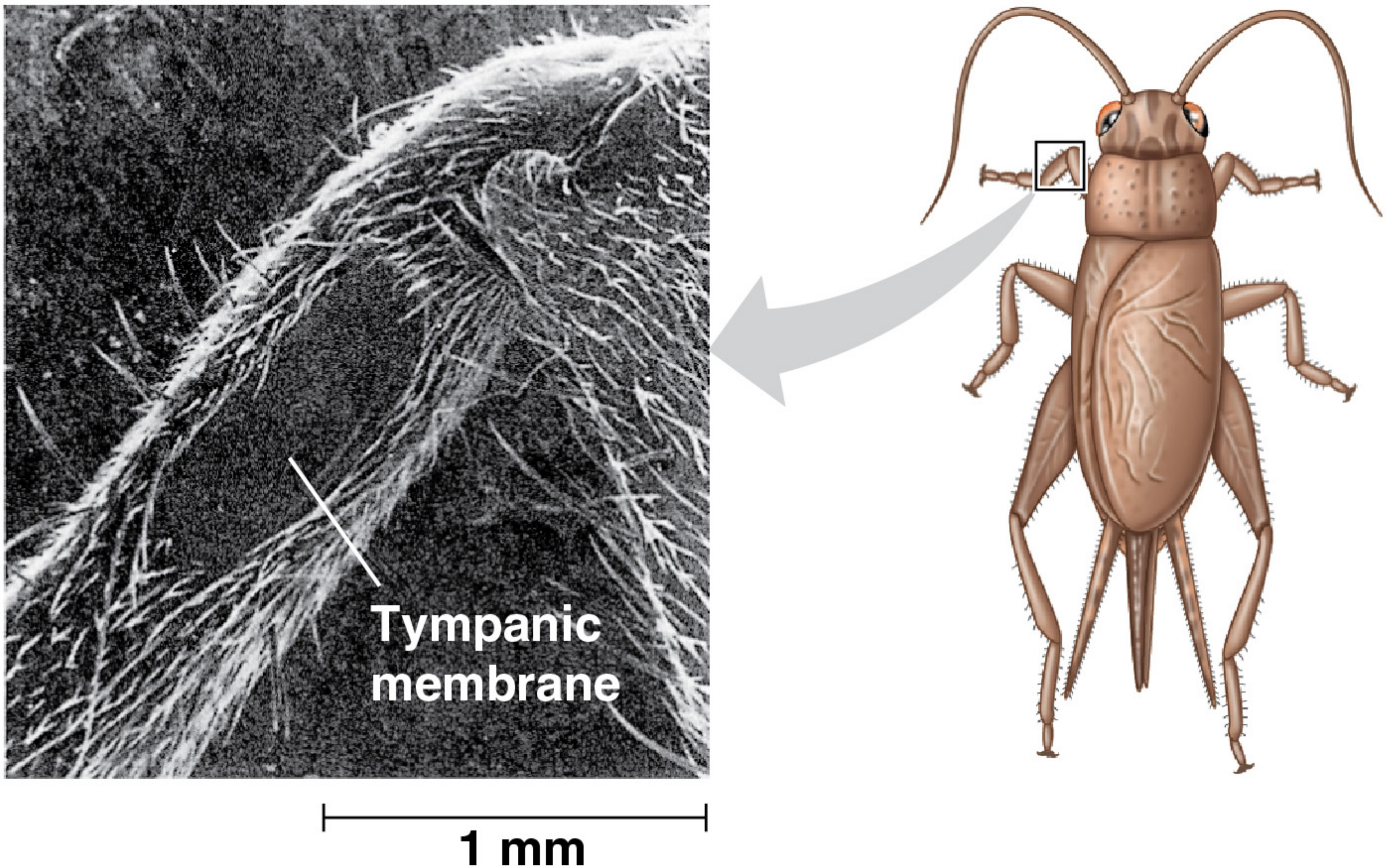
- Most invertebrates maintain equilibrium using mechanoreceptors located in organs called **statocysts**
- Statocysts contain mechanoreceptors that detect the movement of granules called **statoliths**
- Statoliths provide information about the body position with respect to gravity

Figure 50.8


Ciliated receptor cells
Cilia
Statolith
Sensory nerve fibers (axons)

- Many insects have body hairs that vibrate in response to sound waves
- Many also detect sound with localized organs consisting of a tympanic membrane stretched over an internal air chamber

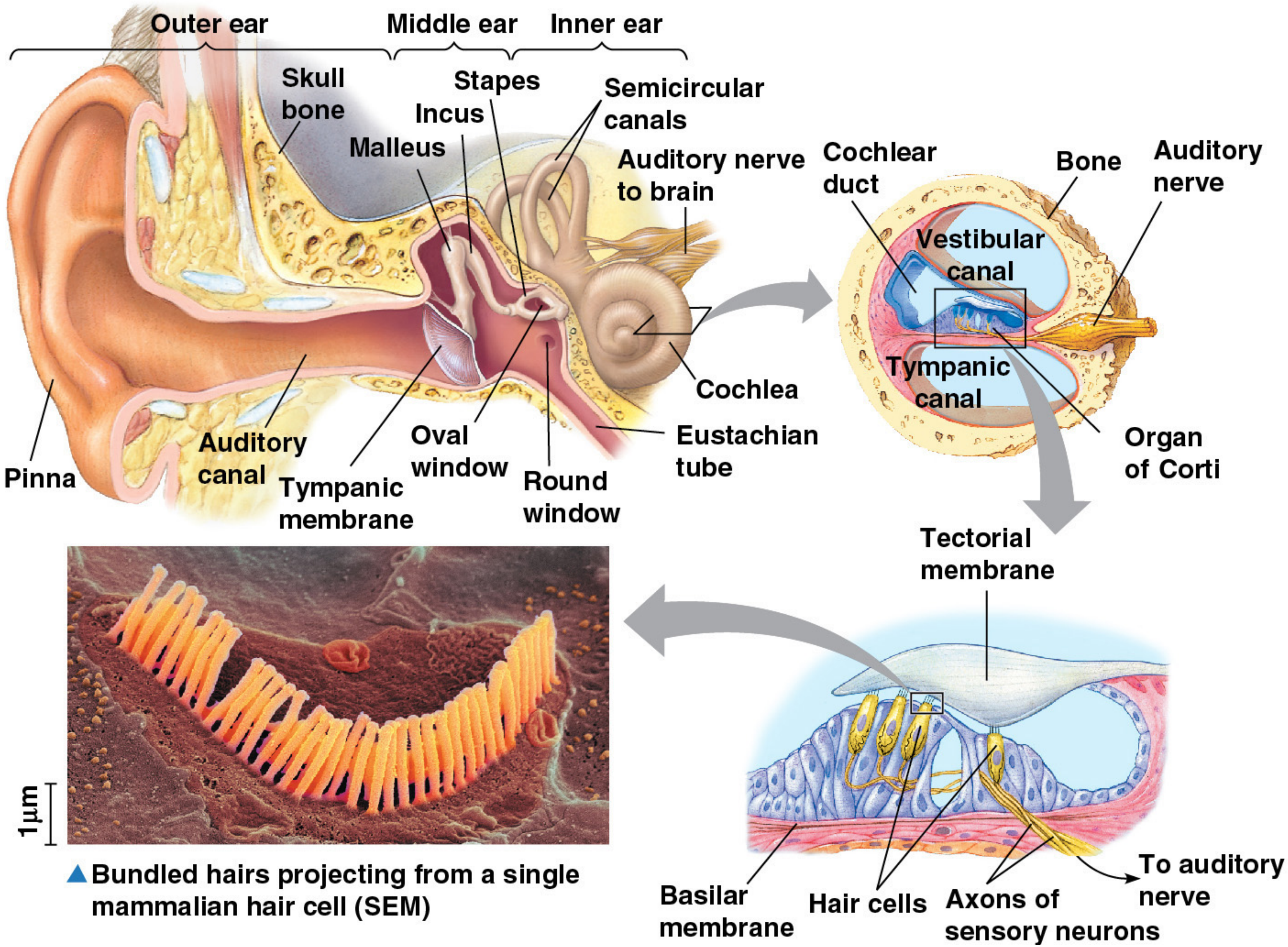
Figure 50.9



Hearing and Equilibrium in Mammals

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

Figure 50.10



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

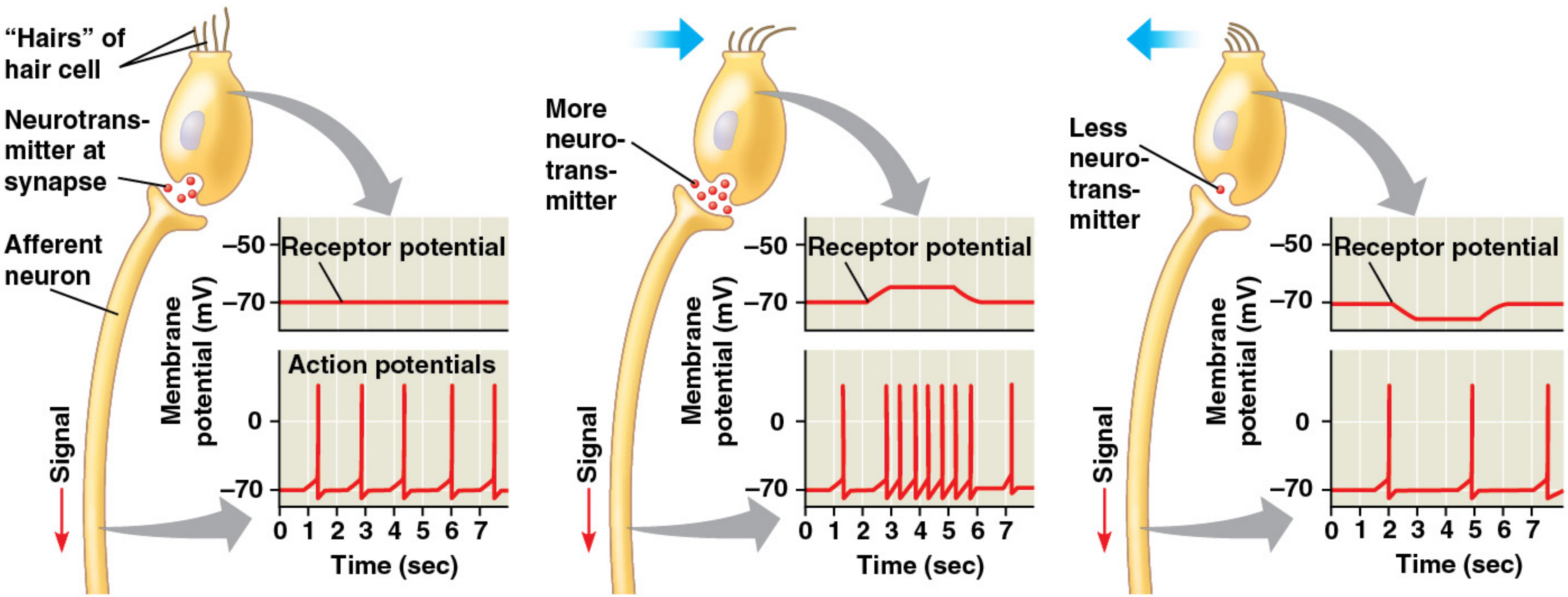
Hearing

- Vibrating objects create pressure waves in the air
- The ear transduces this stimulus into nerve impulses
- To hear sounds, we rely on **hair cells**, sensory cells with hairlike projections that detect motion
- Moving air reaches the outer ear and causes vibration of the **tympanic membrane**
- The three bones of the middle ear transmit the vibrations to the **oval window**

- When one of the three bones, the stapes, vibrates again the oval window, it creates pressure waves in the fluid inside the **cochlea**
- Fluid pressure waves push down on the cochlear duct and basilar membrane
- The basilar membrane and the attached hair cells vibrate up and down

- The bending of hair cells depolarizes the membranes of mechanoreceptors and sends action potentials to the brain via the auditory nerve
- The fluid waves dissipate when they strike the **round window** at the end of the tympanic canal
- This damping of sound resets the apparatus for the next vibrations that arrive

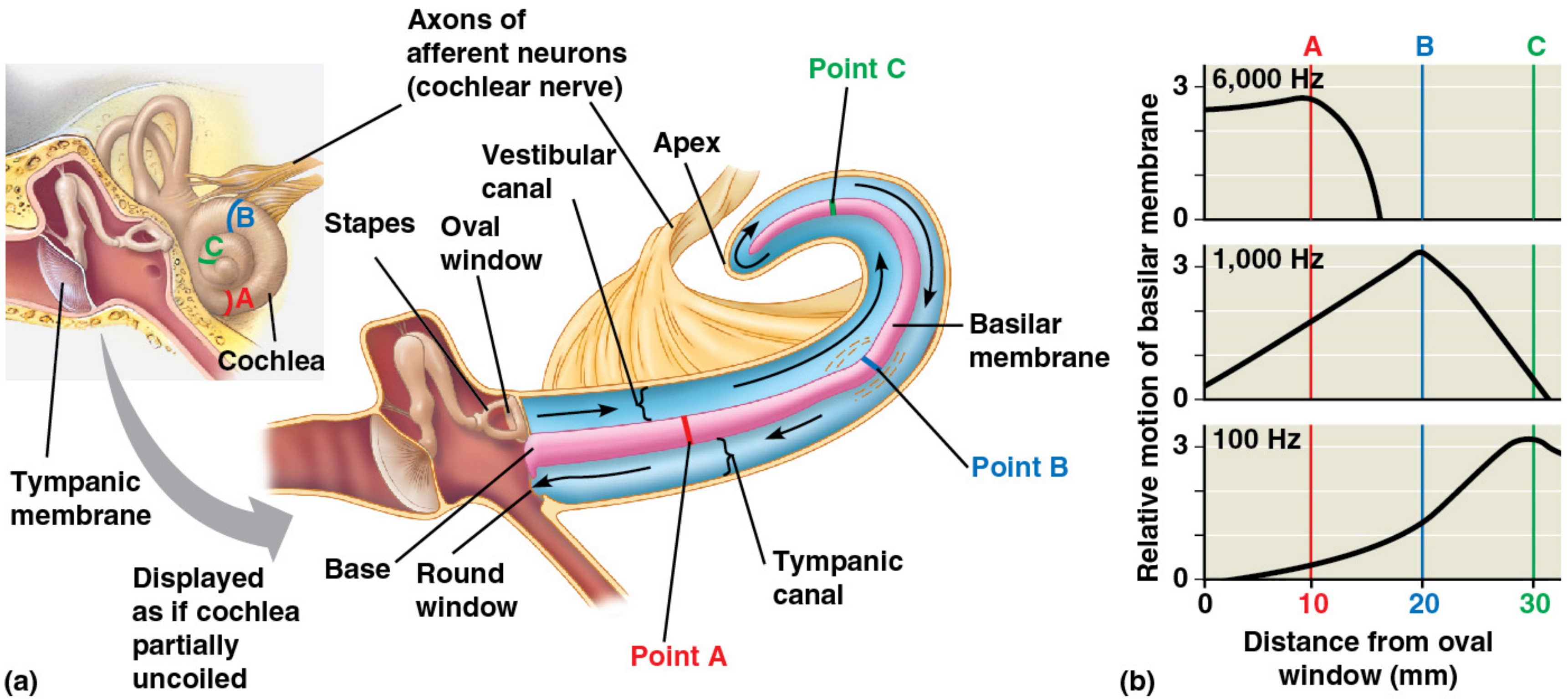
Figure 50.11



(a) No bending of hairs (b) Bending of hairs in one direction (c) Bending of hairs in other direction

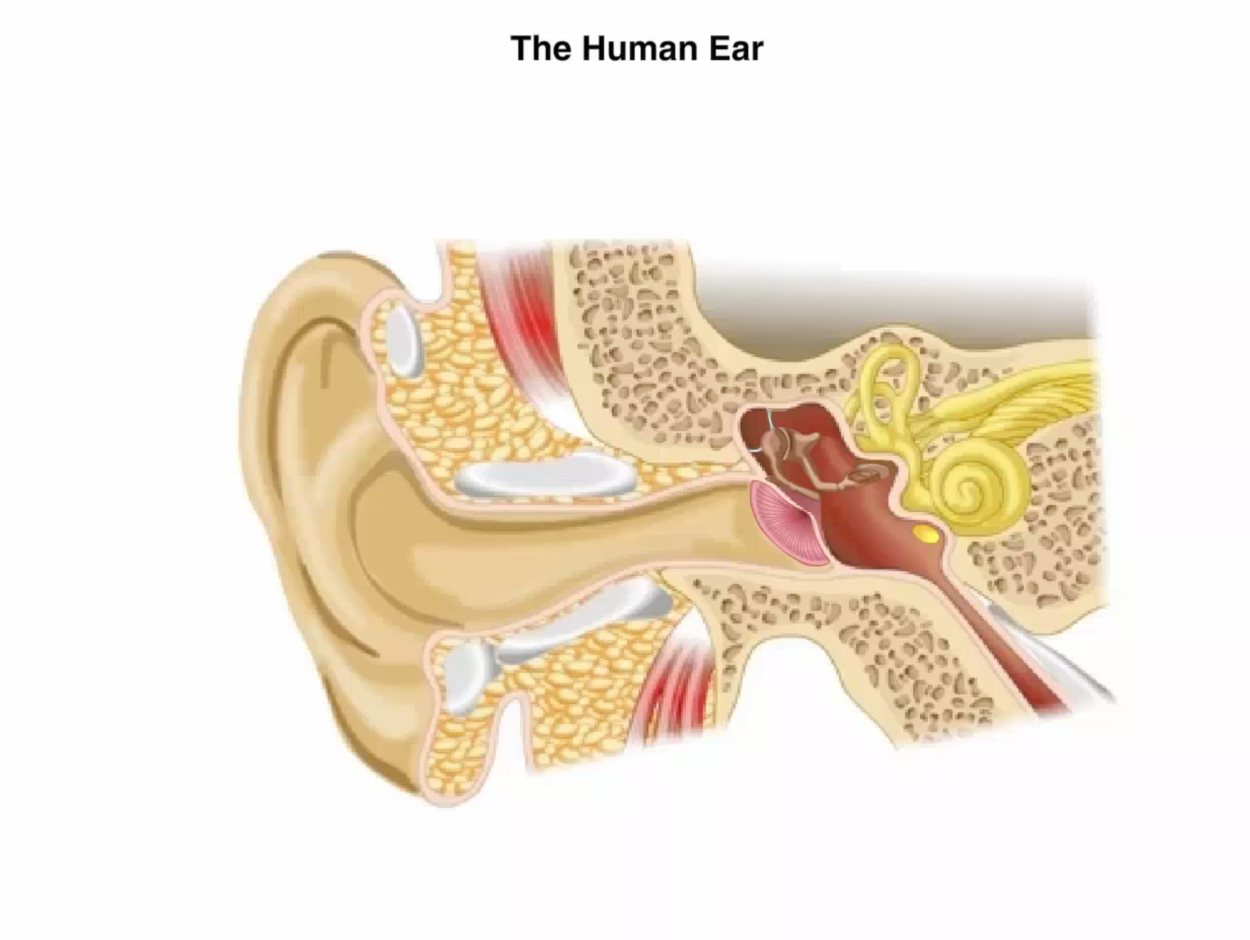
- The ear captures information about
  - Volume (loudness), the amplitude of the sound wave
  - Pitch, the frequency of the sound wave
- The cochlea can distinguish pitch because the basilar membrane is not uniform along its length
- Each region of the basilar membrane is tuned to a particular vibration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

Figure 50.12



Axons of afferent neurons (cochlear nerve)
Point C
Apex
Vestibular canal
Stapes
Oval window
B
C
A
Cochlea
Basilar membrane
Point B
Tympanic membrane
Displayed as if cochlea partially uncoiled
Base
Round window
Tympanic canal
Point A
(a)
A
B
C
6,000 Hz
1,000 Hz
100 Hz
3
0
Relative motion of basilar membrane
0
10
20
30
Distance from oval window (mm)
(b)

Animation: The Human Ear

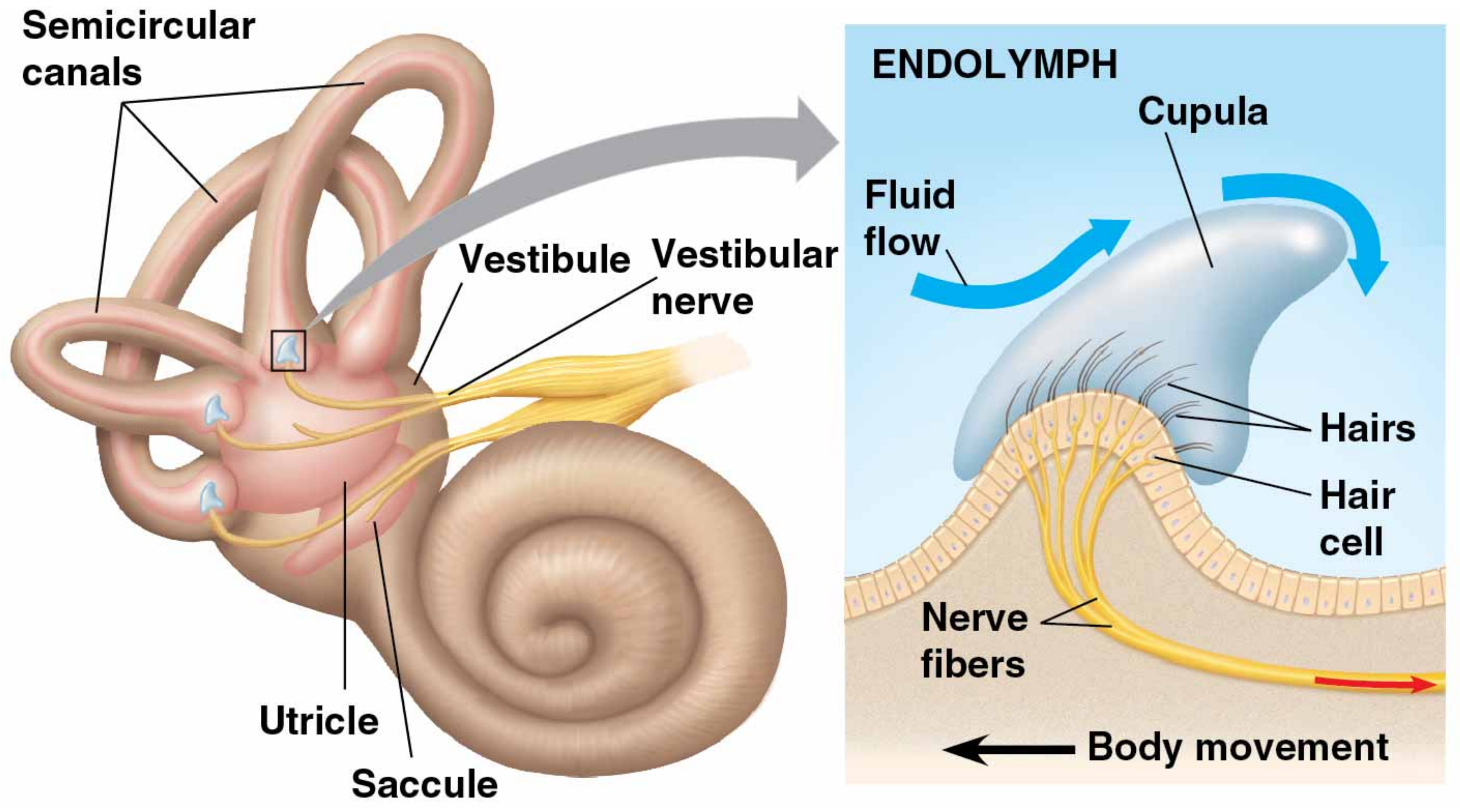


Equilibrium

- Several organs in the inner ear detect body movement, position, and balance
  - The utricle and saccule contain hair cells projecting into a gelatinous material
  - Embedded in the gel are granules called otoliths that allow us to perceive position relative to gravity or linear movement
  - Three semicircular canals contain hair cells and fluid

- The hair cells in the semicircular canals form a cluster in a cap called a cupula
- The three canals are arranged in the three spatial planes
- This allows the detection of angular motion of the head in any direction

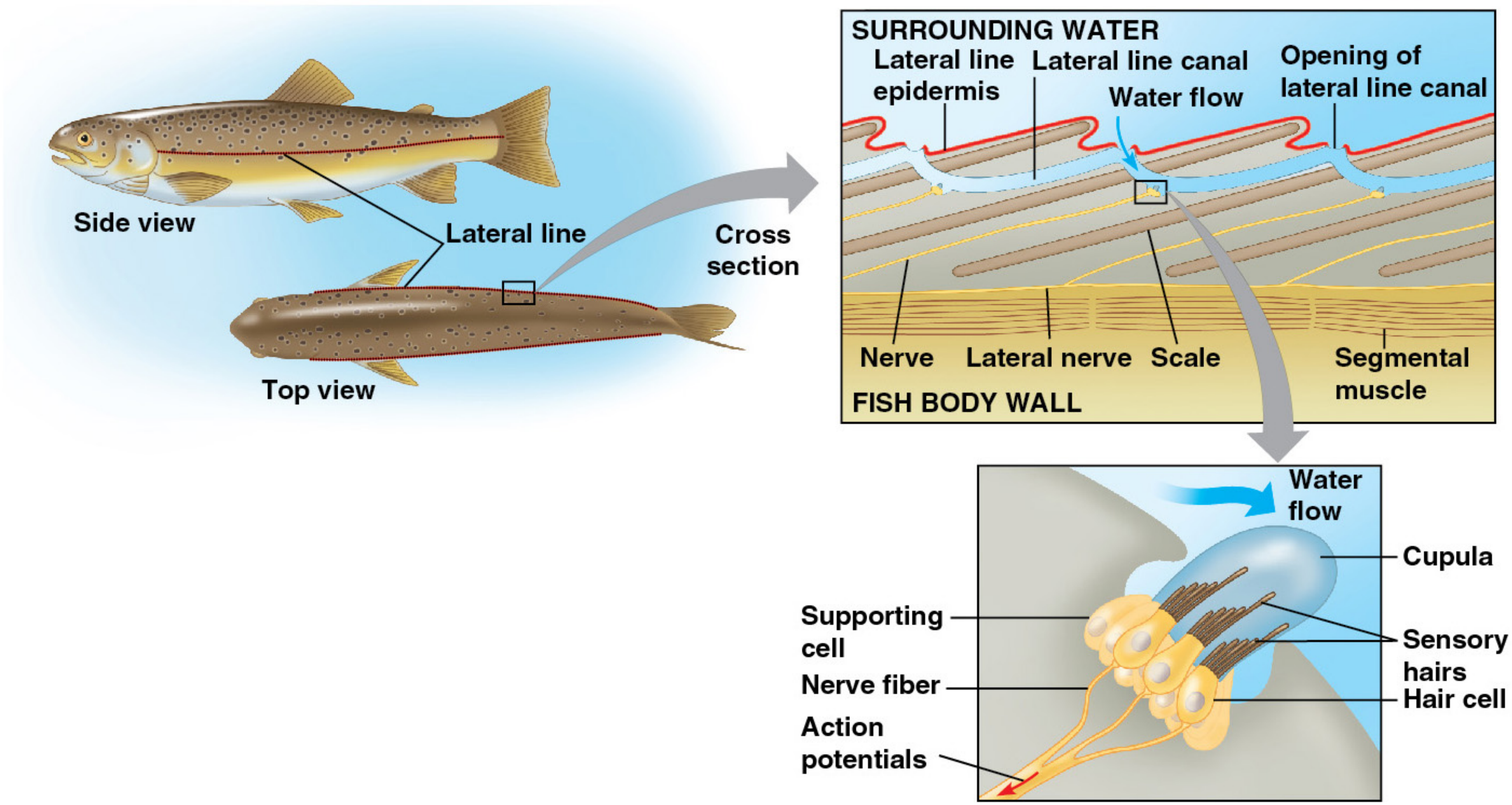
Figure 50.13


Semicircular canals
Vestibule
Vestibular nerve
Utricle
Saccule
ENDOLYMPH
Cupula
Fluid flow
Hairs
Hair cell
Nerve fibers
Body movement

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


Side view
Lateral line
Top view
Cross section
SURROUNDING WATER
Lateral line epidermis
Lateral line canal
Water flow
Opening of lateral line canal
Nerve
Lateral nerve
Scale
Segmental muscle
FISH BODY WALL
Water flow
Cupula
Supporting cell
Sensory hairs
Nerve fiber
Hair cell
Action potentials

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

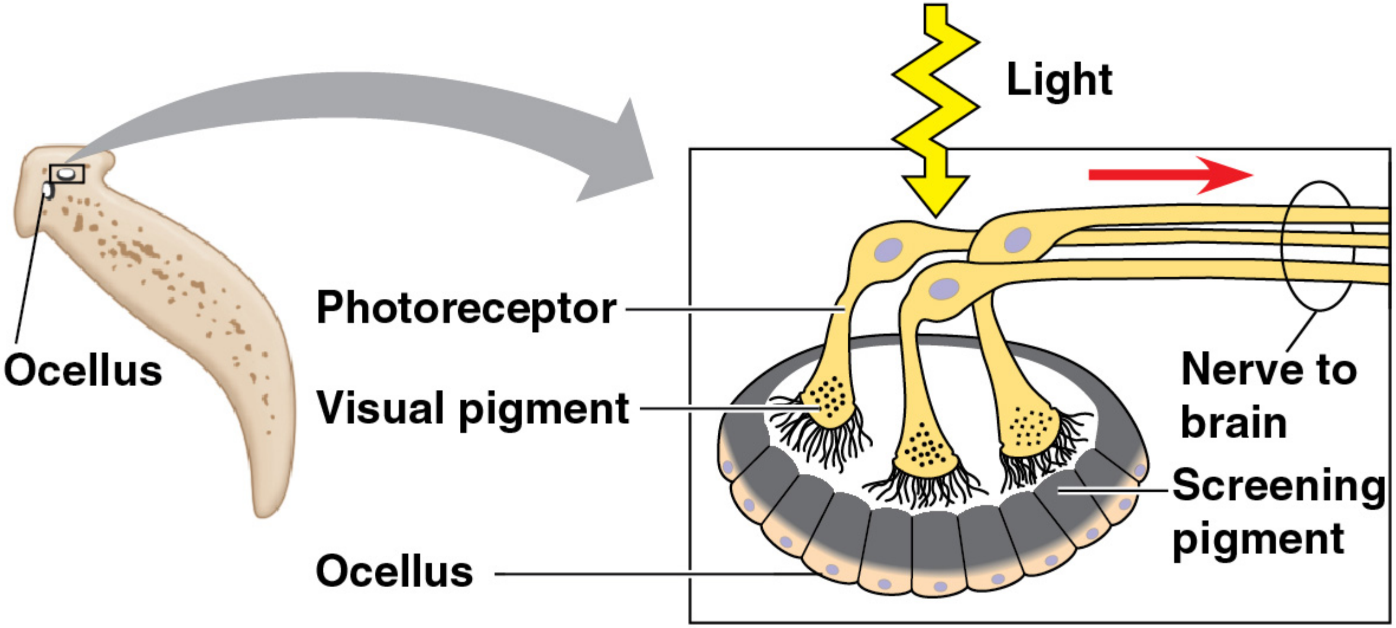
- Light detectors in the animal kingdom range from simple clusters of cells that detect direction and intensity of light to complex organs that form images
- Light detectors all contain **photoreceptors**, cells that contain light-absorbing pigment molecules

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 in the head region
- These allow planarians to move away from light and seek shaded locations

Figure 50.15

(a)

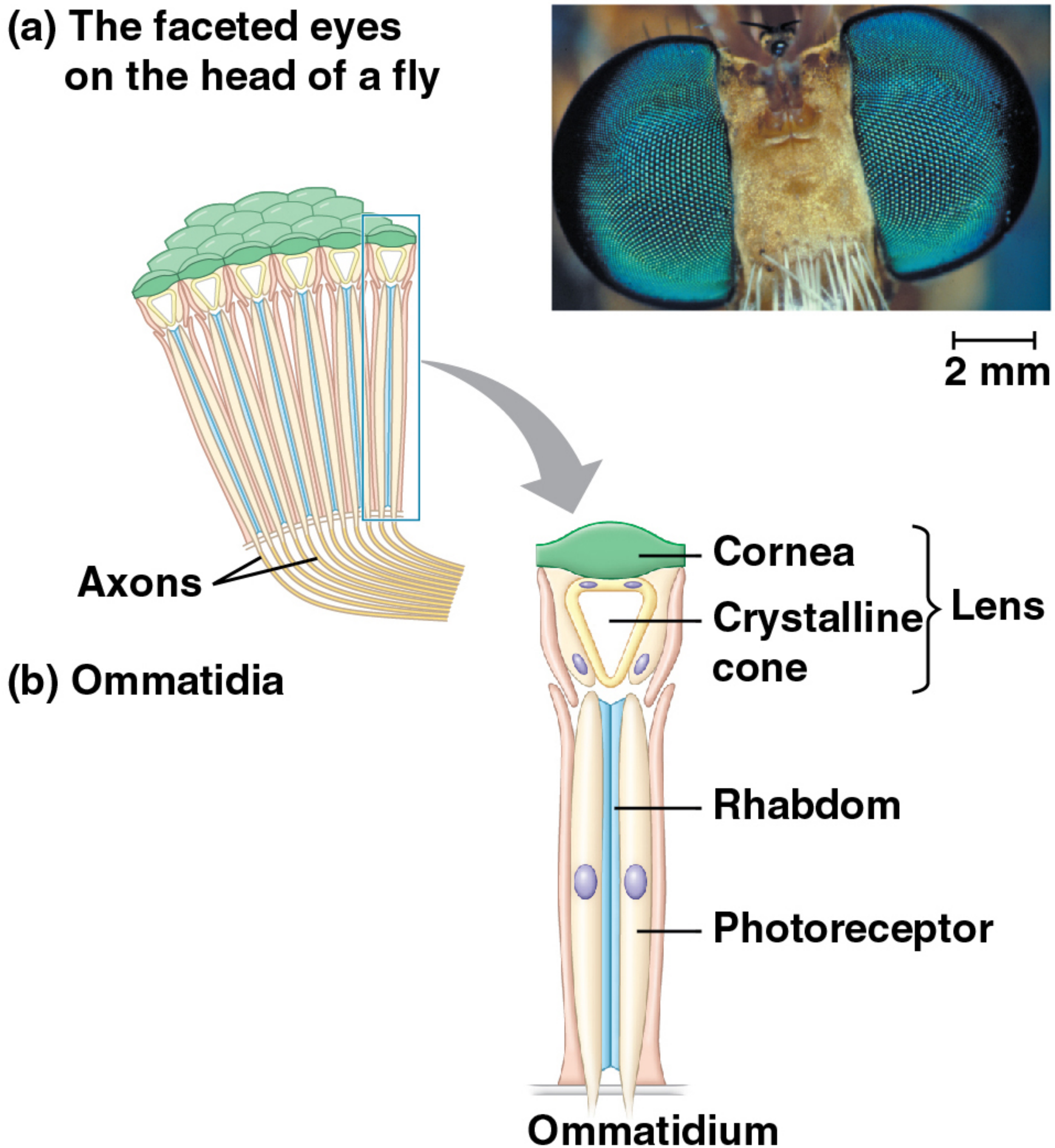


(b)

Compound Eyes

- Insects, crustaceans, and some polychaete worms have **compound eyes**, consisting 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



(a) The faceted eyes on the head of a fly
2 mm
Axons
(b) Ommatidia
Cornea
Crystalline cone
Lens
Rhabdom
Photoreceptor
Ommatidium

Single-Lens Eyes

- Among invertebrates, **single-lens eyes** are found in some jellies and polychaete worms, as well as 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

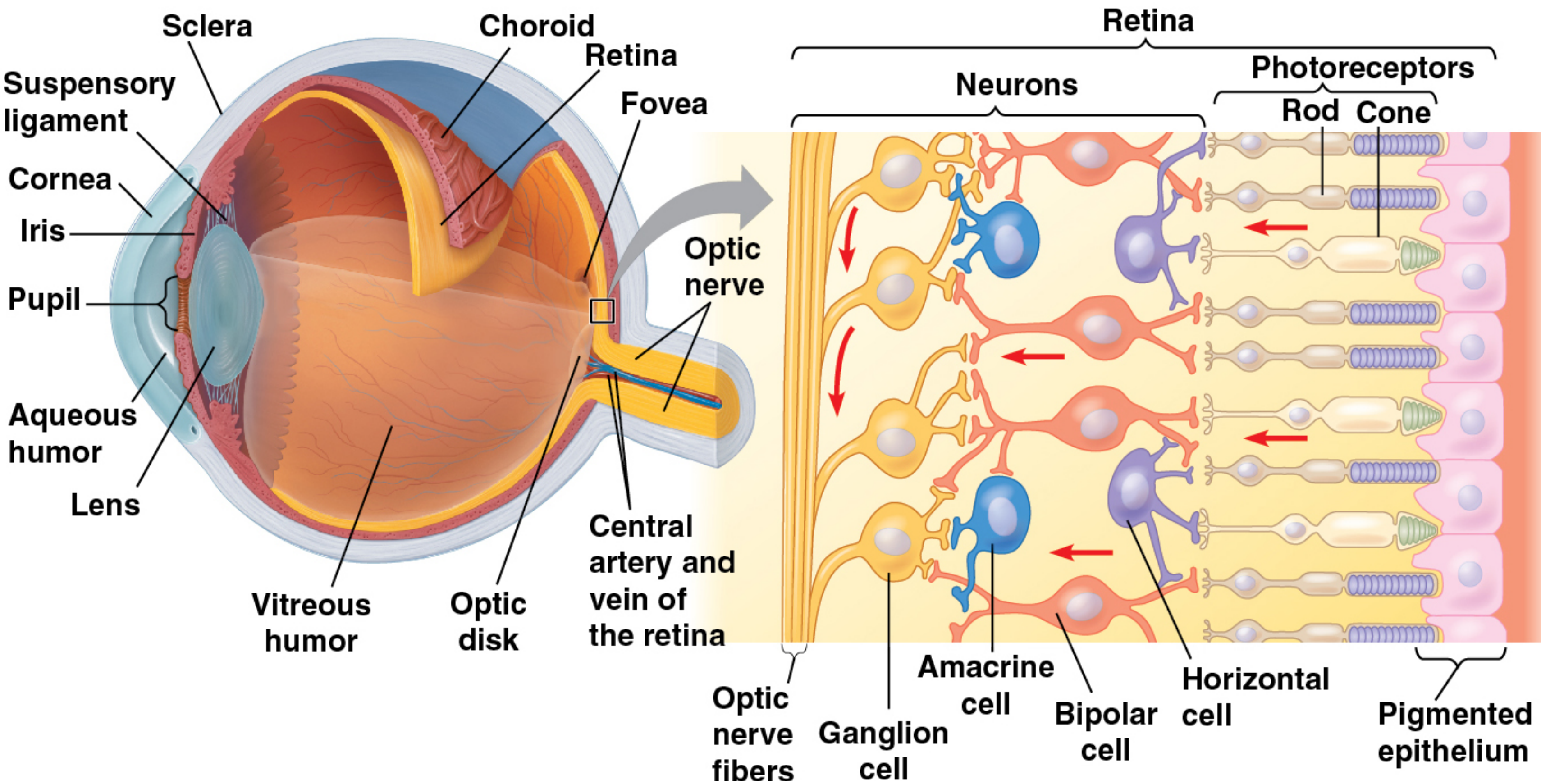
The Vertebrate Visual System

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

- The human eye is surrounded by several layers
- Just inside the choroid (a thin, pigmented layer) are the neurons and photoreceptors of the **retina**
- The **lens** is a transparent disk of protein
- In front of the lens is the clear and watery aqueous humor and behind it is the jellylike vitreous humor

- Light entering the eye strikes the retina, reaching the rods and cones, two types of photoreceptors
- The neurons of the retina then relay visual information to the optic nerve and brain
- The optic disk, in the retina, lacks photoreceptors and thus forms a blind spot, where light is not detected

Figure 50.17



Sclera
Choroid
Retina
Suspensory ligament
Fovea
Cornea
Iris
Pupil
Optic nerve
Aqueous humor
Lens
Central artery and vein of the retina
Vitreous humor
Optic disk
Retina
Neurons
Photoreceptors
Rod
Cone
Optic nerve fibers
Ganglion cell
Amacrine cell
Bipolar cell
Horizontal cell
Pigmented epithelium

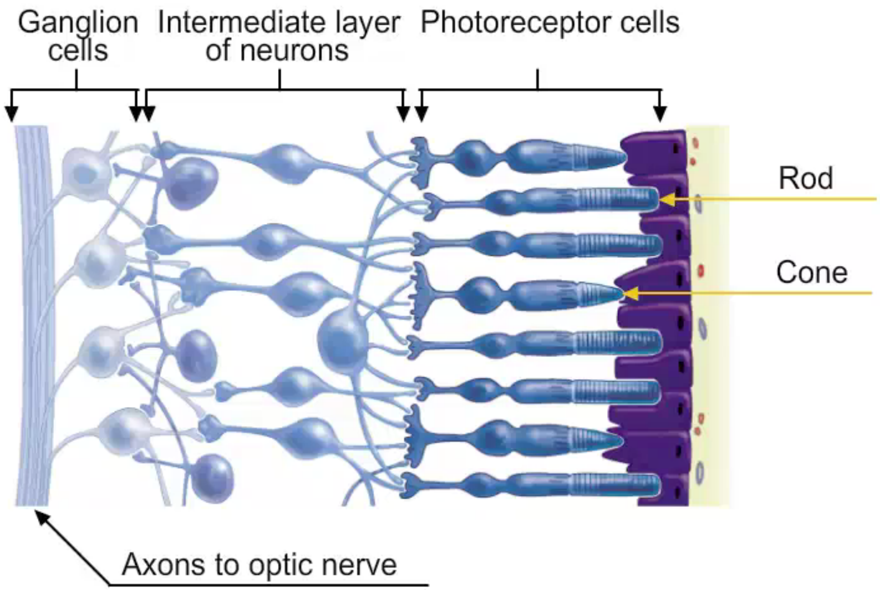
Animation: Structure and Function of the Eye

Structure and Function of the Eye

- Humans have two main types of photoreceptor cells
  - **Rods** are more sensitive to light, but do not distinguish colors
  - **Cones** provide color vision, but contribute very little to night vision

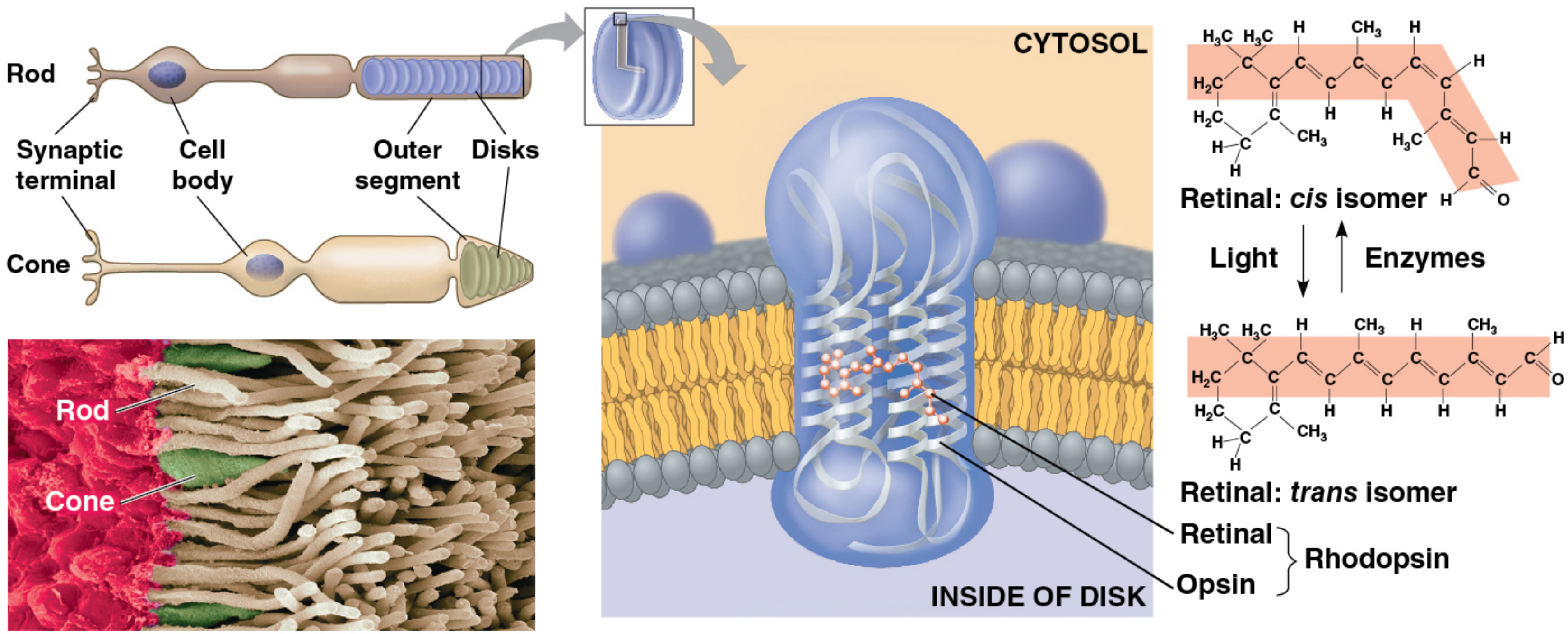
Animation: Photoreception

Photoreception



- Vertebrate visual pigments consist of **retinal**, a light-absorbing pigment bound to a membrane protein called an **opsin**
- One such pigment is called **rhodopsin**
- Absorption of light causes a shape change in retinal, from the *trans*- to the *cis*- form

Figure 50.17

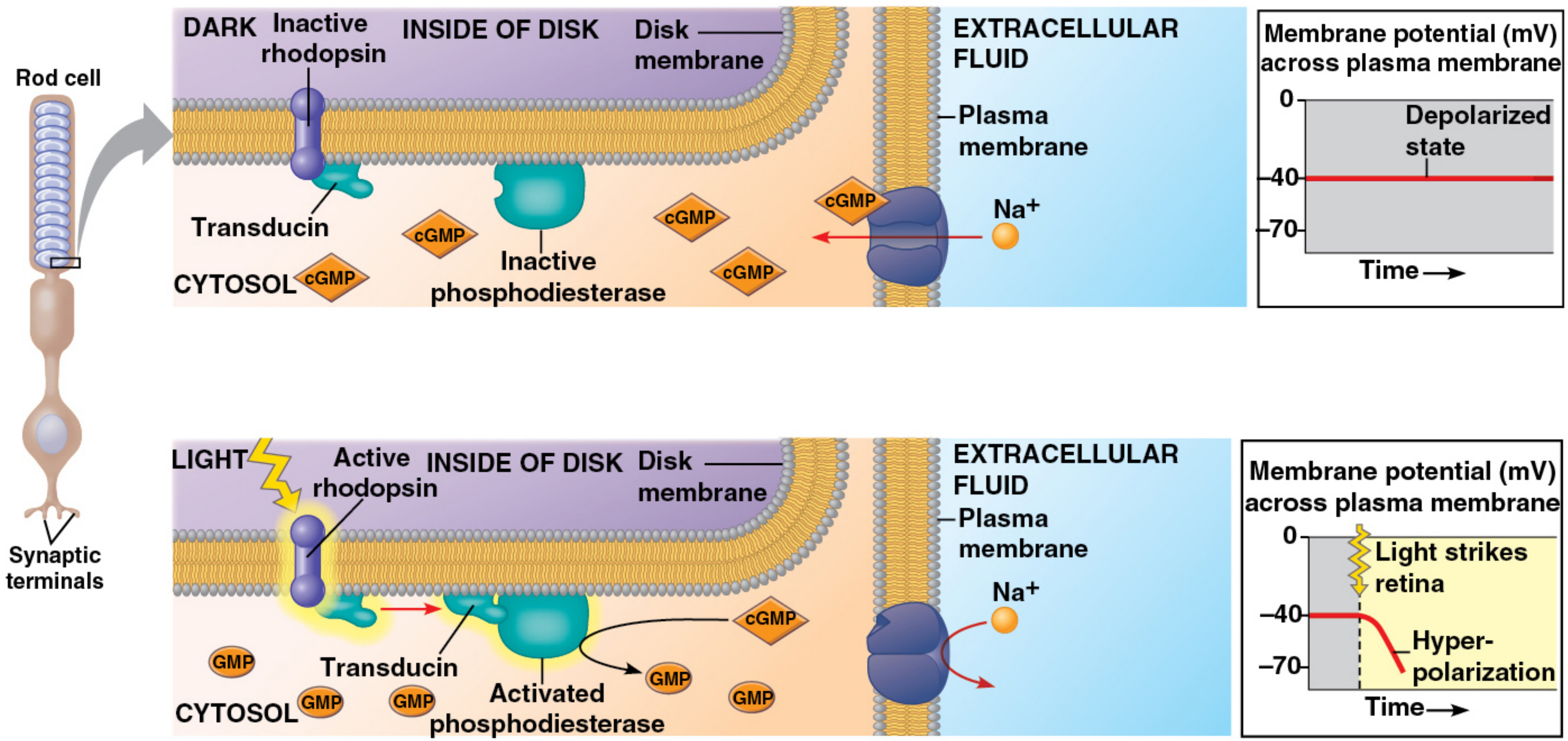

Rod
Synaptic terminal
Cell body
Outer segment
Disks
Cone
Rod
Cone
CYTOSOL
INSIDE OF DISK
Retinal: *cis* isomer
Light
Enzymes
Retinal: *trans* isomer
Retinal
Opsin
Rhodopsin

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
- Cyclic GMP in the dark binds sodium ion channels and keeps them open

- 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



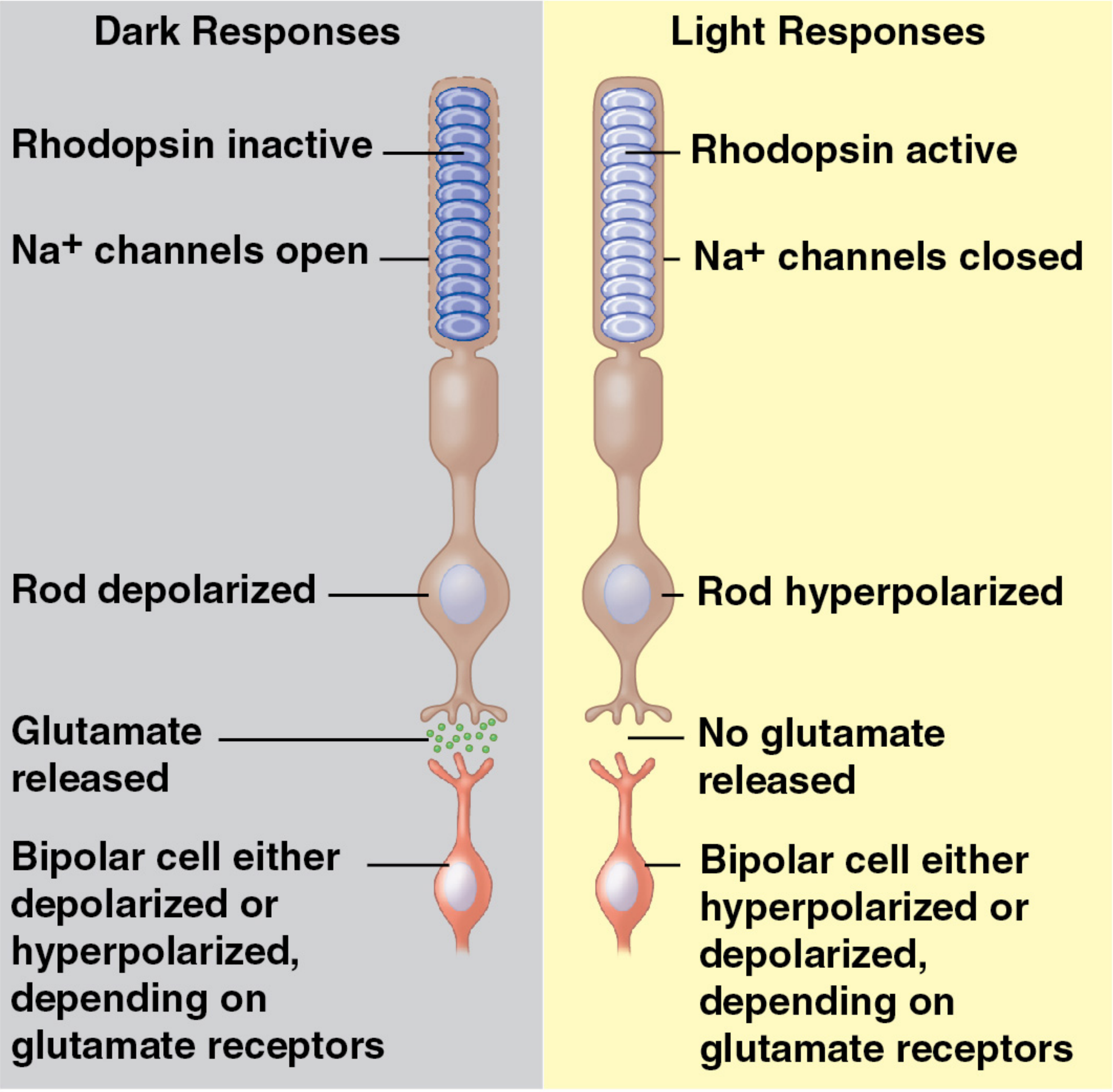
Rod cell
Synaptic terminals
DARK
Inactive rhodopsin
INSIDE OF DISK
Disk membrane
EXTRACELLULAR FLUID
Plasma membrane
Transducin
cGMP
Inactive phosphodiesterase
CYTOSOL
Na+
Membrane potential (mV) across plasma membrane
0
Depolarized state
–40
–70
Time
LIGHT
Active rhodopsin
INSIDE OF DISK
Disk membrane
EXTRACELLULAR FLUID
Plasma membrane
Na+
GMP
Transducin
Activated phosphodiesterase
CYTOSOL
Membrane potential (mV) across plasma membrane
Light strikes retina
Hyper-polarization
Time

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
- When light strikes the rods and cones, they hyperpolarize, shutting off their release of glutamate
- The decrease in glutamate changes the membrane potential of bipolar cells

- Lateral inhibition is when a rod or cone stimulates a horizontal cell and the horizontal cell then inhibits more distant photoreceptors and bipolar cells
- In this way, regions receiving light appear lighter and dark surroundings even darker
- This enhances contrast in an image

Figure 50.19

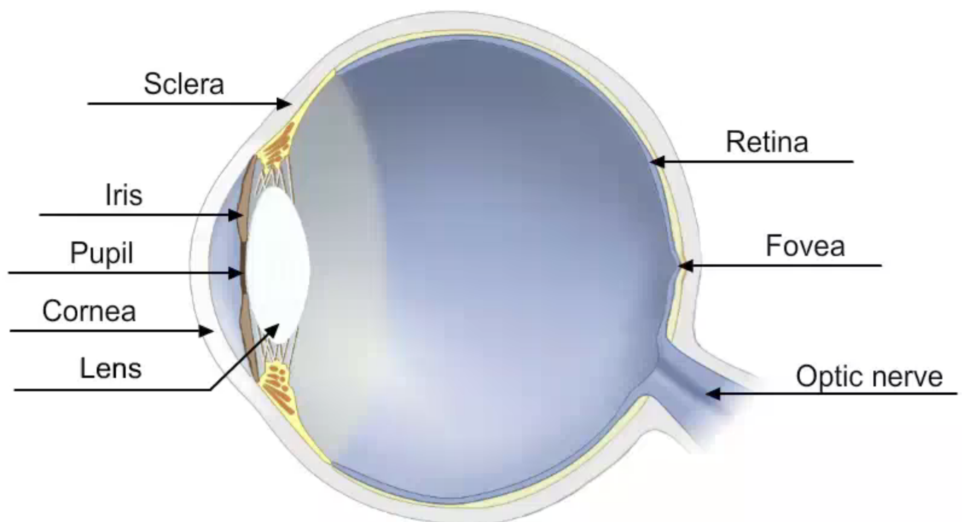


Dark Responses
Light Responses
Rhodopsin inactive
Na+ channels open
Rod depolarized
Glutamate released
Bipolar cell either depolarized or hyperpolarized, depending on glutamate receptors
Rhodopsin active
Na+ channels closed
Rod hyperpolarized
No glutamate released
Bipolar cell either hyperpolarized or depolarized, depending on glutamate receptors

- A single ganglion receives information from an array of rods and cones
- Together, the rods and cones that are feeding information to one ganglion cell define a receptive field
- A smaller receptive field typical results in a sharper image

Animation: Function of the Retina

Function of the Retina

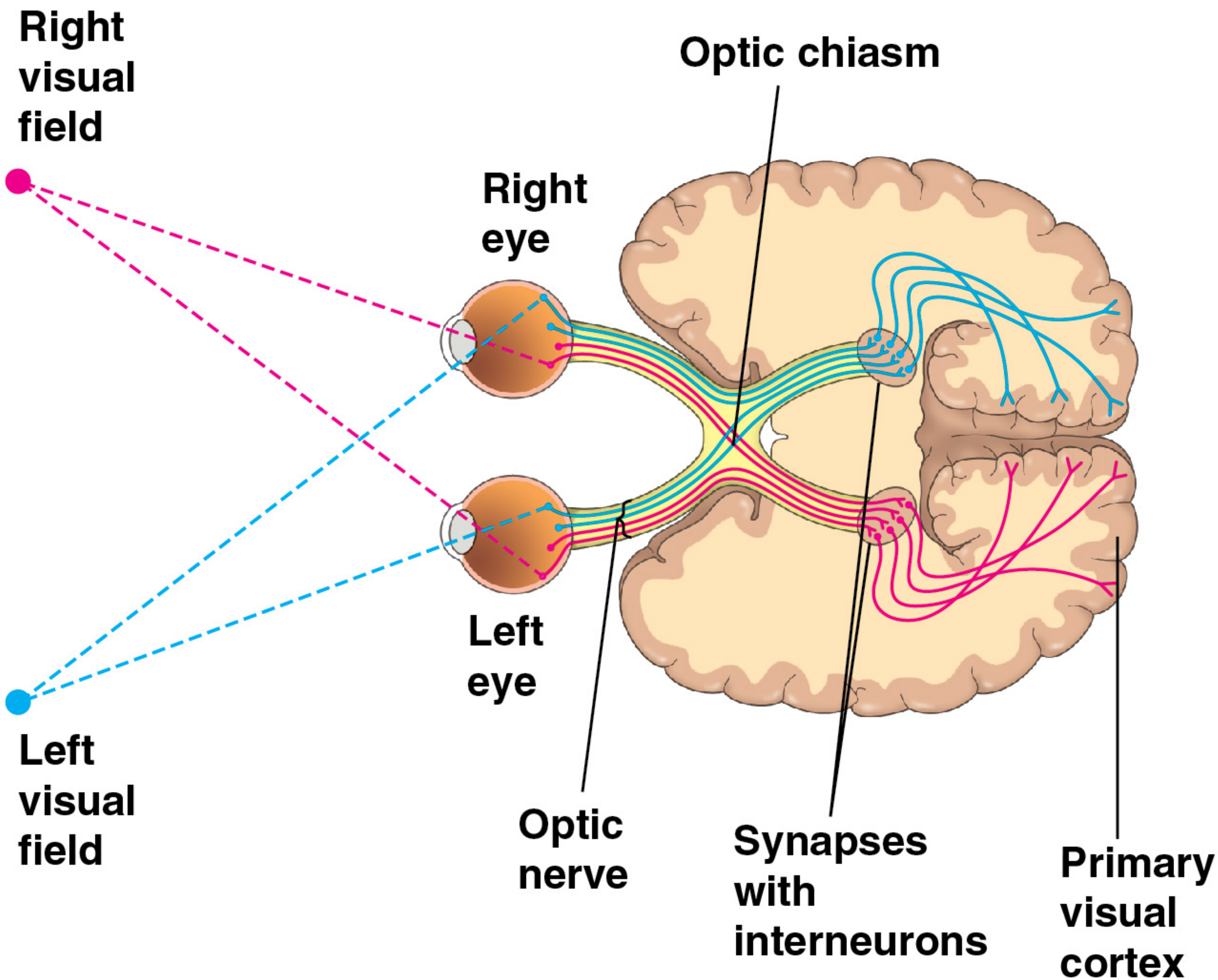


Processing of Visual Information in the Brain

- The optic nerves meet at the optic chiasm near the center of the base of 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


Right
visual
field
Optic chiasm
Right
eye
Left
eye
Left
visual
field
Optic
nerve
Synapses
with
interneurons
Primary
visual
cortex

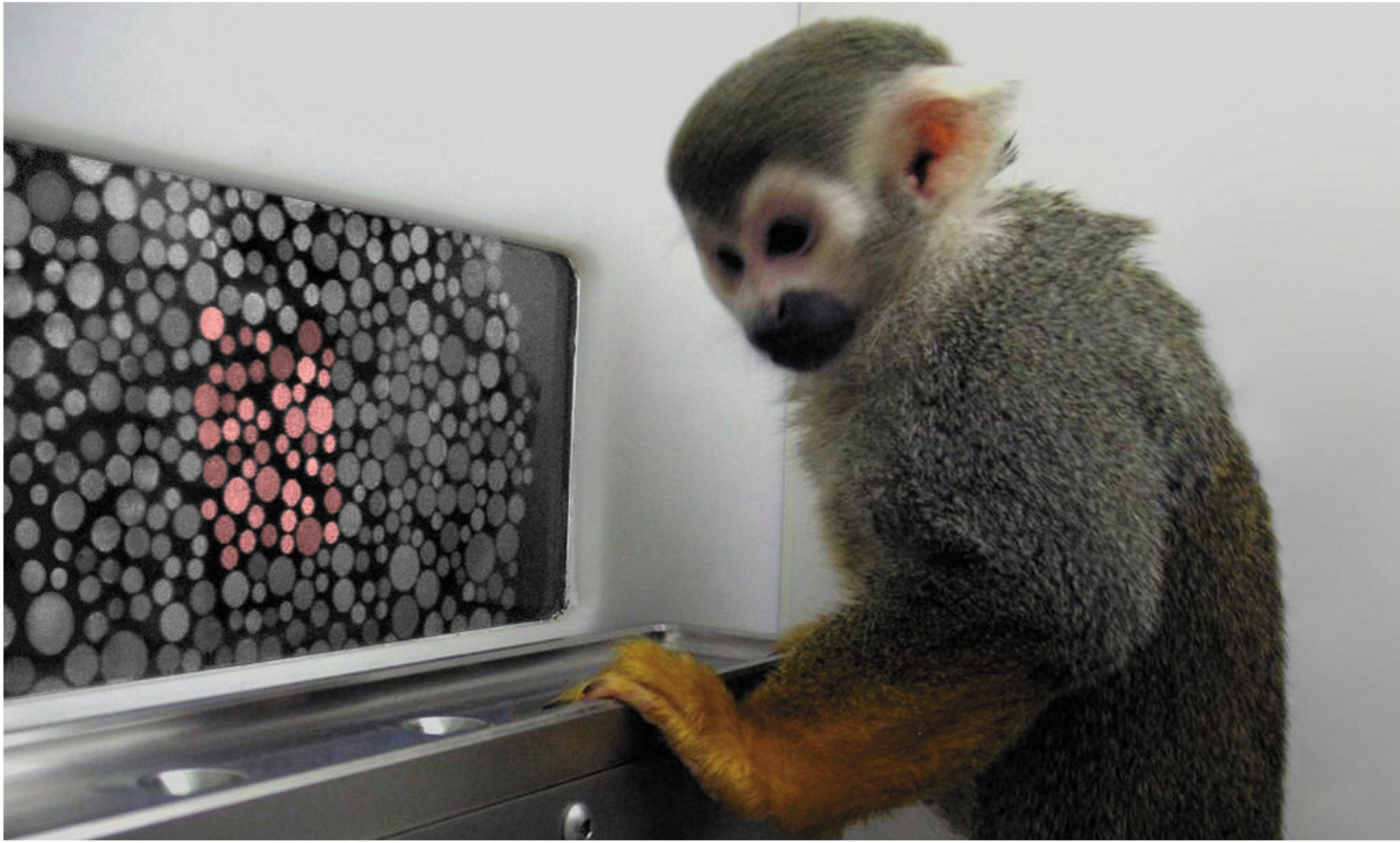
Color Vision

- Among vertebrates, most fishes, 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, such as cats, usually have a high proportion of rods in the retina and probably see a pastel world during the day

- 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 mutations in the genes for one or more photopsin proteins
- Researchers studying color vision in squirrel monkeys made a breakthrough in gene therapy
- Male squirrel monkeys are red-green color-blind
- When researchers introduced the missing gene using a virus, full color vision was apparent

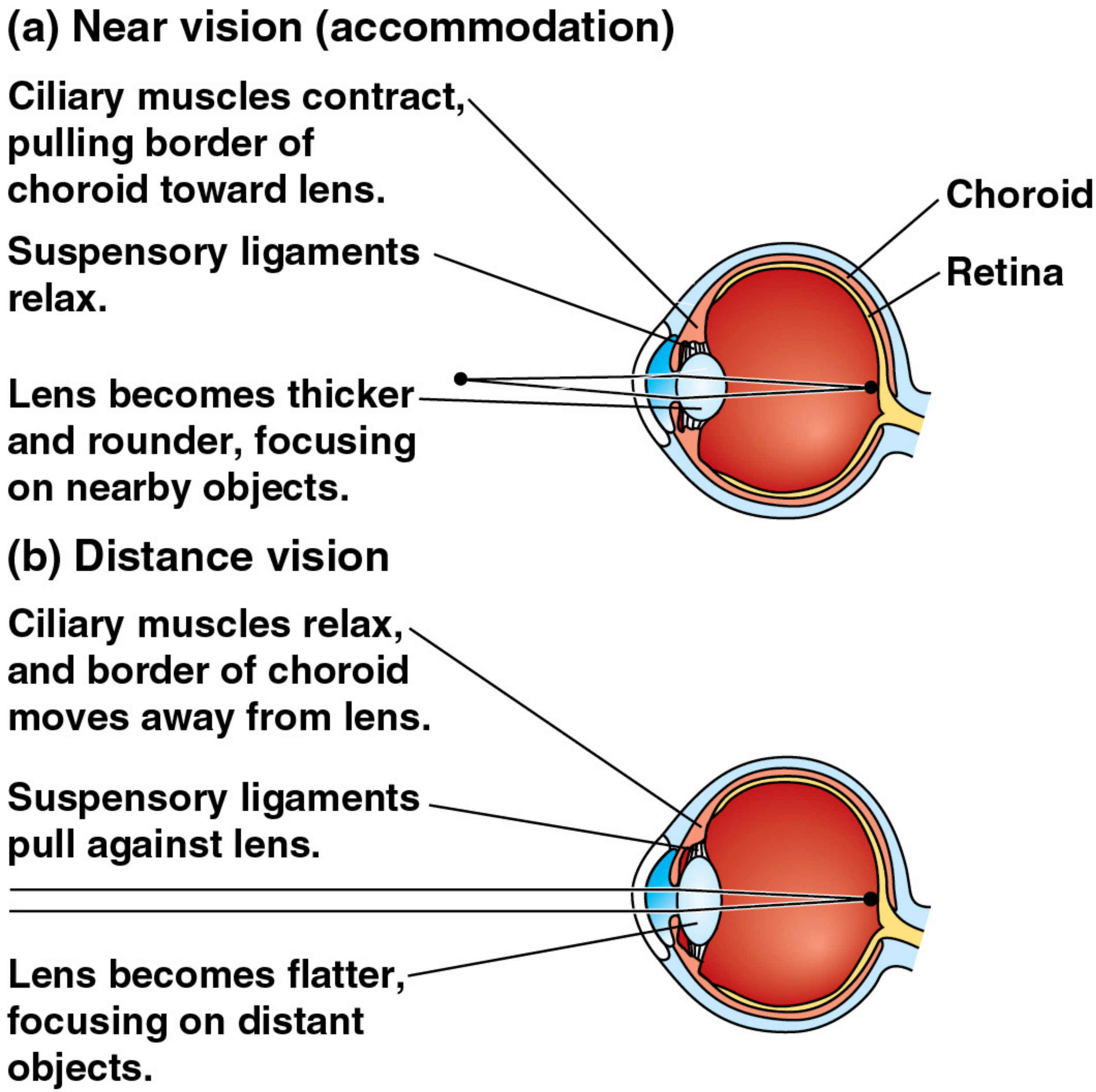
Figure 50.21



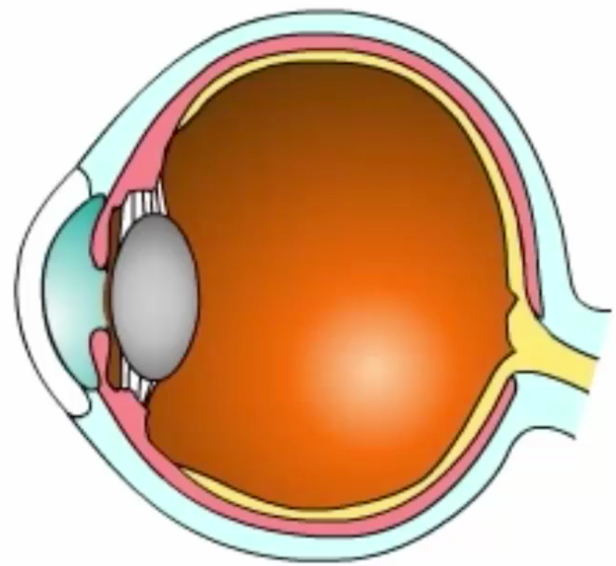
The Visual Field

- 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


(a) Near vision (accommodation)
Ciliary muscles contract, pulling border of choroid toward lens.
Suspensory ligaments relax.
Lens becomes thicker and rounder, focusing on nearby objects.
Choroid
Retina
(b) Distance vision
Ciliary muscles relax, and border of choroid moves away from lens.
Suspensory ligaments pull against lens.
Lens becomes flatter, focusing on distant objects.

Animation: Near and Distance Vision



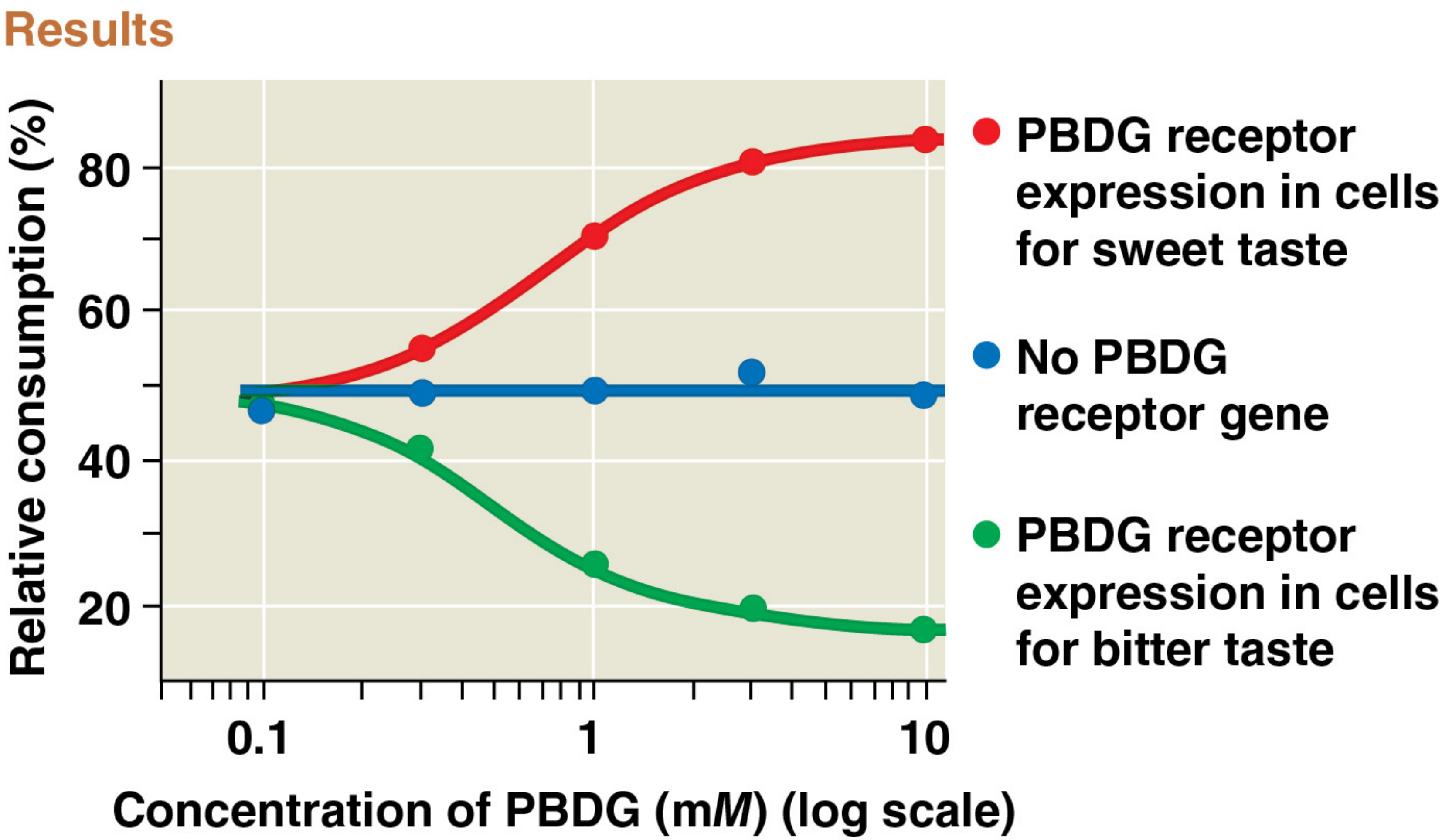
CONCEPT 50.4: The senses of taste and smell rely on similar sets of sensory receptors

- In terrestrial animals
  - **Gustation** (taste) is dependent on the detection of chemicals called **tastants**, present in a solution
  - **Olfaction** (smell) is dependent on the detection of **odorant** molecules, carried through the air
- In aquatic animals there is no distinction between taste and smell
- Taste receptors of insects are in sensory hairs located on feet and in mouthparts

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
- Experiments show that an individual taste cell expresses one receptor type and detects one of the five tastes

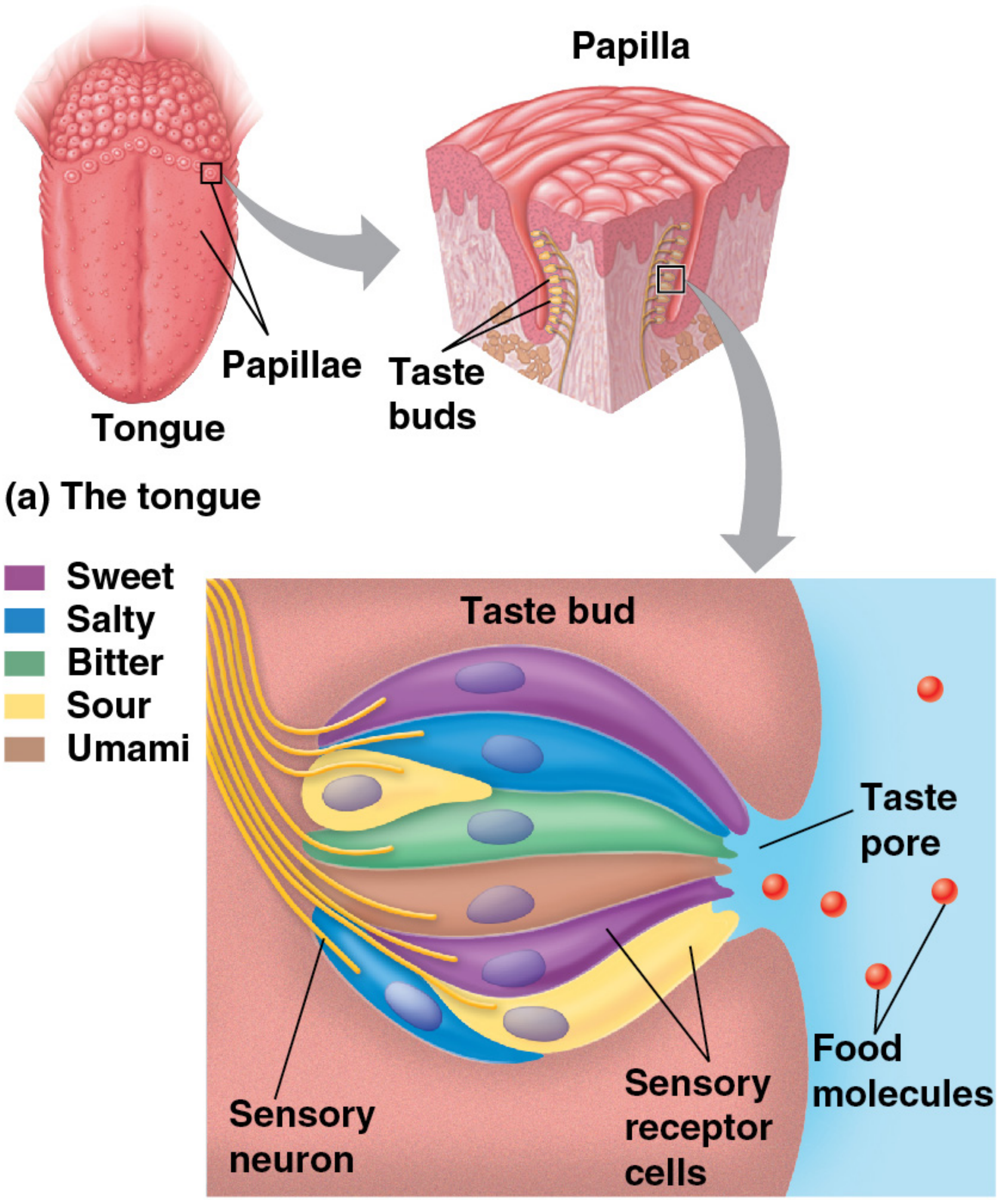
Figure 50.23



Data from K. L. Mueller et al., The receptors and coding logic for bitter taste, *Nature* 434:225–229 (2005).

- 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



(a) The tongue

(b) A taste bud

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

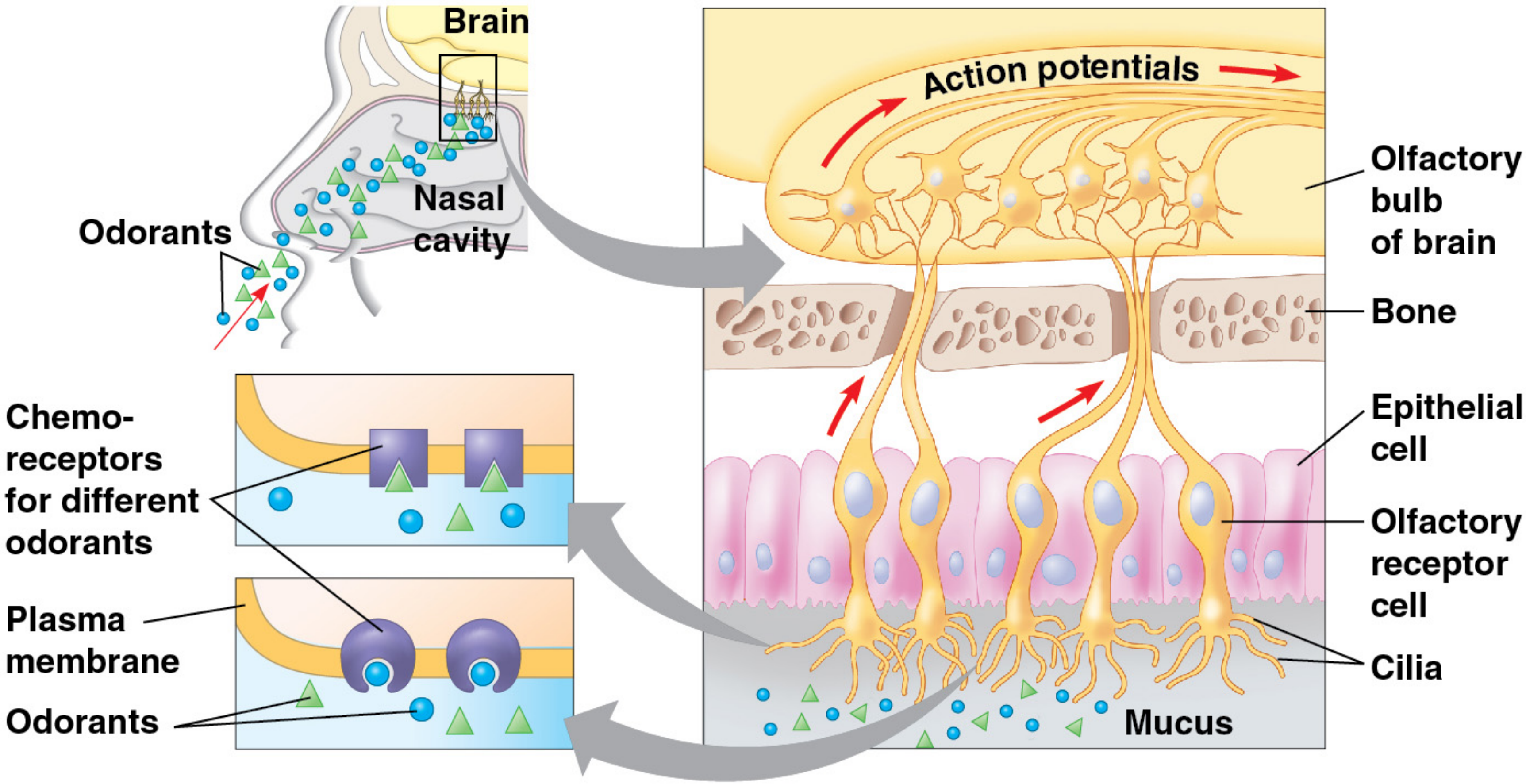
Smell in Humans

- 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, generating action potentials that travel to the olfactory bulb of the brain

- Mammals can distinguish thousands of different odors; they have hundreds, or thousands of genes that encode olfactory receptors (ORs)
- Identification of particular odors relies on two properties of the olfactory system
  - Each olfactory receptor cell expresses on OR (olfactory receptor) gene
  - Those cells that express the same OR gene transmit action potentials to the same small region of the olfactory bulb

- After odorants are detected, information from olfactory receptors is collected and integrated
- Signals from the nervous system regulate this process, increasing or decreasing the response to particular odorants
- Although receptors and brain pathways for taste and smell are independent, the two senses do interact
- Much of the flavor experienced by humans is due to our sense of smell

Figure 50.25



Brain
Nasal cavity
Odorants
Action potentials
Olfactory bulb of brain
Bone
Epithelial cell
Olfactory receptor cell
Cilia
Mucus
Chemo- receptors for different odorants
Plasma membrane
Odorants

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

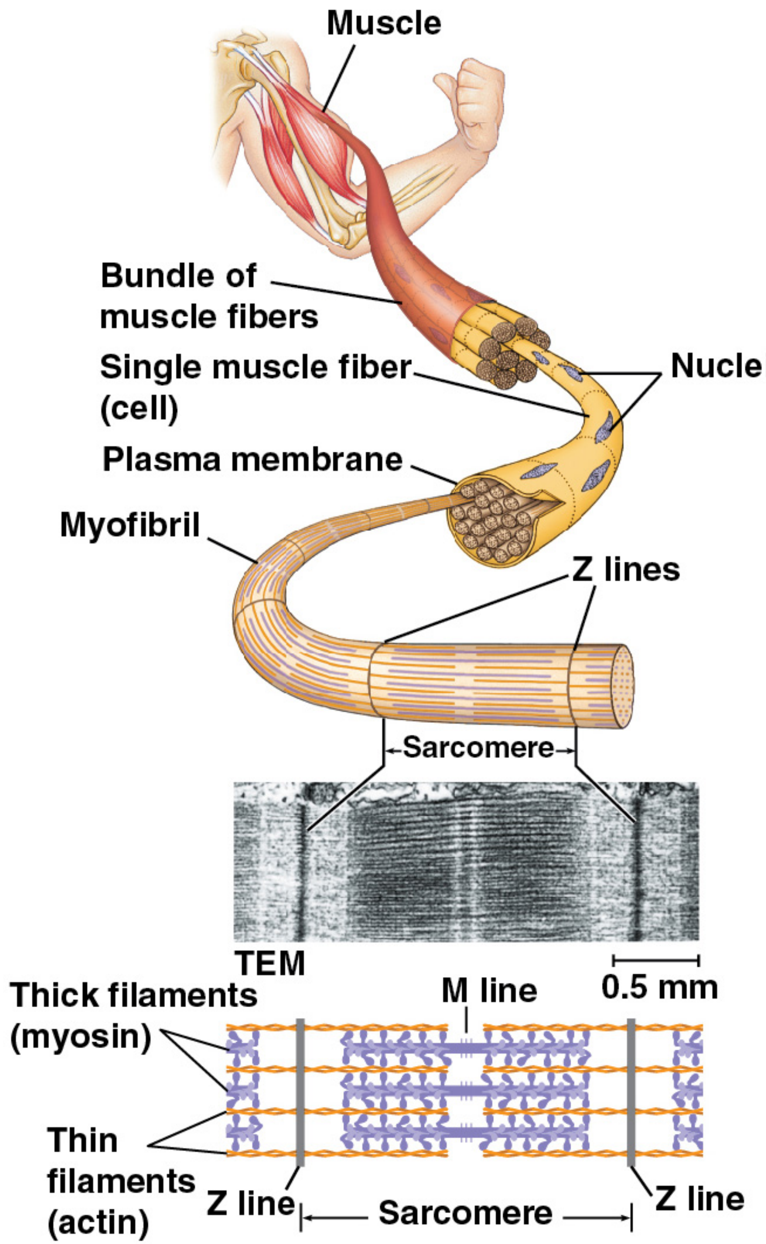
- Muscle activity is a response to input from the nervous system
- Muscle cell contraction relies on the interaction between **thin filaments**, composed mainly of actin, and **thick filaments**, staggered arrays of myosin

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 along 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

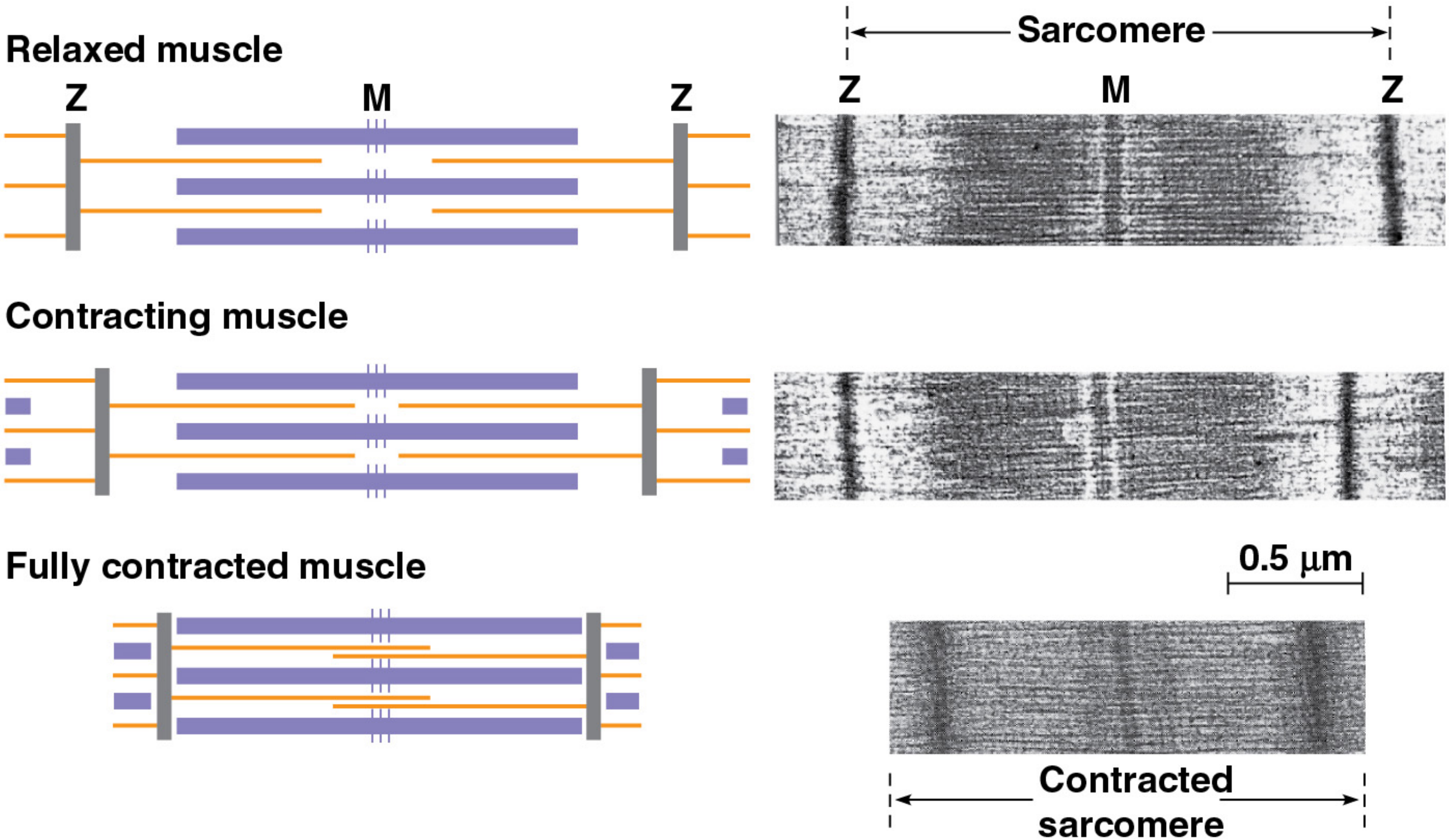
Figure 50.26


Muscle
Bundle of muscle fibers
Single muscle fiber (cell)
Plasma membrane
Myofibril
Nuclei
Z lines
Sarcomere
TEM
0.5 mm
Thick filaments (myosin)
M line
Thin filaments (actin)
Z line
Sarcomere
Z line

The Sliding-Filament Model of Muscle Contraction

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

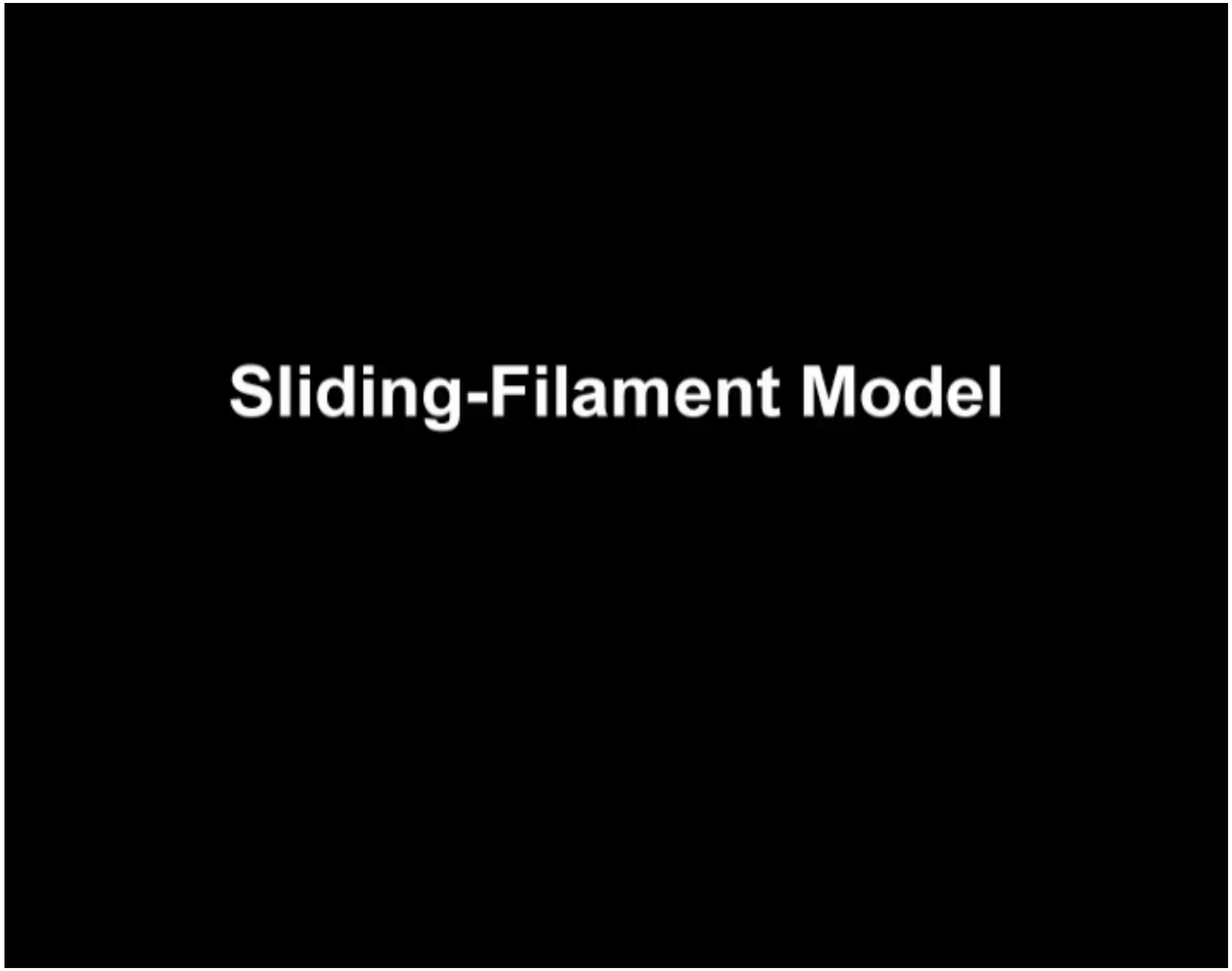
Figure 50.27



Relaxed muscle
Z
M
Z
Sarcomere
Z
M
Z
Contracting muscle
Fully contracted muscle
0.5 µm
Contracted sarcomere

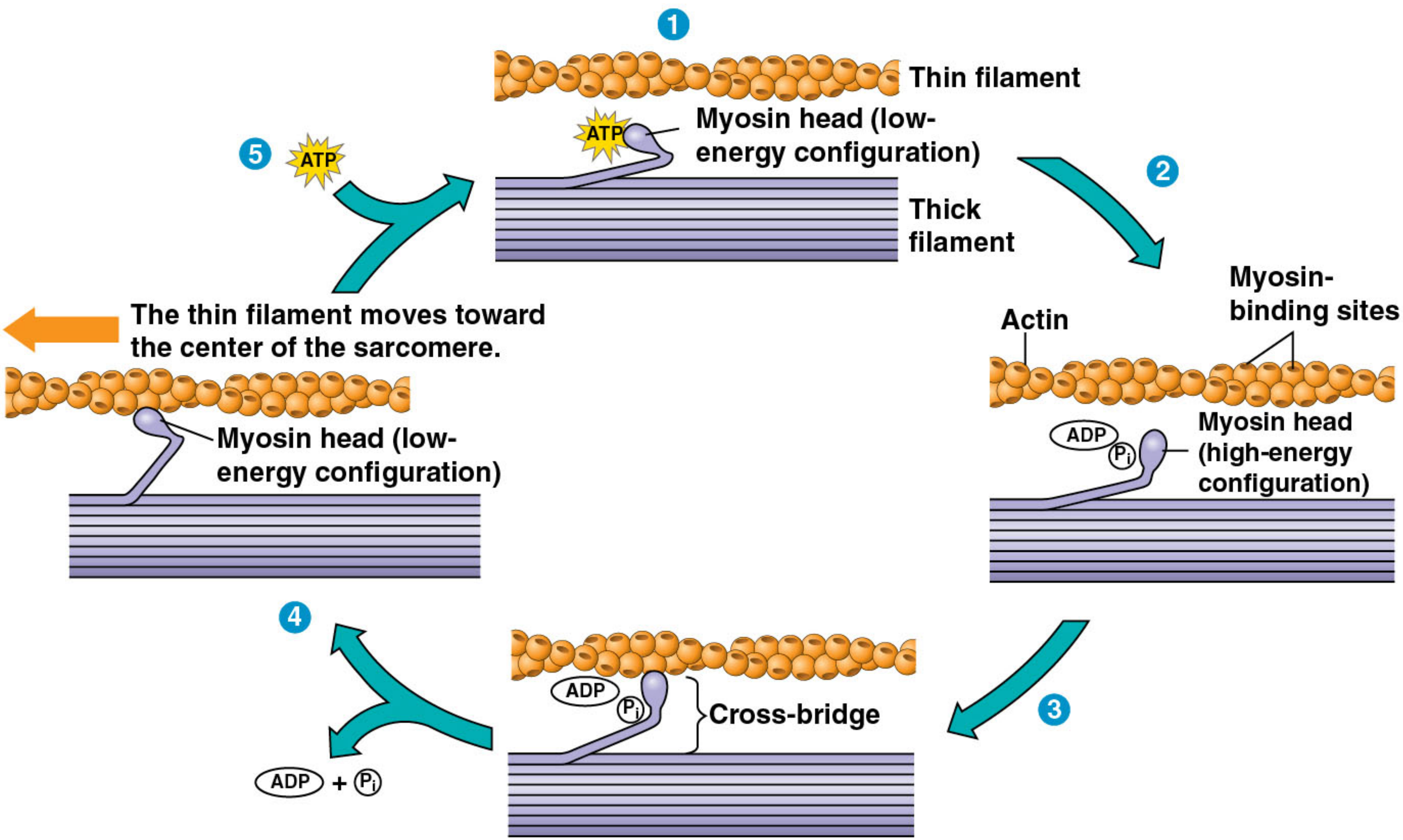
- Each myosin has a long “tail” region and a globular “head” region
- The head of a myosin molecule binds to an actin filament, forming a cross-bridge and pulling the thin filament toward the center of the sarcomere
- Muscle contraction requires repeated cycles of this binding and release

BioFlix® Animation: Sliding-filament model of muscle contraction



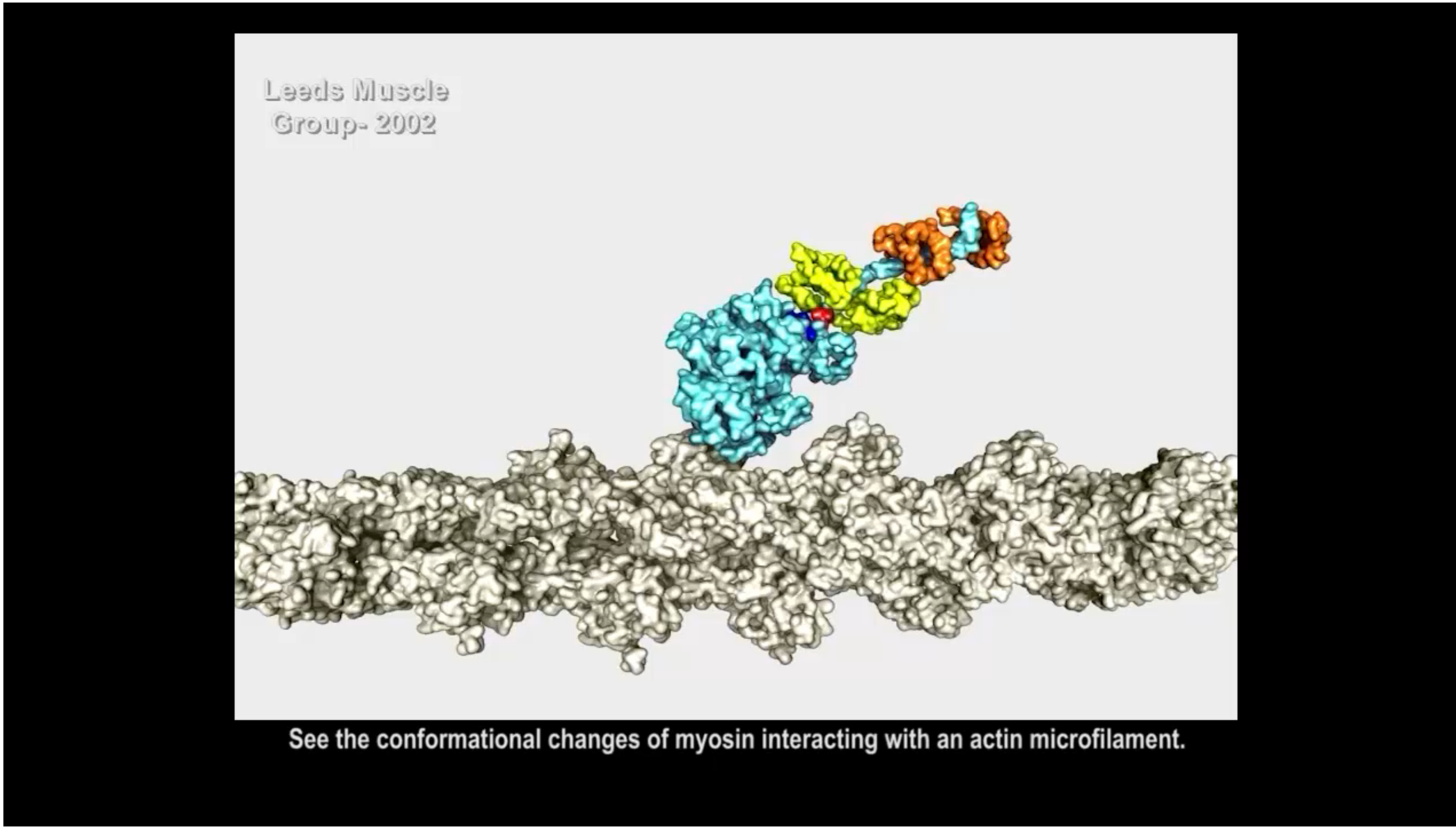
- Glycolysis and aerobic respiration generate the ATP needed to sustain muscle contraction
- During intense muscle activity, oxygen becomes limiting and ATP is generated instead by lactic acid fermentation
- This activity generates less ATP per glucose than glycolysis and can sustain contraction for only about 1 minute

Figure 50.28



1
Thin filament
ATP
Myosin head (low-energy configuration)
Thick filament
2
Actin
Myosin-binding sites
ADP
P_i
Myosin head (high-energy configuration)
3
ADP
P_i
Cross-bridge
4
ADP + P_i
The thin filament moves toward the center of the sarcomere.
Myosin head (low-energy configuration)
5
ATP

Video: Myosin-Actin Interaction

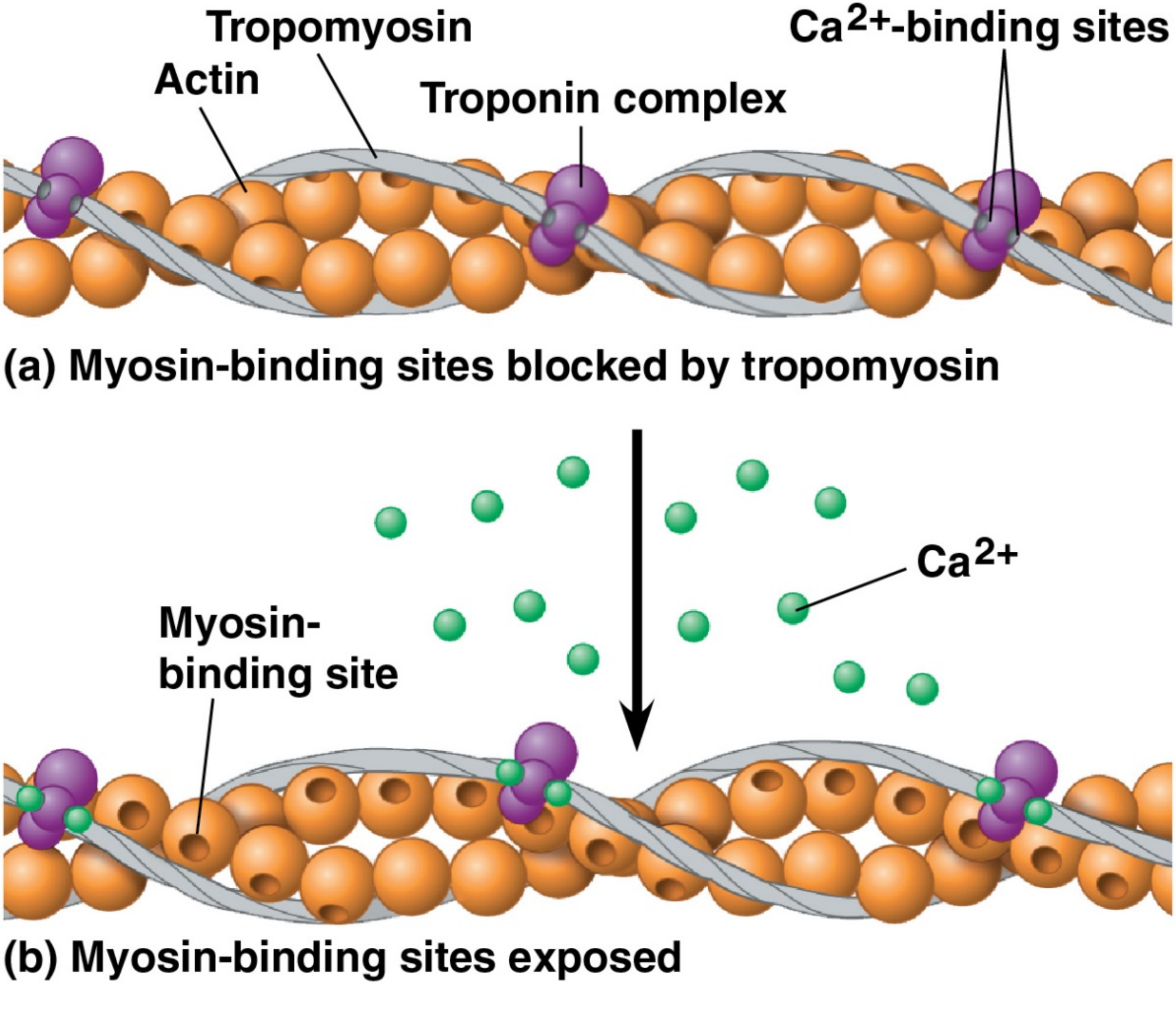


The Role of Calcium and Regulatory Proteins

- 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 exposed
- 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



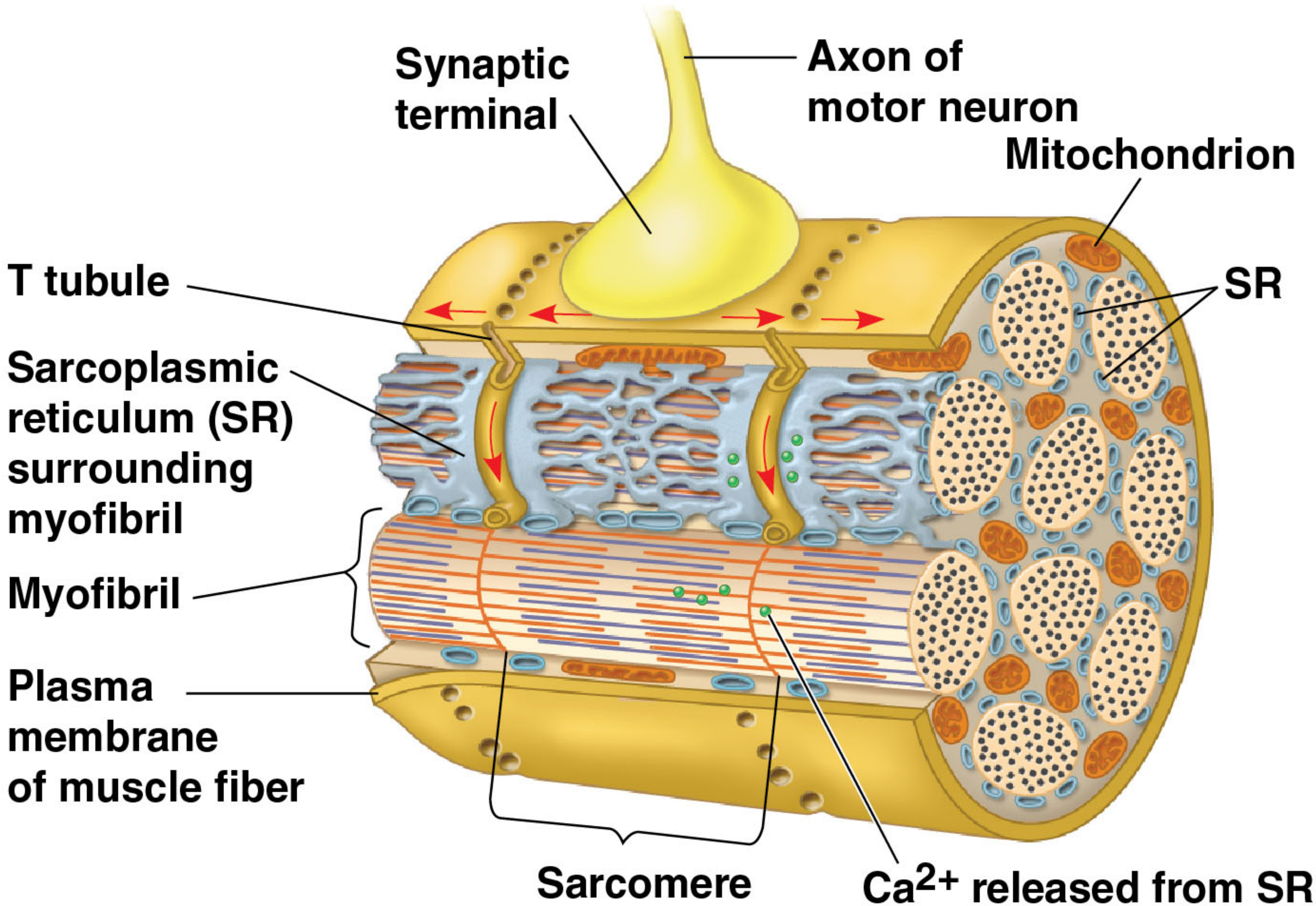
(a) Myosin-binding sites blocked by tropomyosin

(b) Myosin-binding sites exposed

- 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, initiating the muscle fiber contraction

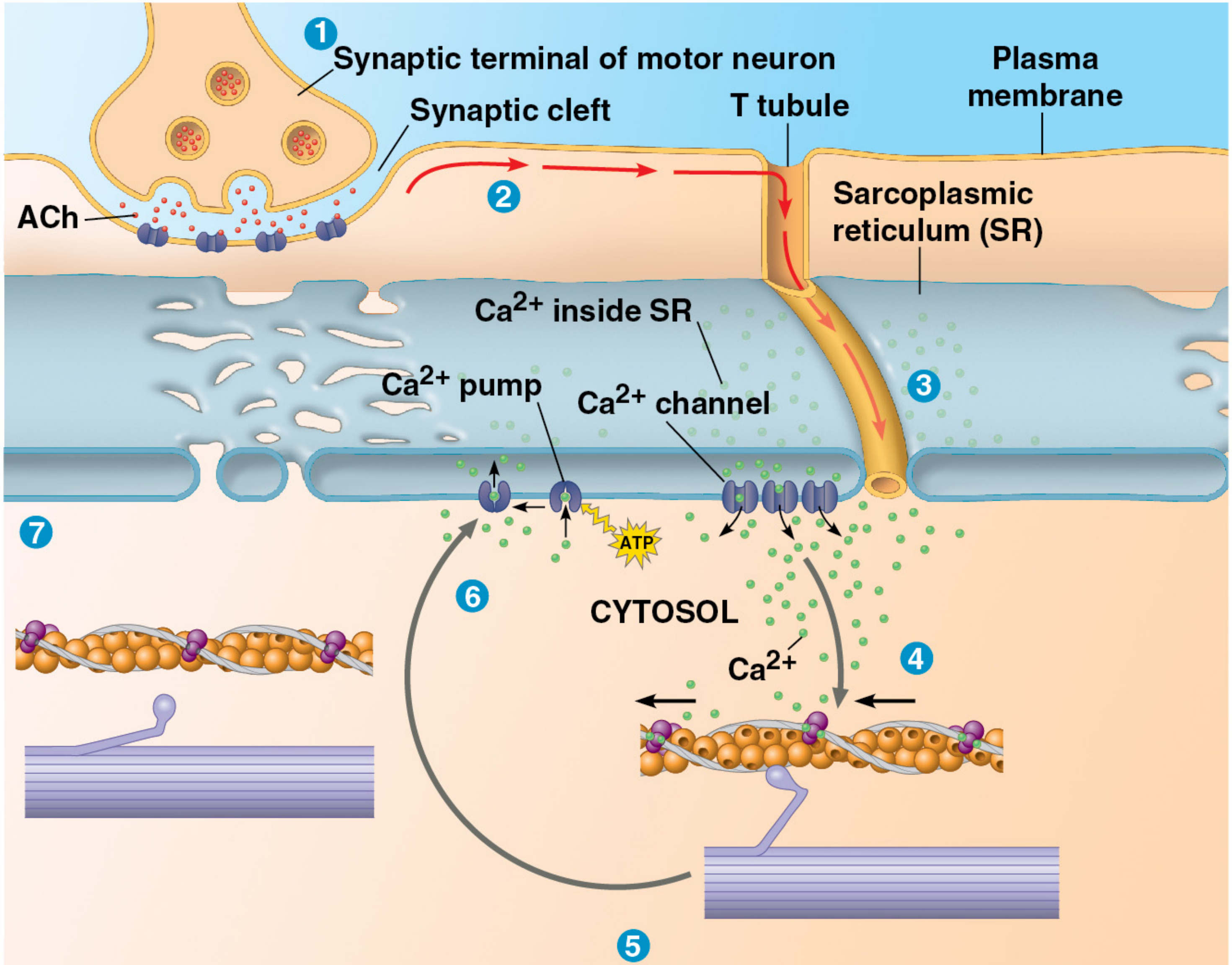
Figure 50.30



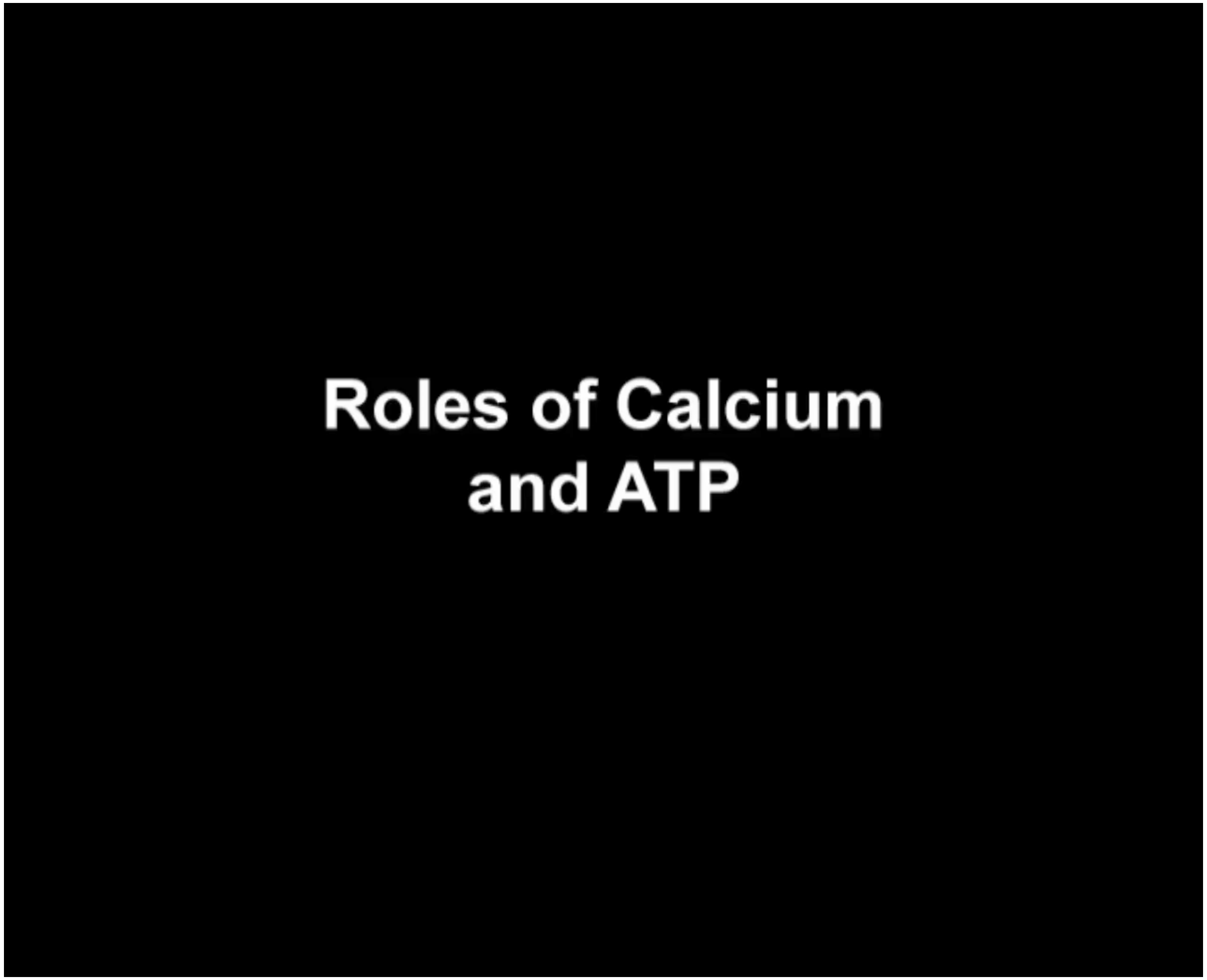
Synaptic terminal
Axon of motor neuron
Mitochondrion
T tubule
SR
Sarcoplasmic reticulum (SR) surrounding myofibril
Myofibril
Plasma membrane of muscle fiber
Sarcomere
Ca2+ released from SR

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

Figure 50.31


1
Synaptic terminal of motor neuron
Synaptic cleft
T tubule
Plasma membrane
ACh
2
Sarcoplasmic reticulum (SR)
Ca2+ inside SR
3
Ca2+ pump
Ca2+ channel
ATP
7
6
CYTOSOL
Ca2+
4
5

BioFlix® Animation: Roles of Calcium and ATP in Muscle Contraction



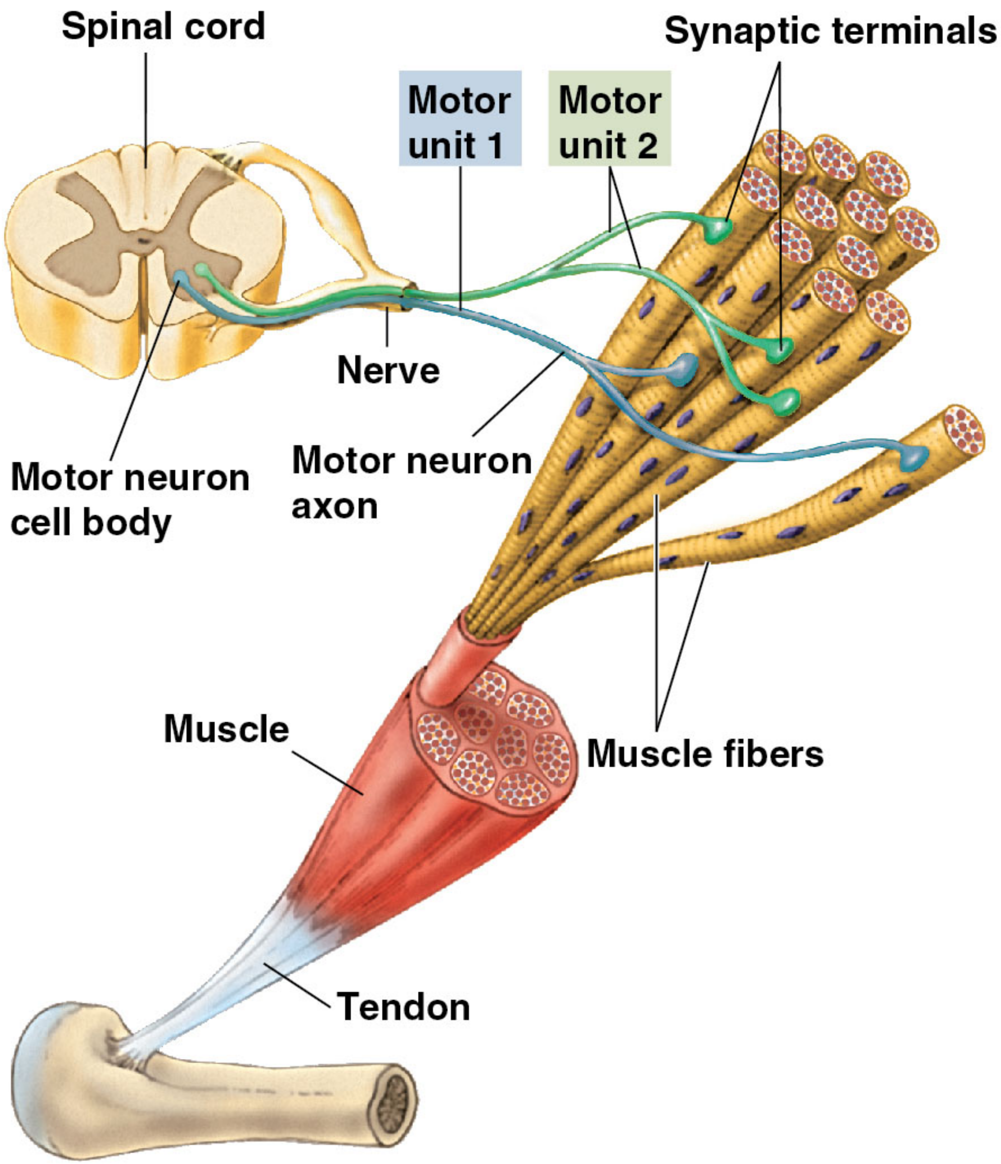
- Amyotrophic lateral sclerosis (ALS) interferes with the excitation of skeletal muscle fibers
- This disease is progressive and usually fatal within five years of symptoms appearing
- Myasthenia gravis is an autoimmune disease that attacks acetylcholine receptors on muscle fibers
- It can generally be controlled with drugs that inhibit acetylcholinesterase or suppress the immune system

Nervous Control of Muscle Tension

- Contraction of a whole muscle is graded; 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

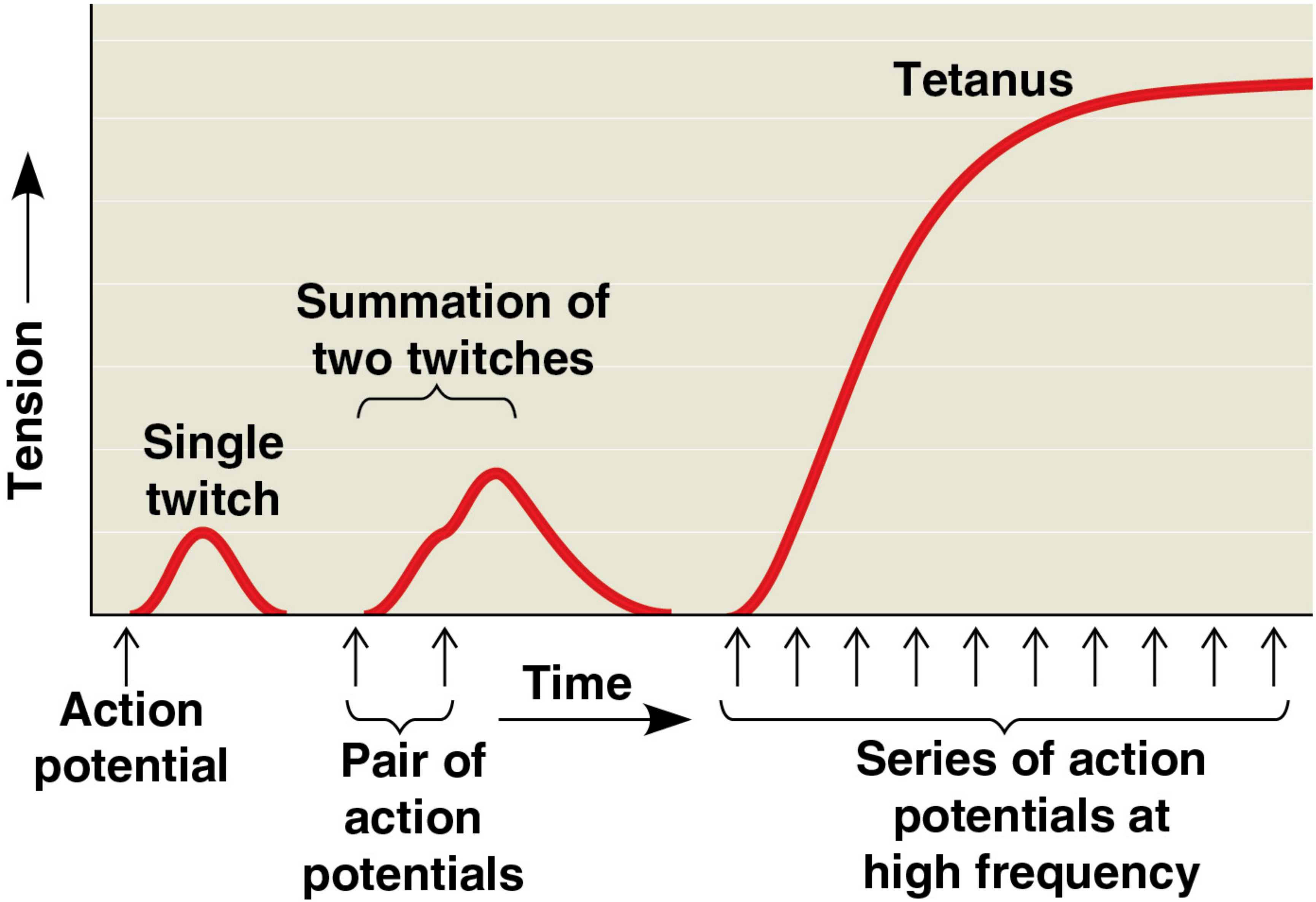
- In vertebrates, each motor neuron may synapse with multiple muscle fibers, although each fiber is controlled by only one motor neuron
- A **motor unit** consists of a single motor neuron and all the muscle fibers it controls

Figure 50.32


Spinal cord
Synaptic terminals
Motor unit 1
Motor unit 2
Nerve
Motor neuron cell body
Motor neuron axon
Muscle
Muscle fibers
Tendon

- Recruitment is the process by which more and more motor neurons are activated
- As recruitment proceeds, the force developed by a muscle increases
- A twitch results from a single action potential in a motor neuron
- More rapidly delivered action potentials produce a graded contraction through summation

Figure 50.33



Tetanus
Summation of two twitches
Single twitch
Tension
Action potential
Pair of action potentials
Time
Series of action potentials at high frequency

- **Tetanus** is a state of smooth and sustained contraction produced when the rate of stimulation is so high that muscle fibers cannot relax between stimuli

Types of Skeletal Muscle Fibers

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

Table 50.1 Types of Skeletal Muscle Fibers			
	Slow-Twitch	Fast-Twitch	
	Oxidative	Oxidative	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 (1 of 2)

- 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

Oxidative and Glycolytic Fibers (2 of 2)

- Glycolytic fibers use glycolysis as their primary source of ATP
- Glycolytic fibers have less myoglobin and a larger diameter than oxidative fibers
- They also 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 (1 of 3)

- **Fast-twitch fibers** enable brief, rapid, powerful contractions
- Fast-twitch fibers can be either glycolytic or oxidative

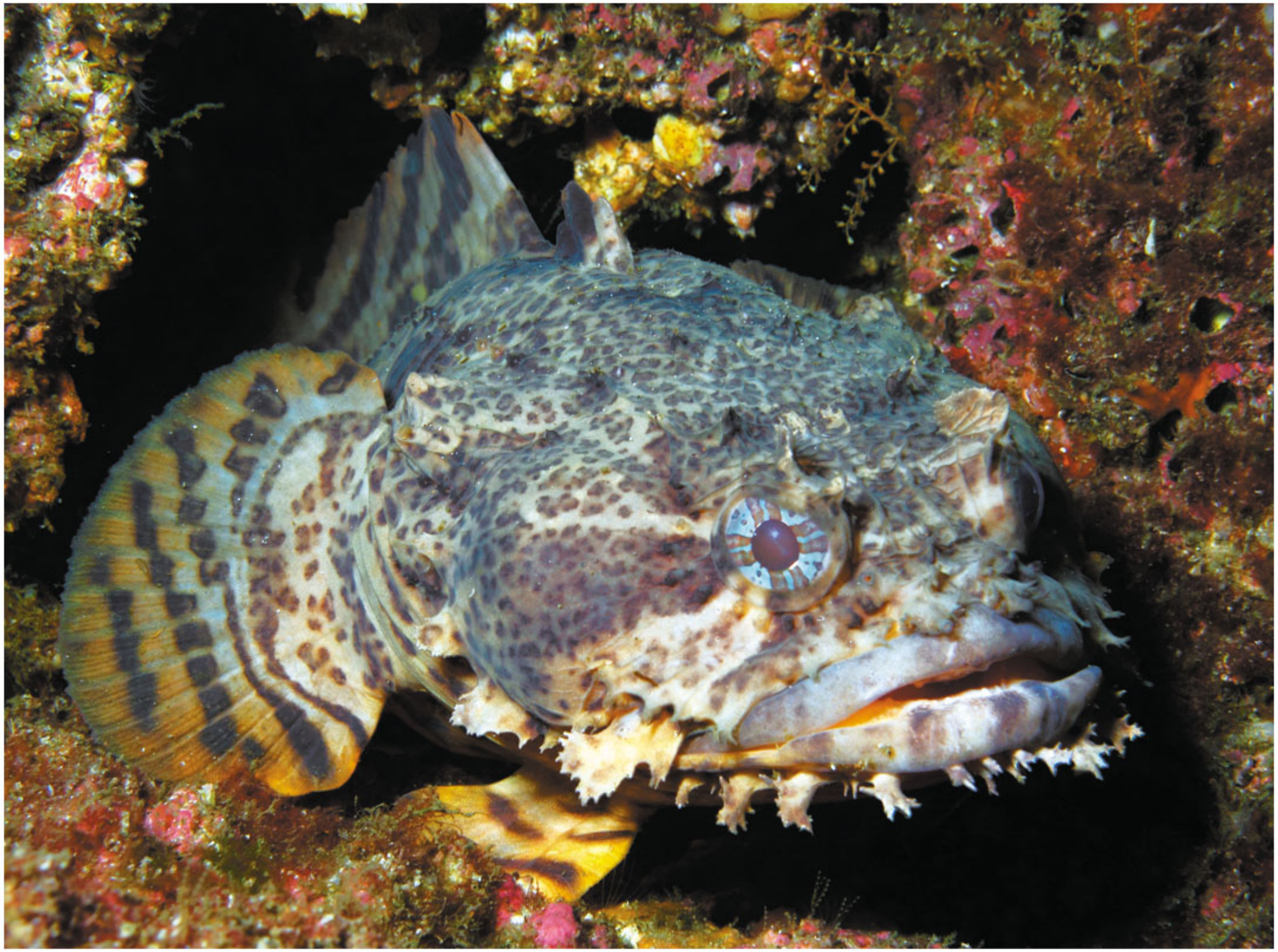
Fast-Twitch and Slow-Twitch Fibers (2 of 3)

- **Slow-twitch fibers** contract more slowly but sustain longer contractions
- Slow fibers have less sarcoplasmic reticulum than fast fibers and pump Ca^{2+} more slowly
- All slow-twitch fibers are oxidative

Fast-Twitch and Slow-Twitch Fibers (3 of 3)

- Most human 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 oyster toadfish can contract and relax certain muscles more than 200 times per second

Figure 50.34



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

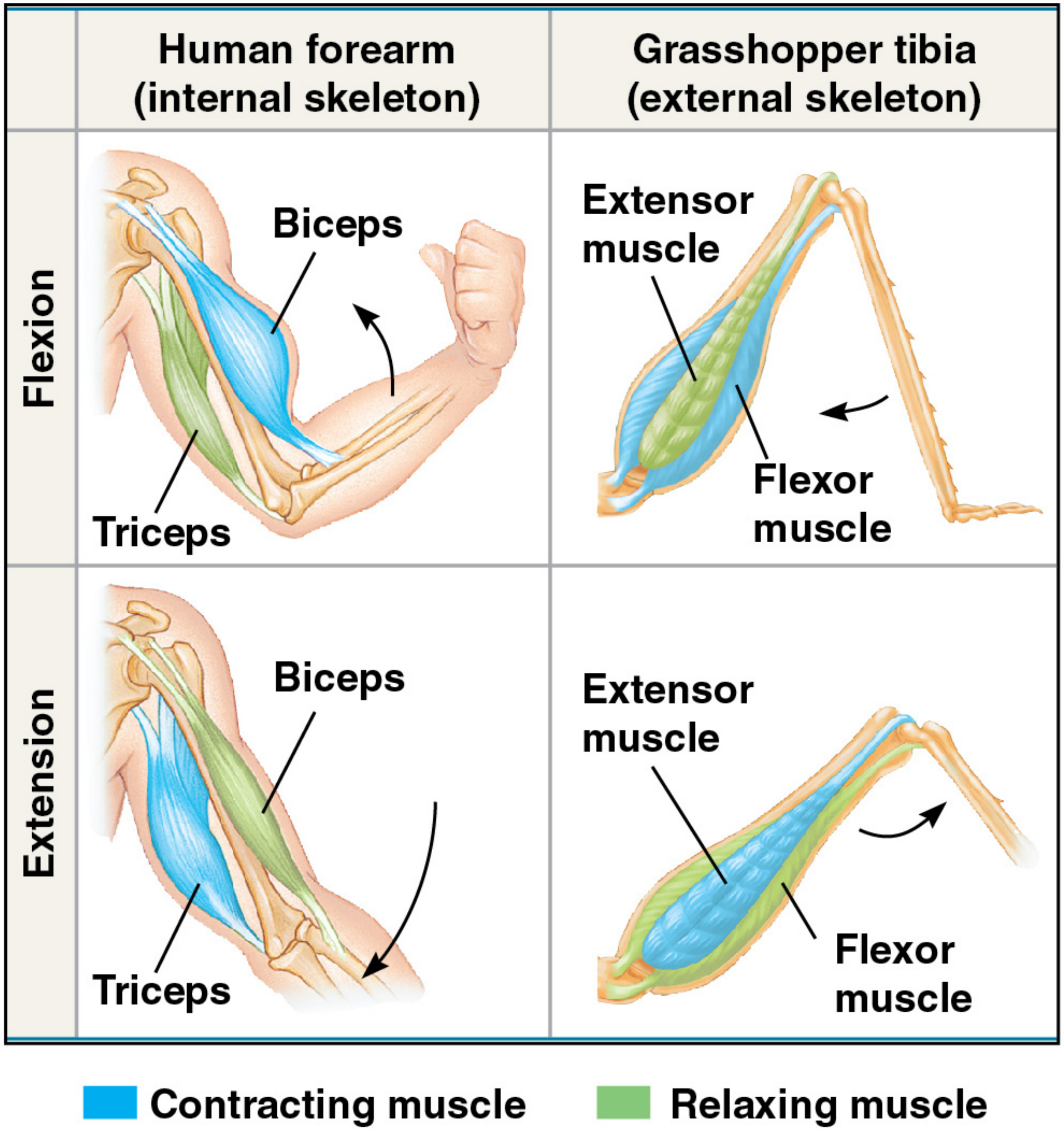
- **Smooth muscle** is found mainly in walls of hollow organs such as those of the circulatory, digestive, and reproductive systems
- Smooth muscle lacks striations, because the actin and myosin filaments are not regularly arrayed
- Contractions are slow and may be caused by stimulation from neurons in the autonomic nervous system
- Contractions may also be initiated by the muscles themselves

- Calcium regulates smooth muscle contraction but smooth muscle cells have no troponin complex or T tubules
- Their sarcoplasmic reticulum is not well developed
- Calcium ions enter the cytosol through the plasma membrane; they cause contraction by binding the protein calmodulin
- Calmodulin activates an enzyme that phosphorylates the myosin head, enabling cross-bridge activity

CONCEPT 50.6: Skeletal systems transform muscle contraction into locomotion

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

Figure 50.35


Human forearm (internal skeleton)
Grasshopper tibia (external skeleton)
Flexion
Extension
Biceps
Triceps
Biceps
Triceps
Extensor muscle
Flexor muscle
Extensor muscle
Flexor muscle
Contracting muscle
Relaxing muscle

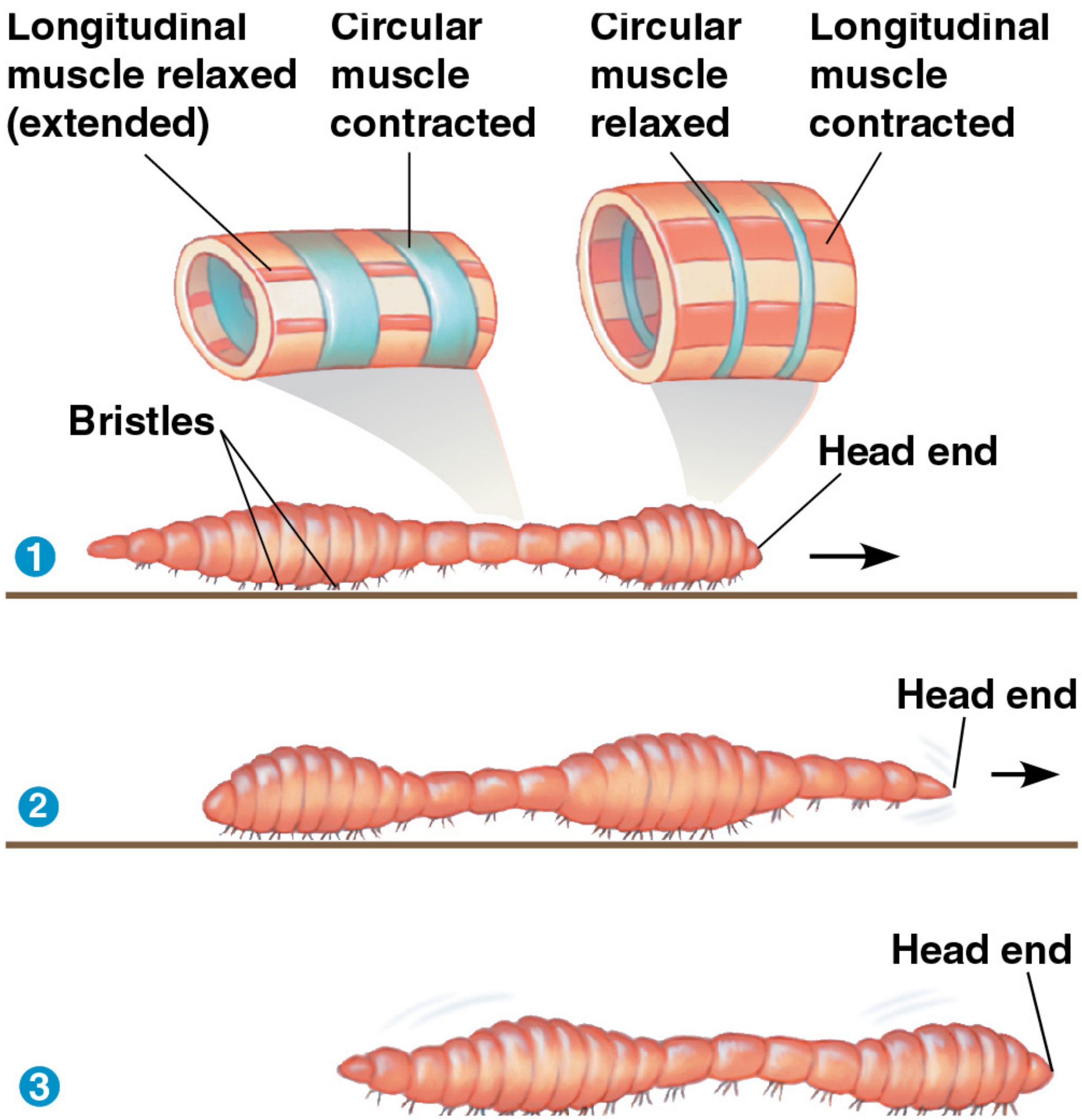
Types of Skeletal Systems

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

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
- Hydrostatic skeletons are well suited for aquatic life

Figure 50.36



Longitudinal muscle relaxed (extended)
Circular muscle contracted
Circular muscle relaxed
Longitudinal muscle contracted
Bristles
Head end
1
2
Head end
3
Head end

Video: Earthworm Locomotion

Video: Echinoderm tube feet

Video: Jelly Swimming

Video: Thimble Jellies

Exoskeletons

- An **exoskeleton** is a hard covering 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 the 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
- Vertebrate endoskeletons consist of cartilage, bone, or a combination of these
- A mammalian skeleton has more than 200 bones, some fused together, others connected at joints by ligaments

Figure 50.37

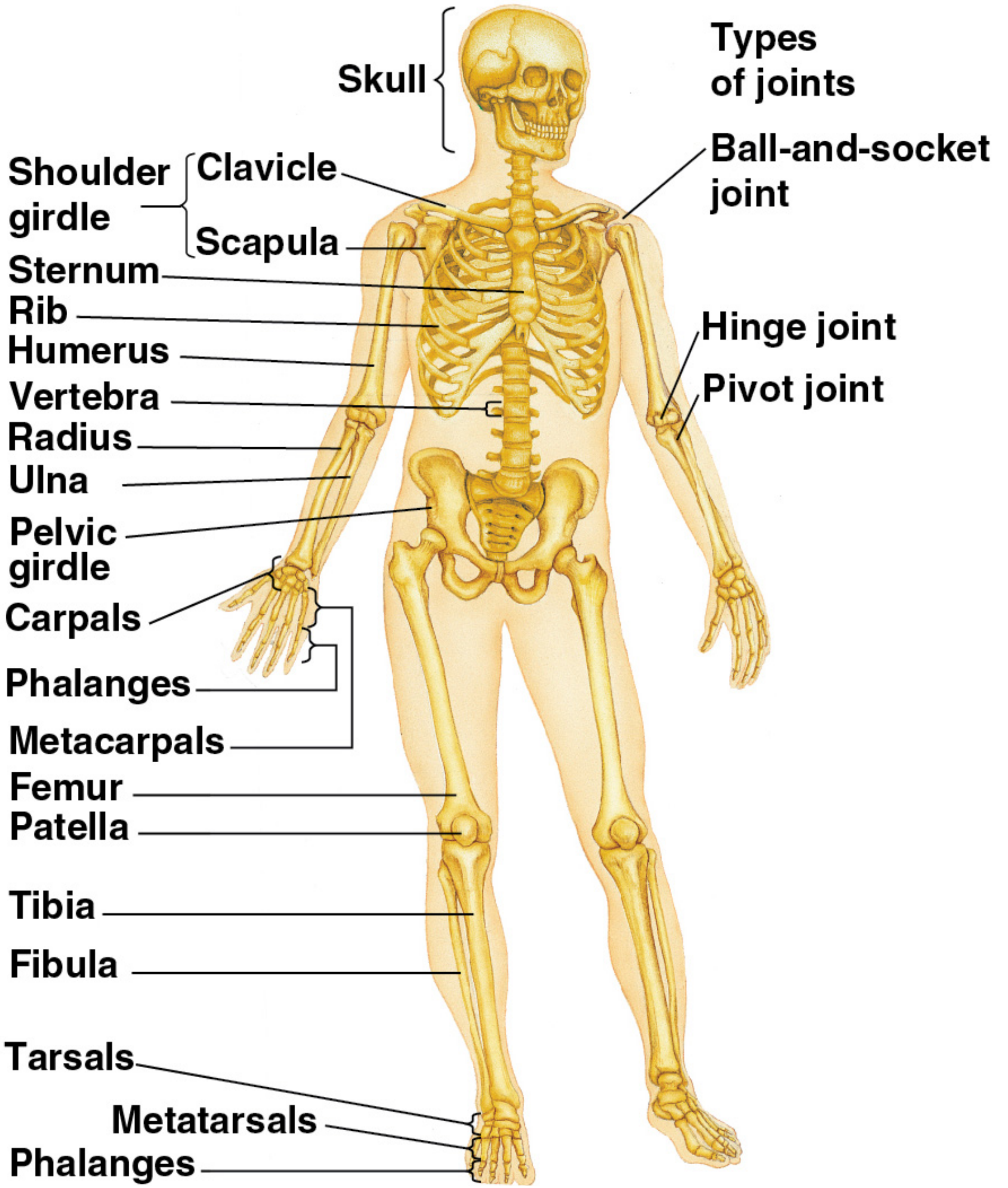
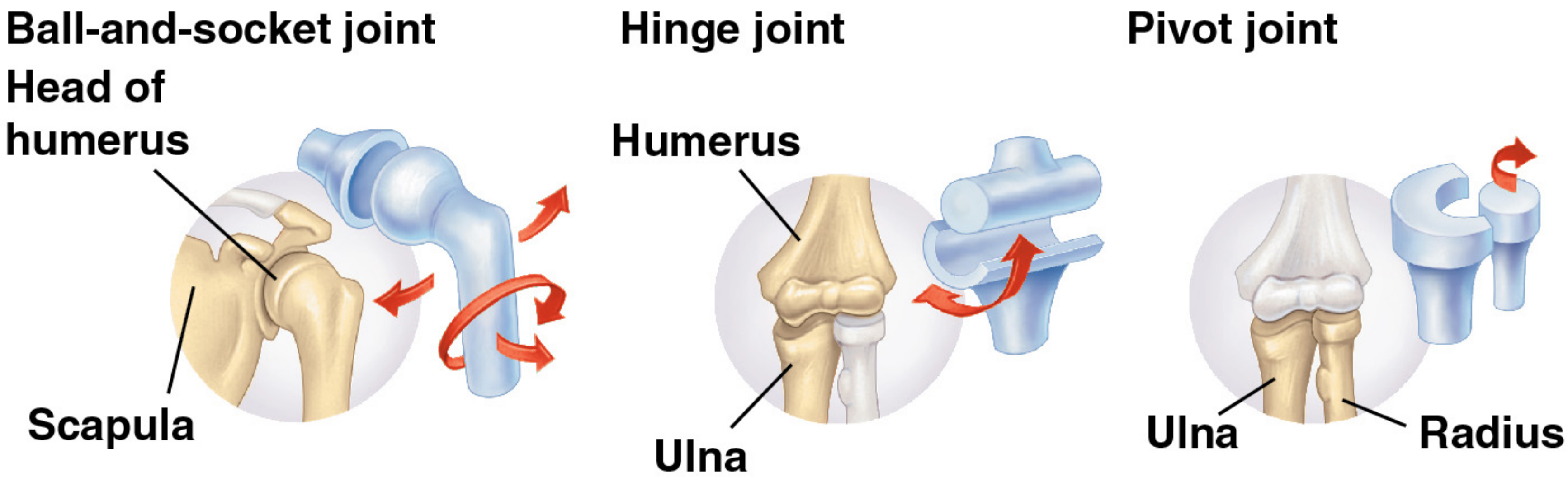

Skull
Types of joints
Shoulder girdle
Clavicle
Scapula
Ball-and-socket joint
Sternum
Rib
Humerus
Hinge joint
Pivot joint
Vertebra
Radius
Ulna
Pelvic girdle
Carpals
Phalanges
Metacarpals
Femur
Patella
Tibia
Fibula
Tarsals
Metatarsals
Phalanges

Figure 50.38



Ball-and-socket joint
Head of humerus
Scapula
Hinge joint
Humerus
Ulna
Pivot joint
Ulna
Radius

- 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**, 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 50.39

- 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

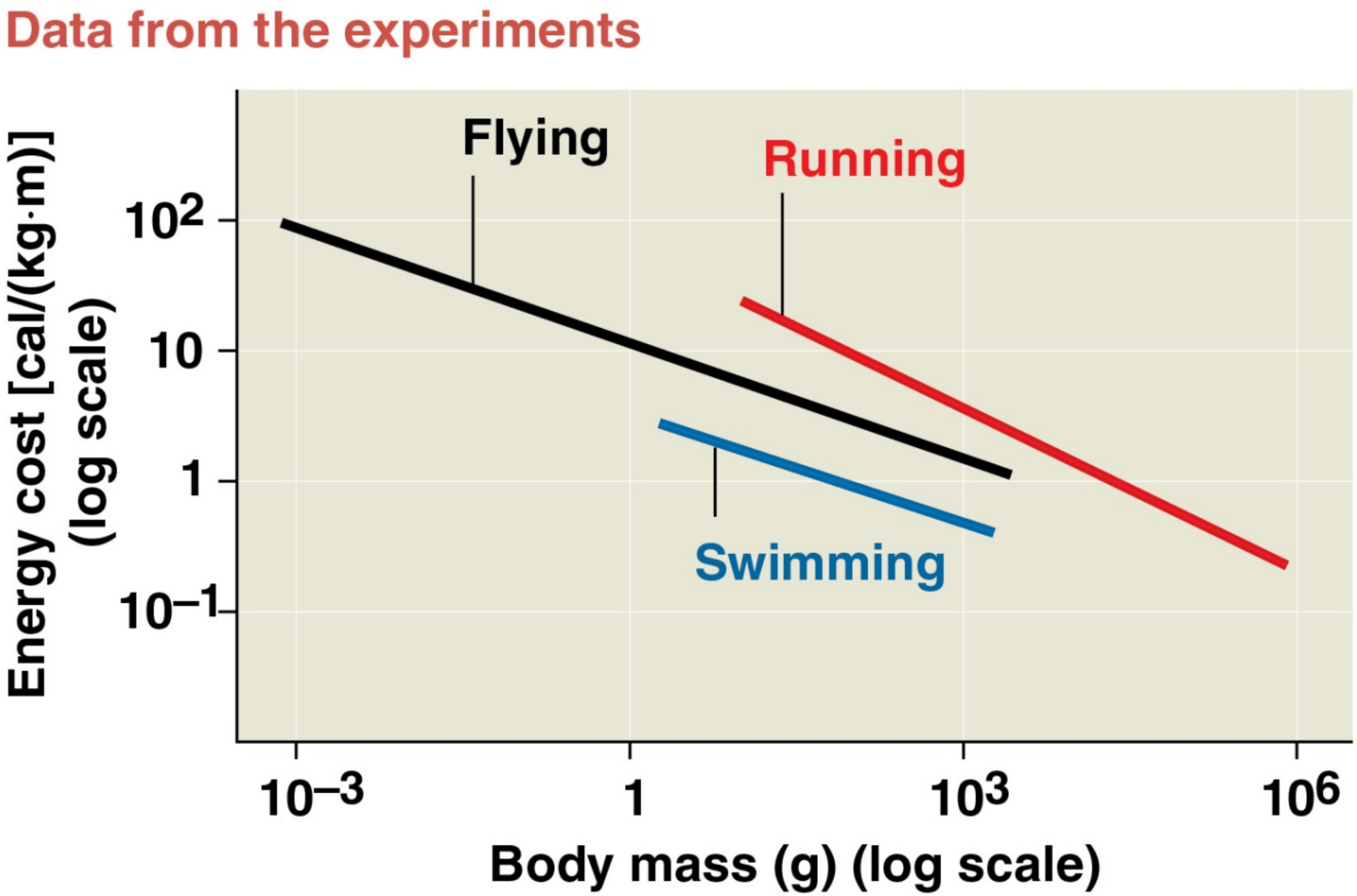
Swimming

- 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.UN01



Data from K. Schmidt-Nielsen, Locomotion: Energy cost of swimming, flying, and running, *Science* 177:222–228 (1972). Reprinted with permission from AAAS

Figure 50.UN02

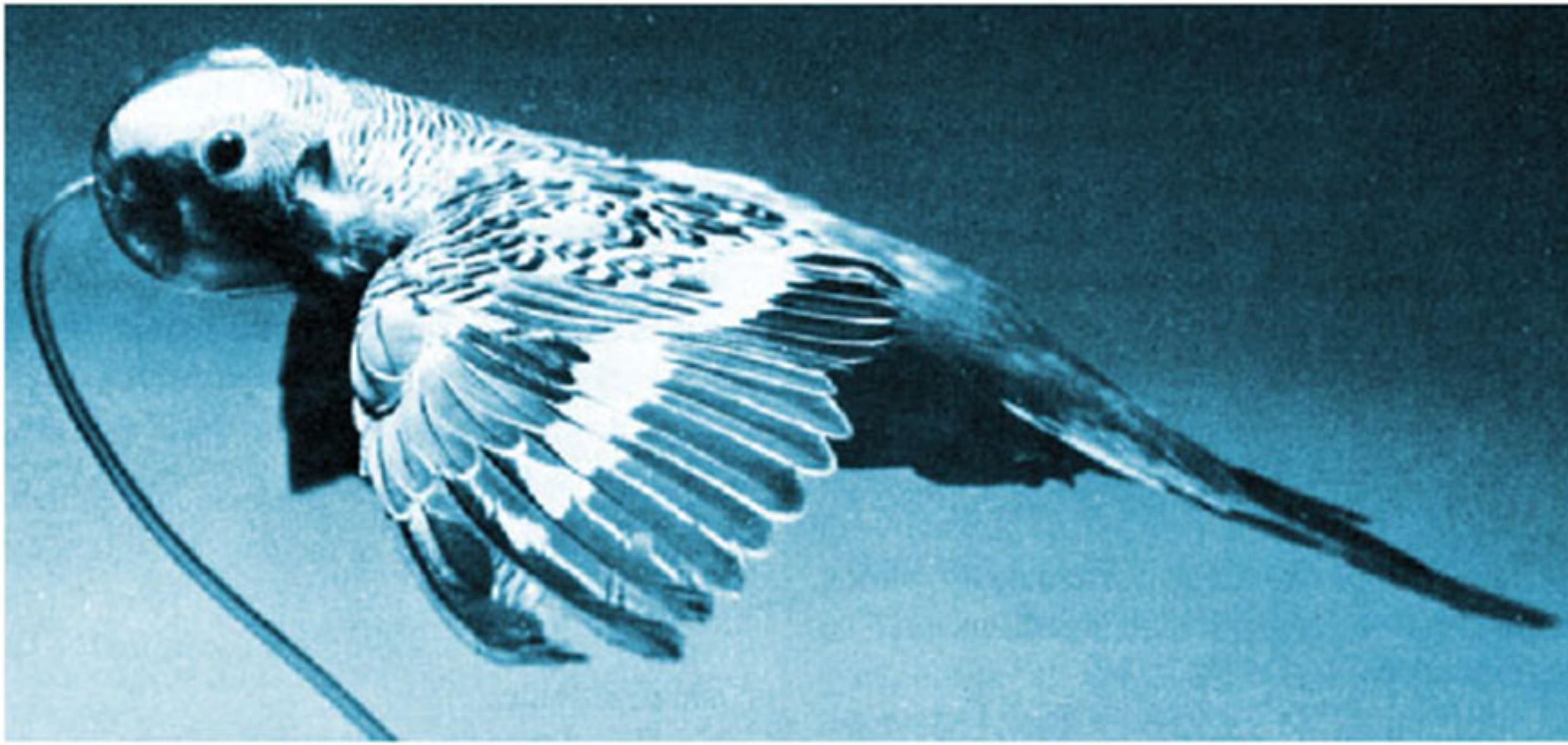


Figure 50.UN03

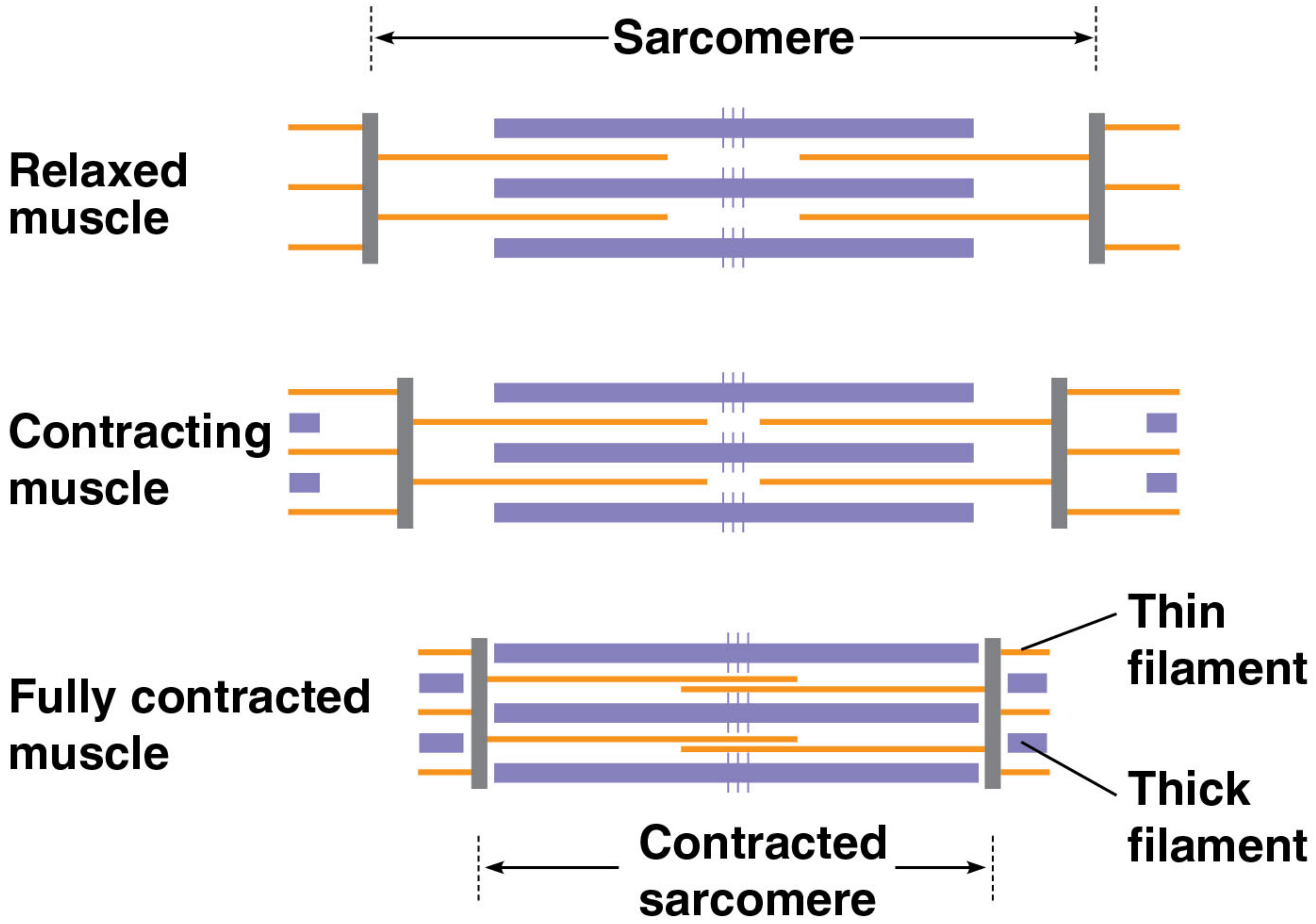


Figure 50.UN04

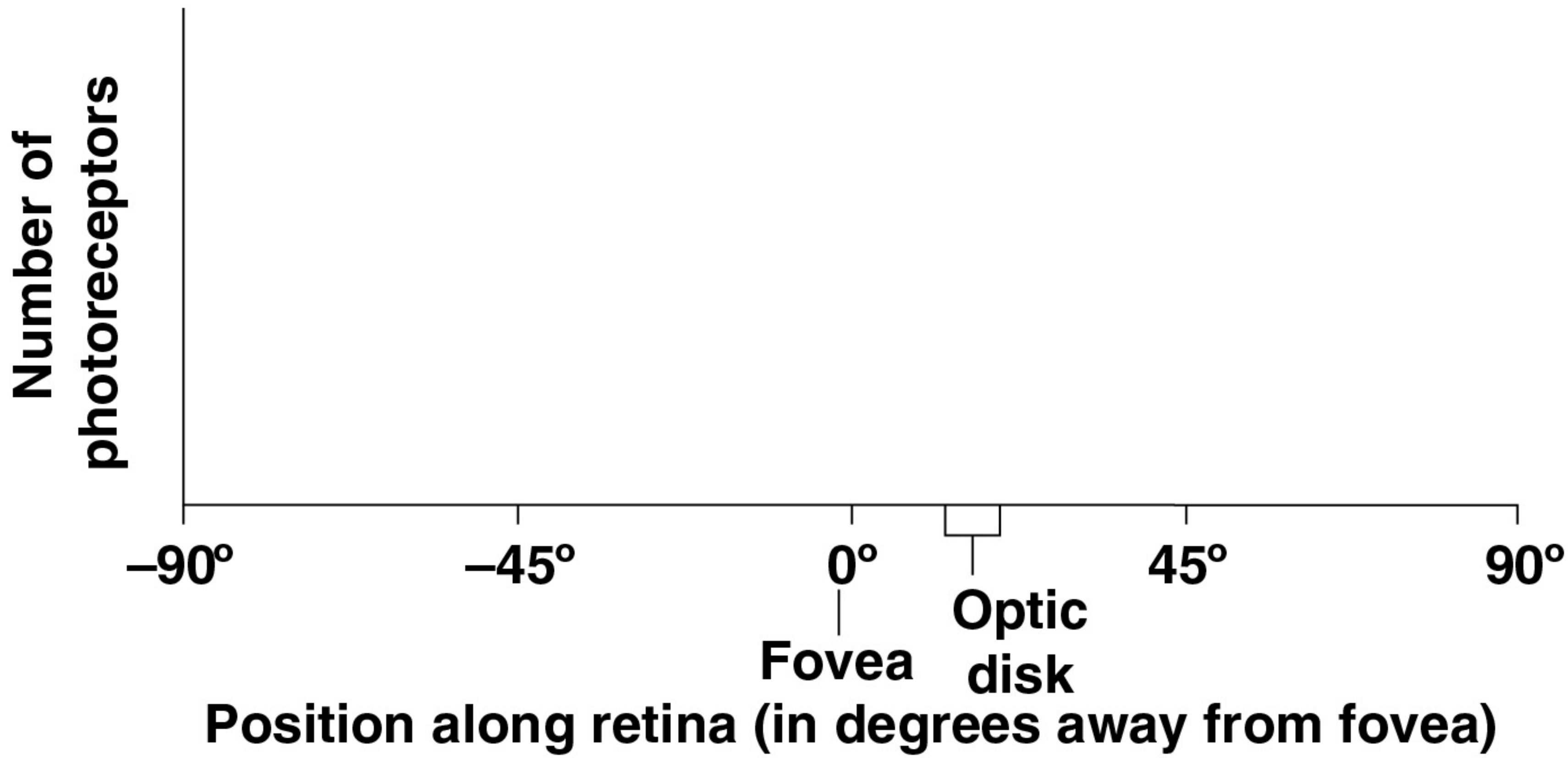


Figure 50.UN05

Frequency (hops/sec)	Energy used (joules/sec)
1.85	735
0.92	716

Figure 50.UN06