6.1 Evolution and Roles of Senses

- Sensory cells
  - Organisms must gather information about their environment and internal state
  - **Sensory cells** respond to specific stimuli
  - **Transduction** is the conversion of the energy of a stimulus into electrical energy
    - Linked to the opening and closing of gated ion channels
  - Sensory cells arose long before the evolution of the nervous system (e.g. **paramecium** respond to a variety of environmental stimuli)

6.1 Evolution and Roles of Senses

- Sensors are categorized by the specific **modalities** to which they respond.
  - **Mechanoreceptors** -- mechanical energy (e.g. touch and pressure)
  - **Chemoreceptors** -- specific chemicals
  - **Thermoreceptors** -- heat and cold
  - **Photoreceptors** -- photic energy
  - **Electroreceptors** -- electric fields
  - **Magnetoreceptors** -- magnetic fields

  - **Nociceptors** (pain receptors) respond to tissue damage; may be chemoreceptors or mechanoreceptors

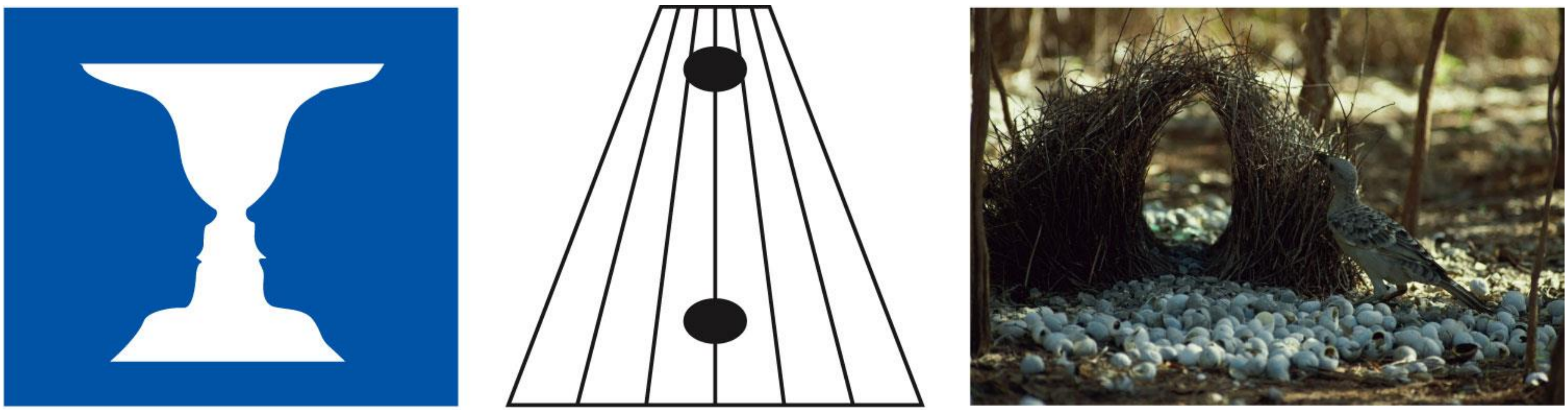
6.1 Evolution and Roles of Senses

- Primary roles of receptor cells
  - **Interoreceptors** detect information about **internal body fluids** crucial to homeostasis
    - In blood vessels and gut fluids
  - **Proprioceptors** monitor **body movement** and **position**
    - In muscles, tendons and joints
  - **Exteroreceptors** detect **external stimuli**
    - **Somesthetic senses** arise from body surface
    - **Special senses** -- highly localized, specialized senses in distinct sensory organs

6.1 Evolution and Roles of Senses

- **Perception** is an animal's interpretation of the external world
  - Sensors detect a limited number of energy forms
  - Stimuli are **filtered** during precortical processing
  - Data are further manipulated by the **cerebral cortex**
  - **Optical illusions** can make objects look smaller or larger than they are (ex. great bowerbird nests)

6.1 Evolution and Roles of Senses



(a) (b) (c)

6.2 Receptor Cell Physiology

- **Doctrine of specific nerve energies**
  - Each type of receptor is specialized to respond to one type of stimulus (**adequate stimulus**)
    - Example: The adequate stimulus for **photoreceptors** in the eye is **light**
  - Even when activated by a different stimulus, the sensation is the one usually detected by that receptor type

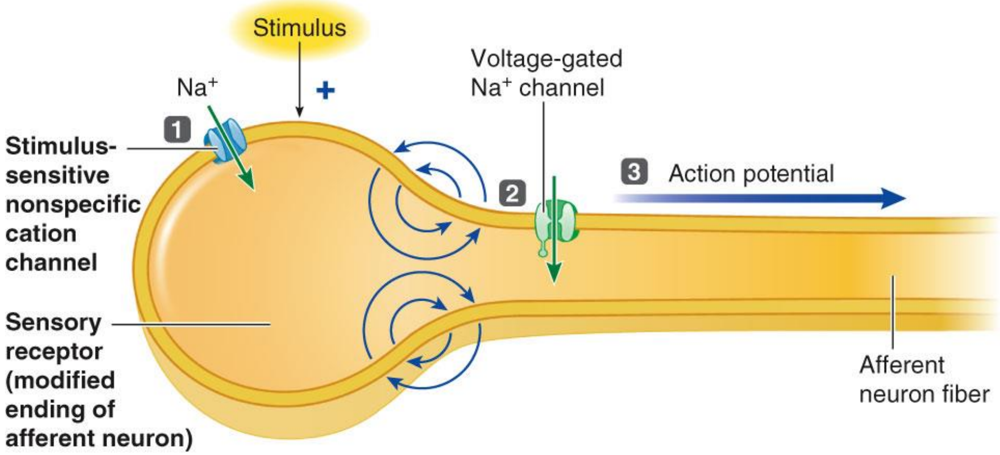
6.2 Receptor Cell Physiology

- Receptor potential
  - Stimulation of receptor opens gated Na^+ channels
    - Inward flux of Na^+ **depolarizes** the receptor membrane
    - **Receptor potential** in receptor cells
    - **Generator potential** in afferent neurons
  - Receptor potential is **graded** -- the greater the stimulus, the larger the receptor potential
  - Receptor potential must be converted into **action potentials** for long-distance transmission

6.2 Receptor Cell Physiology

- Receptor potentials may initiate action potentials
  - In a specialized afferent ending, local current from receptor potentials reaches trigger zone
    - If **threshold** is reached, voltage-gated Na^+ channels open, producing action potentials
  - In separate receptor cells, receptor potential triggers release of **neurotransmitters** that reach the afferent neuron
    - Opens **chemically gated** Na^+ channels
    - If **threshold** is reached, voltage-gated Na^+ channels open, producing action potentials
  - The stronger the stimulus the greater the **frequency** of action potentials

6.2 Receptor Cell Physiology

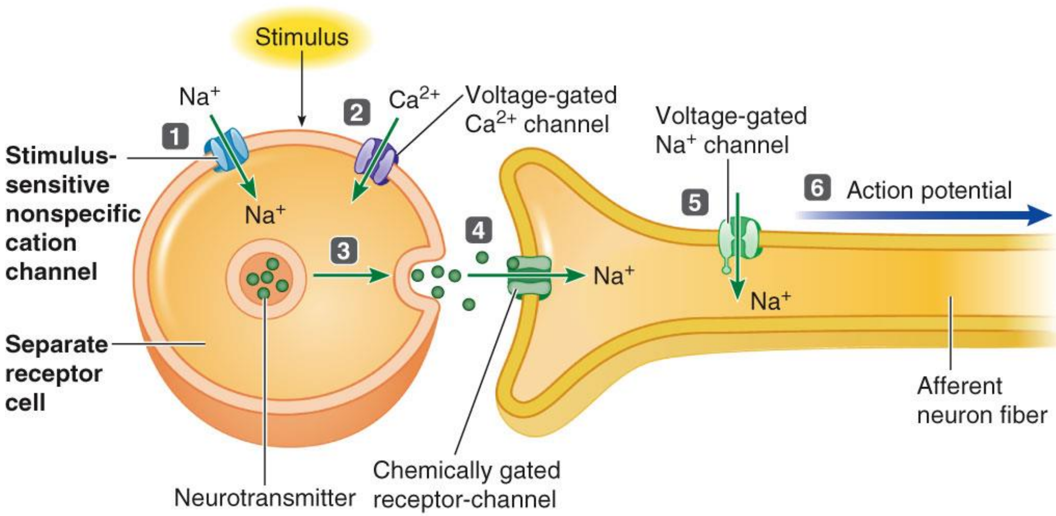


(a) Receptor potential in specialized afferent ending

1 In sensory receptors that are specialized afferent neuron endings, stimulus opens stimulus-sensitive channels, permitting net Na^+ entry that produces receptor potential.

2 Local current flow between depolarized receptor ending and adjacent region opens voltage-gated Na^+ channels.

3 Na^+ entry initiates action potential in afferent fiber that self-propagates to CNS.



(b) Receptor potential in separate receptor cell

1 In sensory receptors that are separate cells, stimulus opens stimulus-sensitive channels, permitting net Na^+ entry that produces receptor potential.

2 This local depolarization opens voltage-gated Ca^{2+} channels.

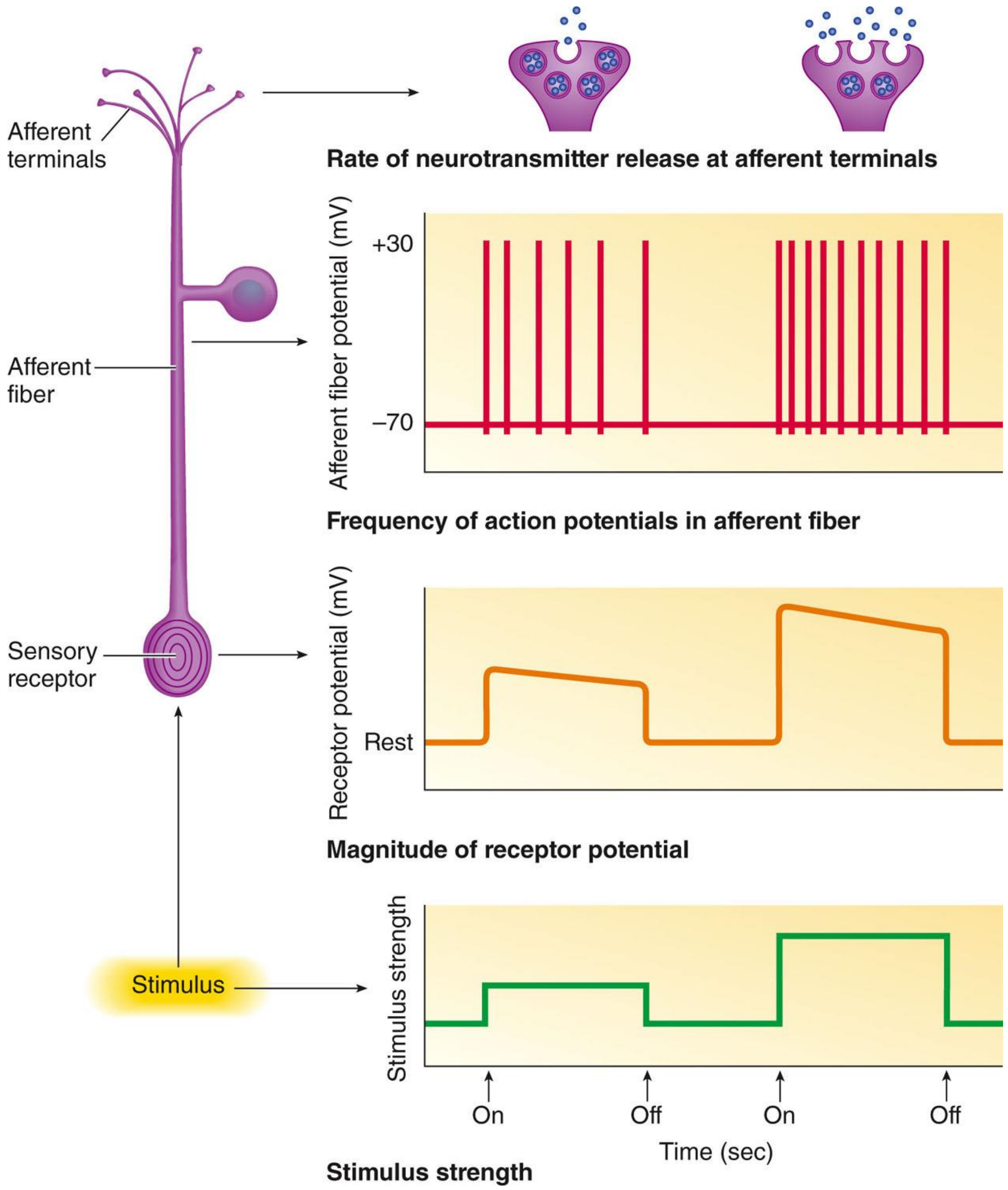
3 Ca^{2+} entry triggers exocytosis of neurotransmitter.

4 Neurotransmitter binding opens chemically gated receptor-channels at afferent ending, permitting net Na^+ entry.

5 Resultant depolarization opens voltage-gated Na^+ channels in adjacent region.

6 Na^+ entry initiates action potential in afferent fiber that self-propagates to CNS.

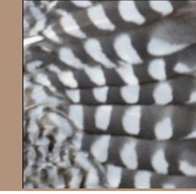
6.2 Receptor Cell Physiology

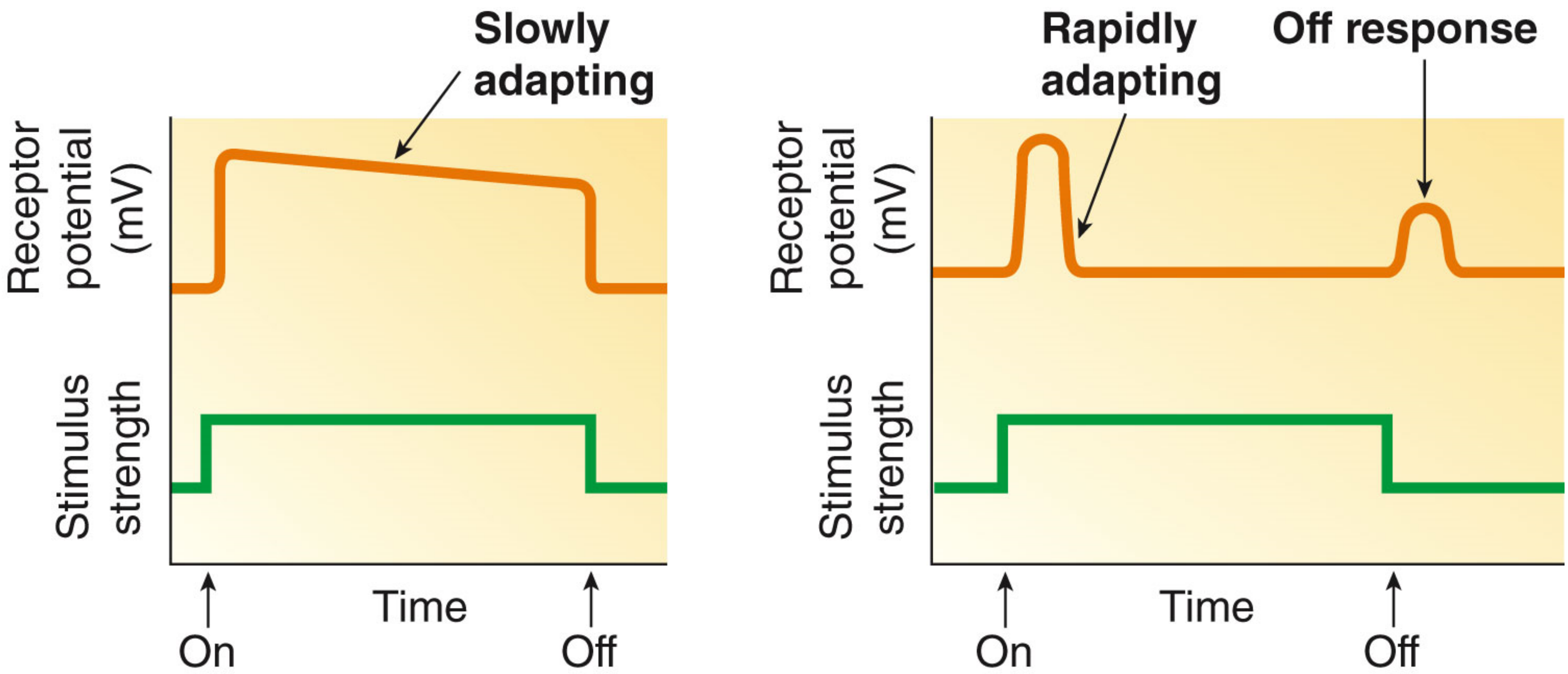


6.2 Receptor Cell Physiology

- Receptor adaptation
  - **Tonic receptors** do not adapt at all, or adapt slowly
  - **Phasic receptors** adapt rapidly
    - Depolarization **diminishes** despite a sustained stimulus
    - **Off response** -- depolarization when the stimulus is removed

6.2 Receptor Cell Physiology

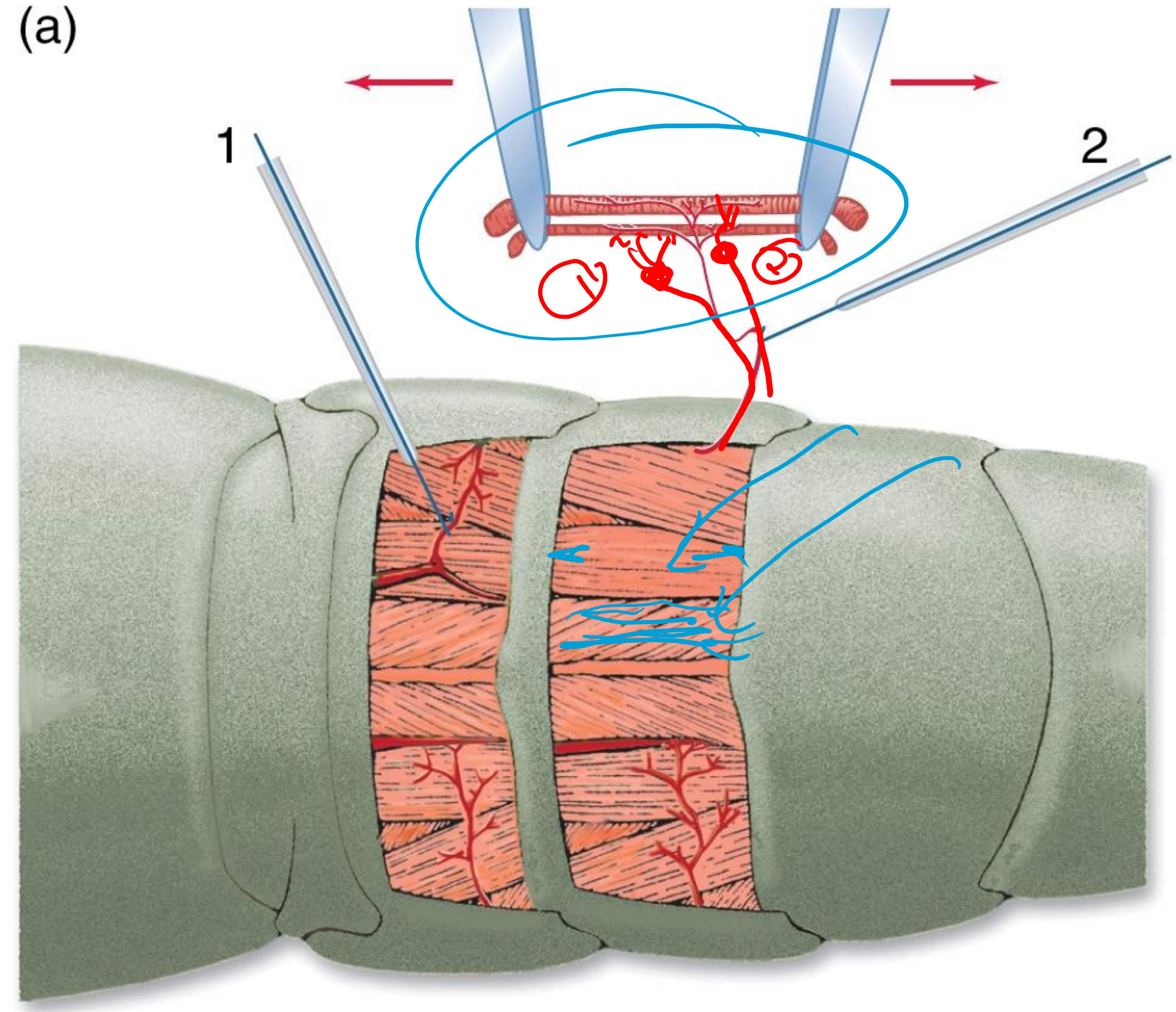


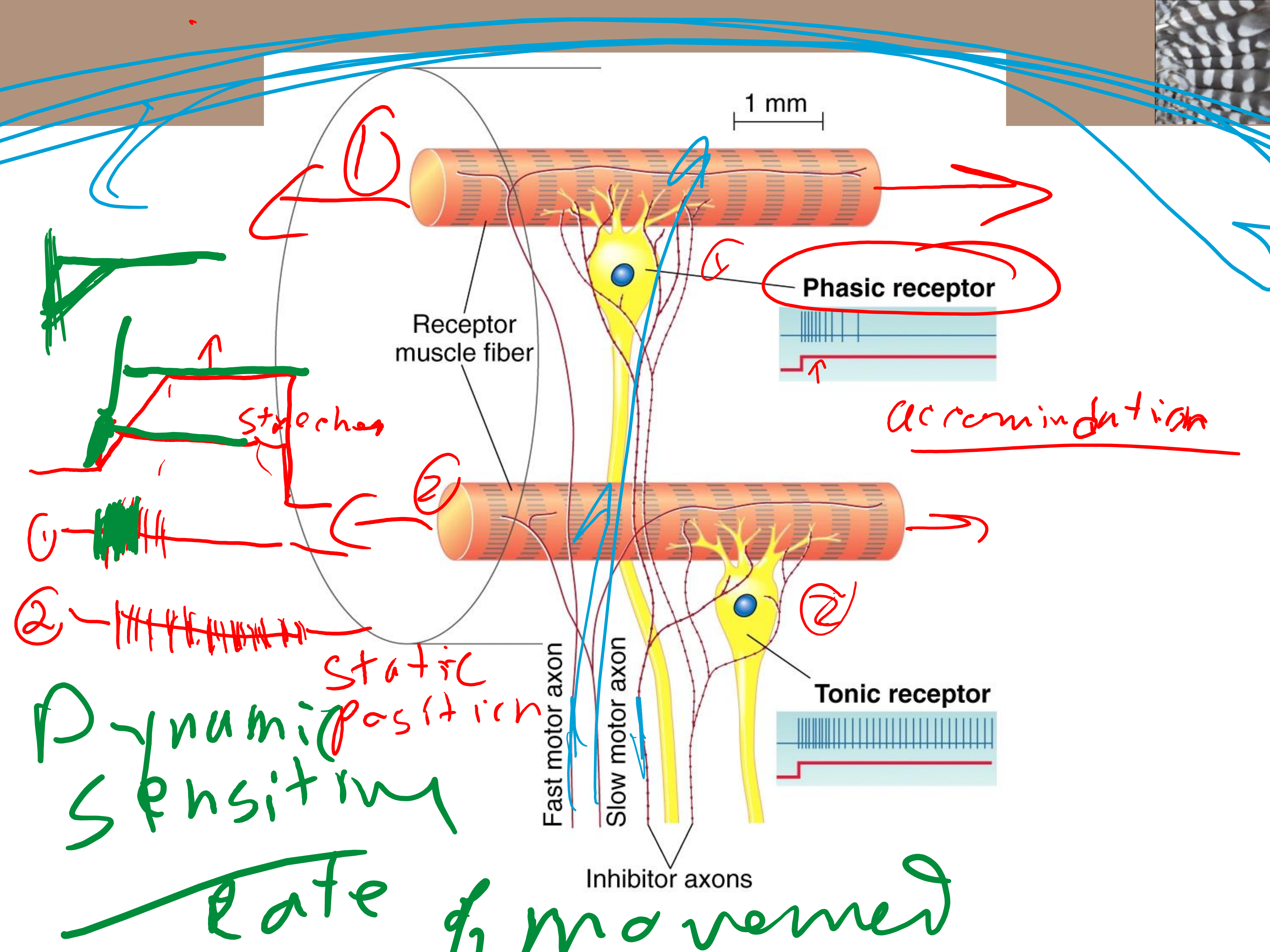


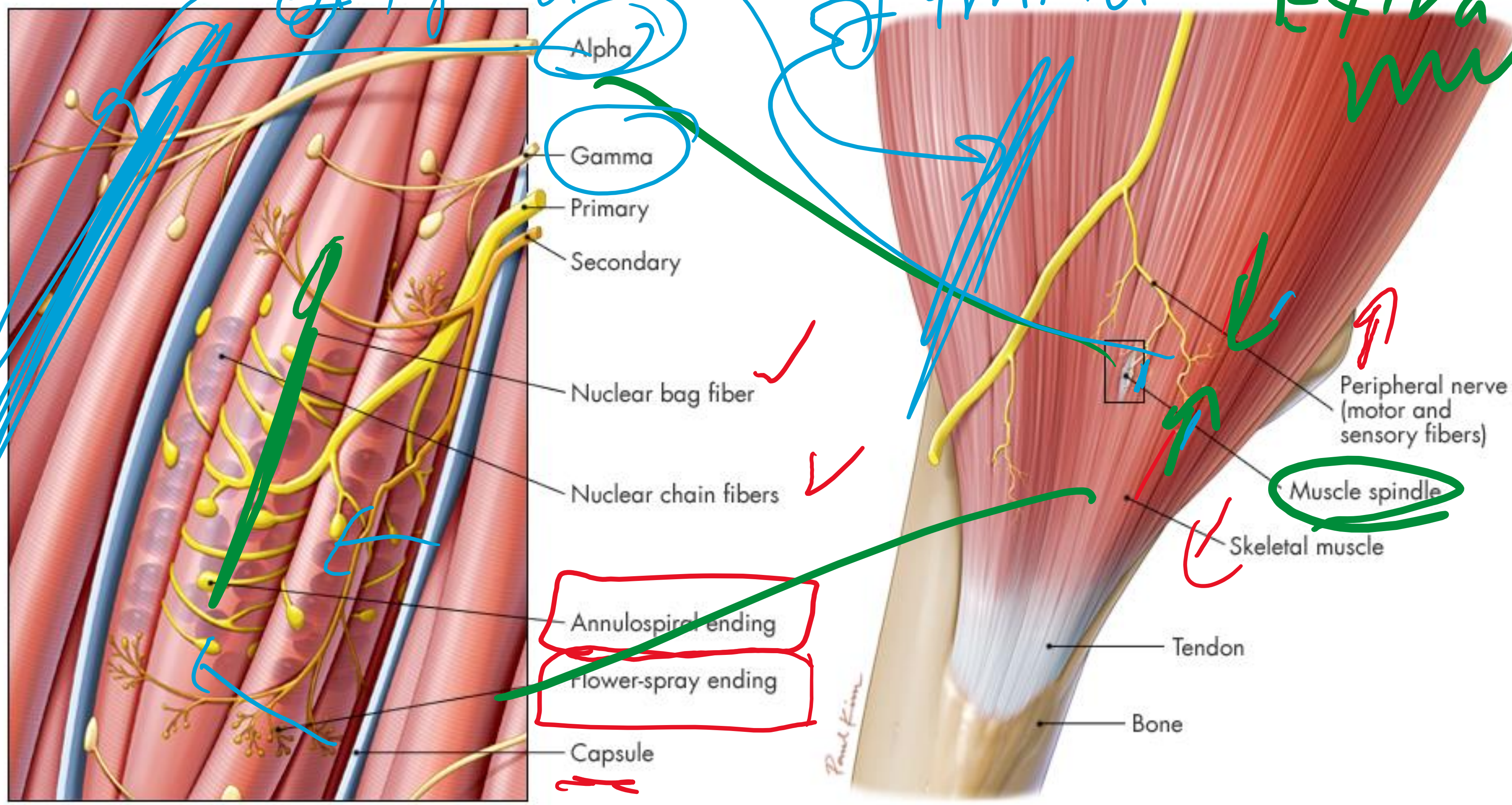
(a) Tonic receptor

(b) Phasic receptor

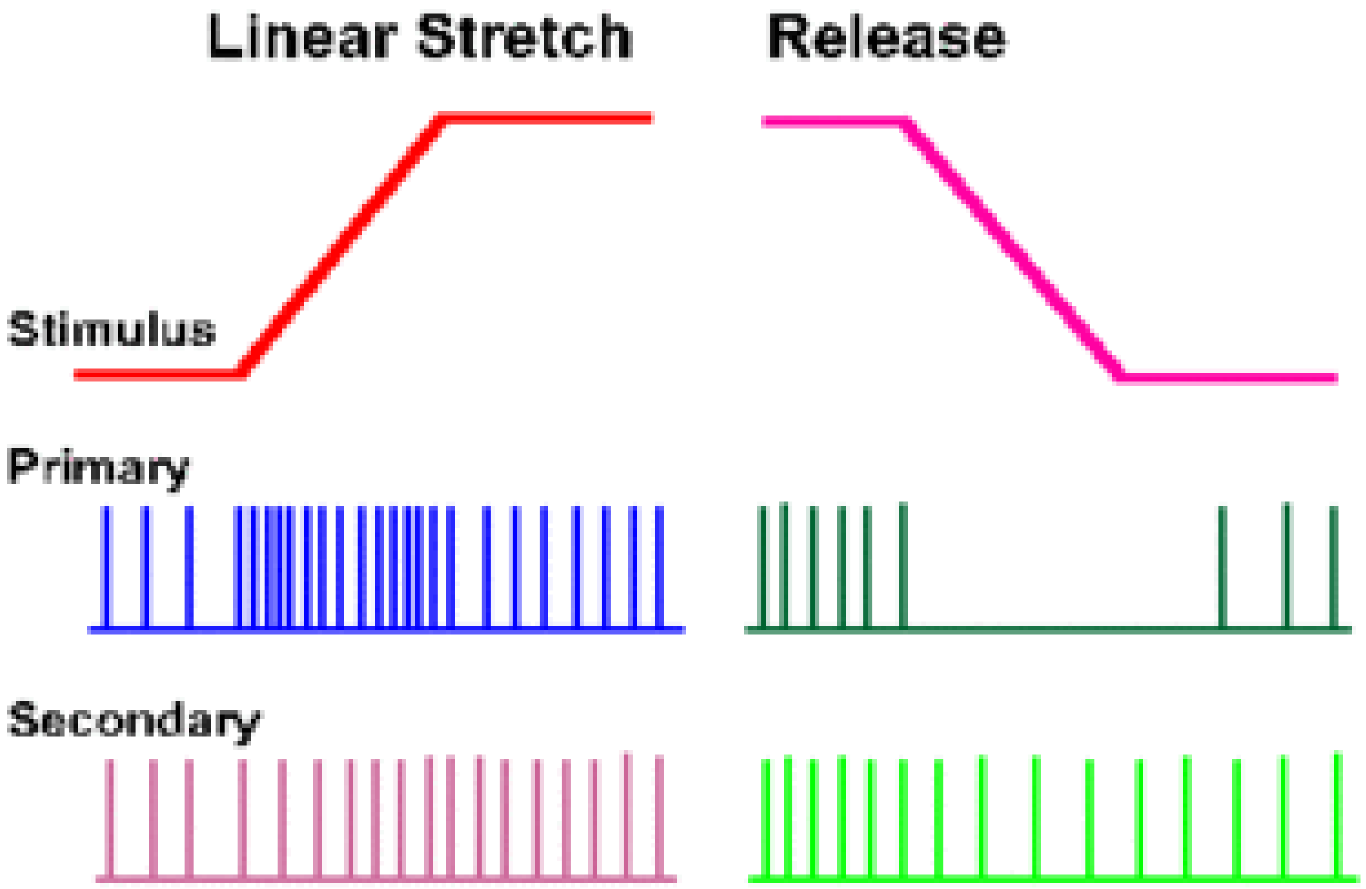
http://www.boredpanda.com/new-crayfish-species-discovered-cherax-pulcher-christian-lukhaup-indonesia/


(a)
1
2


1 mm
Receptor muscle fiber
Phasic receptor
Tonic receptor
Fast motor axon
Slow motor axon
Inhibitor axons



http://www.pkmedillus.com/portfolio/



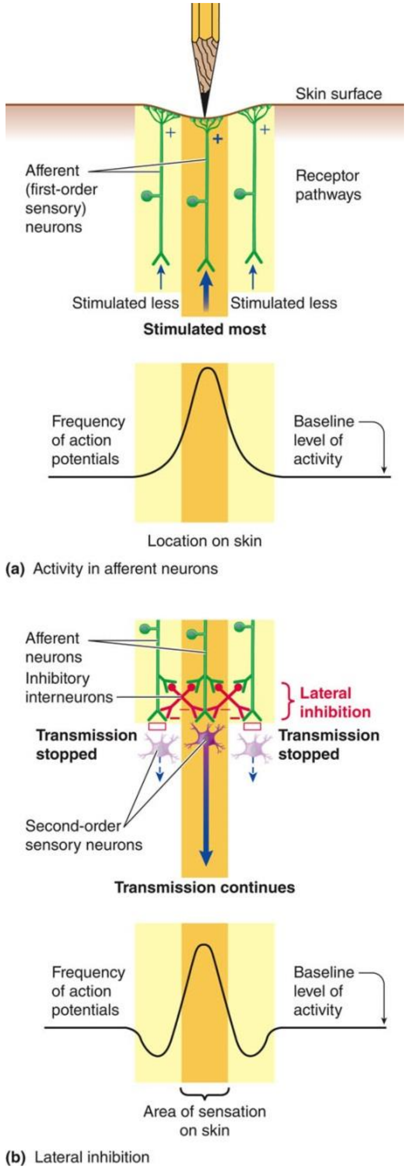
https://kin450-neurophysiology.wikispaces.com/Muscle+Spindle

Therefore …… we are like crayfish in this regard

6.2 Receptor Cell Physiology

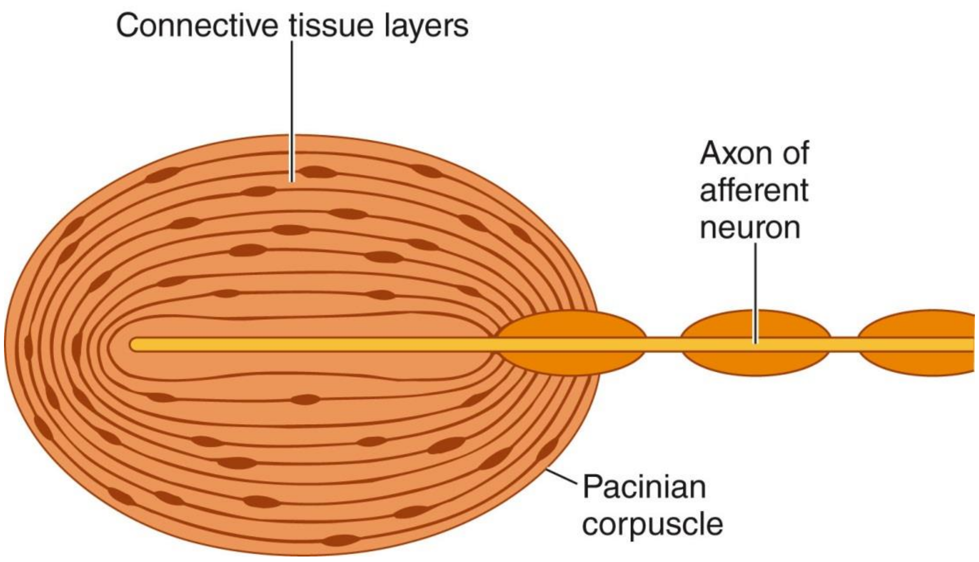
- Receptive fields
  - Each sensory neuron responds to stimuli in a specific area -- **receptive field**
  - The **smaller** the receptive fields, the greater the **density** of receptors
    - Smaller receptive fields produce **greater acuity** or discriminative ability (e.g. fingertips)
  - Amount of **cortical representation** on the sensory homunculus corresponds with receptor density
  - Strong signal in center of receptive field inhibits pathways in fringe areas -- **lateral inhibition**

6.2 Receptor Cell Physiology

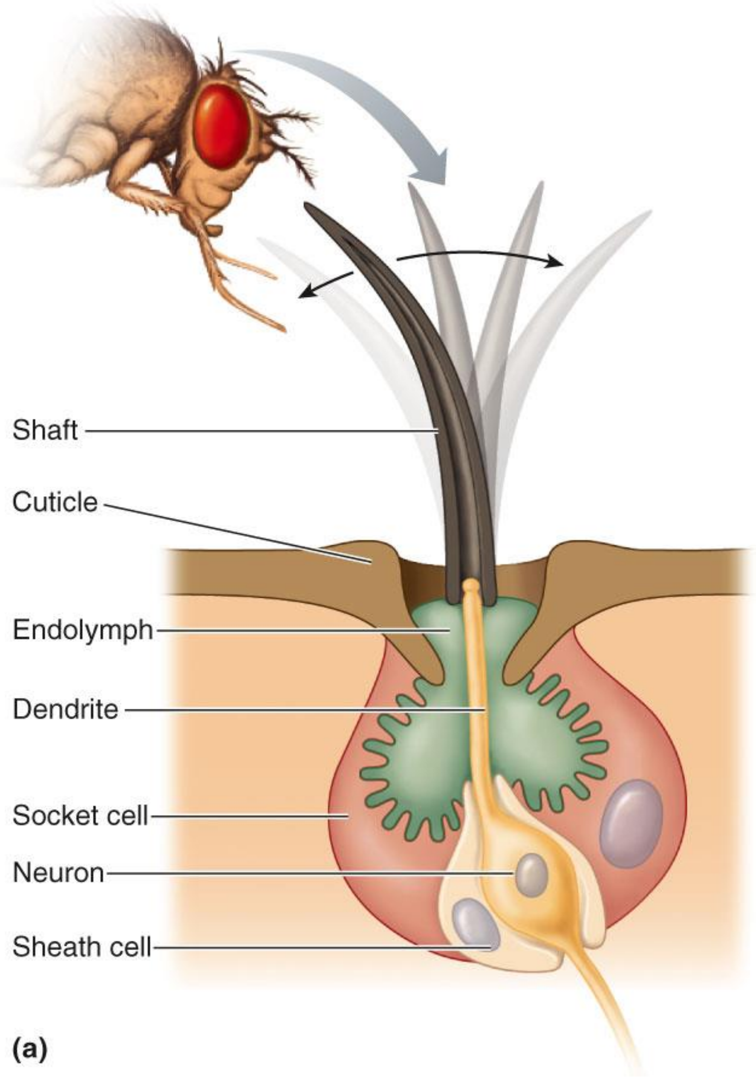


6.3 Mechanoreception: Touch, Pressure, and Proprioception

- Touch and pressure mechanoreceptors in skin
  - **Pacinian corpuscle** -- deep pressure
  - **Touch sensors** -- highly sensitive, closer to skin surface
  - **Touch mechanoreceptors** -- base of hairs or insect bristles



6.3 Mechanoreception: Touch, Pressure, and Proprioception



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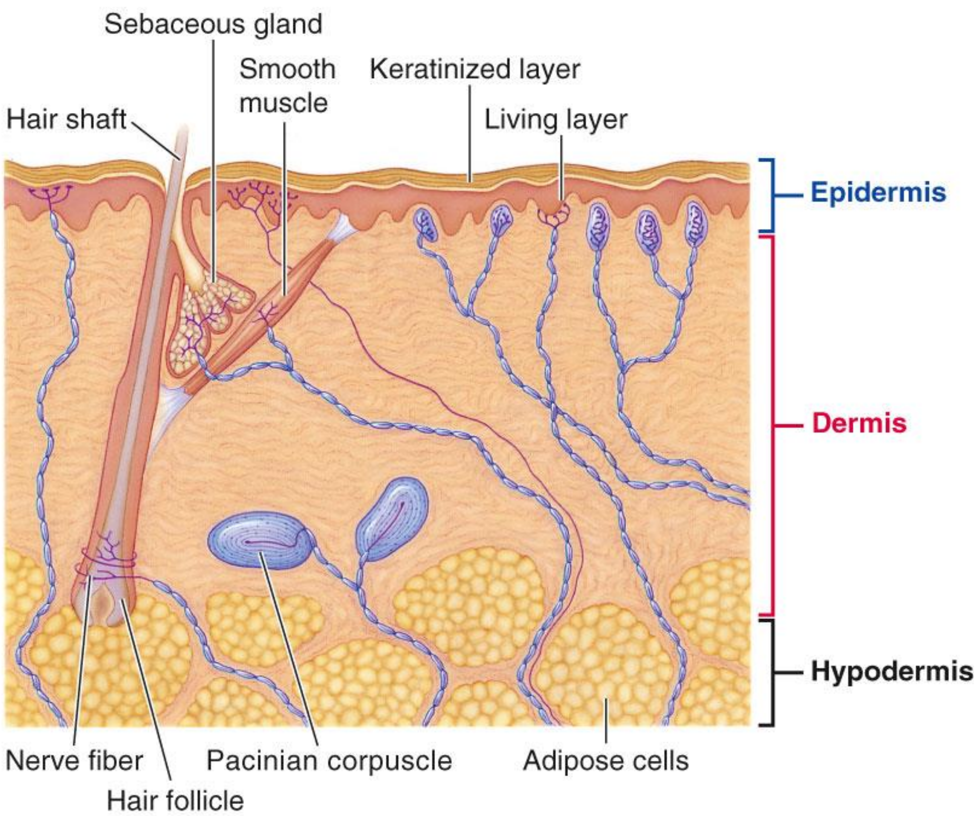

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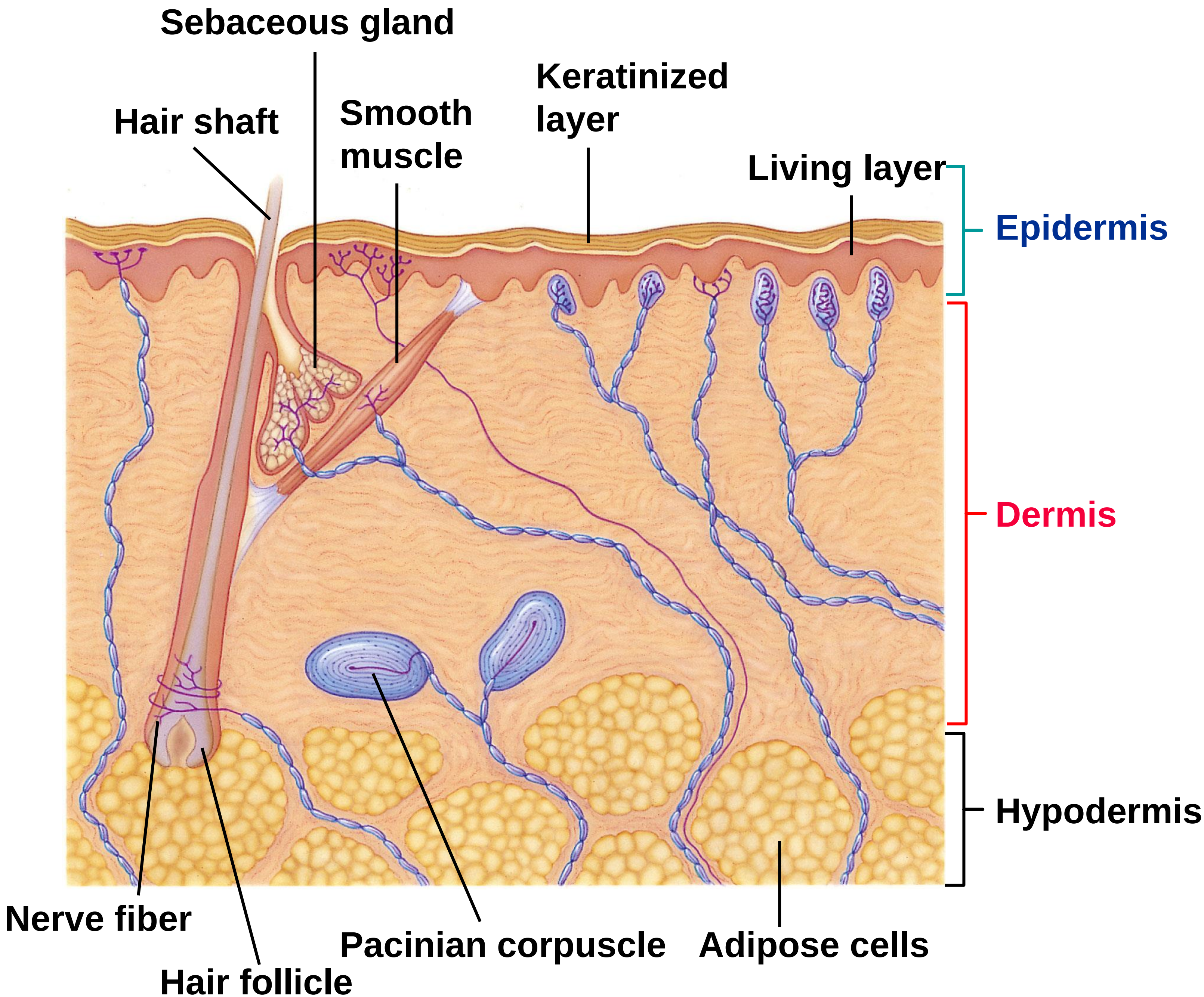
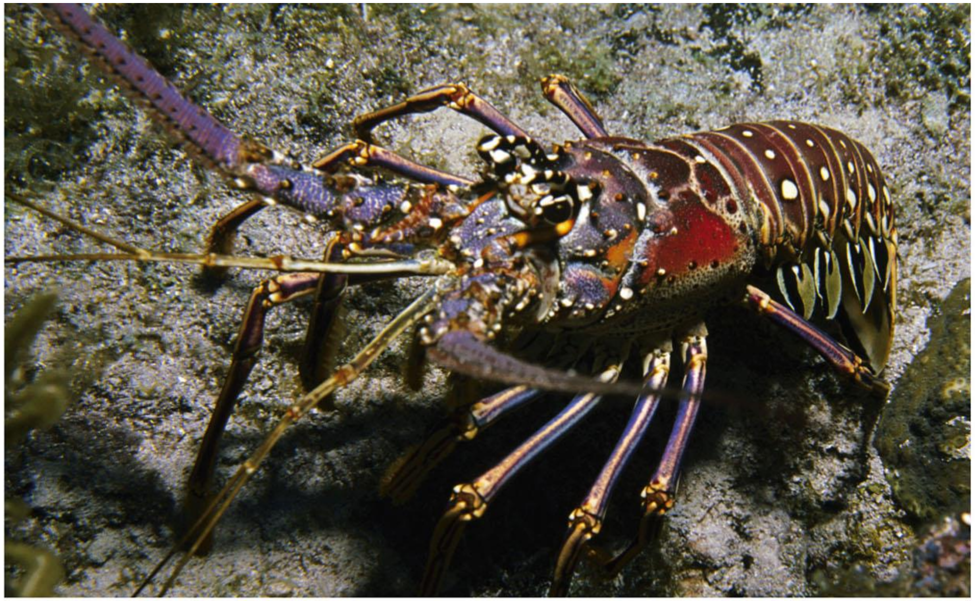


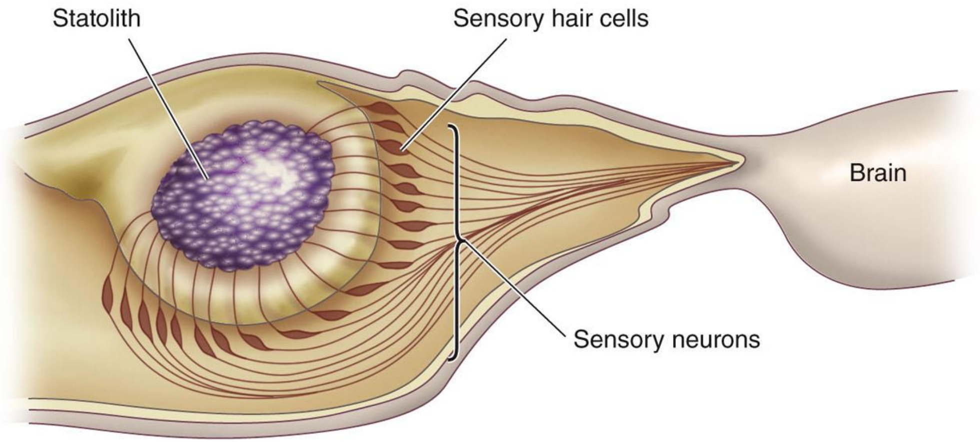
Figure 6-8b p217

6.3 Mechanoreception: Touch, Pressure, and Proprioception

- Proprioceptors give information on body position and motion
  - **Stretch receptors** include muscle spindles and Golgi tendon organs
  - **Statocysts** are gravity receptors -- simplest organs of equilibrium
    - Body movement **tilts** the **statocyst**
    - **Statoliths** move in direction of body movement, bending sensory hairs
    - When **sensory hairs** are bent, mechanically gated channels open and action potentials are generated

6.3 Mechanoreception: Touch, Pressure, and Proprioception

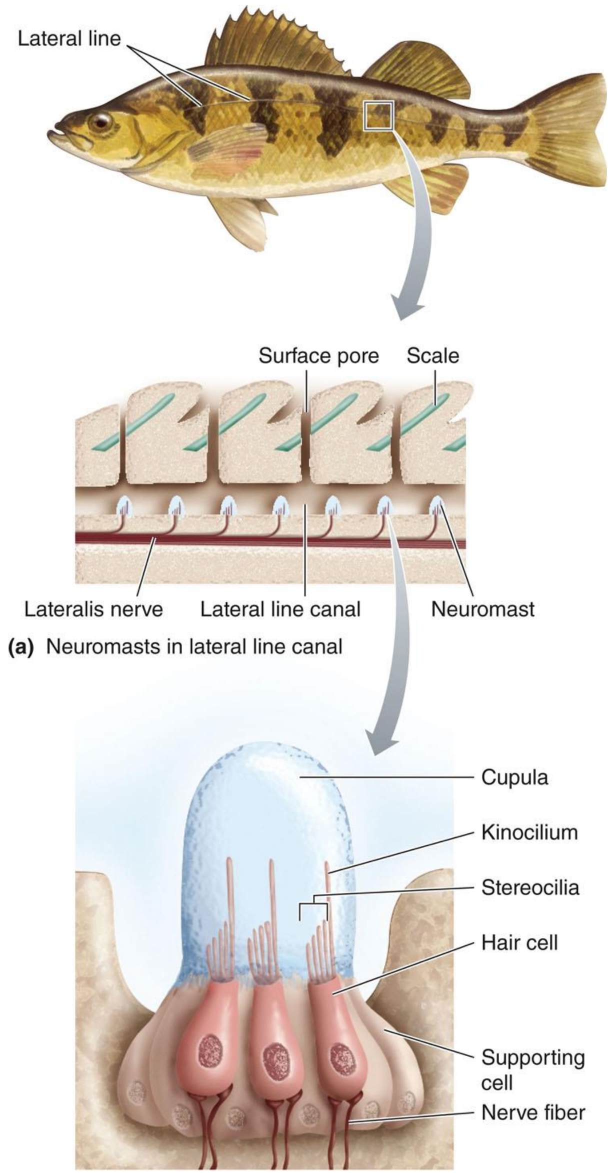




6.3 Mechanoreception: Touch, Pressure, and Proprioception

- **Lateral line** system in fishes
  - **Neuromast cells** are arranged in a line along the length of the body
  - **Stereocilia** are sensory transducers that protrude from sensory hair cells
  - Can detect pressure waves set up by other fishes

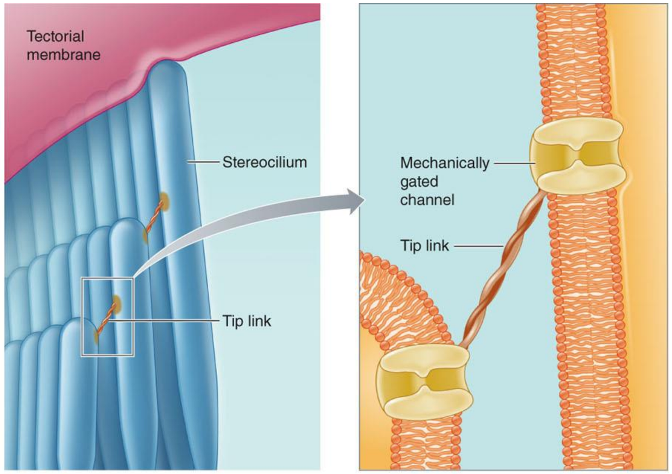
6.3 Mechanoreception: Touch, Pressure, and Proprioception



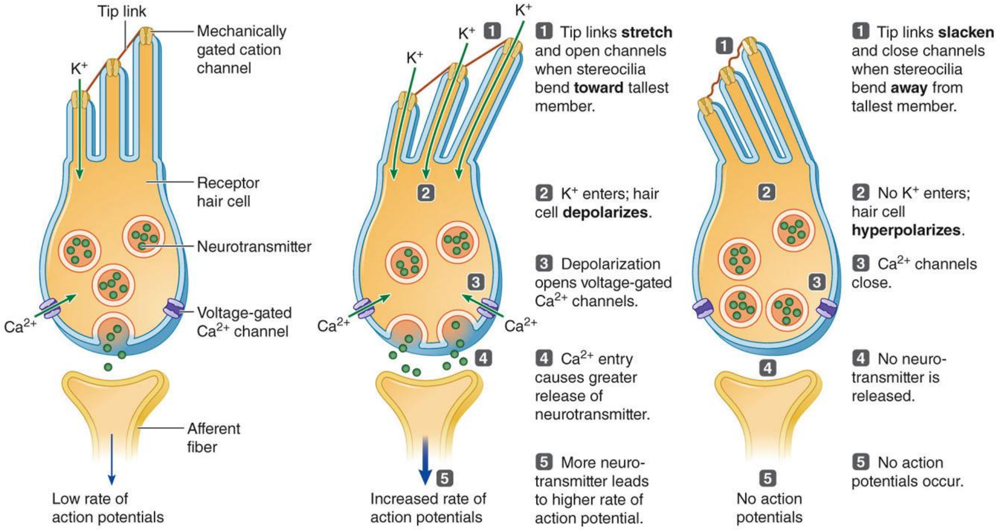
(a) Neuromasts in lateral line canal

(b) Neuromast organ

6.3 Mechanoreception: Touch, Pressure, and Proprioception



(a) Tip link pulling open mechanically gated channel

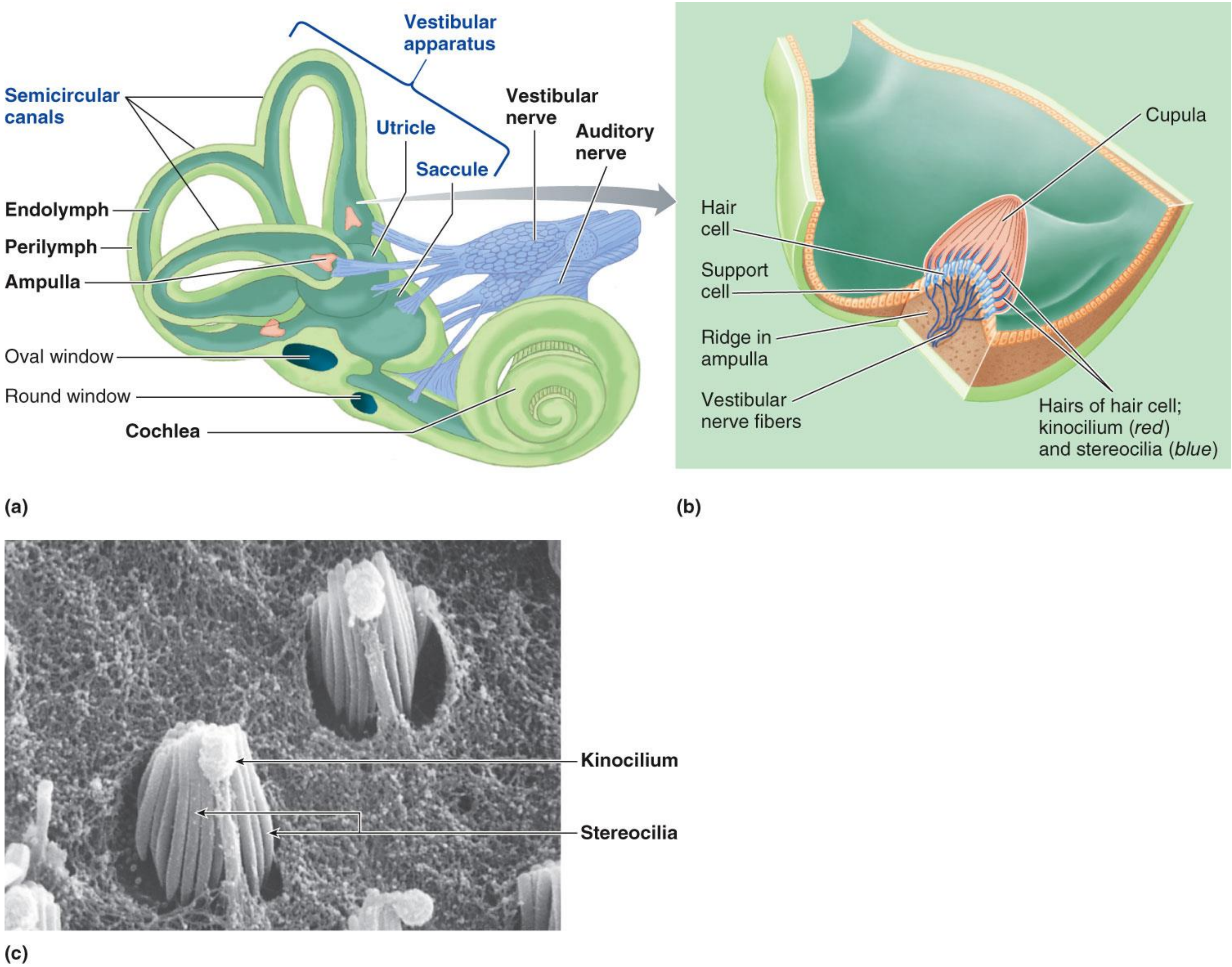


(b) Depolarization and hyperpolarization of receptor hair cell

6.3 Mechanoreception: Touch, Pressure, and Proprioception

- Vestibular apparatus of vertebrate inner ears
  - **Semicircular canals** detect rotational or angular acceleration or deceleration of the head
    - Receptive **hair cells** lie on a ridge in the ampulla
    - Semicircular canals are larger in primates that swing in trees and flying vertebrates
  - **Otolith organs** (**utricle** and **saccule**) provide information about the position of the head
  - Signals from vestibular apparatus are carried through the **vestibulocochlear nerve** to the **cerebellum** and **vestibular nuclei.**

6.3 Mechanoreception: Touch, Pressure, and Proprioception



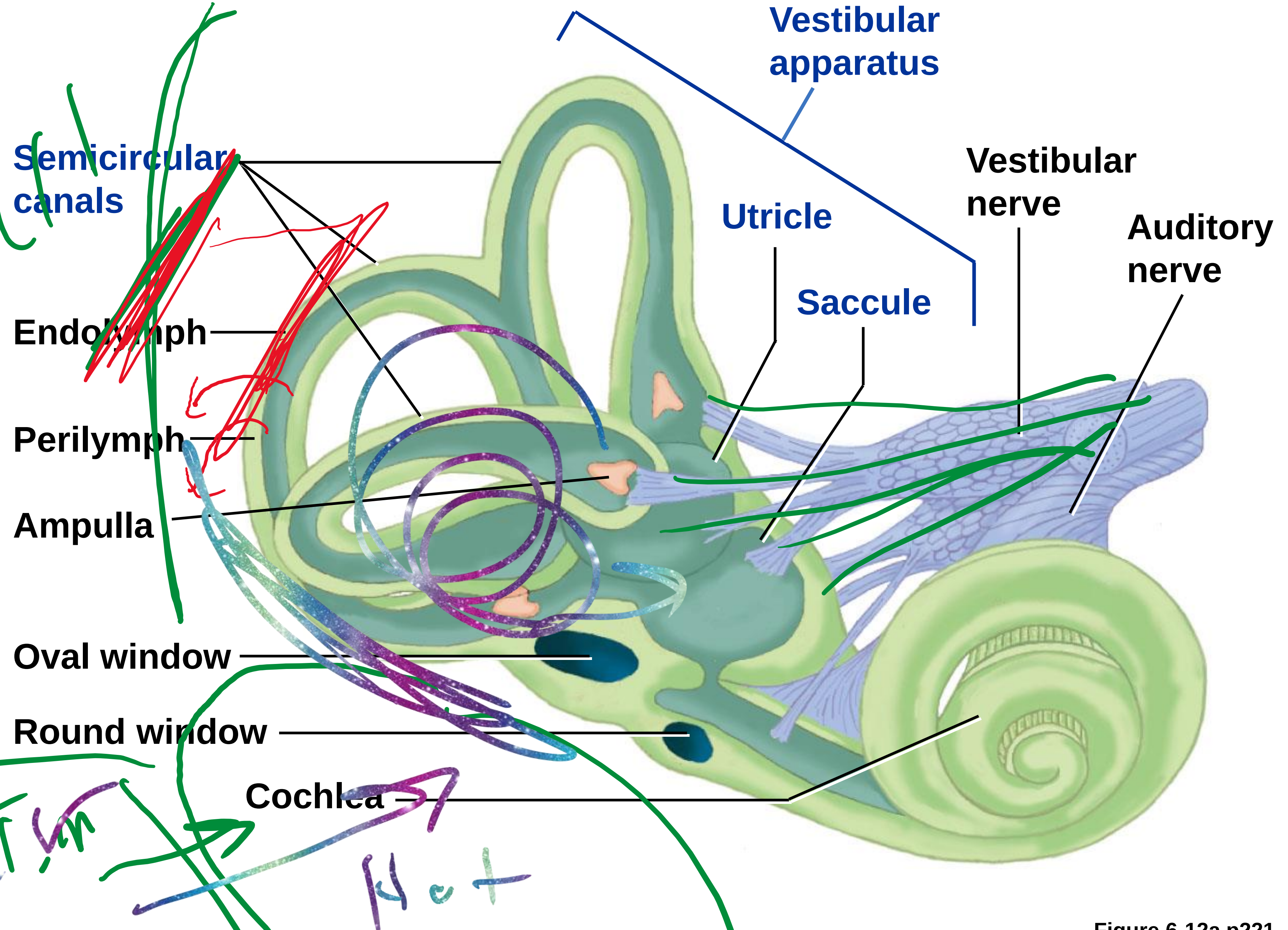


Figure 6-12a p221

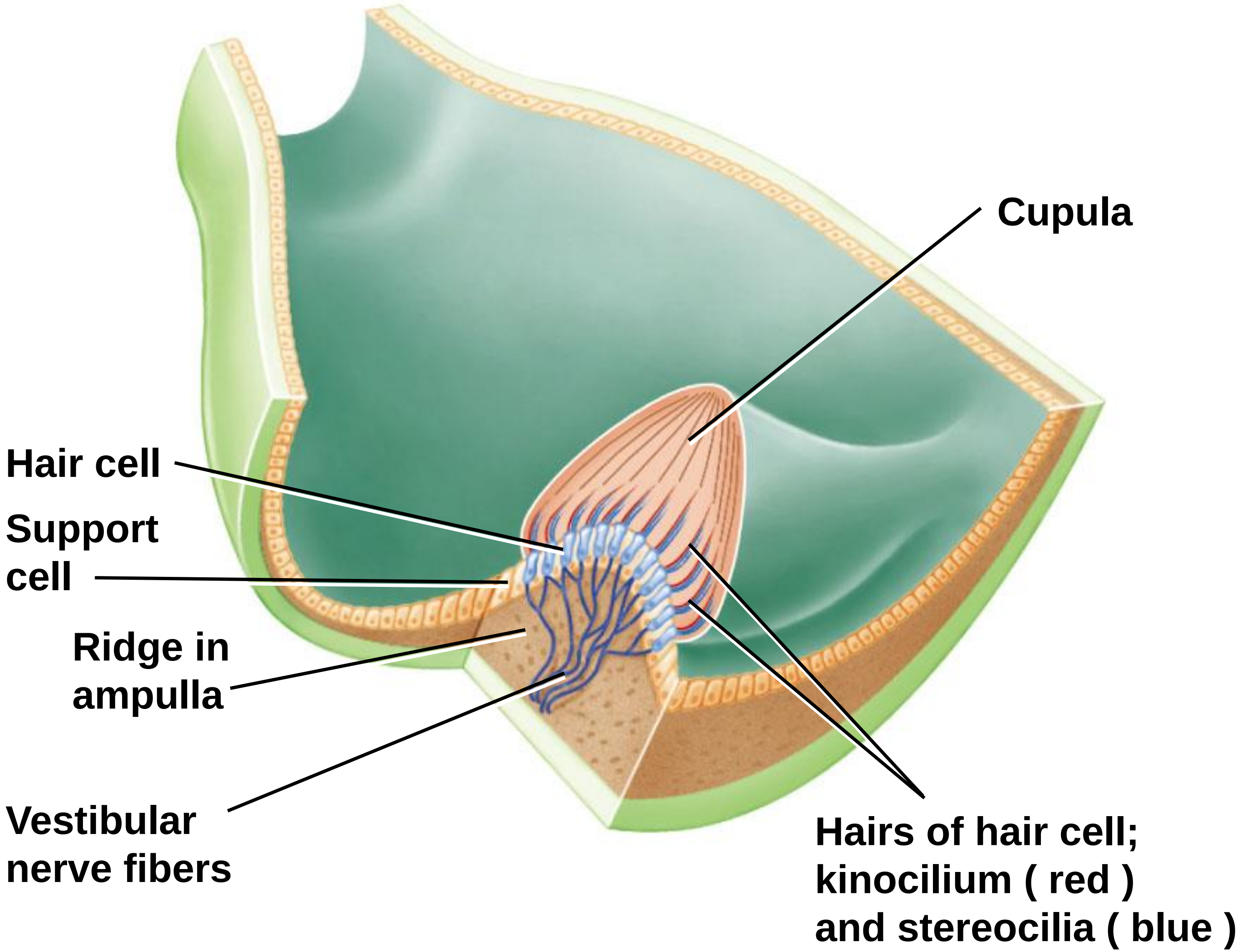


Figure 6-12b p221

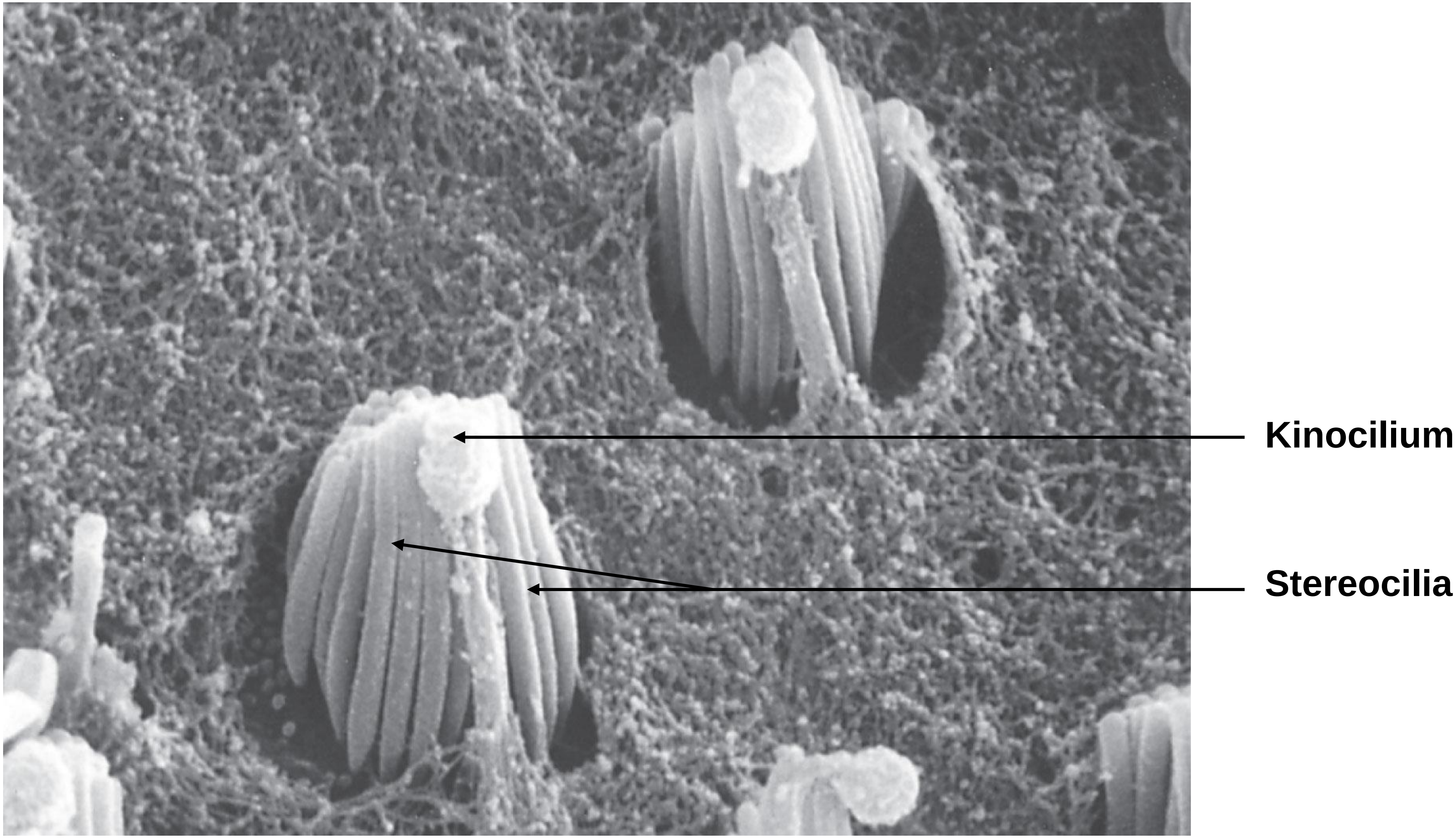
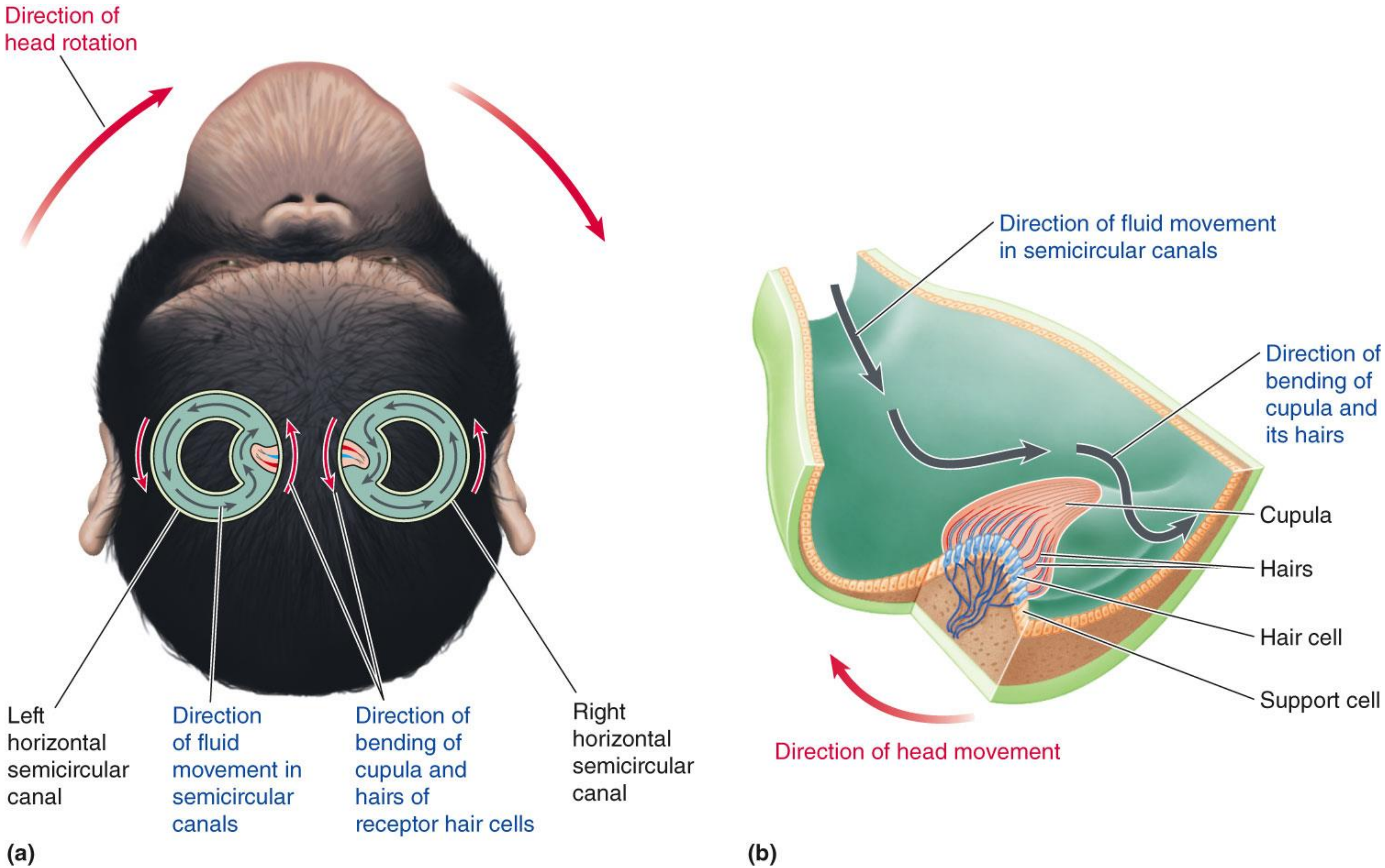
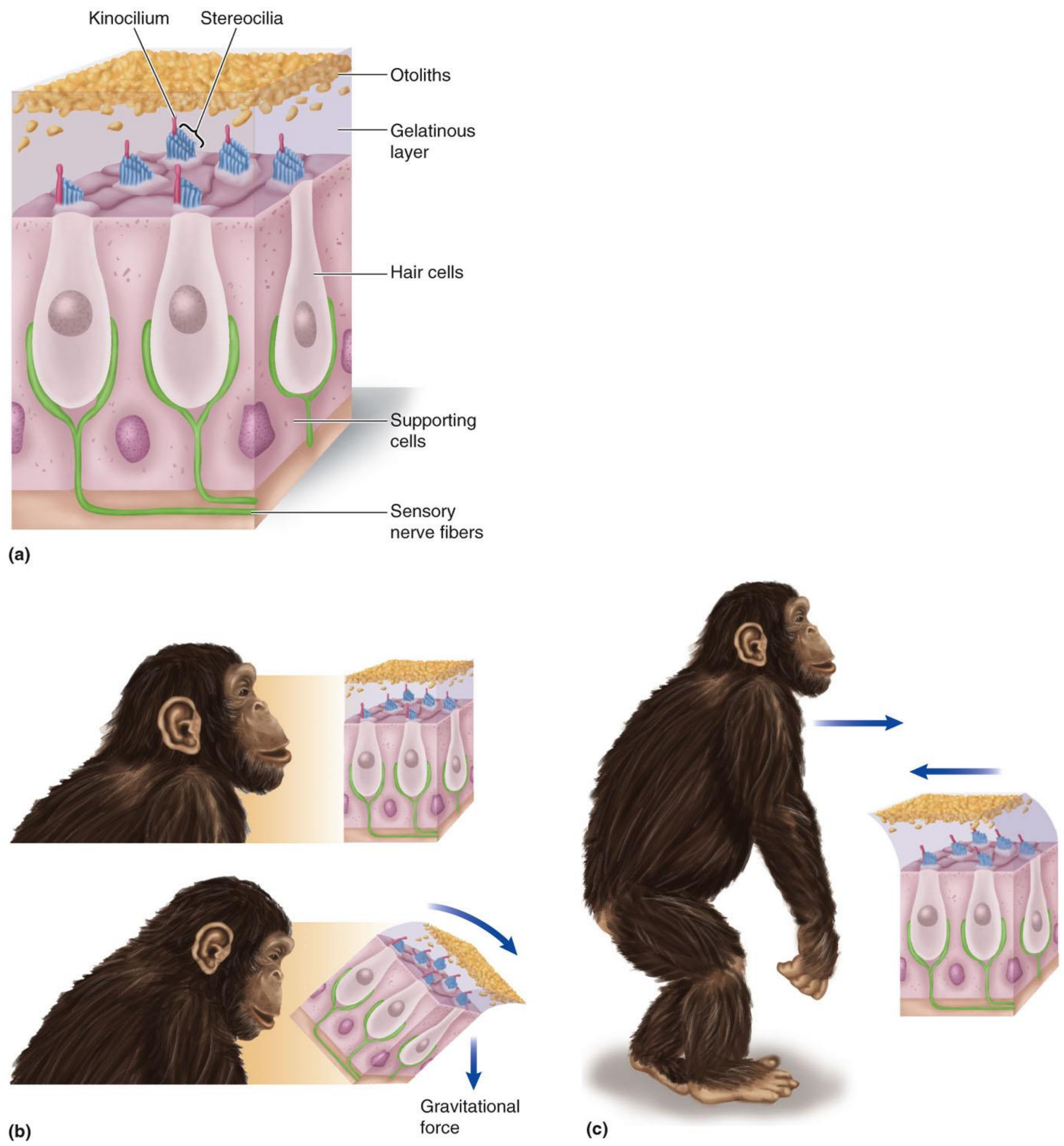


Figure 6-12c p221

6.3 Mechanoreception: Touch, Pressure, and Proprioception



6.3 Mechanoreception: Touch, Pressure, and Proprioception



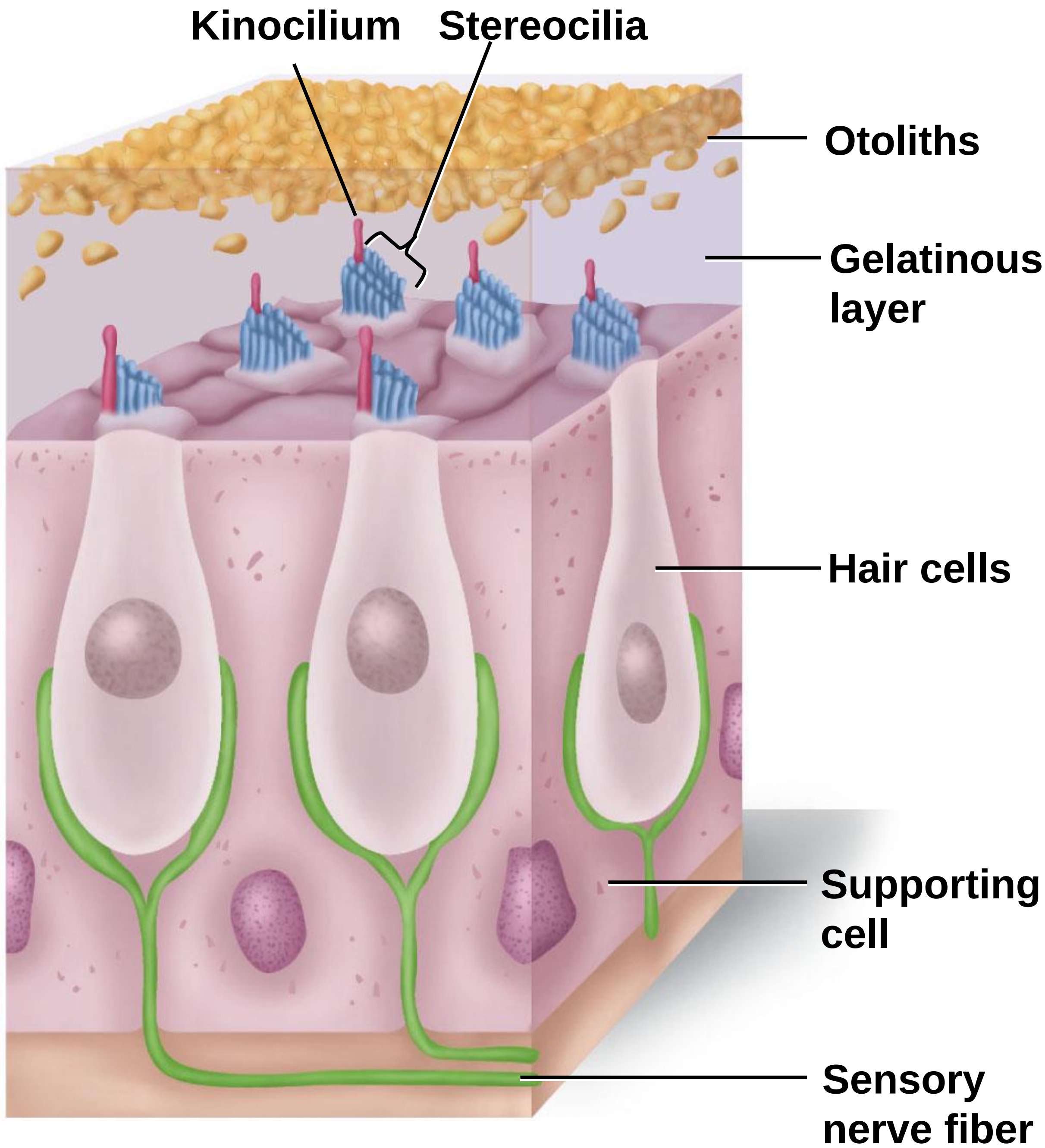
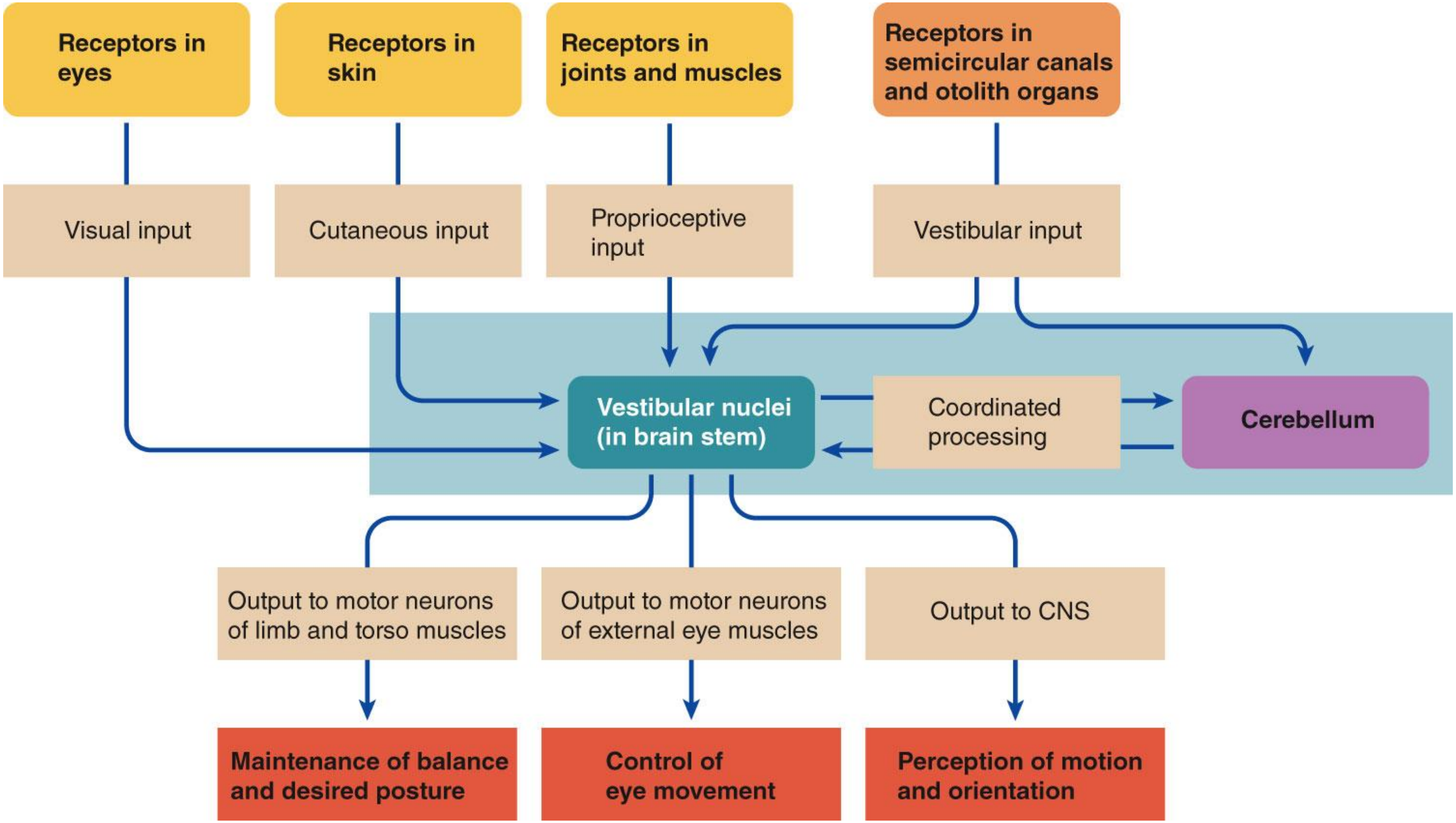


Figure 6-14a p223

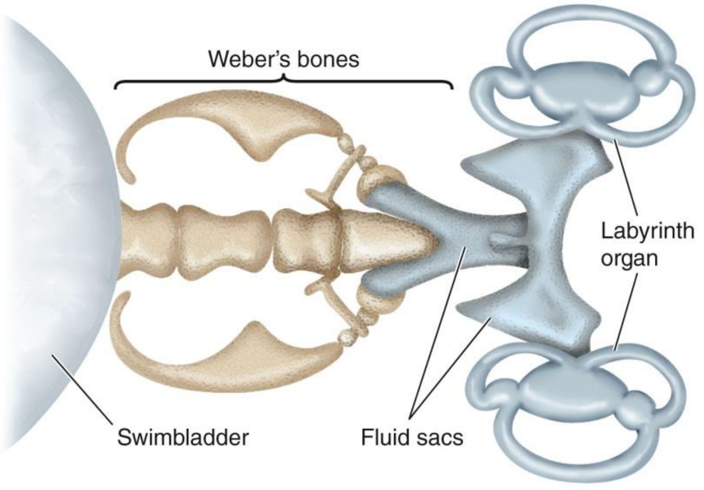
6.3 Mechanoreception: Touch, Pressure, and Proprioception



6.4 Mechanoreception: Ears and Hearing

- **Sound** travels as waves through a medium
  - Detected by **mechanoreceptors**
  - **Ear** is a complex organ of hearing

- Hearing in **fishes**
  - **Lateral lines** detect very-low-frequency sounds
  - **Weberian apparatus** -- transfers sound from gas bladder to inner ear



6.4 Mechanoreception: Ears and Hearing

- **External ear**

  - Vertebrates typically have **two ears**, allowing for localization of sound

  - **Tympanic membrane** vibrates as sound hits
    - Insects have similar structures on their abdominal segments or legs

  - **Amphibians** and some **reptiles** have only a tympanic membrane

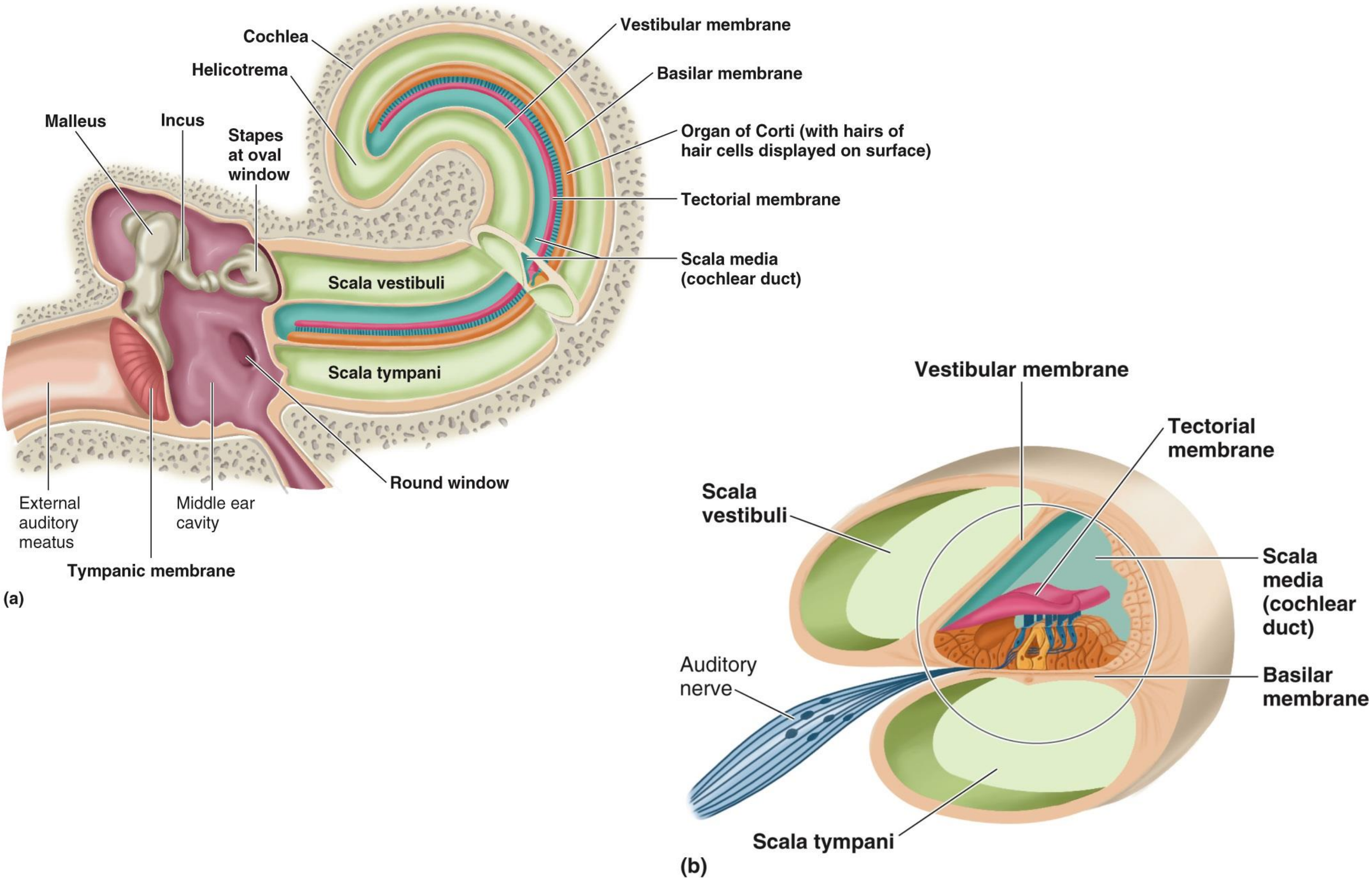
  - Mammalian external ear consists of the **pinna**, **external auditory meatus** and **tympanic membrane**

  - External ear is inconspicuous in **birds**

6.4 Mechanoreception: Ears and Hearing

- **Middle ear**
  - Transfers vibrations of the **tympanic membrane** to the **inner ear**
  - Movable chain of three small bones (**ossicles**) in mammals
    - Evolved from jaw structures
    - **Malleus** is attached to the tympanic membrane
    - **Incus** is between the malleus and stapes
    - **Stapes** is attached to the oval window
    - Single ossicle (**columella**) in anuran amphibians, reptiles and birds
  - Reflex response of middle ear muscles tightens tympanic membrane during loud sound for protection

6.4 Mechanoreception: Ears and Hearing



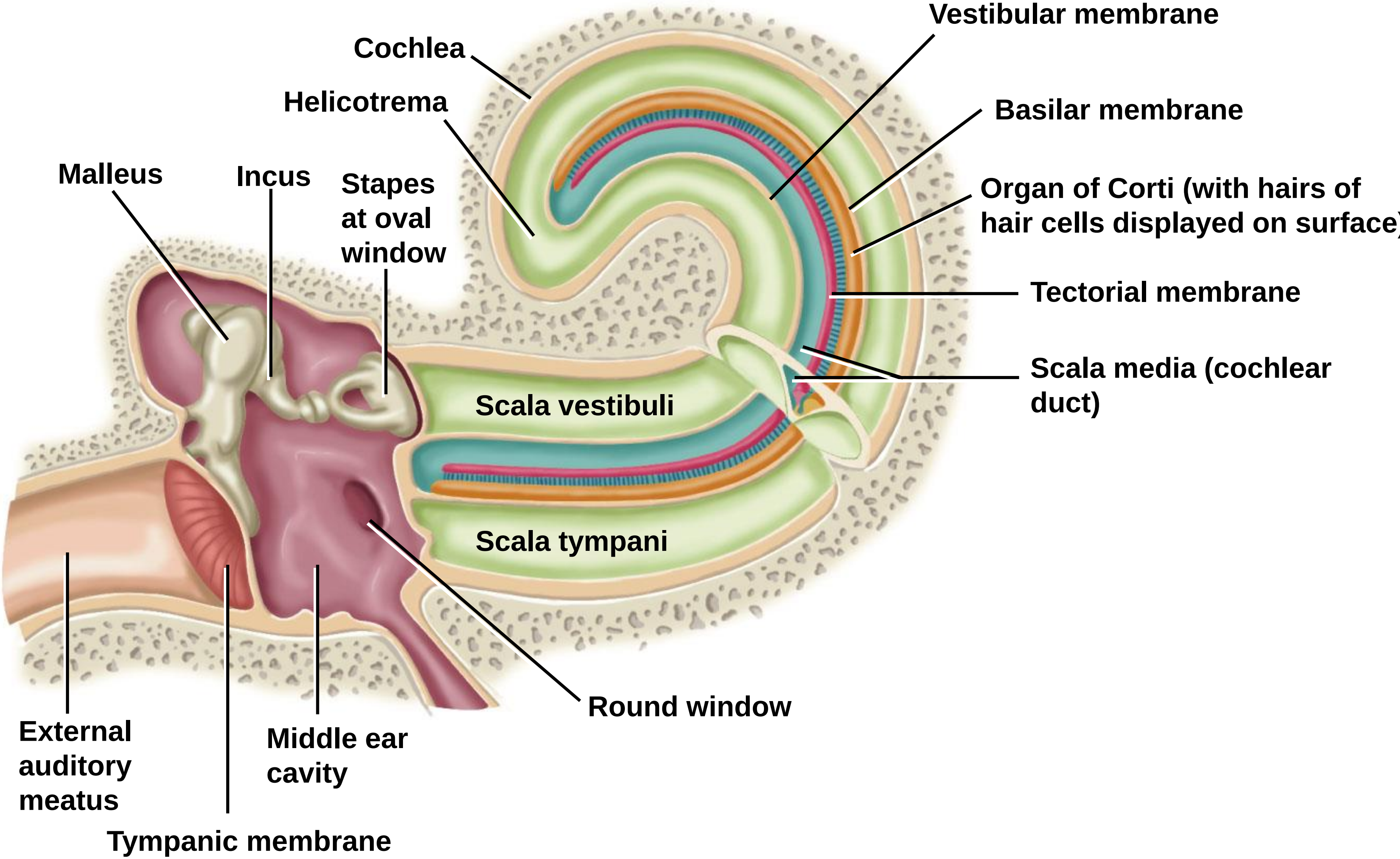


Figure 6-19a p228

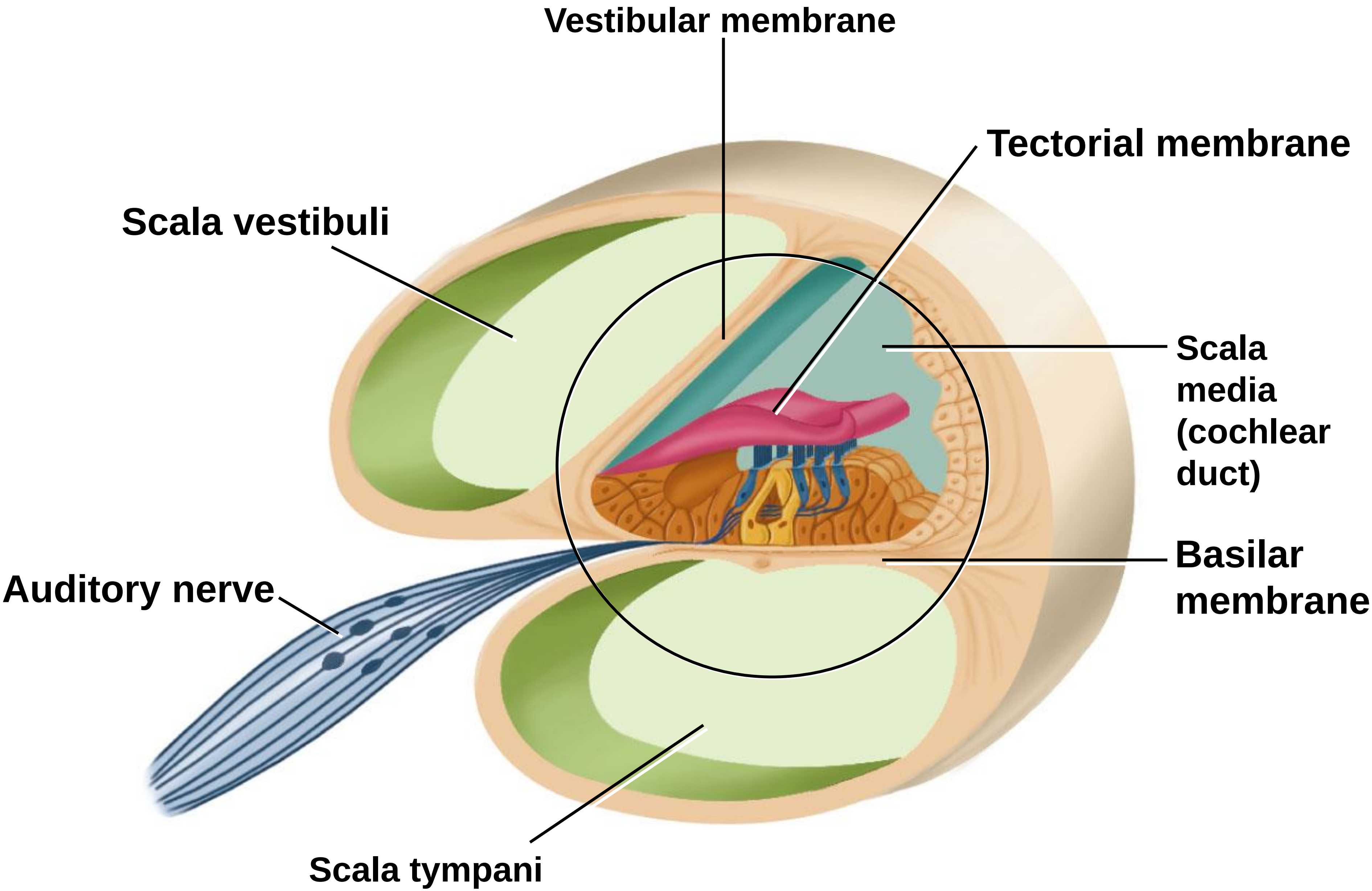
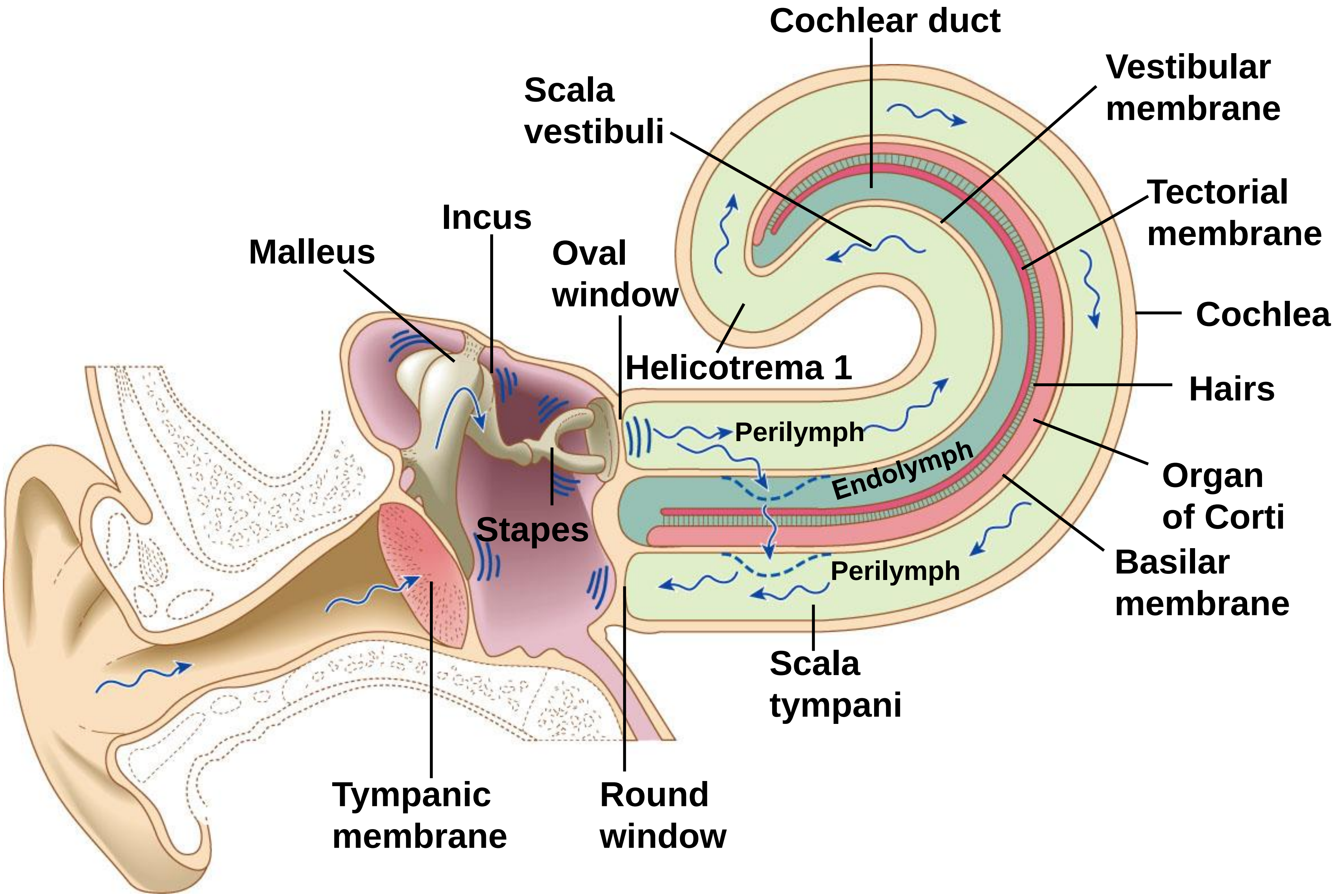


Figure 6-19b p228

6.4 Mechanoreception: Ears and Hearing

- **Inner ear**
  - **Cochlea** is a coiled tubular system with three fluid-filled longitudinal compartments
    - **Scala vestibuli** (upper) -- contains perilymph
    - **Scala media** or **cochlear duct** (middle) -- contains endolymph
    - **Scala tympani** (lower) -- contains perilymph
  - **Organ of Corti** is the sense organ for hearing
    - On top of **basilar membrane** in the floor of the cochlear duct
    - 15,000 **hair cells** arranged in four parallel rows
    - Inner row of hair cells transform cochlear fluid vibration into action potentials



Fluid movement within the perilymph set up by vibration of the oval window follows two pathways:

Figure 6-20a p230

The stereocilia (hairs) from the hair cells of the basilar membrane contact the overlying tectorial membrane. These hairs are bent when the basilar membrane is deflected in relation to the stationary tectorial membrane. This bending of the inner hair cells' hairs opens mechanically gated channels, leading to ion movements that result in a receptor potential.

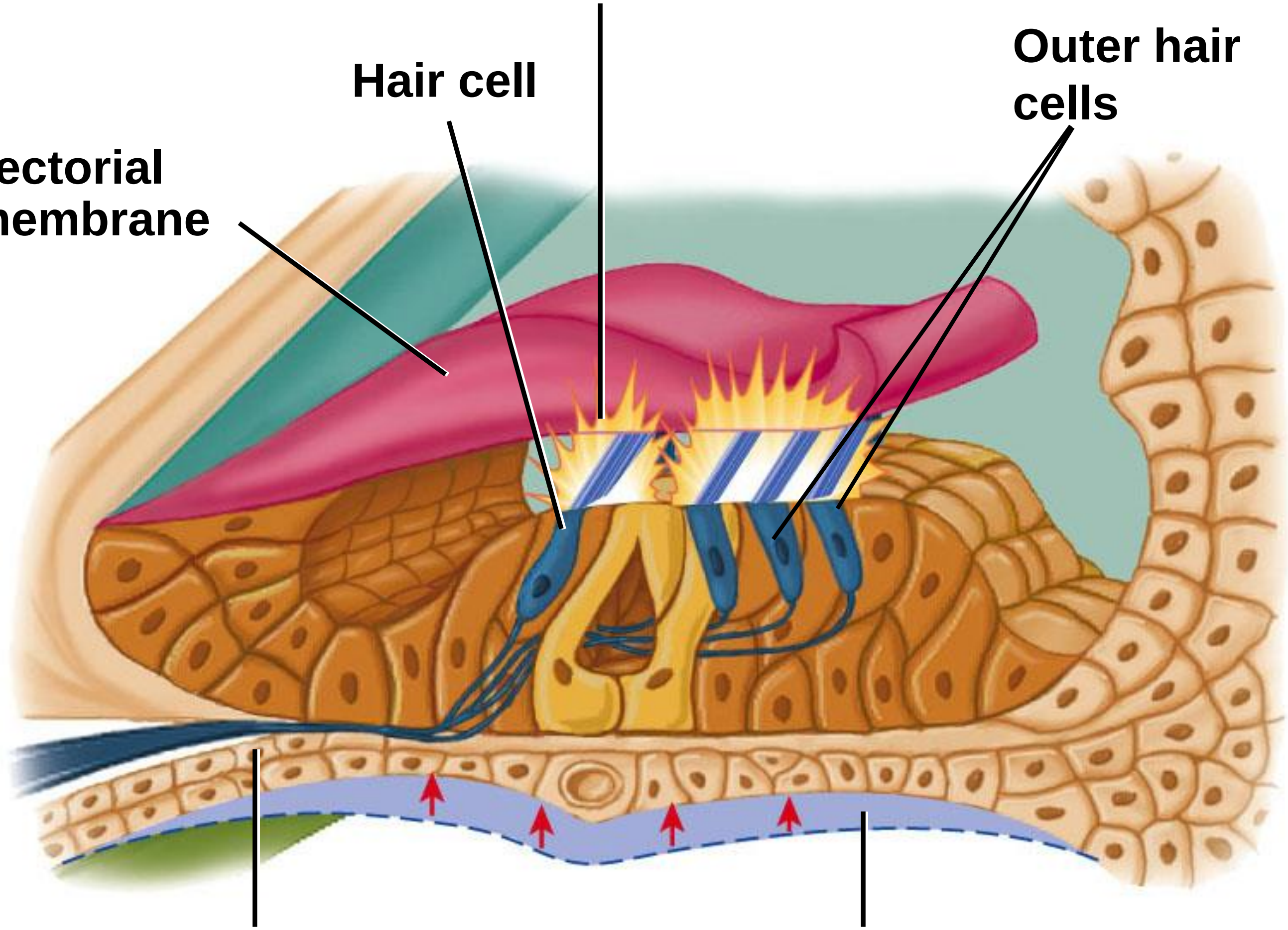
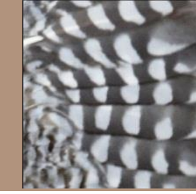


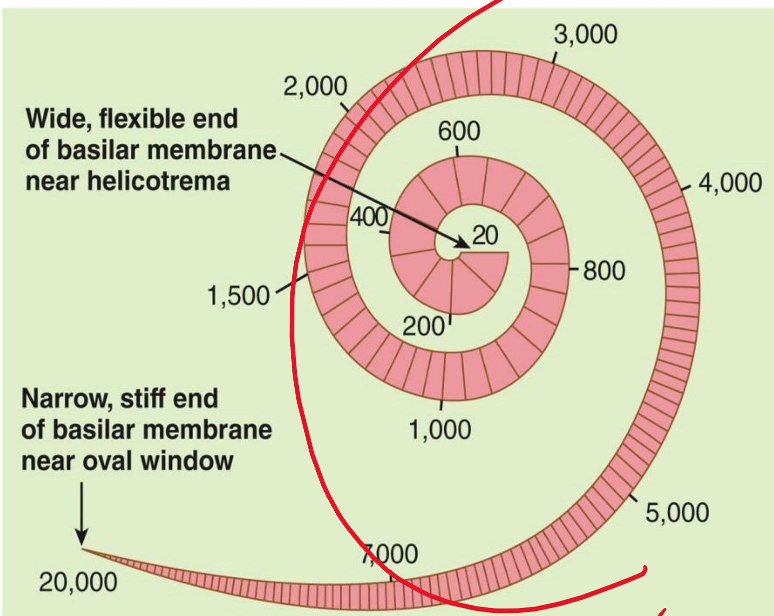
Figure 6-19c p228

6.4 Mechanoreception: Ears and Hearing



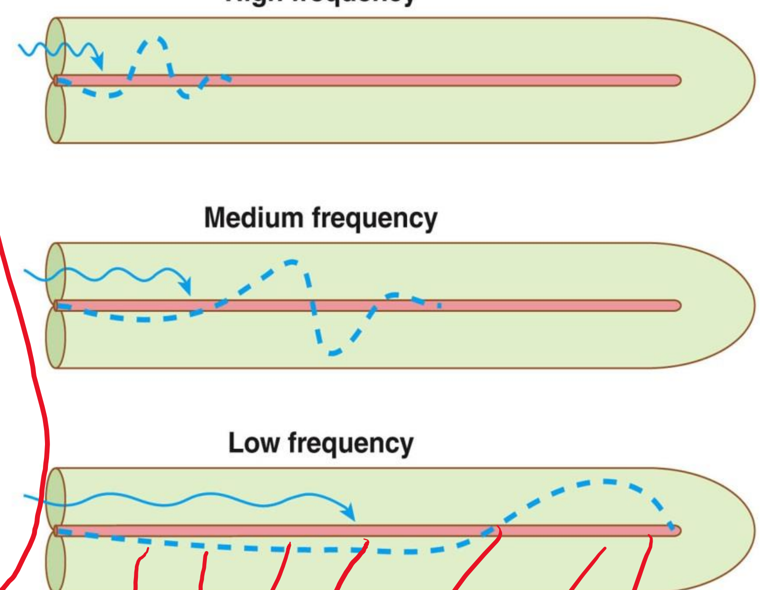
Pathway 1: Through the scala vestibuli, around the heliocotrema, and through the scala tympani, causing the round window to vibrate. This pathway just dissipates sound energy.

(a)



(b) The numbers indicate the frequencies in cycles per second with which different regions of the basilar membrane maximally vibrate.

Pathway 2: A "shortcut" from the scala vestibuli through the basilar membrane to the scala tympani. This pathway triggers activation of the receptors for sound by bending the hairs of hair cells as the organ of Corti on top of the vibrating basilar membrane is displaced in relation to the overlying tectorial membrane.



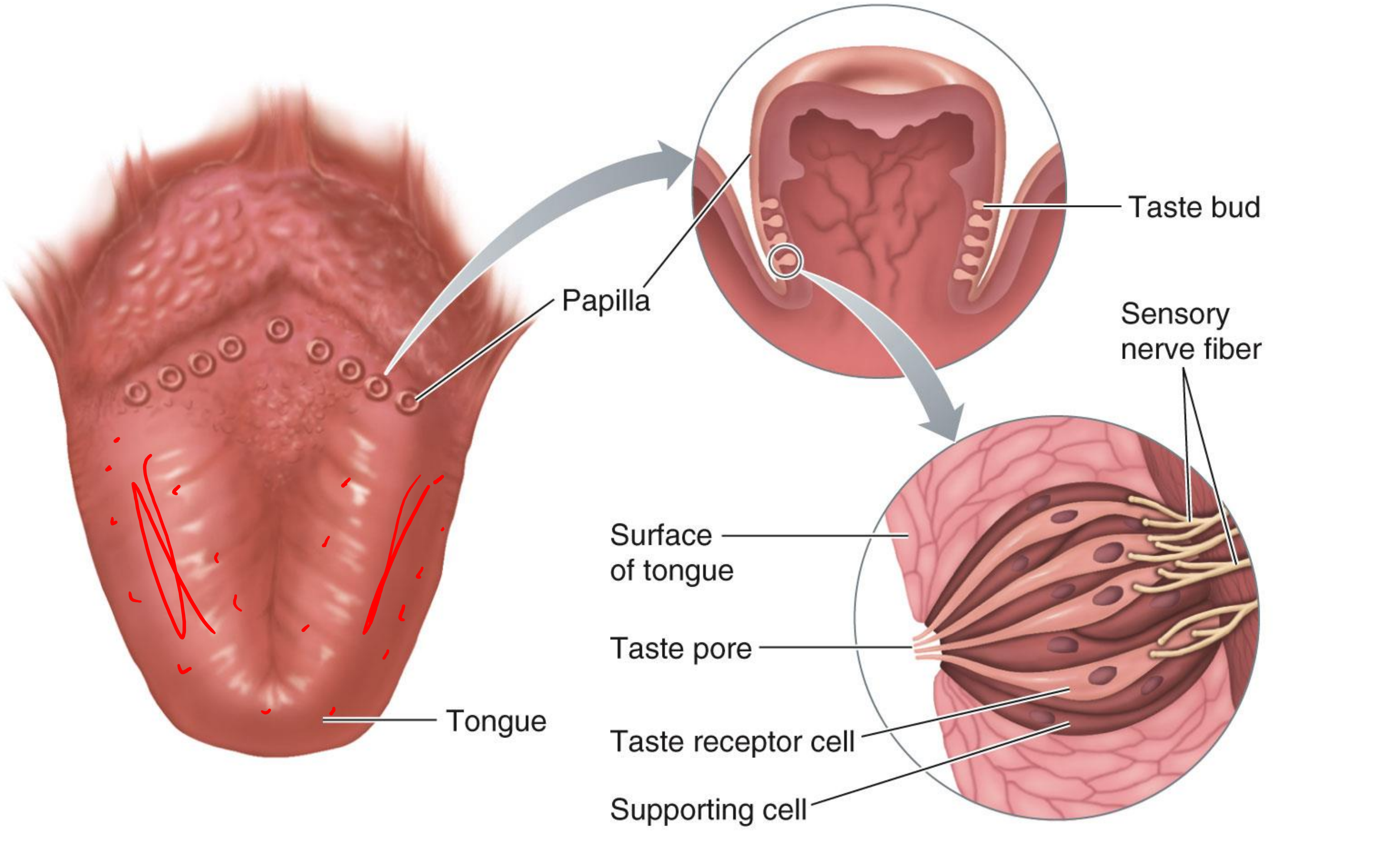
(c)

H. freq
L. freq
Tonotopic array

6.5 Chemoreception: Taste and Smell

- Chemoreceptors for **taste (gustatory)** sensation
  - Each mammalian **taste bud** has about 50 receptor cells, supporting cells and a taste pore
    - Only chemicals in solution can evoke taste sensation
  - Microvilli contain **chemoreceptors**
  - Binding of **tastant** with receptor cell alters ion channels to produce a depolarizing receptor potential
  - Action potentials are carried to the **cortical gustatory area** (parietal lobe), **hypothalamus** and **limbic system**

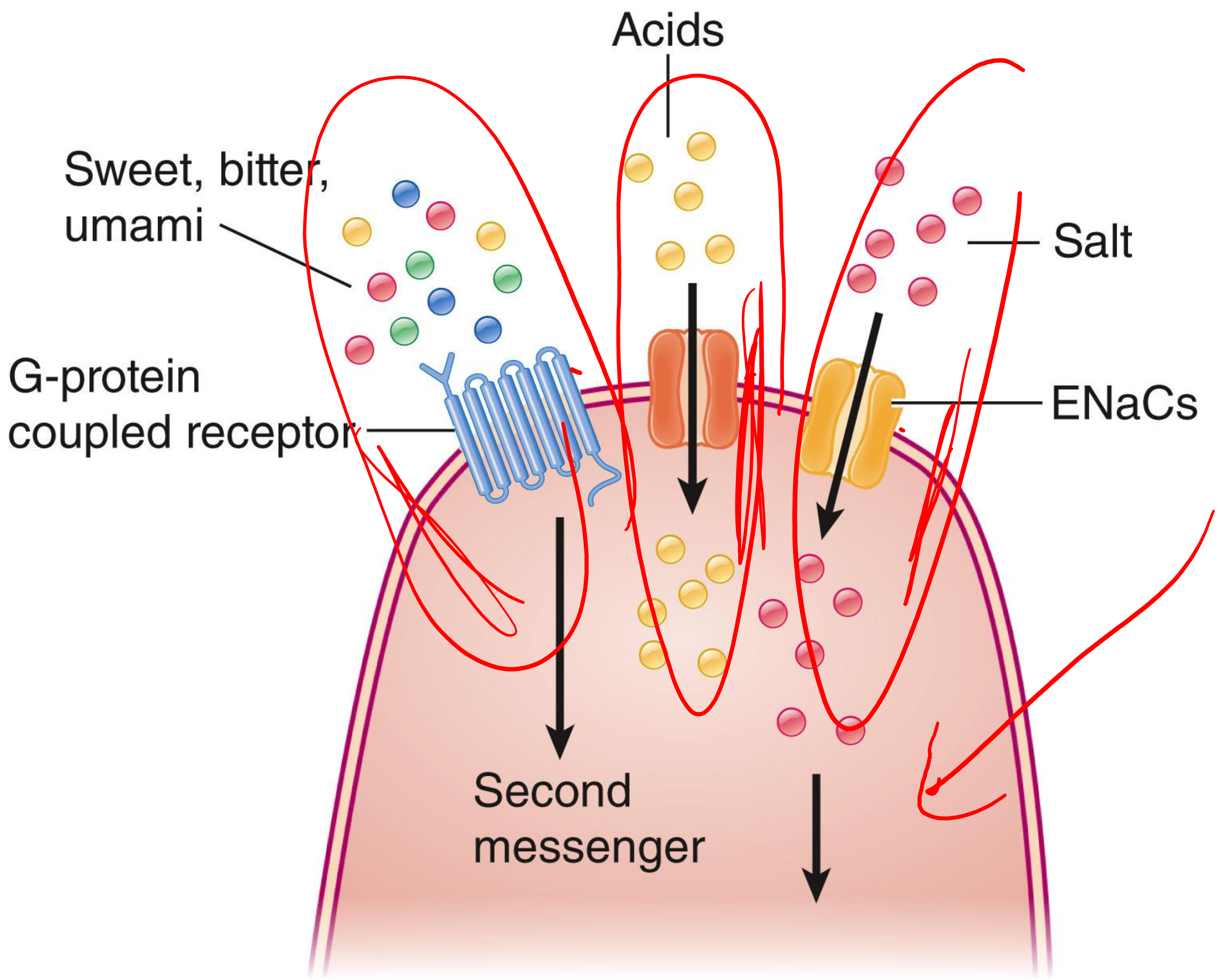
6.5 Chemoreception: Taste and Smell



6.5 Chemoreception: Taste and Smell

- Primary tastes
  - **Salty** (sodium)
    - Direct entry of Na^+ ions through channels in receptor cell membrane
  - **Sour** (acid)
    - H^+ blocks K^+ efflux from cell
  - **Sweet** (sugar)
    - G-protein-coupled receptor stimulates cAMP or IP_3 pathway
  - **Bitter** (plant alkaloids)
    - Variety of G-protein-coupled receptor mechanisms
  - **Umami** (savory)
    - Glutamate binds to G-protein-coupled receptor

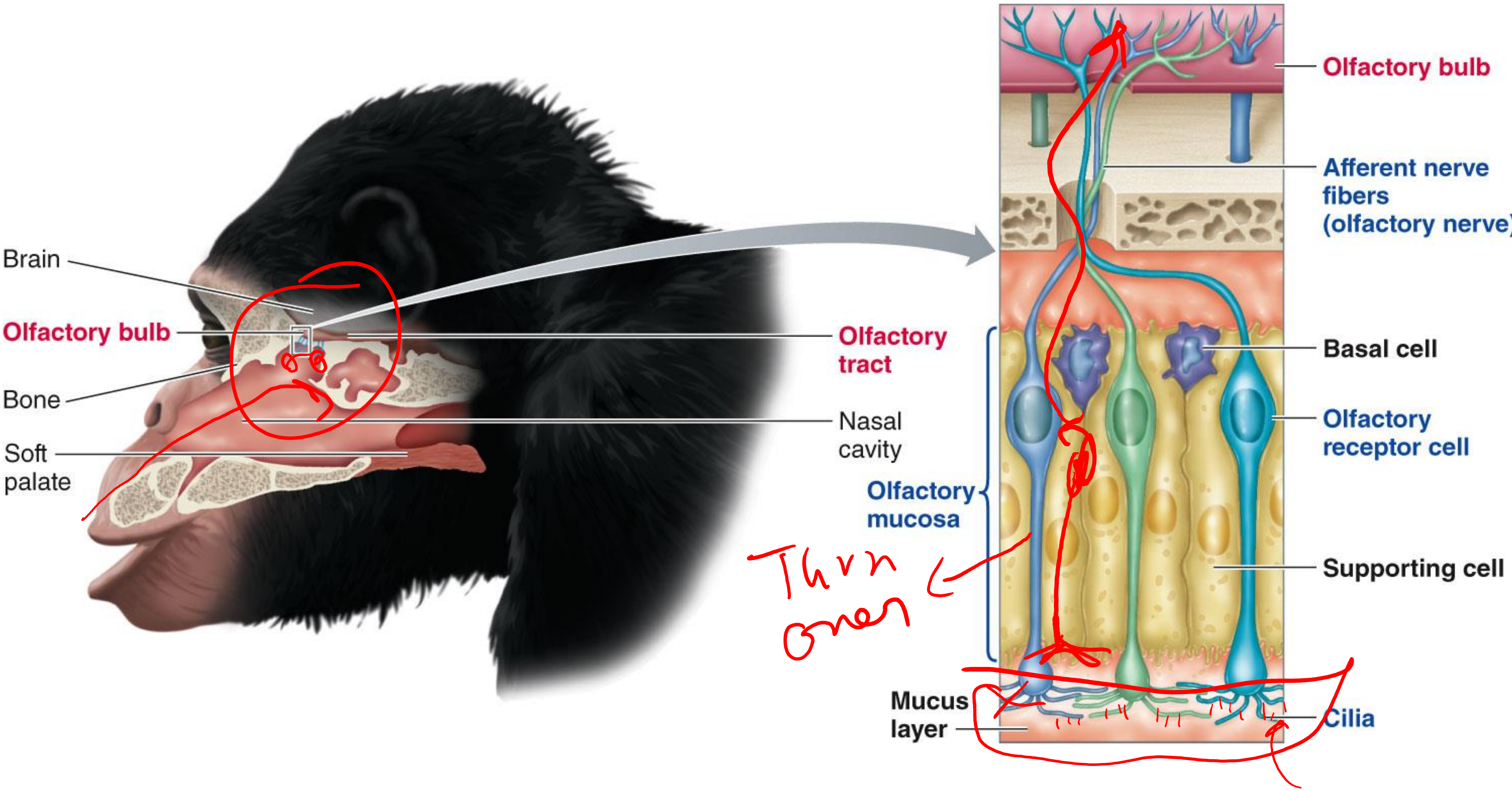
6.5 Chemoreception: Taste and Smell



6.5 Chemoreception: Taste and Smell

- Chemoreceptors for **olfactory** (smell) sensation
  - **Olfactory mucosa** in **nasal fossae** contains olfactory receptors, supporting cells and basal cells
  - Olfactory afferent neurons are the only mammalian neurons that undergo cell division
  - Each receptor responds to only **one discrete component** of an odor
  - Odorant binds to G-protein-coupled receptor

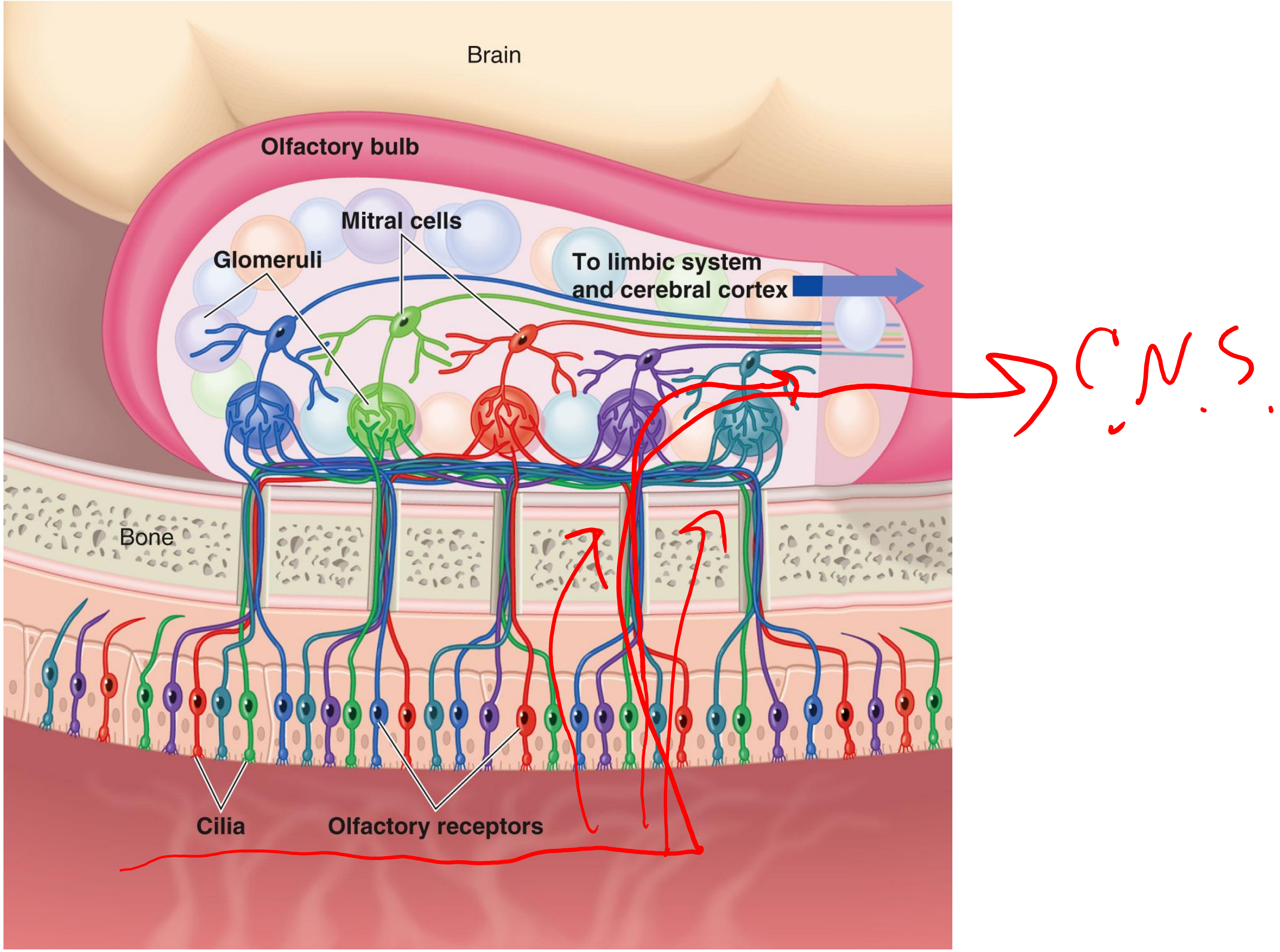
6.5 Chemoreception: Taste and Smell



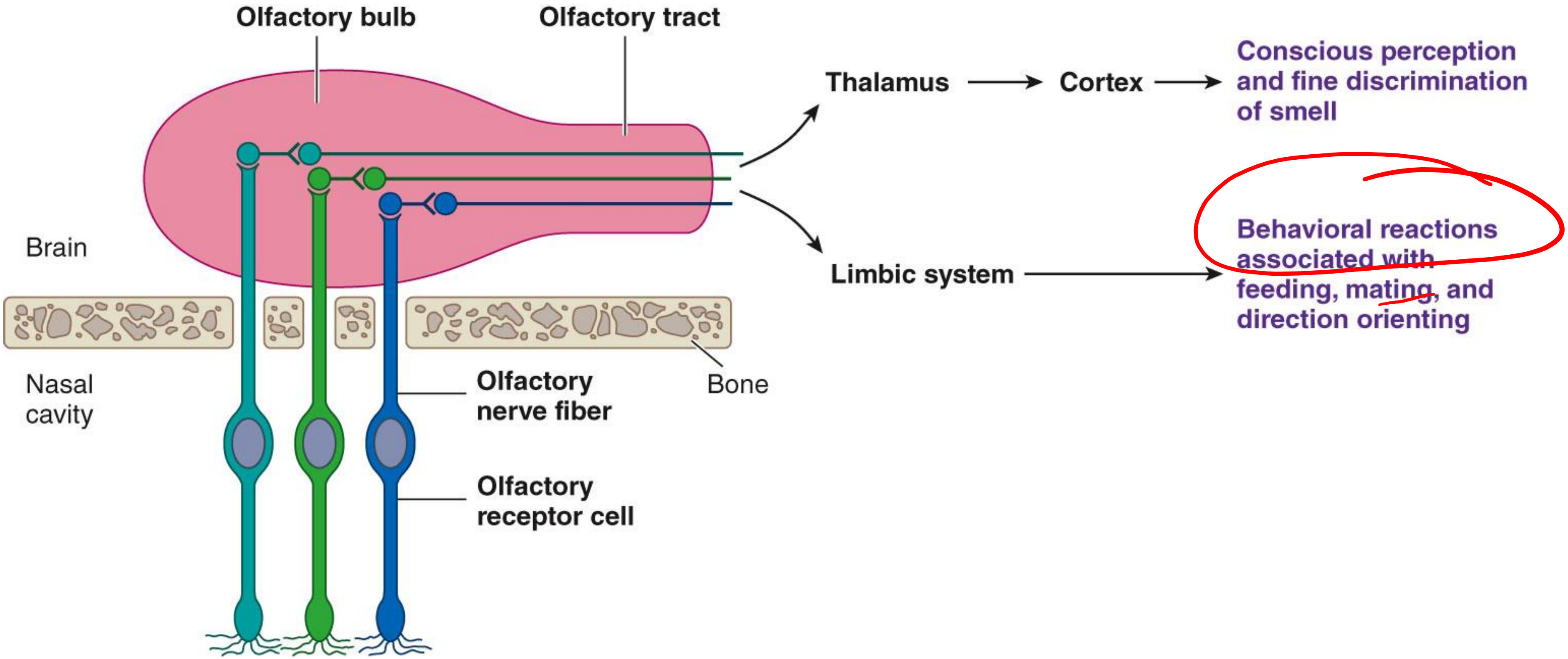
6.5 Chemoreception: Taste and Smell

- Olfactory processing
  - Afferent fibers synapse on **mitral cells** in **glomeruli** of the **olfactory bulb**
    - **Glomeruli** serve as "smell files", each detecting one particular odor component
  - **Mitral cells** refine smell signals and relay them to the brain
    - **Subcortical route** to **primary olfactory cortex** in lower medial temporal lobe associated with memory and behavior
    - **Thalamic-cortical route** permits conscious perception and fine discrimination of smell
  - Cortex can distinguish **20,000 different scents** from 1,000 or fewer different receptor proteins

6.5 Chemoreception: Taste and Smell



6.5 Chemoreception: Taste and Smell



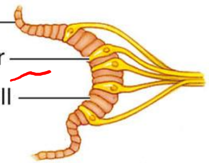
6.5 Chemoreception: Taste and Smell

- Vomeronasal organ (VNO)
  - In noses of mammals and reptiles
  - Governs reproductive and social behaviors by reception of **pheromones**
  - **Pheromones** are volatile chemical messengers released into the environment for intraspecies communication

6.6 Photoreception: Eyes and Vision

- Light sensing organs
  - **Eyespots**
    - Less than 100 photoreceptor cells lining an open cup
    - Permits animal to locate a light source
    - Platyhelminthes, Cnidarians, and Echinoderms
  - **Pinhole eye**
    - Size of cup aperture is reduced
    - Permits formation of an image
  - **Camera eye**
    - Lens enhances light-gathering power
    - Many phyla, including vertebrates and cephalopods
  - **Compound eye**
    - Densely packed units (**ommatidia**), each having its own lens and photoreceptors
    - Arthropods

6.6 Photoreception: Eyes and Vision



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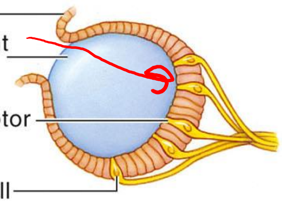

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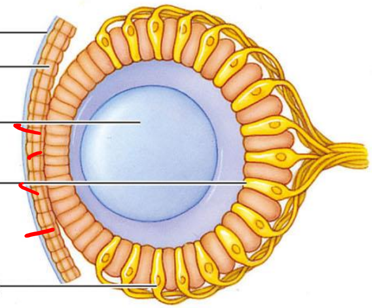
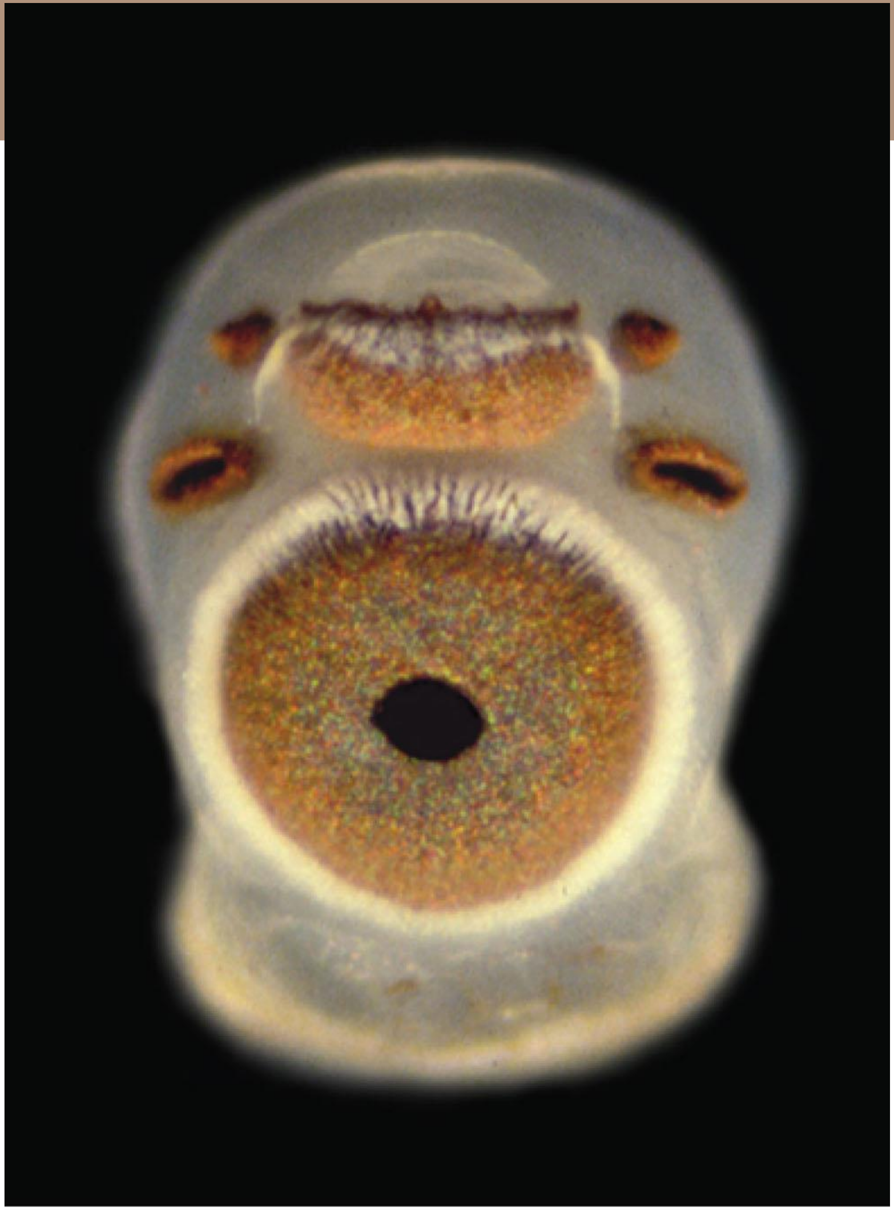


(c)


(d)


(e)

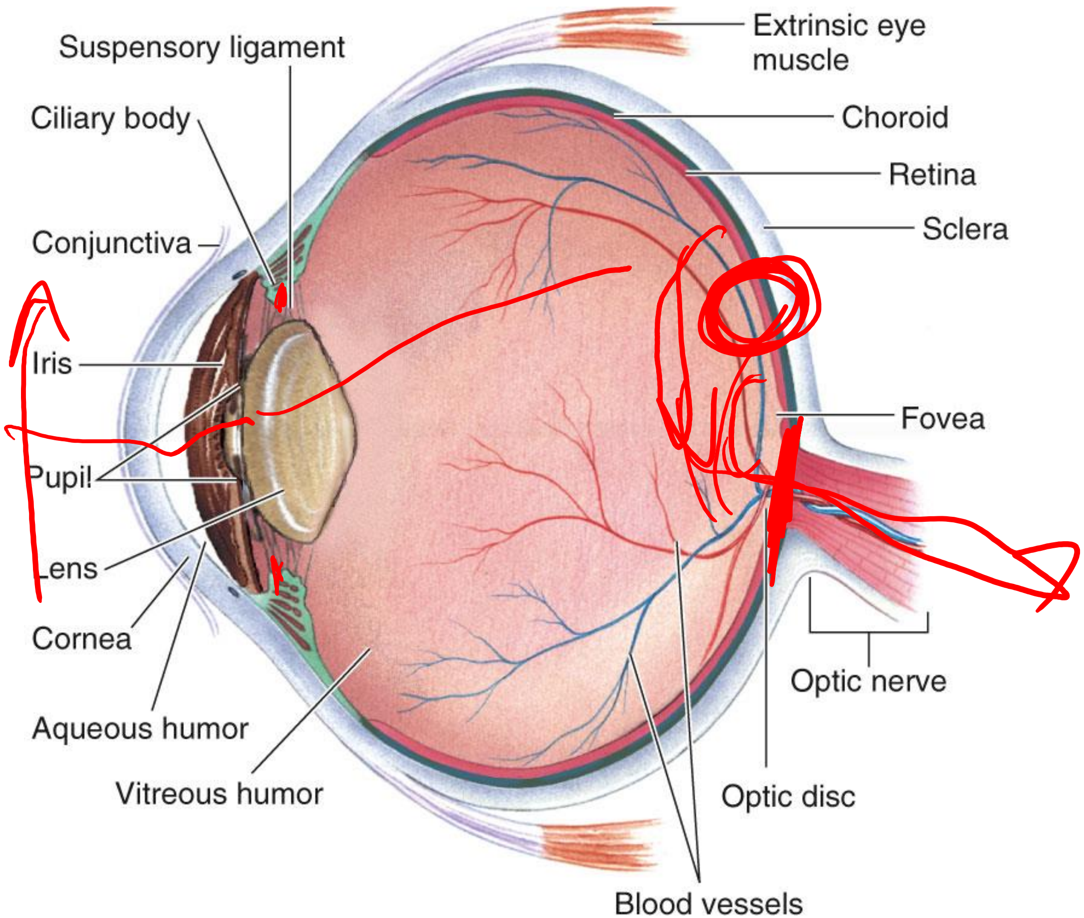


(d)

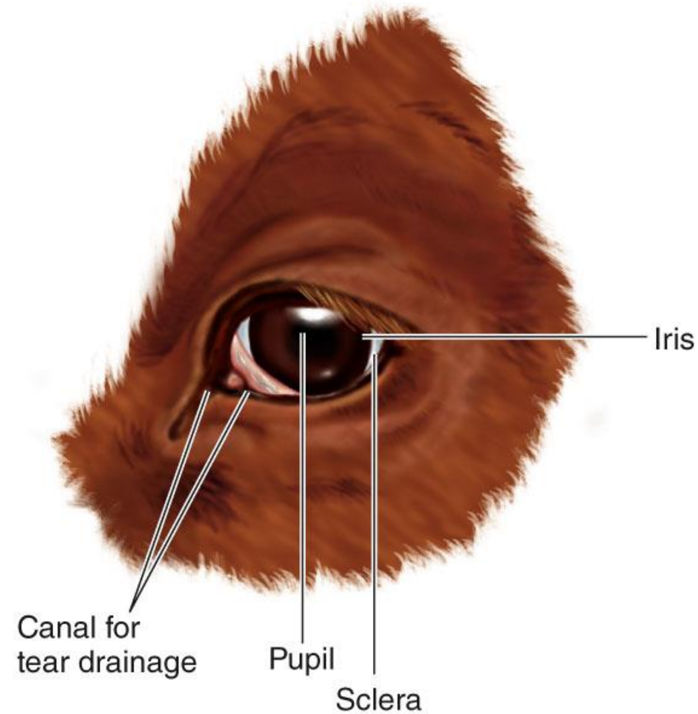
Figure 6-27d p240

(e)

6.6 Photoreception: Eyes and Vision



(a)

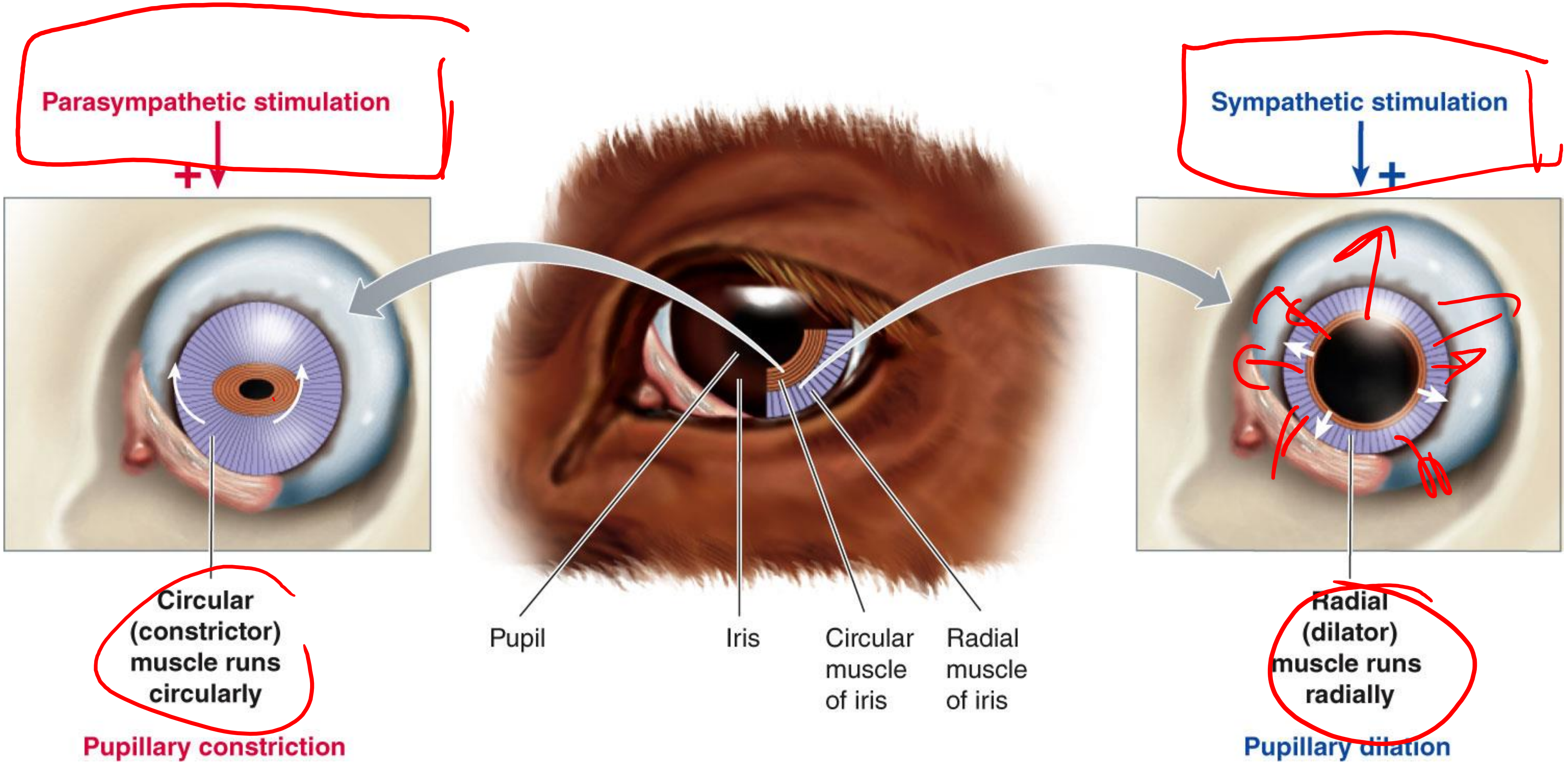


(b)

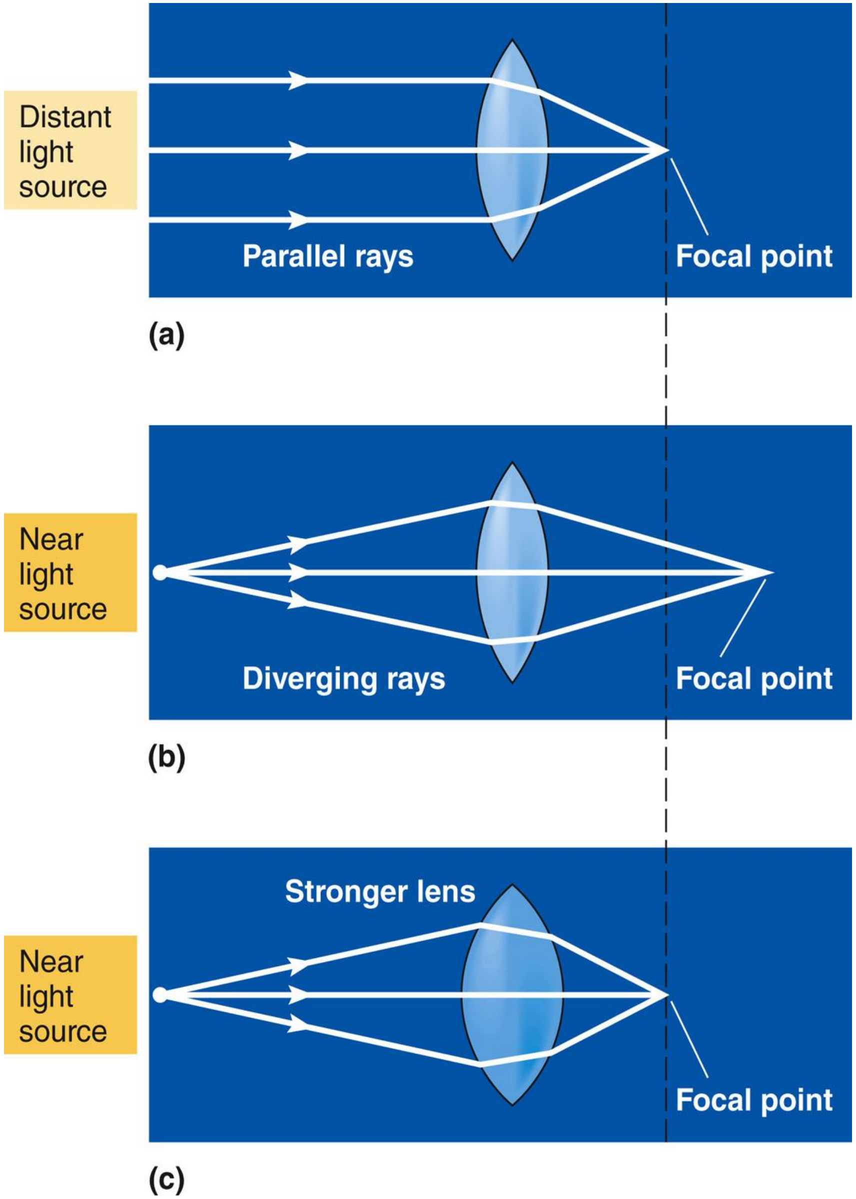
6.6 Photoreception: Eyes and Vision

- The iris controls the amount of light entering the eye.
  - **Iris** is a pigmented ring of smooth muscle
  - Round central opening is the **pupil**
  - **Circular muscle** constricts pupil in response to light
  - **Radial muscle** increases pupil size in dim light
  - Iris muscles are controlled by the **autonomic nervous system**
    - **Parasympathetic** fibers innervate circular muscle
    - **Sympathetic** fibers innervate radial muscle

6.6 Photoreception: Eyes and Vision



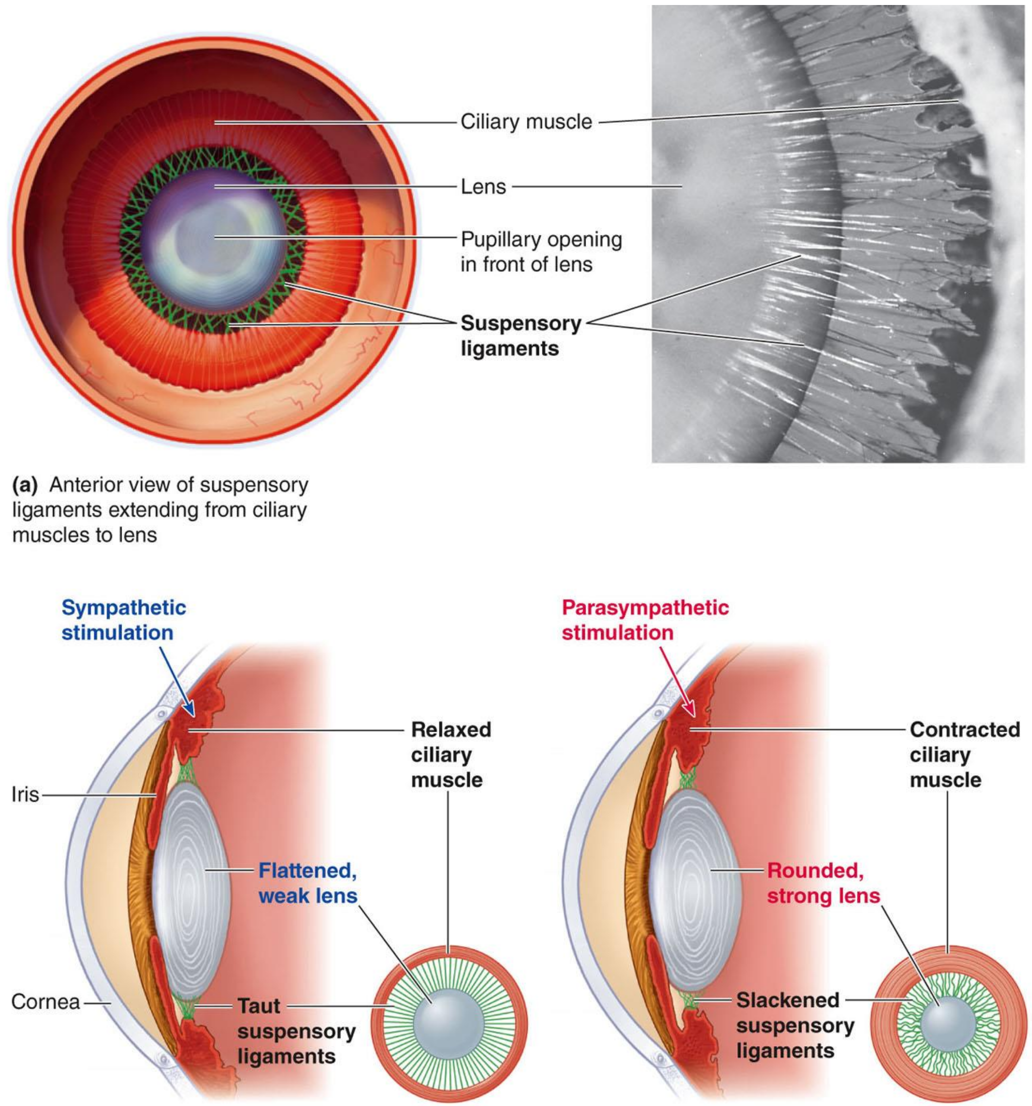
6.6 Photoreception: Eyes and Vision



6.6 Photoreception: Eyes and Vision

- Light is focused on the retina by adjusting the strength of the lens (**accommodation**)
  - **Convex** surfaces of the **cornea** and **lens** determine the eye's refractive ability
  - **Curvature of the lens** is adjusted by the **ciliary muscle** in mammals, birds and some reptiles
  - In fish, the **lens is moved** back and forth to focus, due to the lens' fixed focal length
  - Some annelids alter the distance between the lens and photoreceptors by **changing the fluid volume** of the optic chamber.

6.6 Photoreception: Eyes and Vision

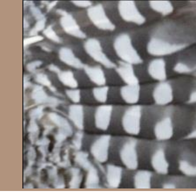


(a) Anterior view of suspensory ligaments extending from ciliary muscles to lens

(b) Sagittal and anterior view when ciliary muscle is relaxed

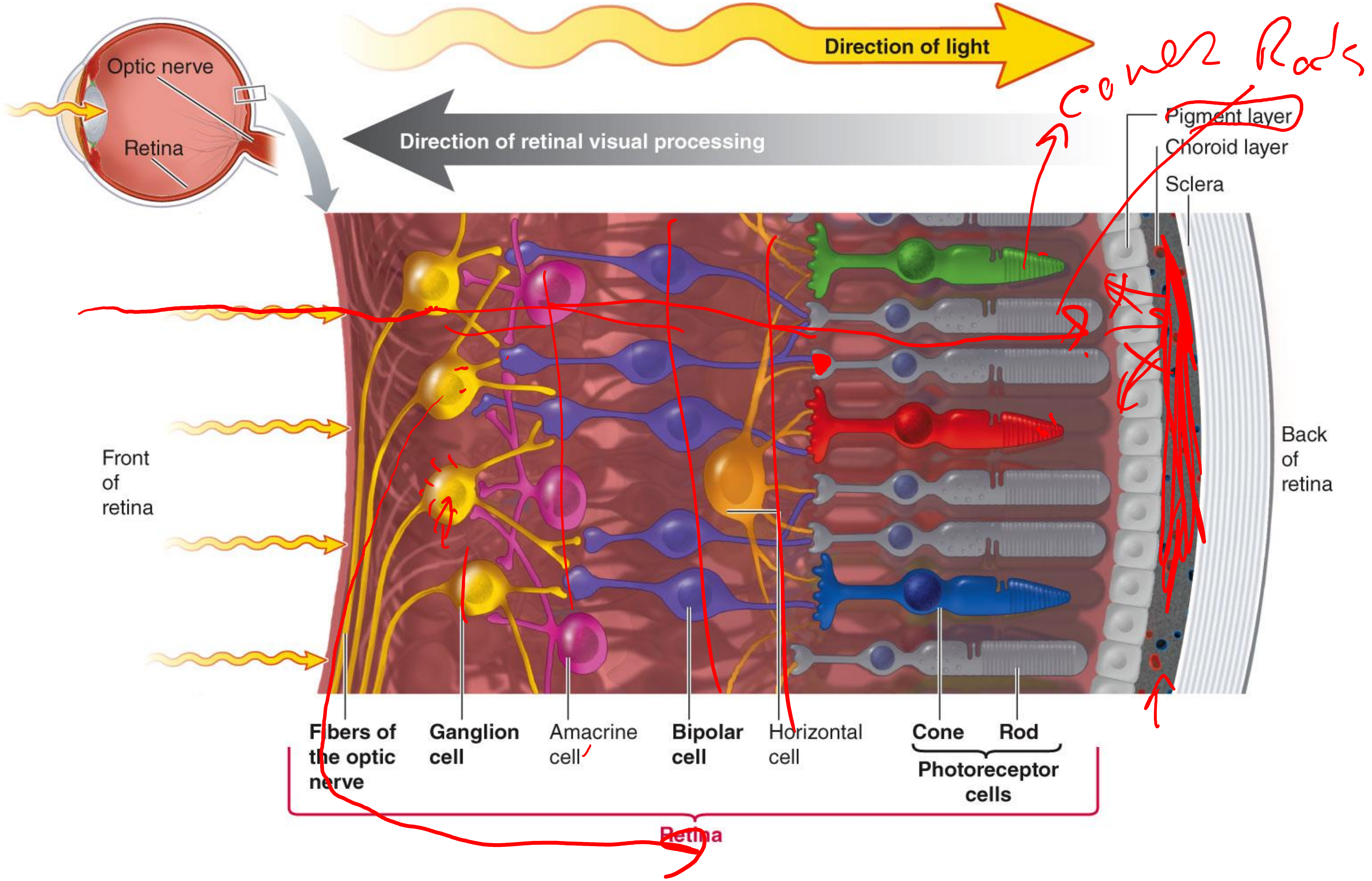
(c) Sagittal and anterior view during accommodation, when ciliary muscle is contracted

6.6 Photoreception: Eyes and Vision

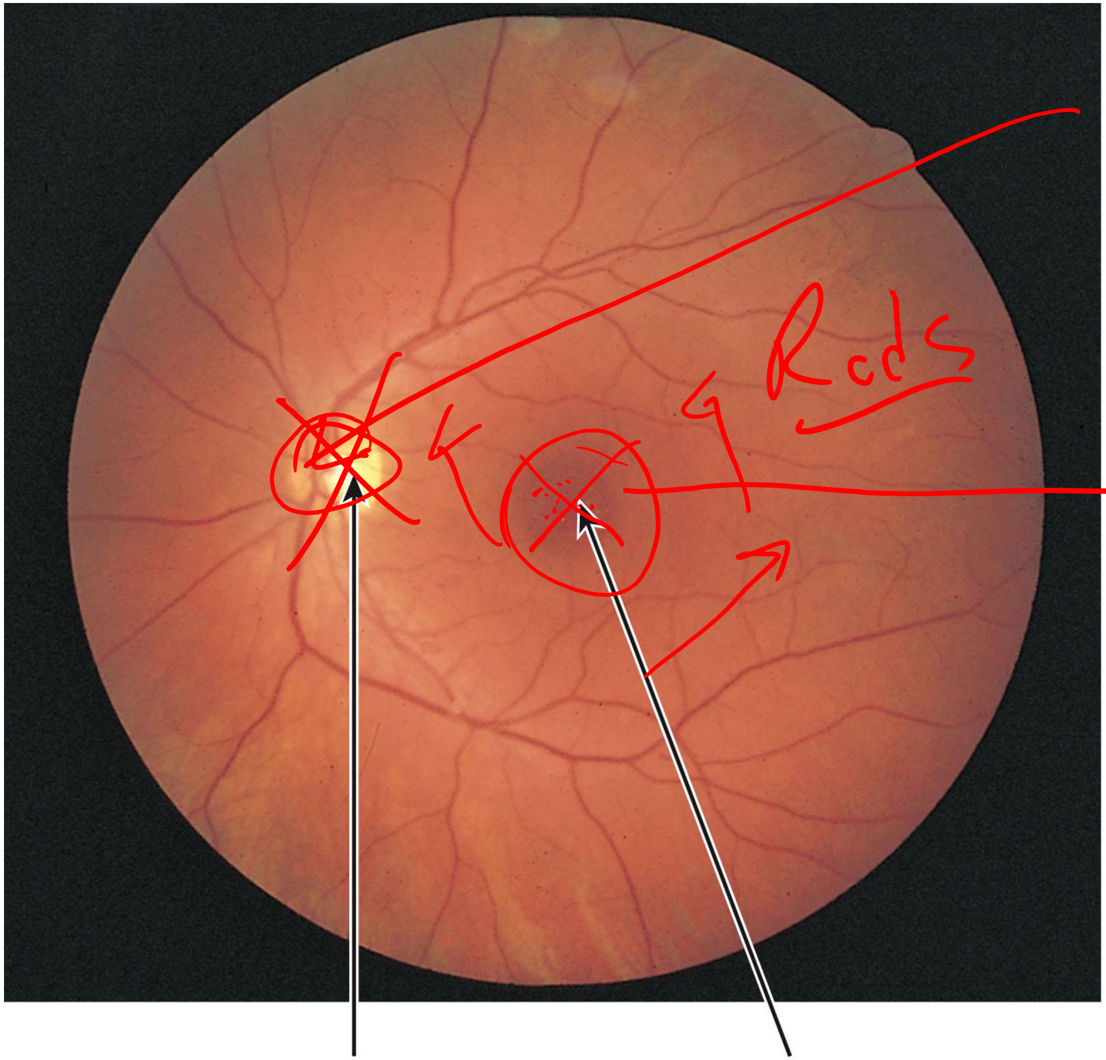


- Structure of the retina
  - **Three layers** of neurons
    - Light must pass through the **ganglion** and **bipolar** layers before reaching the **photoreceptors**
    - A layer of reflecting material (**tapetum lucidum**) enhances vision in dim light in some species
  - **Fovea** is the point of **greatest visual acuity**
  - Axons of ganglion cells form the **optic nerve**
    - Region where optic nerve exits the eye (**optic disc**) is the **blind spot**

6.6 Photoreception: Eyes and Vision



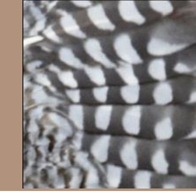
6.6 Photoreception: Eyes and Vision

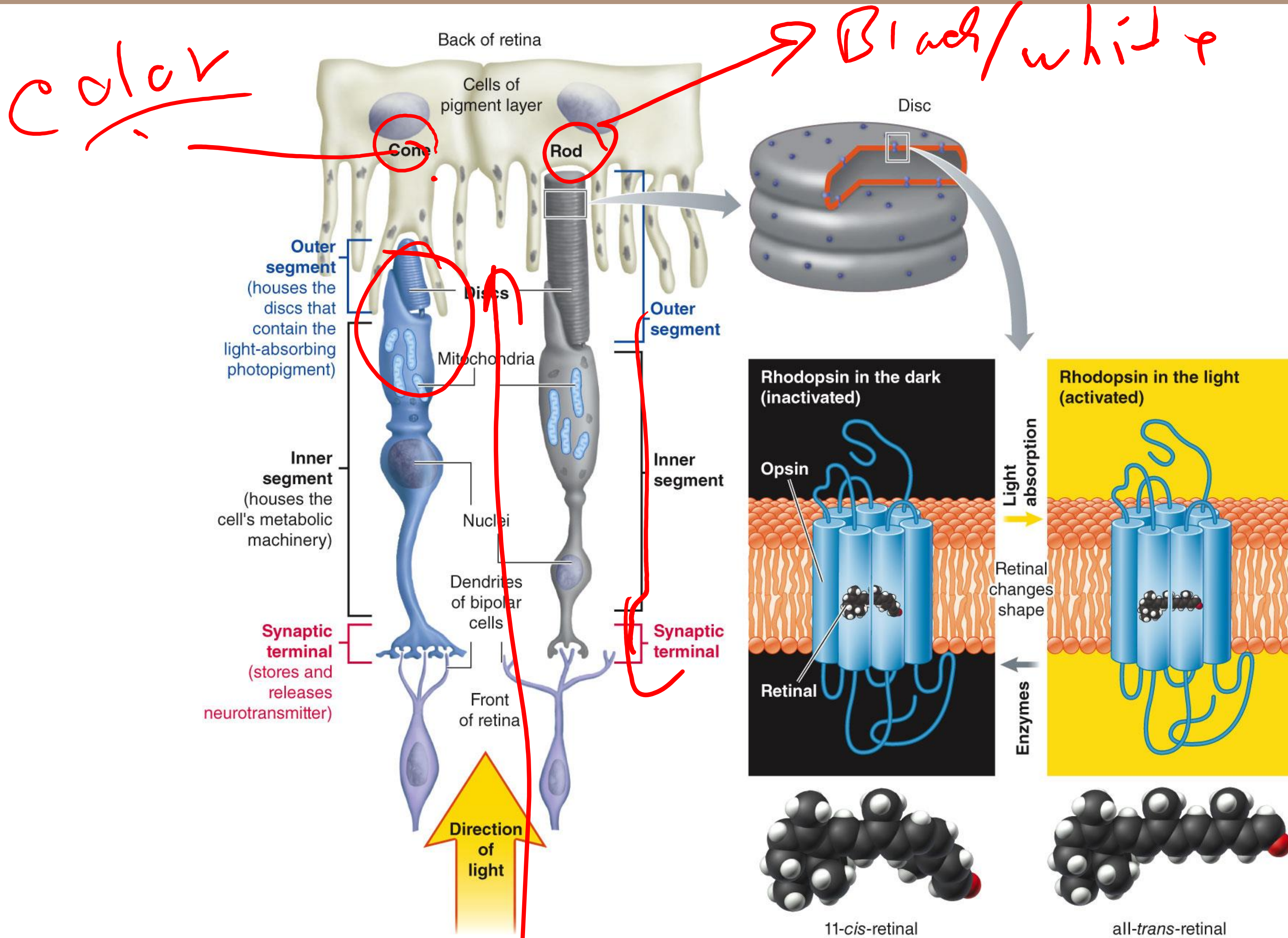


6.6 Photoreception: Eyes and Vision

- Photoreceptors
  - **Outer segment** detects the light stimulus
    - Stacked, flattened, membranous discs containing **photo-pigment molecules**
    - **Rods** and **cones** are named for their shapes
  - **Inner segment** contains the metabolic machinery of the cell
  - **Synaptic terminal** lies closest to the eye's interior

6.6 Photoreception: Eyes and Vision





(a) Structure of rods and cones

(b) Photopigment rhodopsin in the dark and light

6.6 Photoreception: Eyes and Vision

- Photoreceptors are electrically active in the dark

  - In the **absence** of light, cyclic GMP concentration is high in photoreceptors

  - Na^+ channels are **open** ----> depolarization

  - Ca^{2+} channels in synaptic terminal remain **open**

  - **Glutamate** is released

6.6 Photoreception: Eyes and Vision

- Phototransduction

  - In the **presence** of light, a **retinene** molecule **absorbs a photon**

  - Retinine **changes shape** from *cis* to *trans* conformation

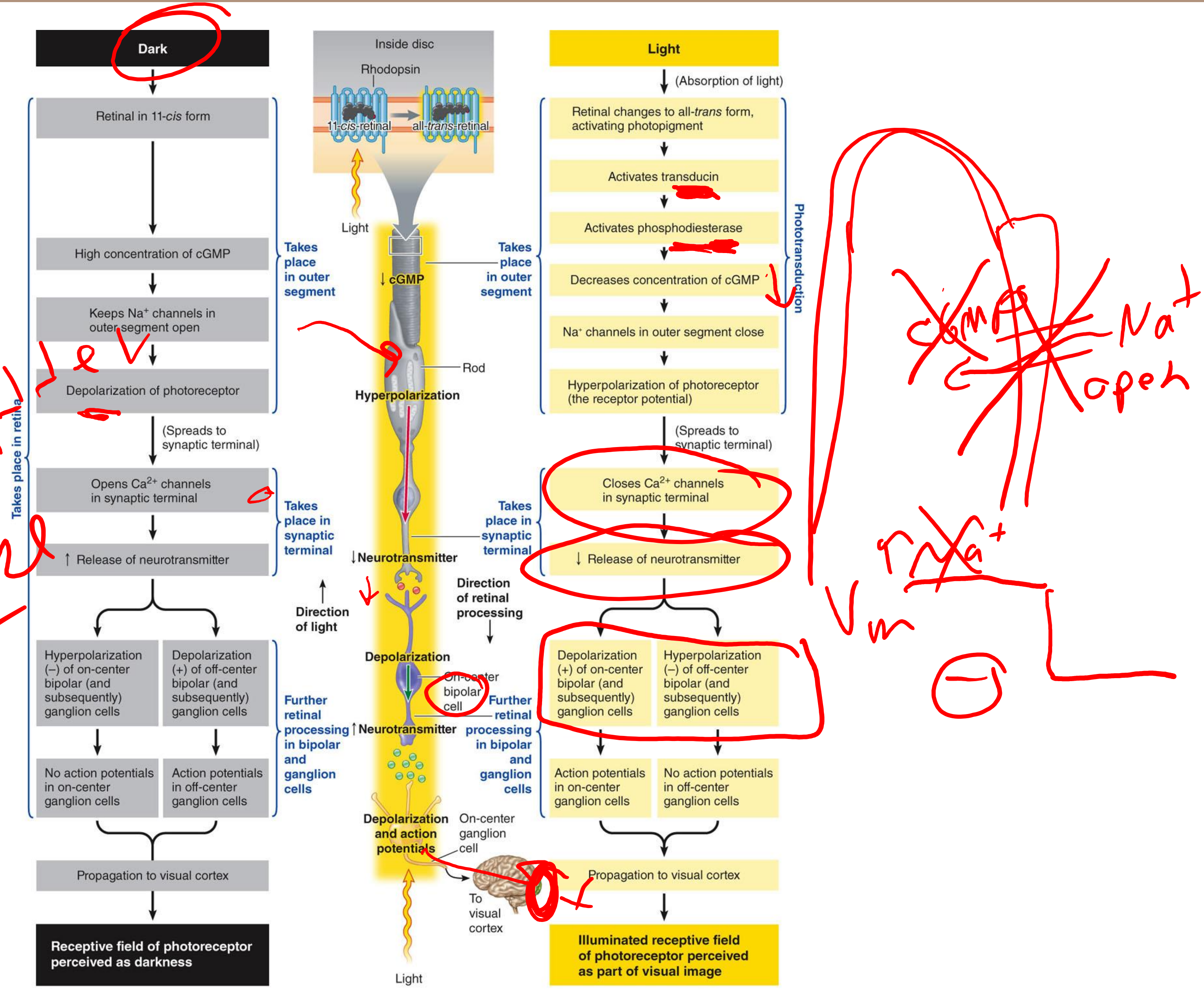
  - Triggers enzymatic activity of **opsin**

  - Activates a G protein called **transducin**

  - Phosphodiesterase **degrades cyclic GMP,** causing **Na^+ channels** to **close**

  - **Hyperpolarizing** receptor potential **reduces** glutamate release

6.6 Photoreception: Eyes and Vision



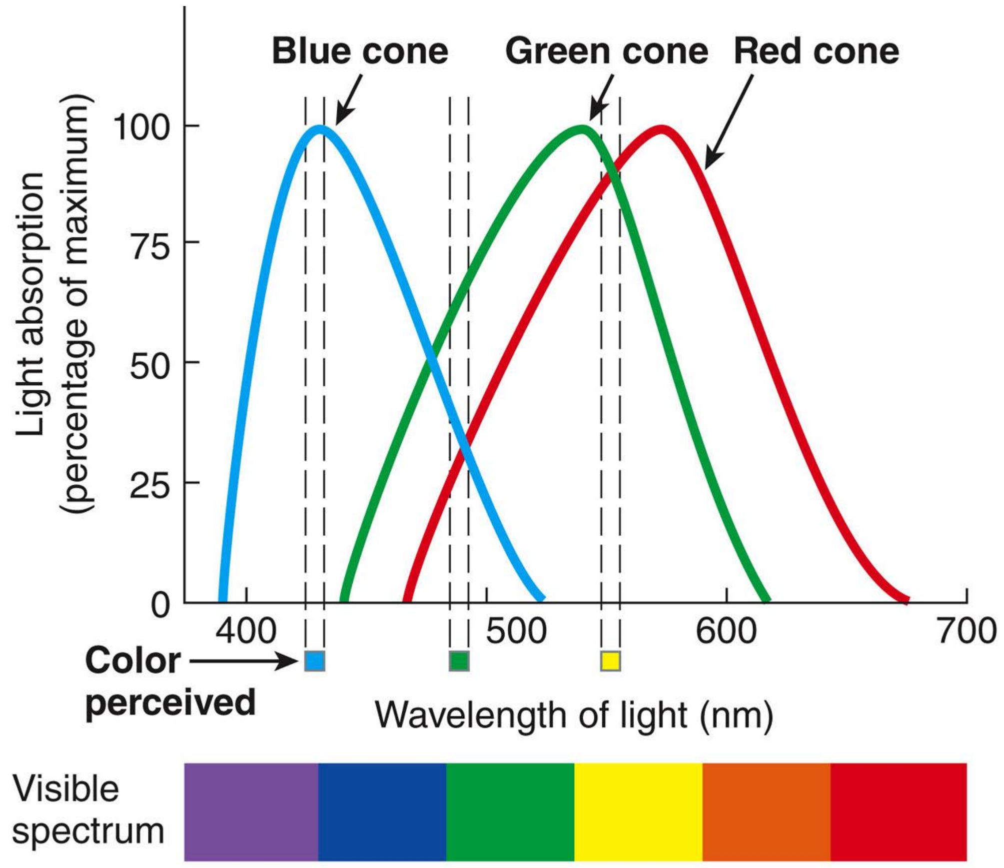
(a) In response to the dark

(b) In response to a light stimulus

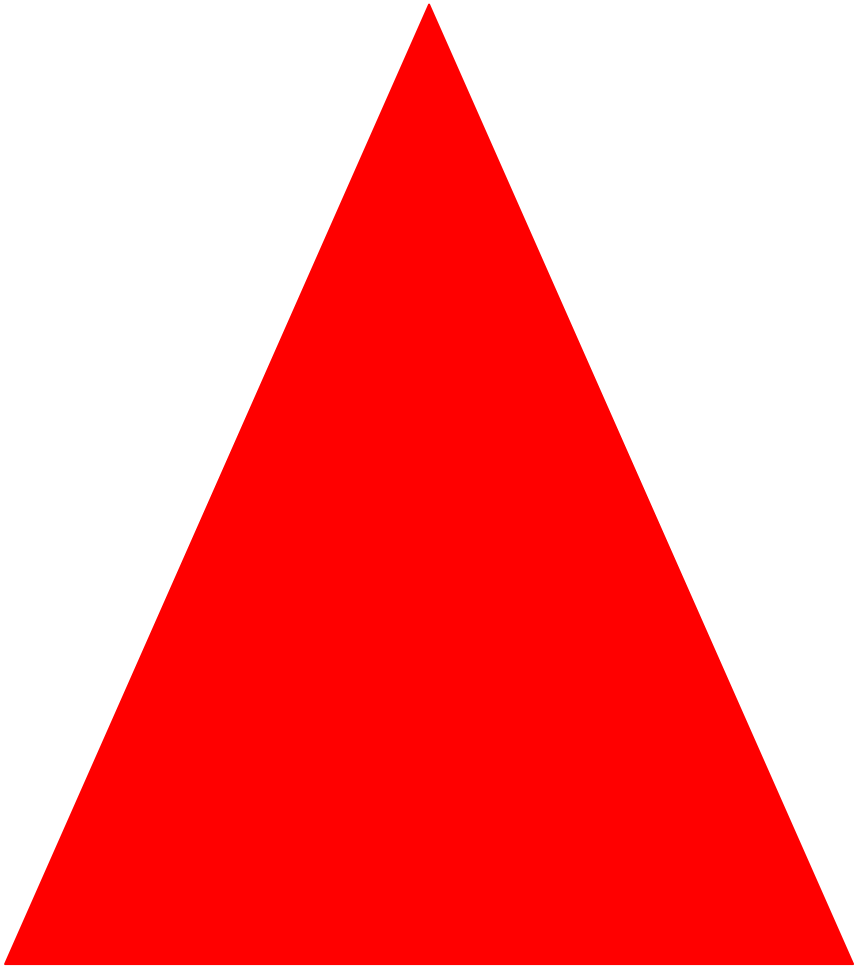
6.6 Photoreception: Eyes and Vision

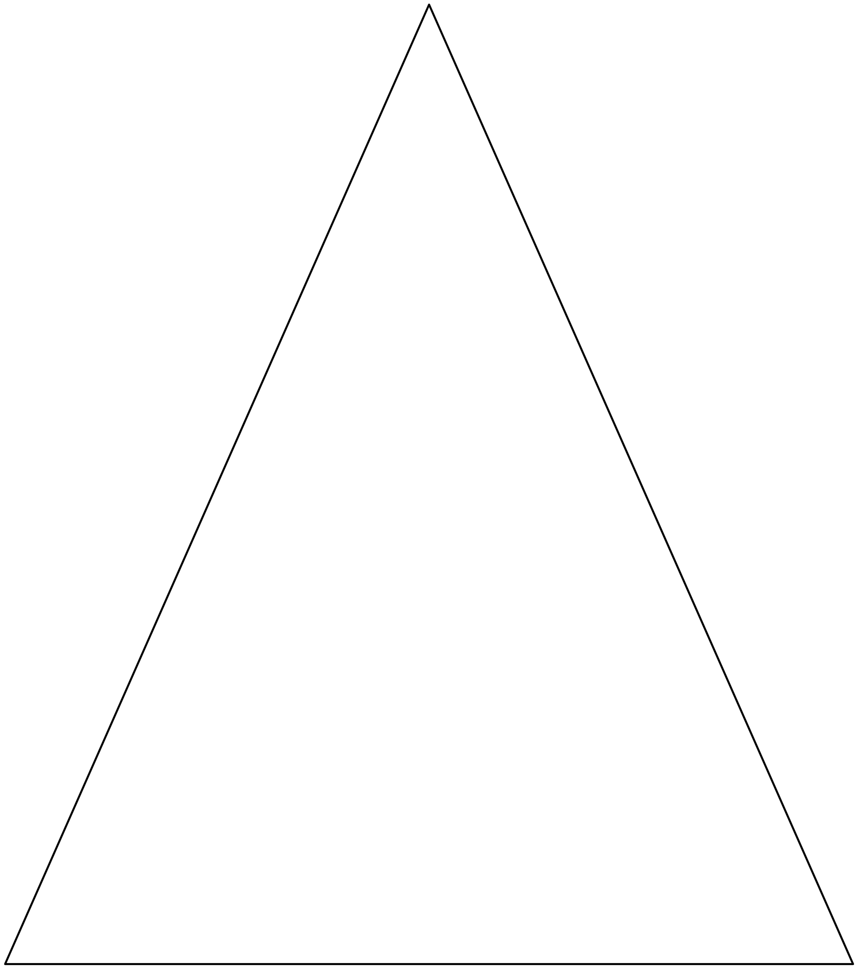
- **Rods**
  - 20 times more rods than cones in human eye
  - Most abundant in **periphery** of retina
  - **High sensitivity** to light
  - **Rhodopsin** absorbs all visible wavelengths with a peak around 500 nm
  - Vision is in **shades of gray**
- **Cones**
  - Most abundant in the **macula/fovea regions**
  - **Lower sensitivity** to light
  - Small receptive fields lead to **highly detailed vision**
  - **Scotopsins** respond to different wavelengths and provide **color vision** (red, green, yellow, blue and ultraviolet)
  - Primates have **three cone types**

6.6 Photoreception: Eyes and Vision



Color perceived	Percentage of maximum stimulation		
	Red cones	Green cones	Blue cones
	0	0	100
	31	67	36
	83	83	0





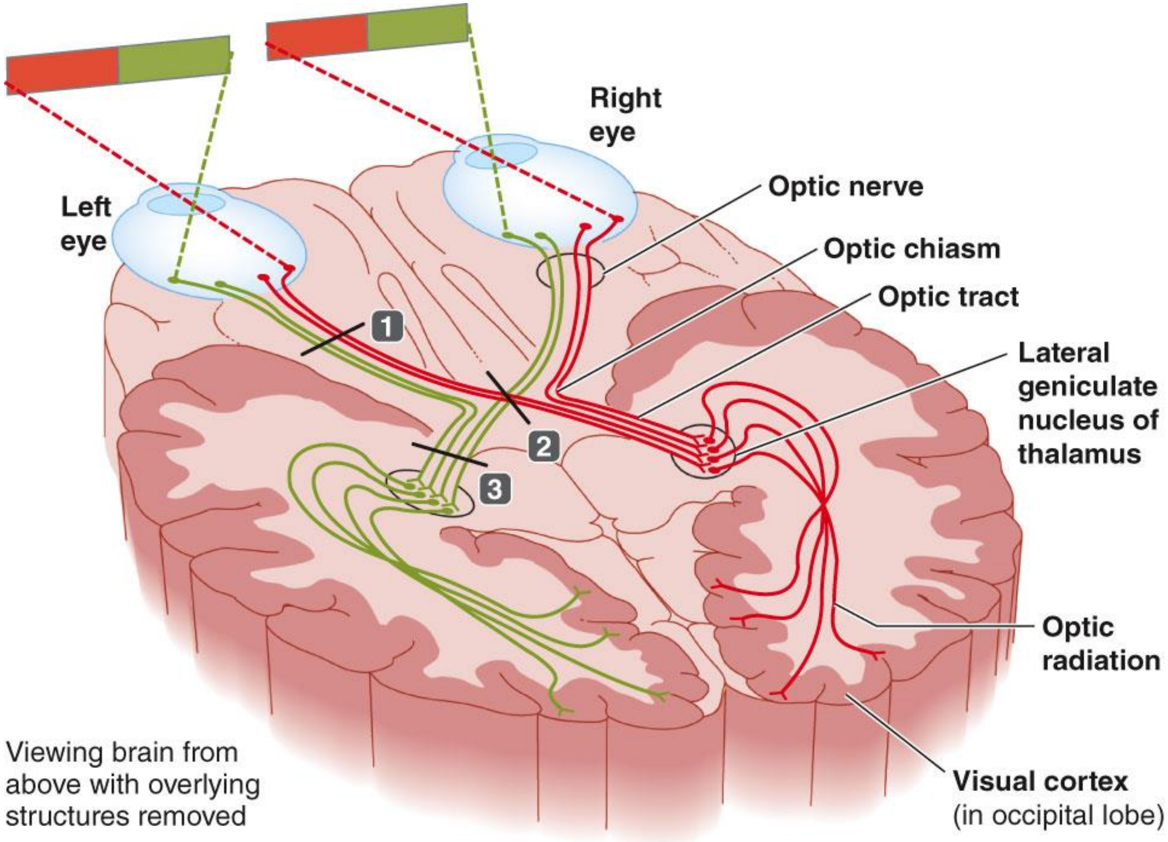
6.6 Photoreception: Eyes and Vision

- Dark adaptation
  - **Pupils dilate**
  - **Photopigments** broken down during light exposure gradually **regenerate**
  - **Increased sensitivity** of rods to light
  - **Night blindness** is caused by dietary deficiency of **vitamin A** (retinene is a derivative of vitamin A)
- Light adaptation
  - **Pupils constrict**
  - Rhodopsin rapidly **breaks down**
  - **Decreased sensitivity** of rods to light

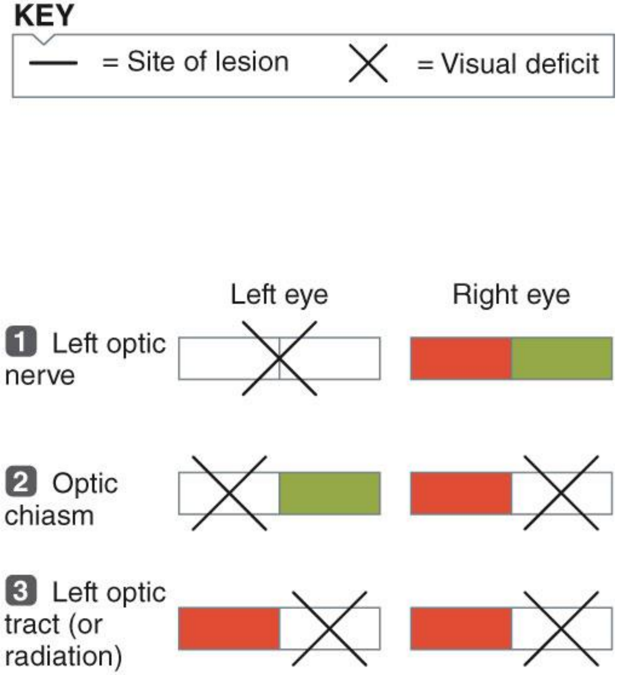
6.6 Photoreception: Eyes and Vision

- Visual pathways
  - Image detected on the retina is **upside down** and **backward**
  - Light rays from **left half** of visual field fall on the **right half** of the retina
  - At the **optic chiasm**, fibers from **medial half** of each retina **cross over**, while fibers from the **lateral half** remain on the same side
  - Information from each half of the visual field is brought together on the **opposite** side of the brain
  - Optic tracts project to the **lateral geniculate nucleus** of the thalamus
  - Fibers terminate in the **visual cortex** in the **occipital lobe**

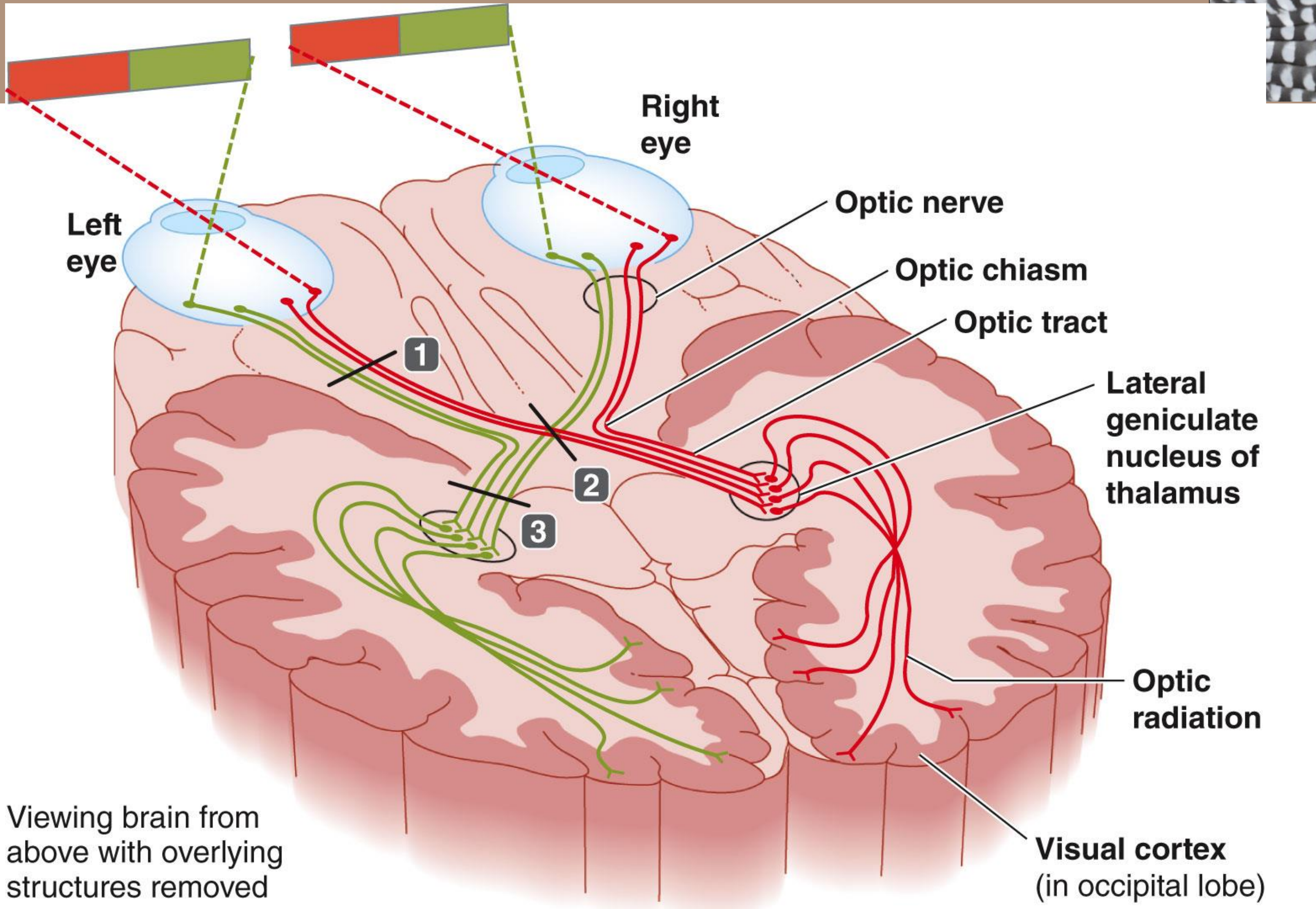
6.6 Photoreception: Eyes and Vision



(a) Visual pathway



(b) Visual deficits with specific lesions in visual pathway



Viewing brain from above with overlying structures removed

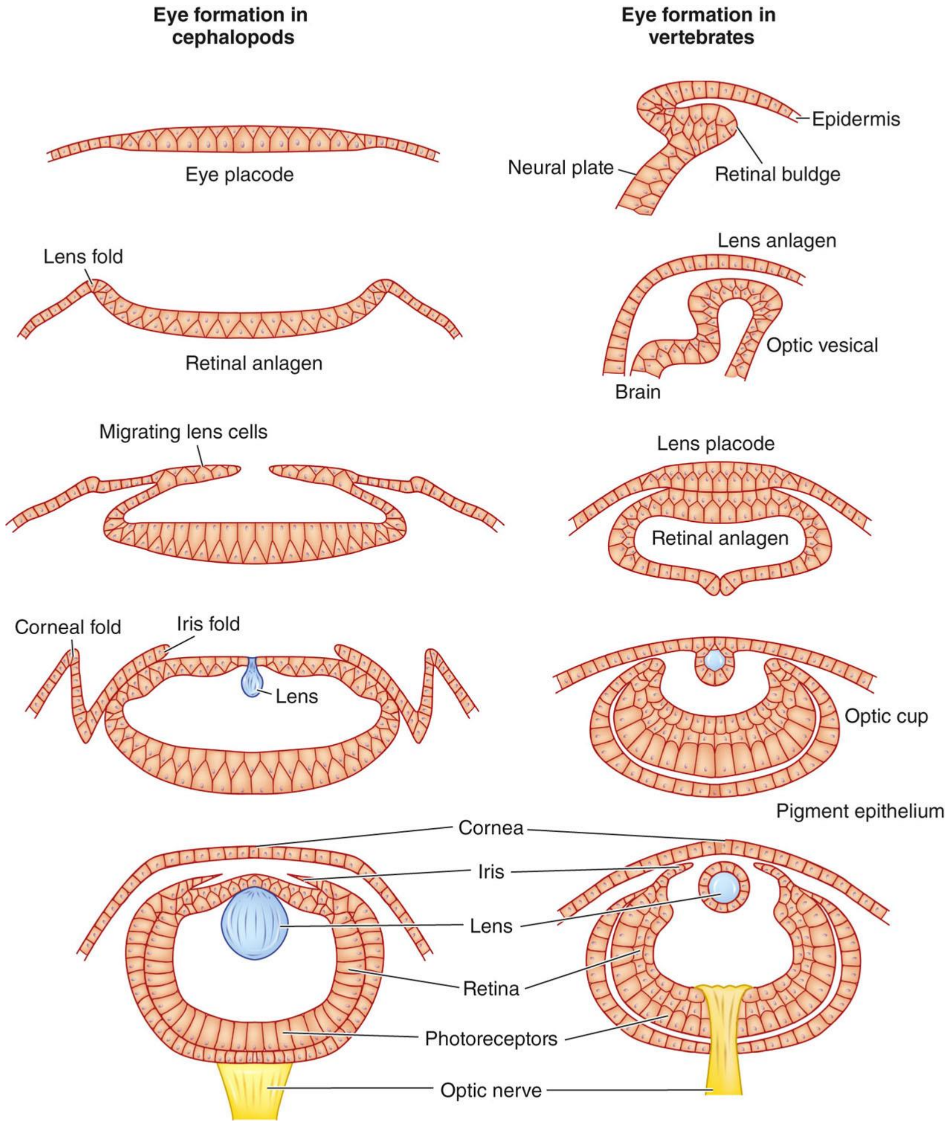
(a) Visual pathway

Figure 6-40a p255

6.6 Photoreception: Eyes and Vision

- **Cephalopod** eyes have cornea, lens, and retina
  - Light-sensing cells are on top of neural cells, receiving light directly from the lens
  - Optic nerve exits from back side (no blind spot)
  - Some cuttlefish see polarized light
- **Compound eyes** of **arthropods** consist of multiple image-forming units (**ommatidia**)
  - Lower visual acuity than vertebrate eyes
  - Rhabdomeric photoreceptors use **rhodopsin**, but **depolarize** in response to light

6.6 Photoreception: Eyes and Vision



Eye formation in cephalopods | Eye formation in vertebrates

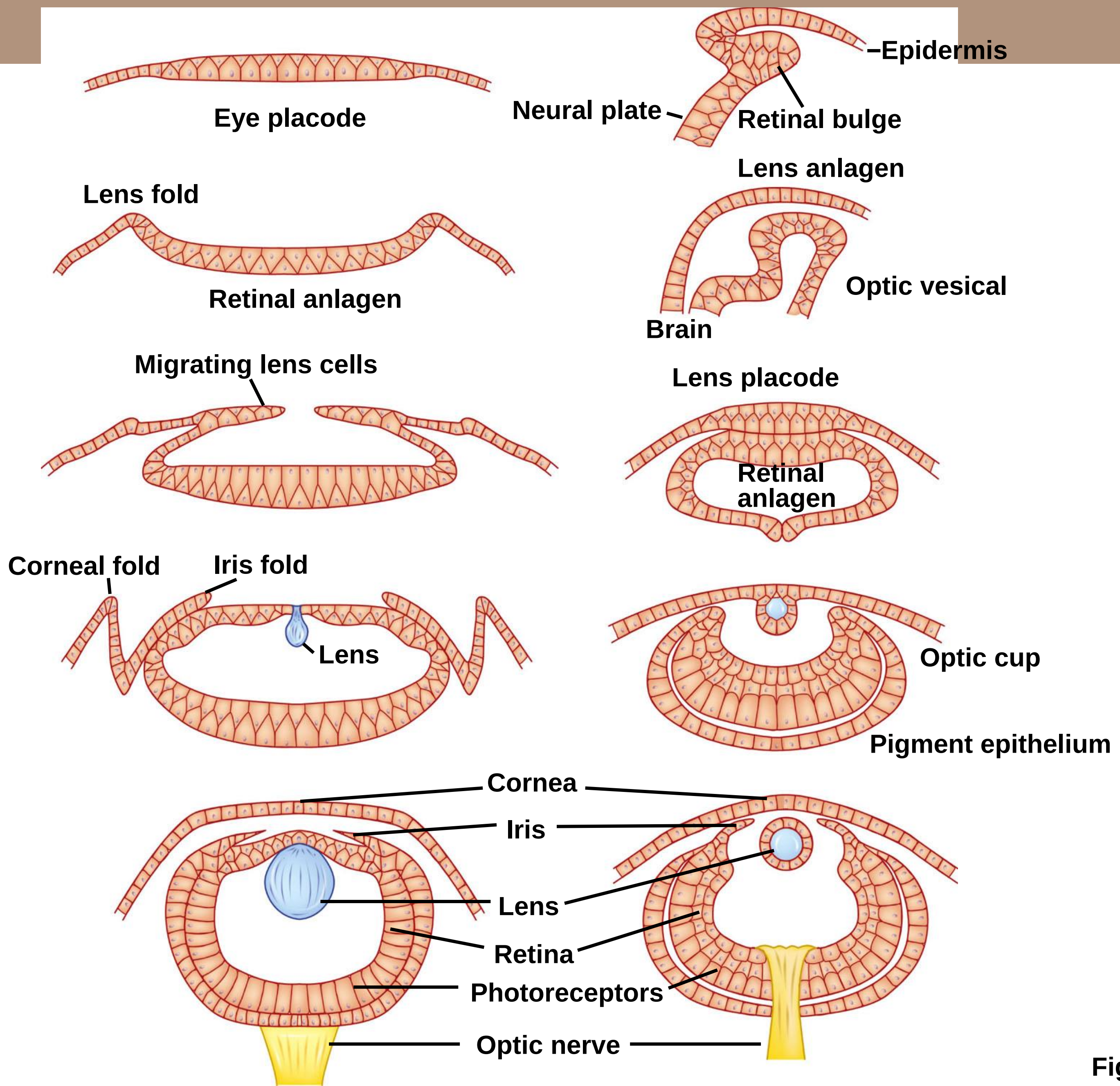
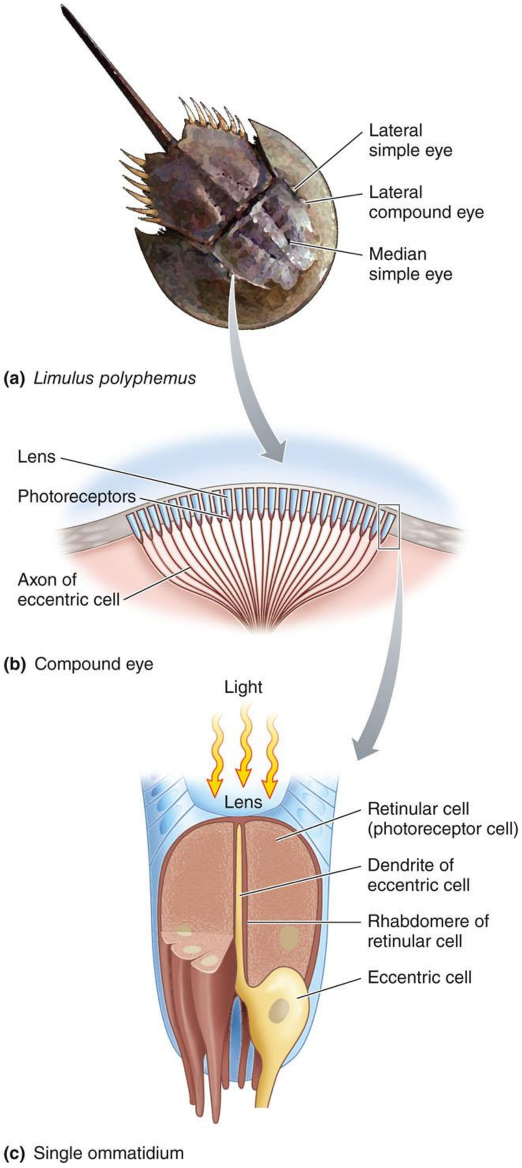
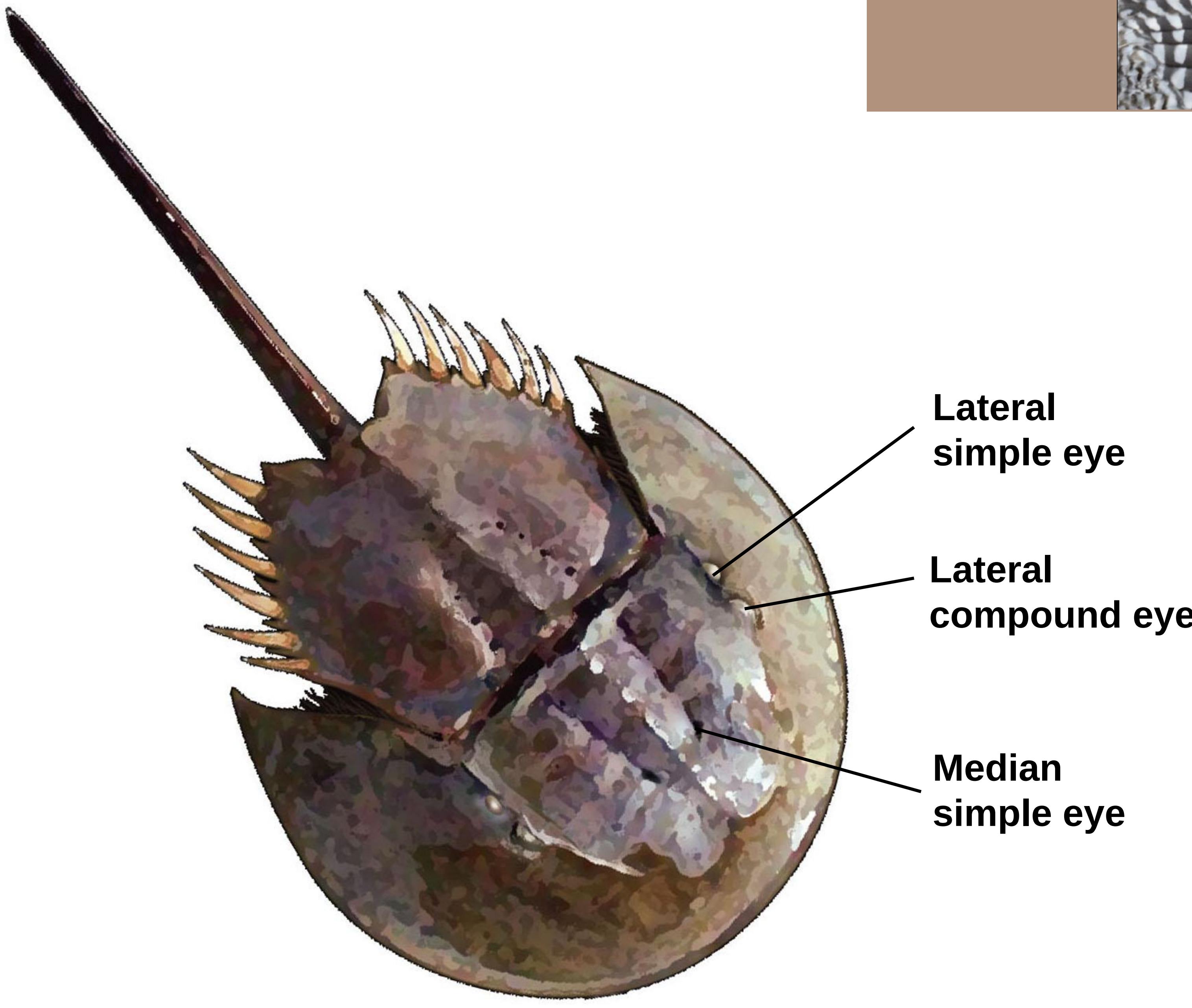


Figure 6-42 p256

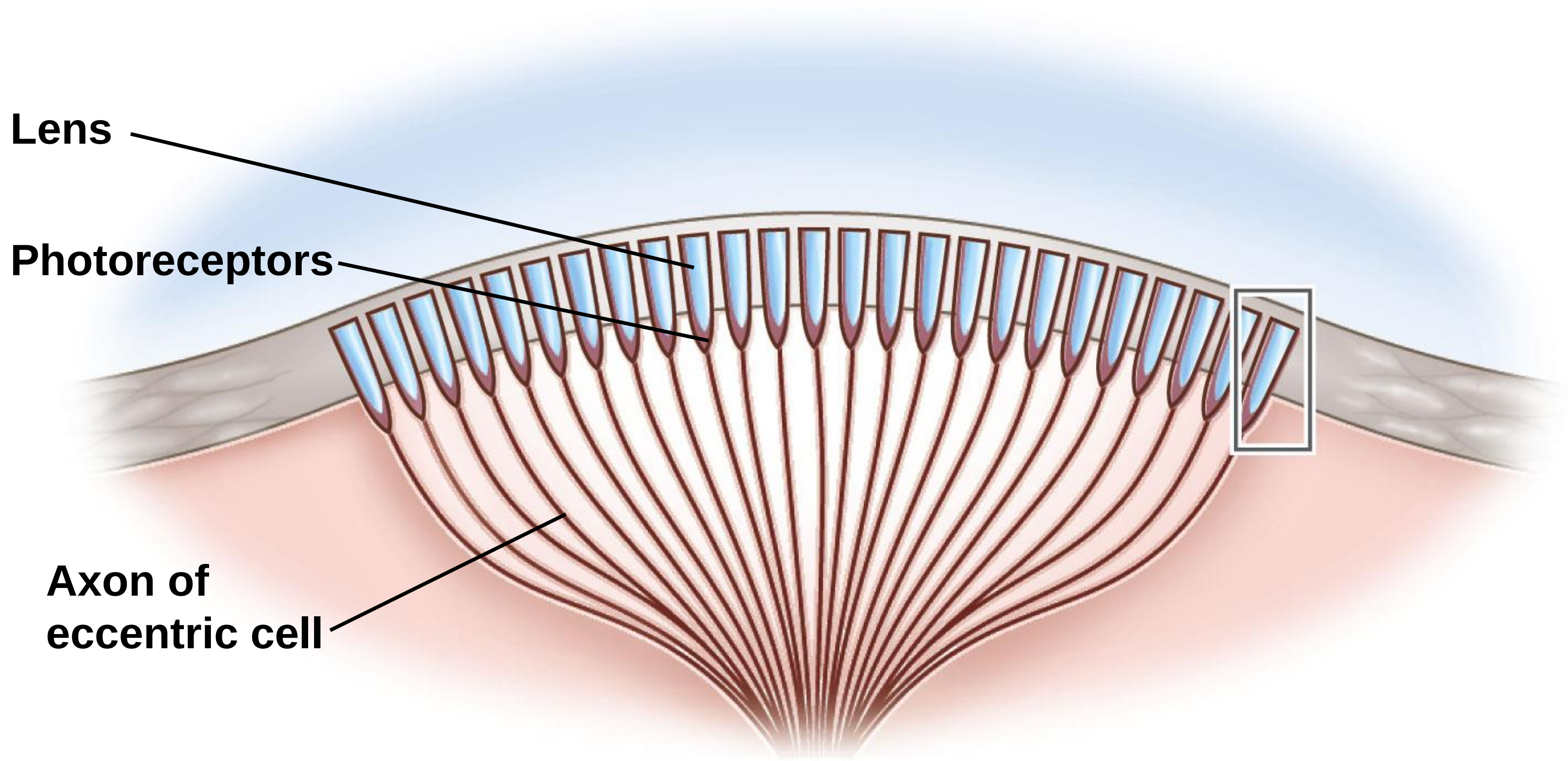
6.6 Photoreception: Eyes and Vision





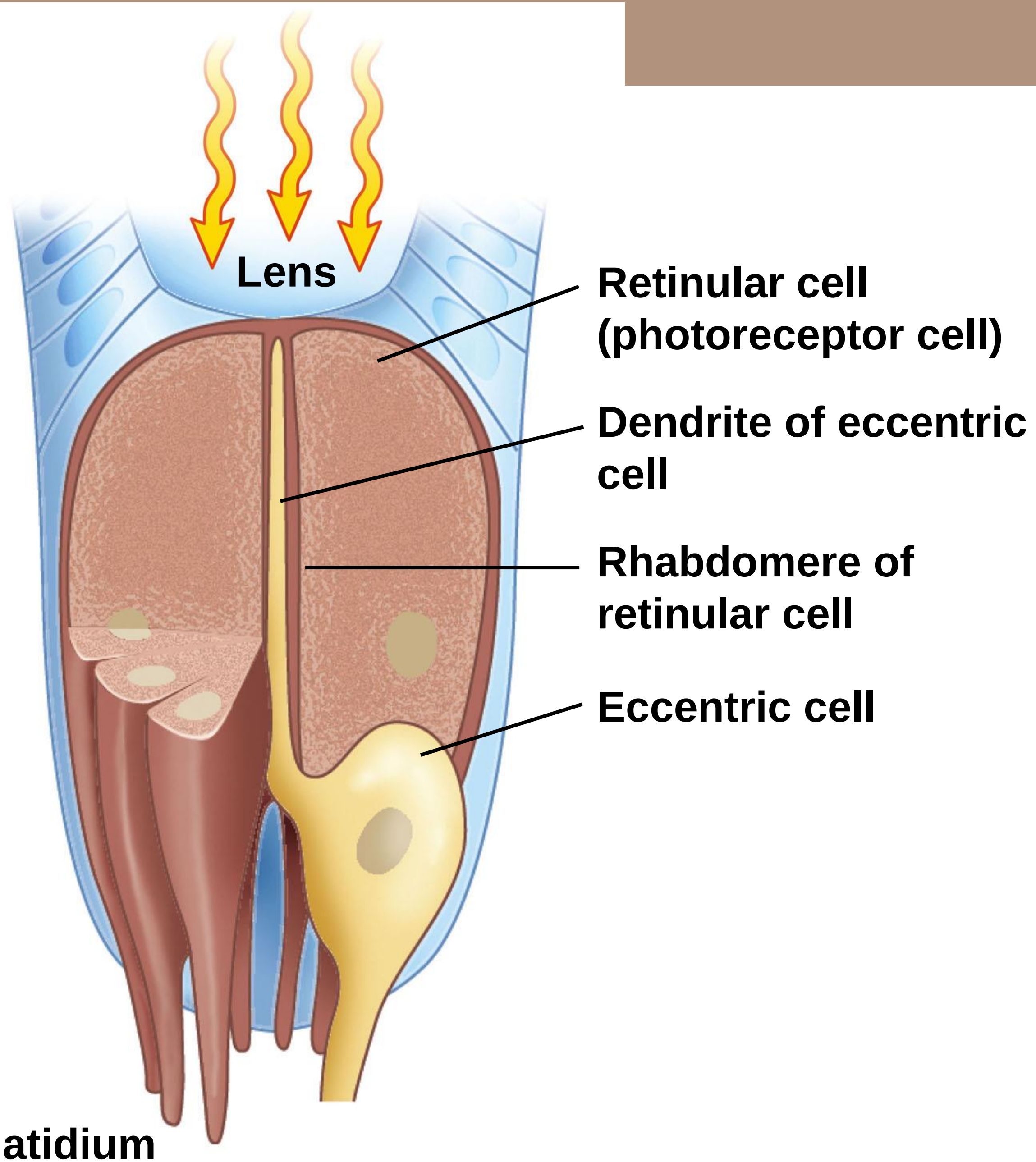
(a) *Limulus polyphemus*

Figure 6-43a p257



(b) Compound eye

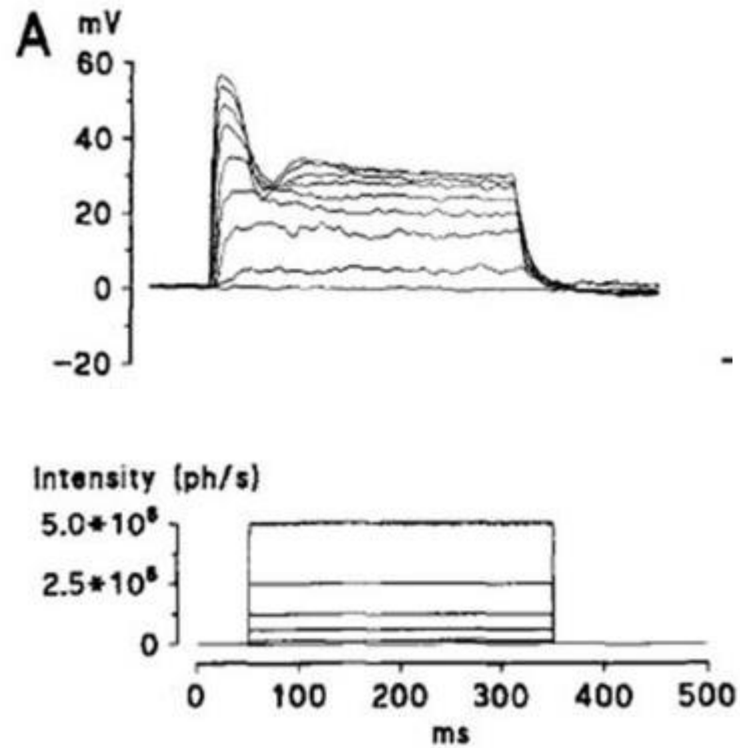
Figure 6-43b p257



(c) Single ommatidium

Figure 6-43c p257

A compound eye is characterized by a variable number (a few to thousands) of small eyes, ommatidia.



DEPOLARIZATION of sensory neuron with light

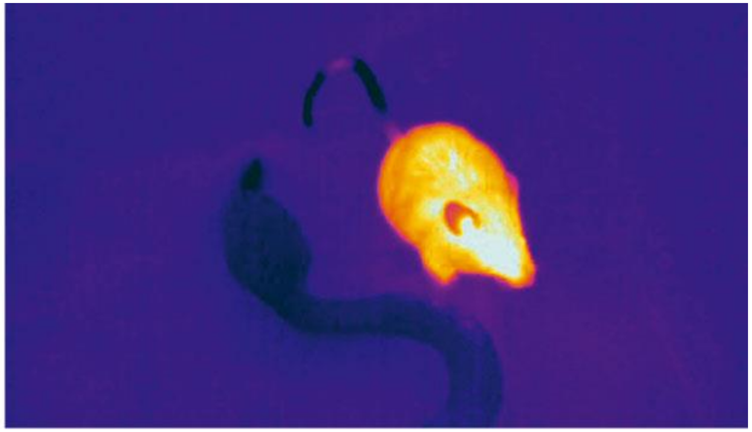
http://www.scholarpedia.org/article/File:Photoreceptor_and_LMC_responses.jpg

6.7 Thermoreception

- **Warm** and **cold thermoreceptors** respond to changes in skin temperature
  - Heat-gated and cold-gated ion channels
  - Used primarily for thermoregulation
- **Infrared thermoreceptors**
  - Located in small pits in skin of pit vipers, pythons and boas
  - Detect warm mammalian prey
  - Used in first strike to capture prey

6.7 Thermoreception

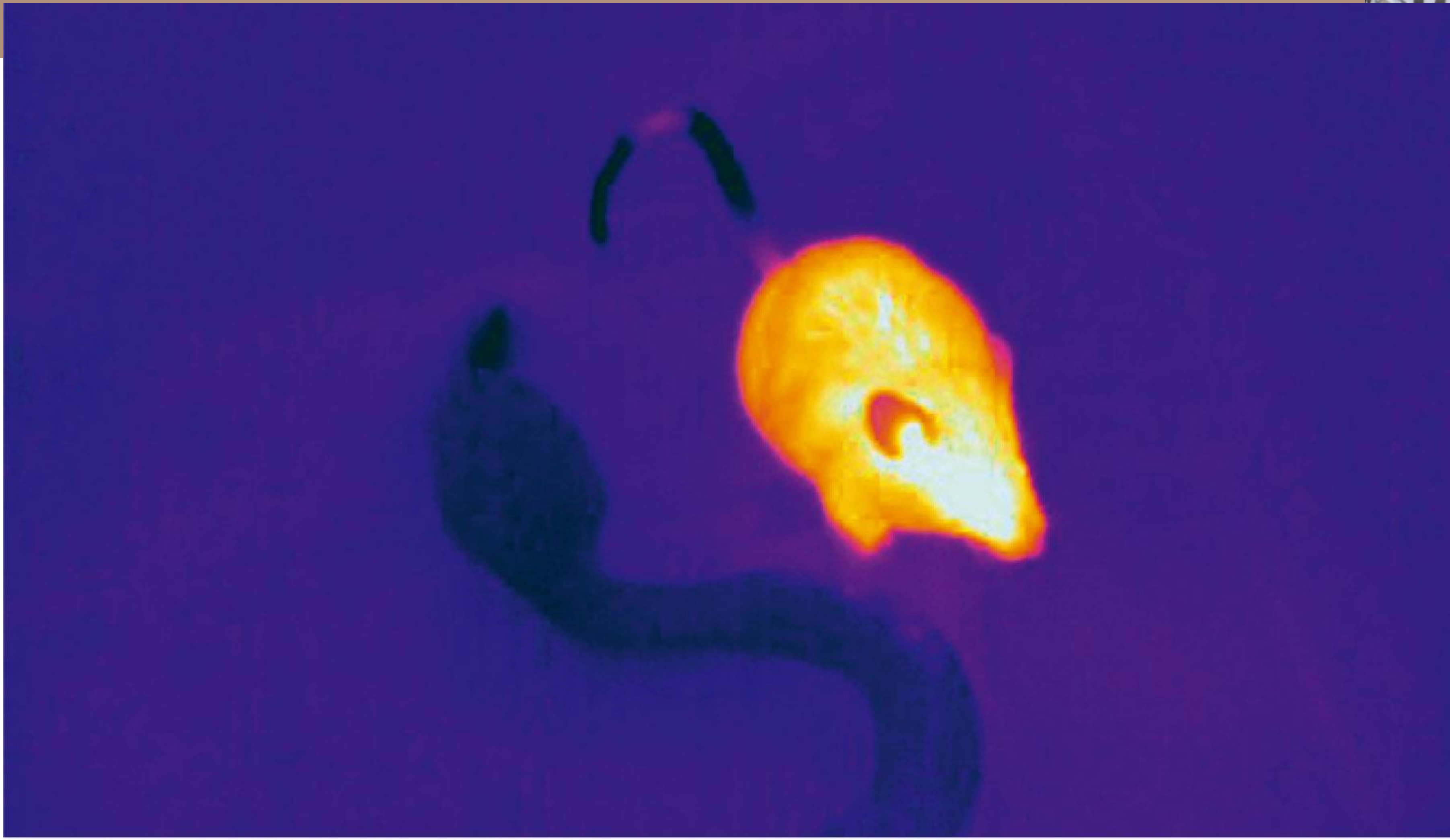
(a)



(b)

(a)

Figure 6-45a p259



(b)

Figure 6-45b p259

6.8 Nociception: Pain

- Categories of **pain receptors** (**nociceptors**)
  - **Mechanical nociceptors** -- respond to cutting, crushing or pinching
  - **Thermal nociceptors** -- respond to temperature extremes
  - **Polymodal nociceptors** -- respond to all kinds of damaging stimuli, including chemical

6.8 Nociception: Pain

- **Fast pain**
  - Initial pain response arises from **mechanical** or **thermal** nociceptors
  - Easily localized
  - Transmitted rapidly over large, myelinated **A-delta fibers**
  - Fast adapting
- **Slow pain**
  - Dull, aching sensation arises from nociceptors activated by **chemicals** (e.g. bradykinin)
  - Poorly localized
  - Transmitted more slowly by small, unmyelinated **C fibers**
  - Slow adapting

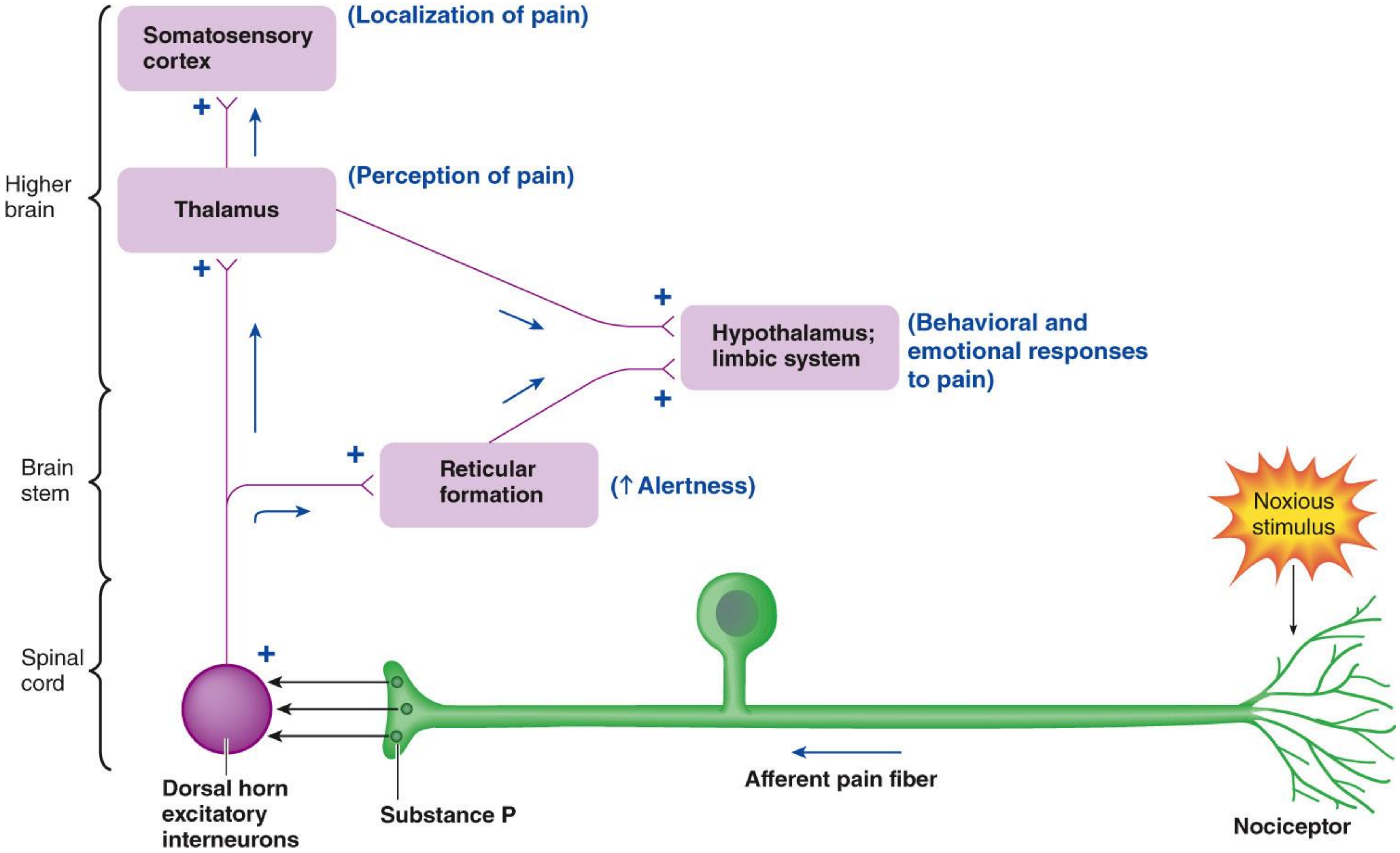
6.8 Nociception: Pain

- **Prostaglandins**
  - Enhance nociceptor response
  - Synthesis is blocked by **aspirin** and other **analgesic** drugs

- **Substance P**
  - Neurotransmitter that activates ascending pain pathways

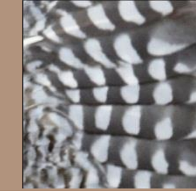
- **Glutamate**
  - Generates action potentials in dorsal horn interneurons
  - Increases excitability of dorsal horn cells
  - Exaggerated sensitivity of an injured area to stimuli

6.8 Nociception: Pain



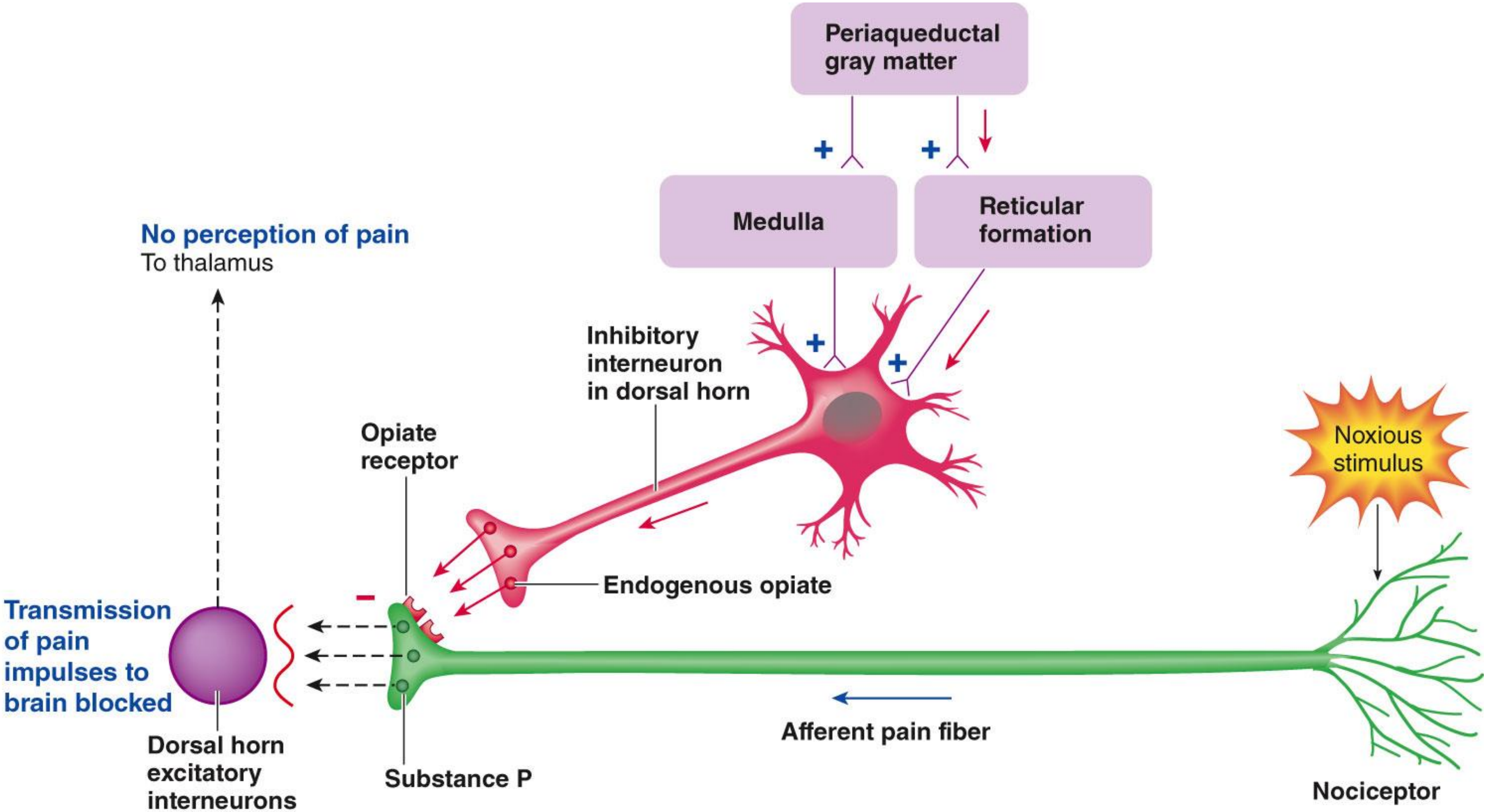
(a) Substance P pain pathway

6.8 Nociception: Pain



- Mammals have a built-in analgesic system.
  - Regulated at the spinal cord level by neurons originating in **periaqueductal gray matter** in brainstem
  - Suppress release of substance P by presynaptic inhibition
  - **Endogenous opioids** (endorphins, enkephalins, dynorphin) bind to opiate receptors as a natural analgesic system
  - **Morphine** produces analgesia through its action on opiate receptors

6.8 Nociception: Pain

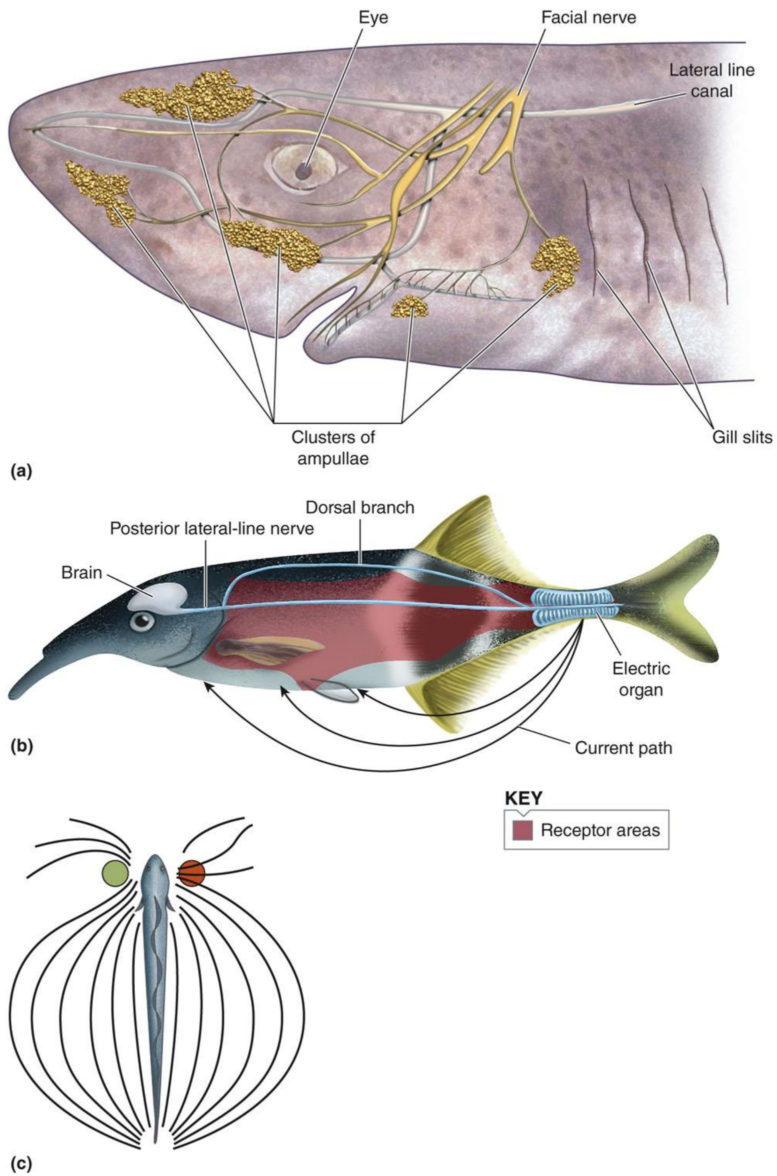


(b) Analgesic pathway

6.9 Electroreception and Magnetoreception

- Passive electroreception
  - **Ampullary electroreceptors** in fishes and some amphibians respond to low-frequency electric signals
  - Used to locate prey (**electrolocation**)
- Active electroreception
  - **Electric organs** emit **electric organ discharges** (EODs)
  - **Tuberous electoreceptors** receive the feedback signal
  - Used in **electrolocation** and **electrocommunication**
  - **Electrosensory lateral line lobe** (ELL) is organized somatotopically

6.9 Electroreception and Magnetoreception



6.9 Electroreception and Magnetoreception

- Navigation by magnetic fields
  - Many animals have an **internal compass** (e.g. migratory birds)
  - Possible mechanisms of **magnetoreception**
    - **Magnetic induction** -- sensitive **electroreceptors** of elasmobranches may detect magnetic fields
    - **Magnetic minerals** -- magnetic crystals arranged in chains (**magnetosomes**) within the cell align with magnetic fields
    - **Magnetochemical reactions** -- light absorption by **cryptochromes** (ancient photoreceptors) causes magnetically sensitive free-radical reactions