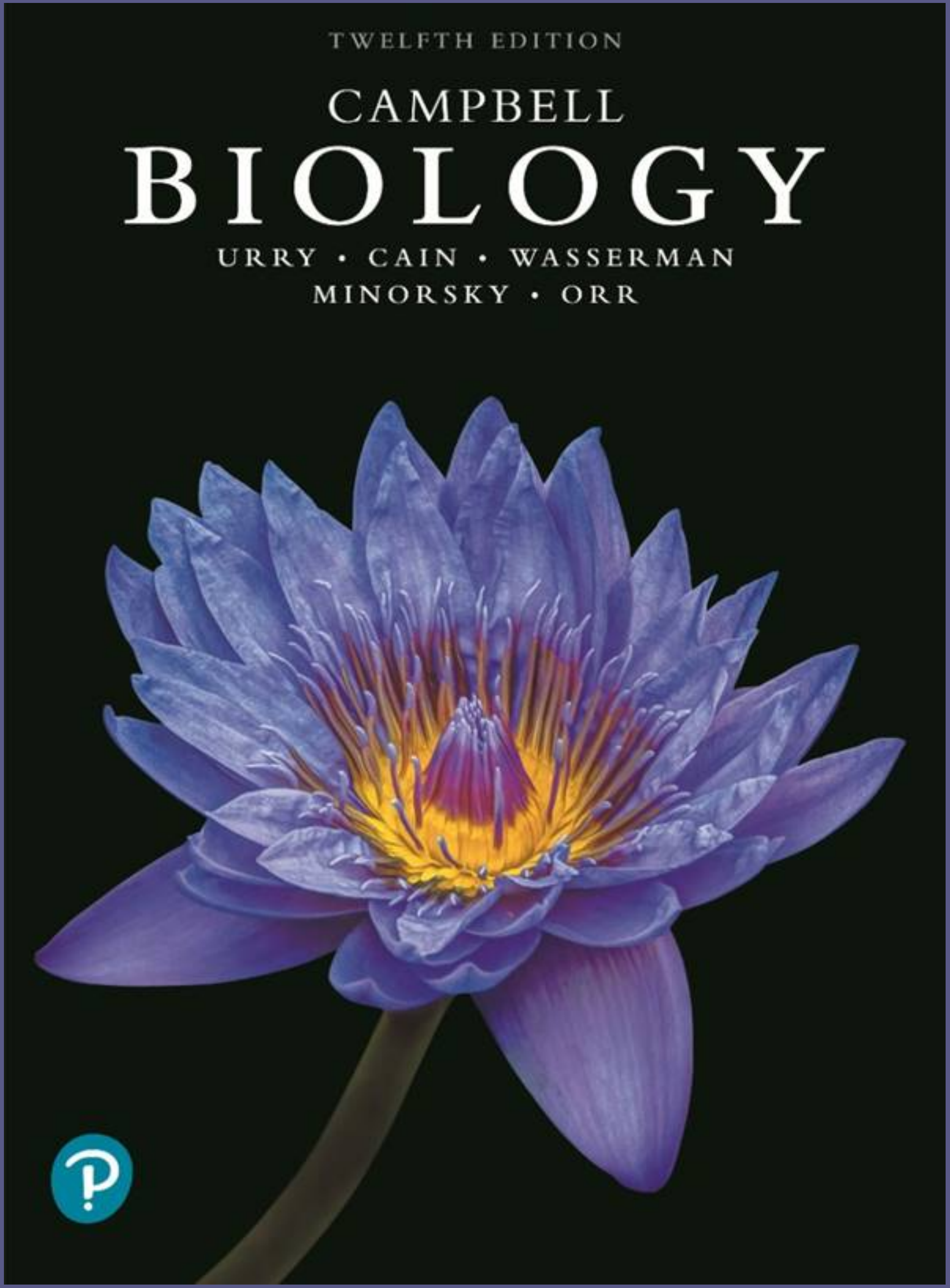
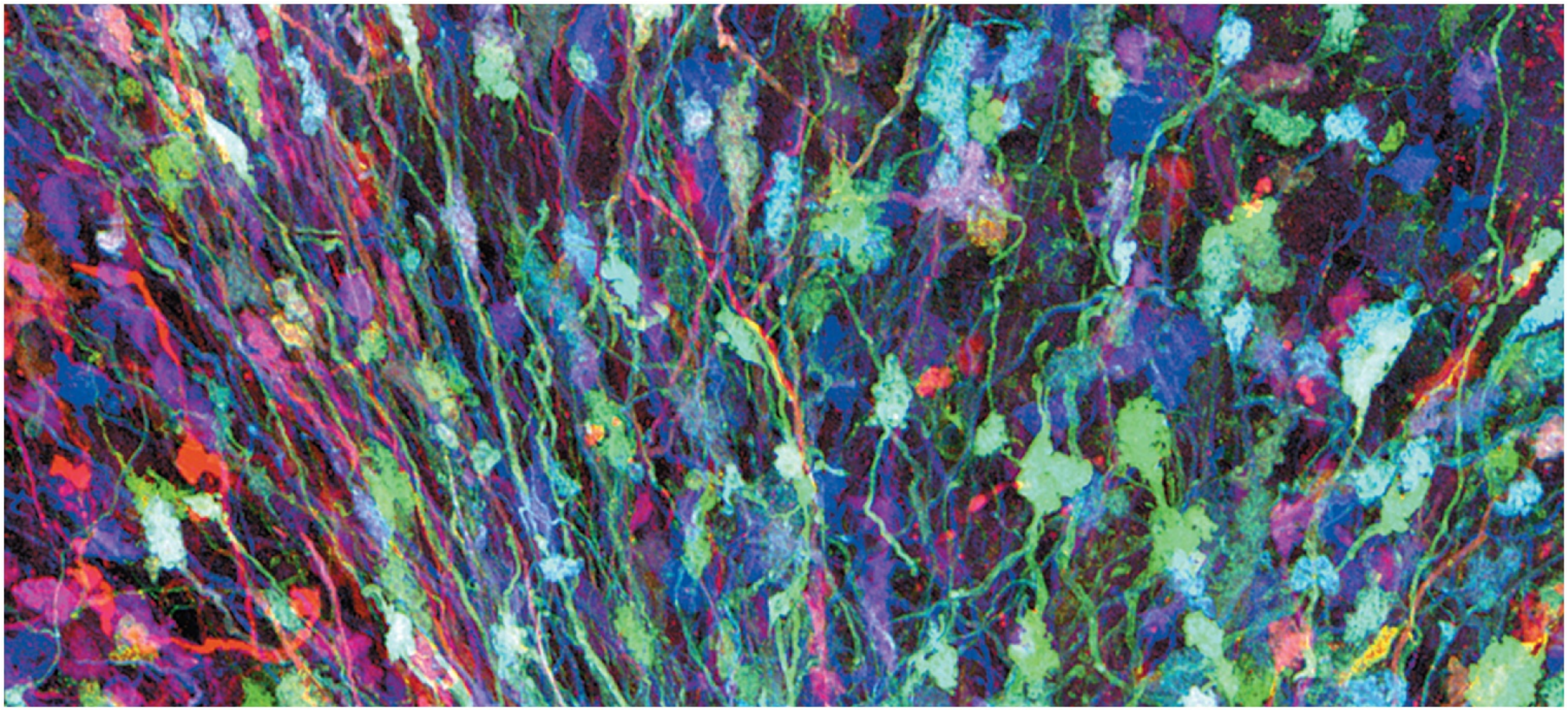


Chapter 49

Nervous Systems

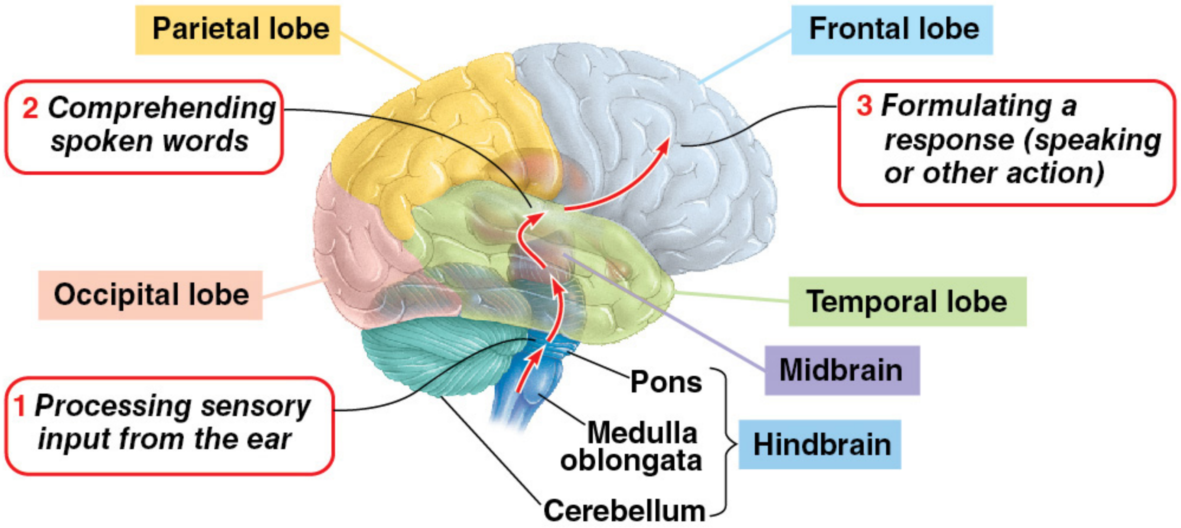
Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 49.1a

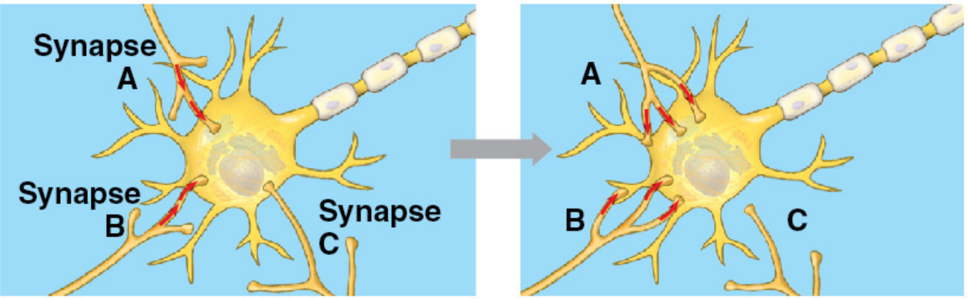


How are billions of neurons organized to perform complex tasks?

Regional specialization



Memory formation

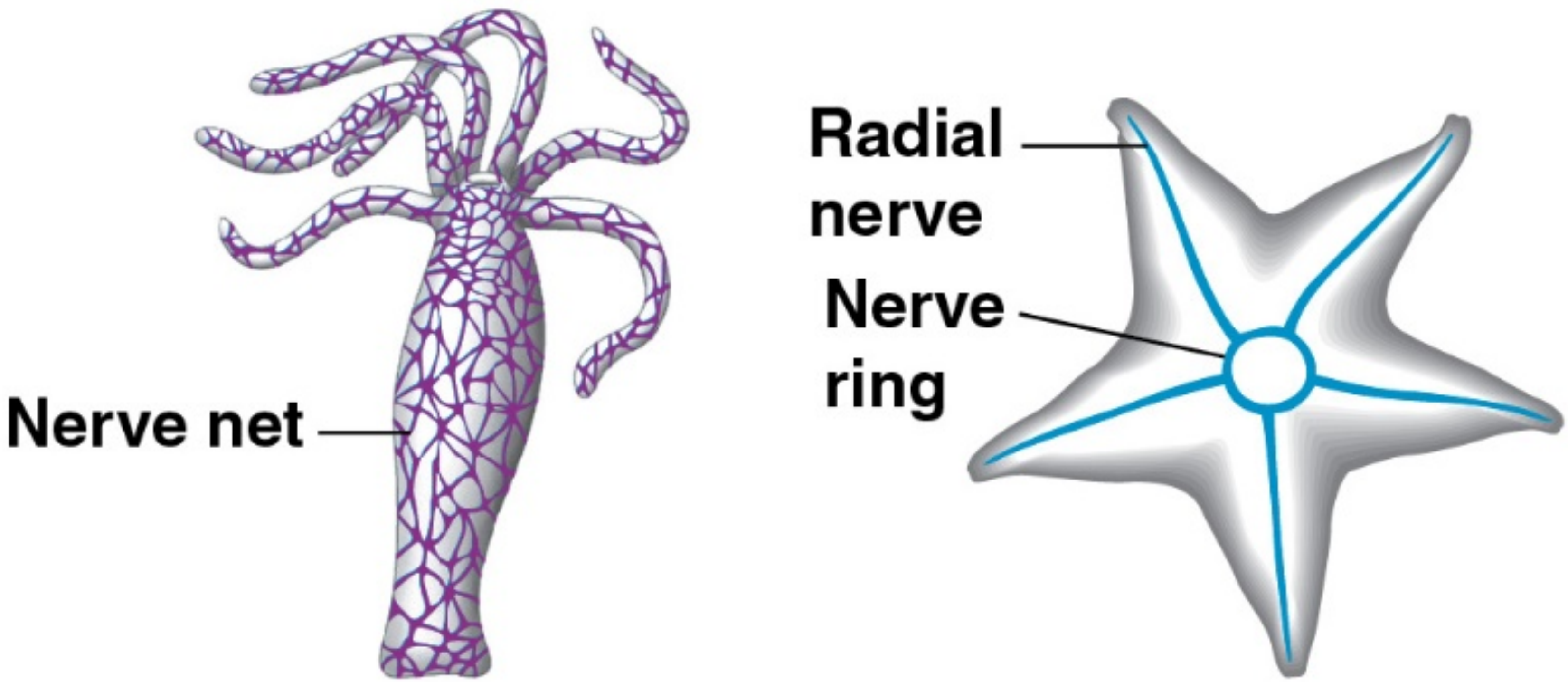


Synapses that are active in synchrony (A and B) are strengthened. Synapses that are not part of an active circuit (C) are weakened or lost.

CONCEPT 49.1: Nervous systems consist of circuits of neurons and supporting cells

- By the time of the Cambrian explosion, more than 500 million years ago, specialized nervous systems had appeared that enable animals to sense their environments and respond rapidly

- The simplest animals with nervous systems, the cnidarians, have interconnected neurons arranged in nerve nets
- More complex animals have **nerves**, in which the axons of multiple neurons are bundled together
- Nerves channel information flow along specific routes through the nervous system
- Sea stars have a set of radial nerves connecting to a central nerve ring

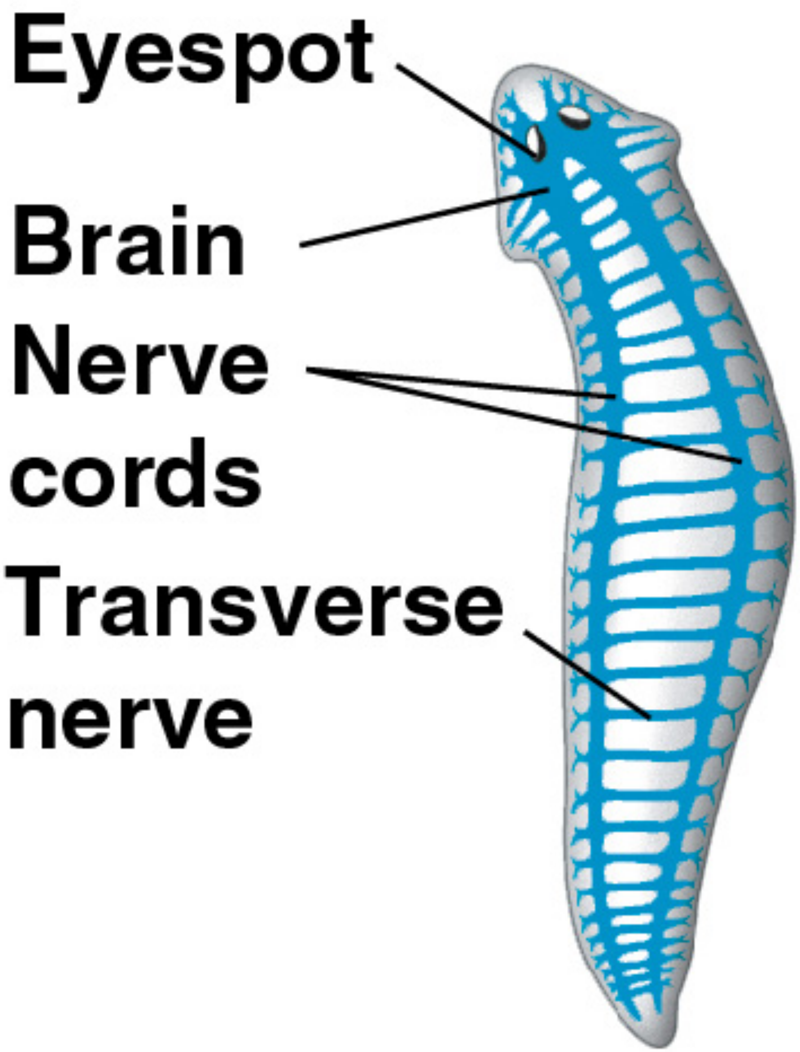


(a) Hydra (cnidarian)

(b) Sea star (echinoderm)

- Bilaterally symmetrical animals exhibit cephalization, the clustering of sensory organs at the front end of the body
- The simplest such animals, flatworms, have a **central nervous system (CNS)** consisting of a small brain and longitudinal nerve cords
- The **peripheral nervous system (PNS)** consists of neurons carrying information into and out of the CNS

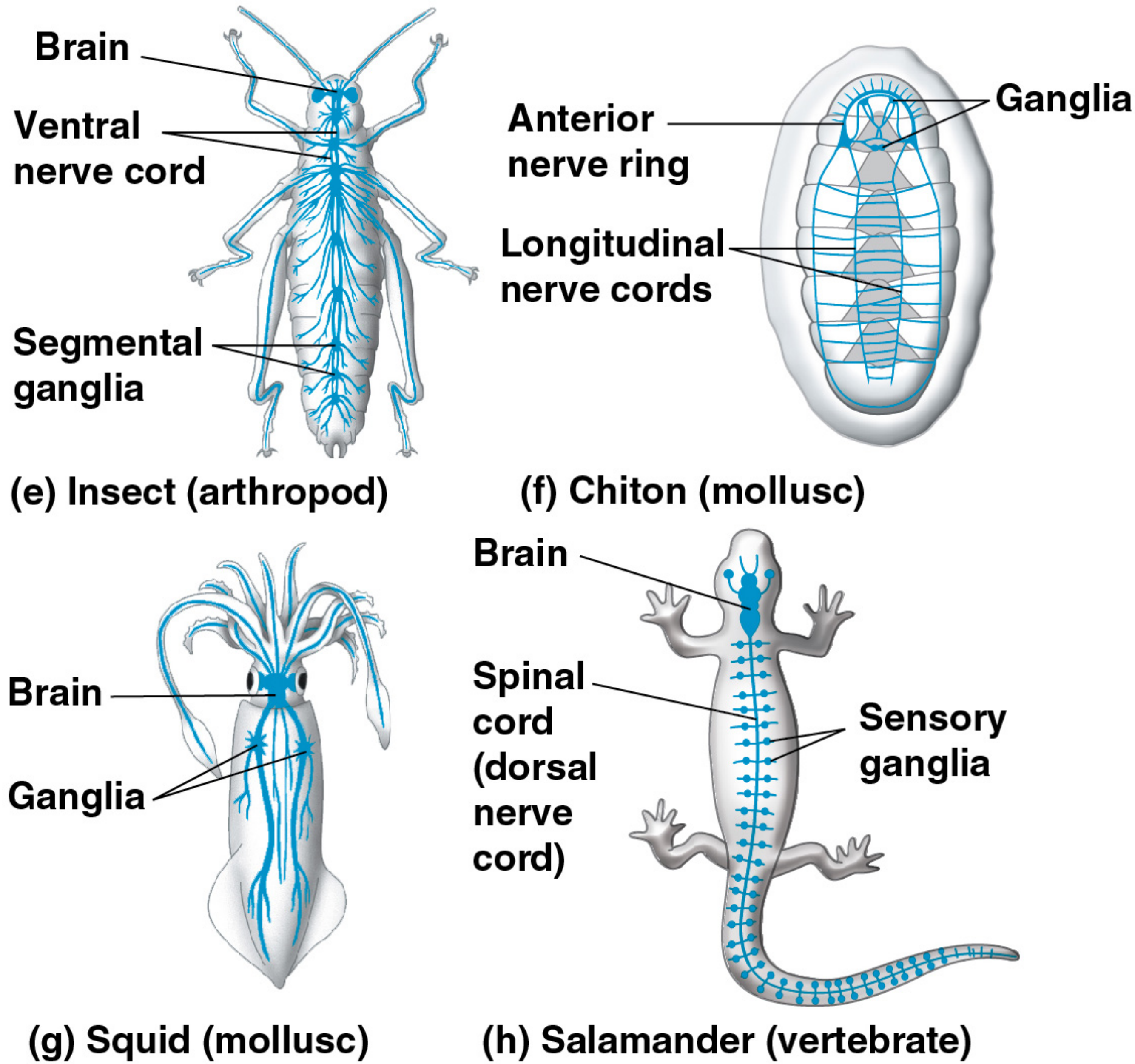
Figure 49.2b



(c) Planarian (flatworm)

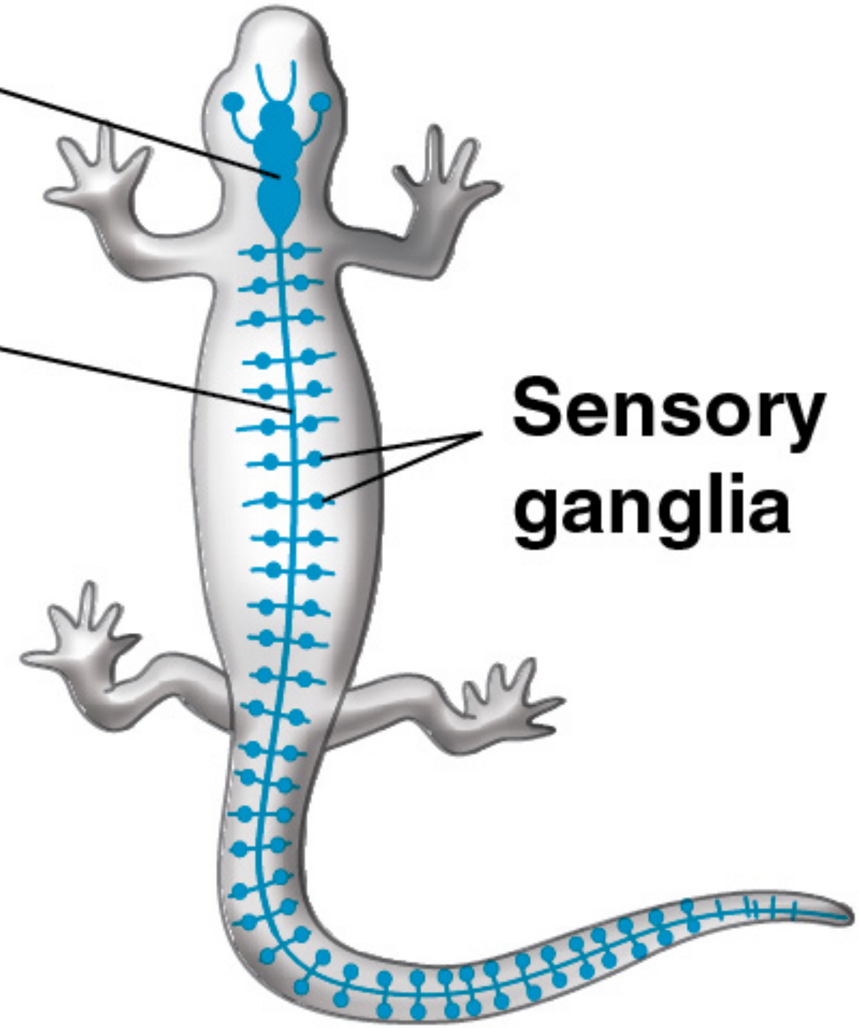
- Annelids and arthropods have segmentally arranged clusters of neurons called **ganglia**
- Nervous system organization usually correlates with lifestyle
- Sessile molluscs (for example, clams and chitons) have simple systems, whereas more complex molluscs (for example, octopuses and squids) have more sophisticated systems

Figure 49.2c



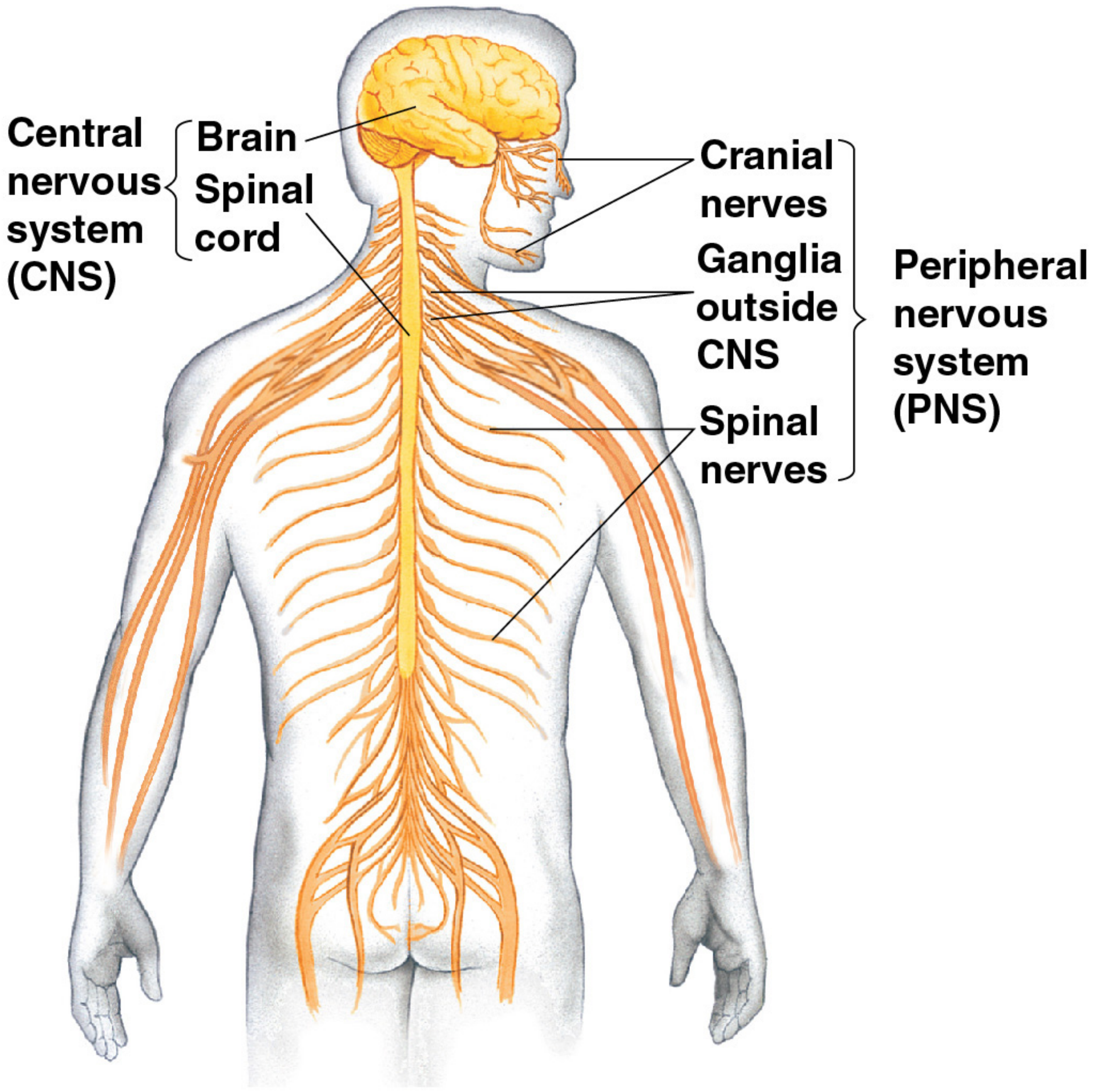
Brain
Ventral nerve cord
Segmental ganglia
(e) Insect (arthropod)
Anterior nerve ring
Ganglia
Longitudinal nerve cords
(f) Chiton (mollusc)
Brain
Ganglia
(g) Squid (mollusc)
Brain
Spinal cord (dorsal nerve cord)
Sensory ganglia
(h) Salamander (vertebrate)

- In vertebrates
  - The CNS is composed of the brain and spinal cord
  - The PNS is composed of nerves and ganglia
- Region specialization is a hallmark of both systems



(h) Salamander (vertebrate)

Figure 49.3



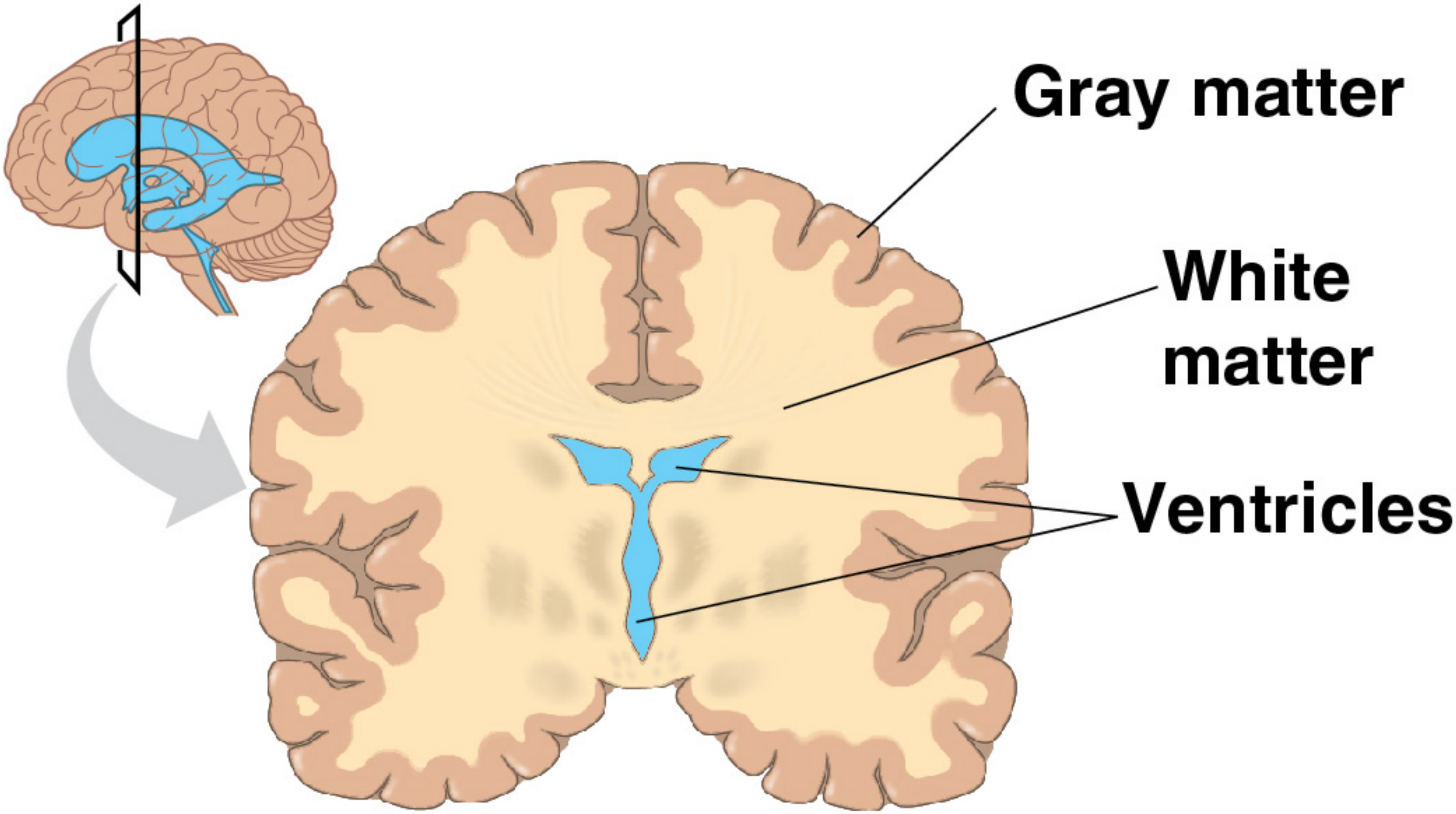
Central nervous system (CNS)
Brain
Spinal cord
Cranial nerves
Ganglia outside CNS
Spinal nerves
Peripheral nervous system (PNS)

Organization of the Vertebrate Nervous System

- The CNS develops from the hollow dorsal nerve cord
- The cavity of the nerve cord gives rise to the narrow central canal of the spinal cord and the ventricles of the brain
- The canal and ventricles fill with cerebrospinal fluid, which supplies the CNS with nutrients and hormones and carries away wastes

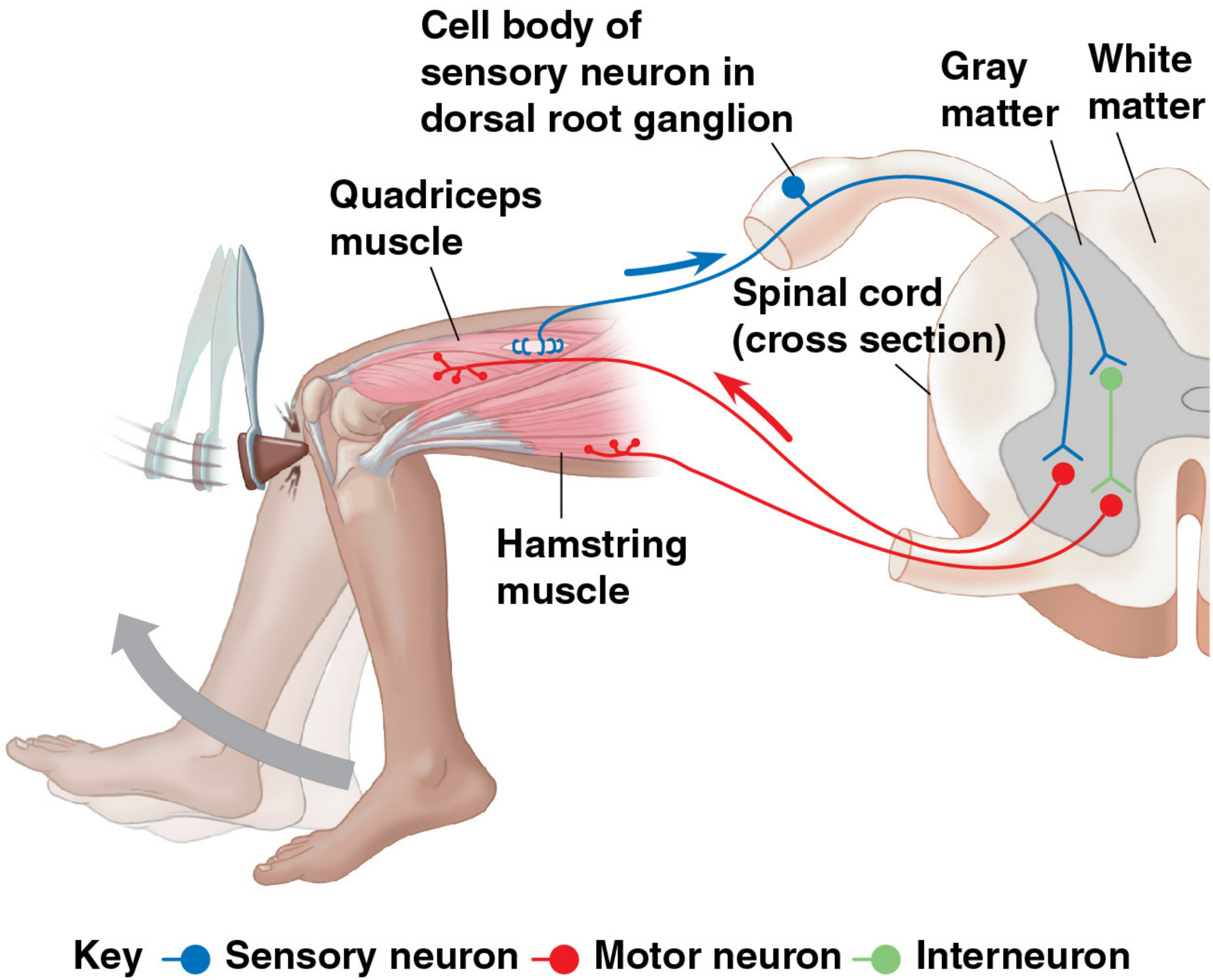
- The brain and spinal cord contain
  - **Gray matter**, which consists of neuron cell bodies, dendrites, and unmyelinated axons
  - **White matter**, which consists of bundles of myelinated axons

Figure 49.4



- The spinal cord conveys information to and from the brain and generates basic patterns of locomotion
- The spinal cord also produces reflexes independently of the brain
- A **reflex** is the body's automatic response to a stimulus
  - For example, a doctor uses a mallet to trigger a knee-jerk reflex

Figure 49.5

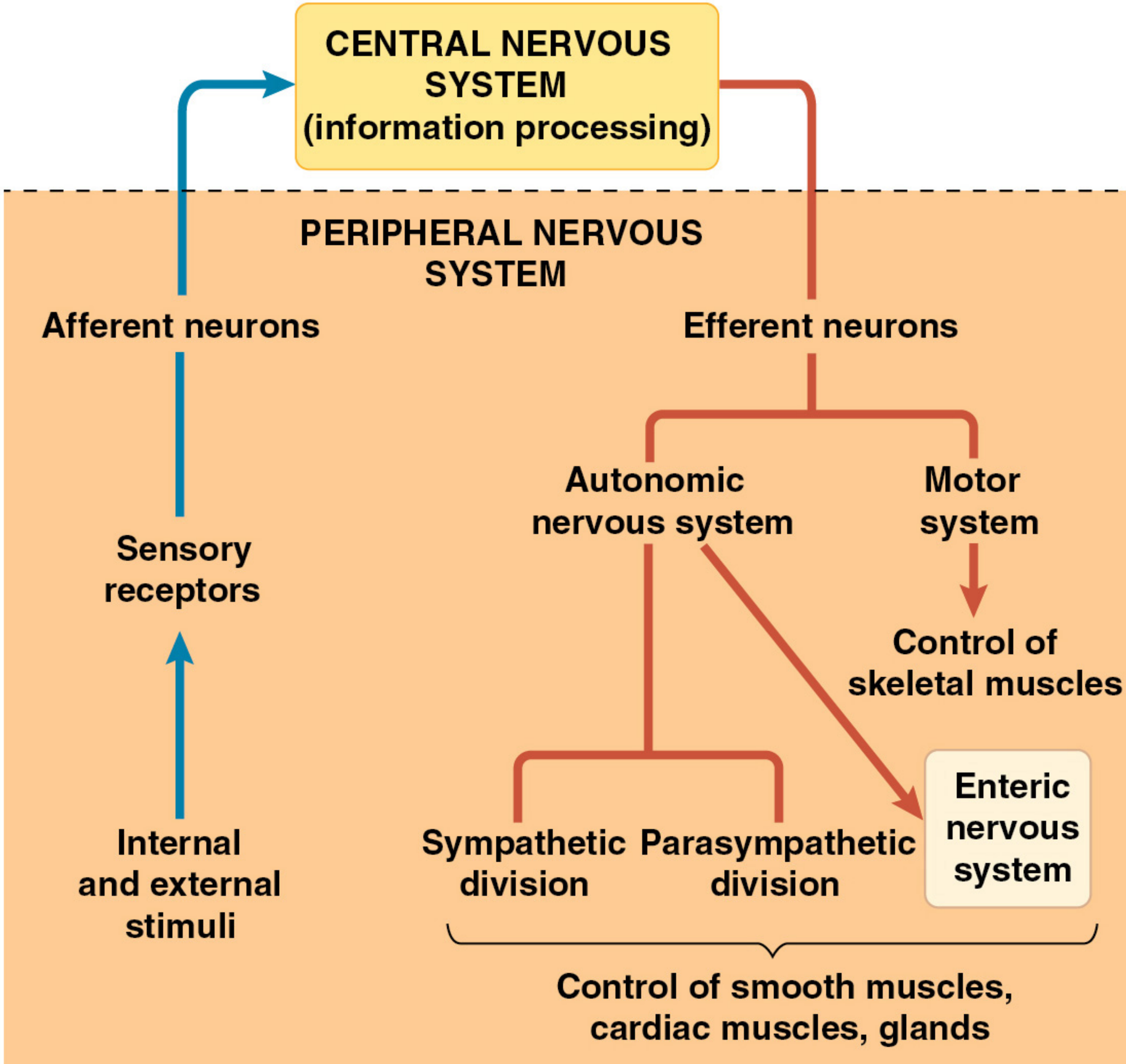


Cell body of sensory neuron in dorsal root ganglion
Gray matter
White matter
Quadriceps muscle
Spinal cord (cross section)
Hamstring muscle
Key
Sensory neuron
Motor neuron
Interneuron

The Peripheral Nervous System

- The PNS transmits information to and from the CNS and regulates movement and the internal environment
- In the PNS, afferent neurons transmit information to the CNS, and efferent neurons transmit information away from the CNS

Figure 49.6

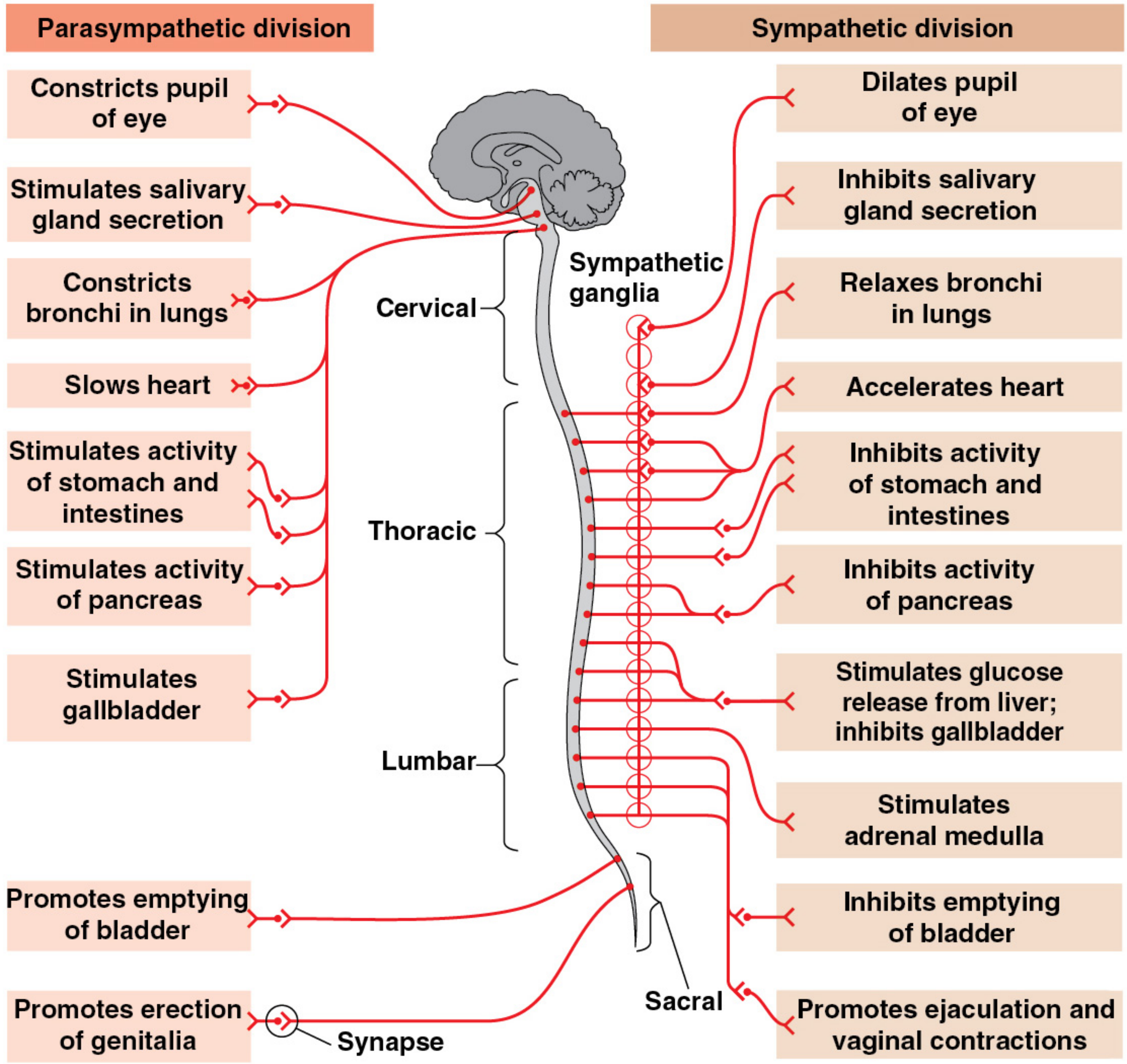


CENTRAL NERVOUS SYSTEM (information processing)
PERIPHERAL NERVOUS SYSTEM
Afferent neurons
Efferent neurons
Sensory receptors
Internal and external stimuli
Autonomic nervous system
Motor system
Control of skeletal muscles
Sympathetic division
Parasympathetic division
Enteric nervous system
Control of smooth muscles, cardiac muscles, glands

- The PNS has two efferent components: the motor system and the autonomic nervous system
- The **motor system** carries signals to skeletal muscles and can be voluntary or involuntary
- The **autonomic nervous system** regulates smooth and cardiac muscles and is generally involuntary
- The **enteric nervous system** exerts direct, partially independent, control over the digestive tract, pancreas, and gallbladder

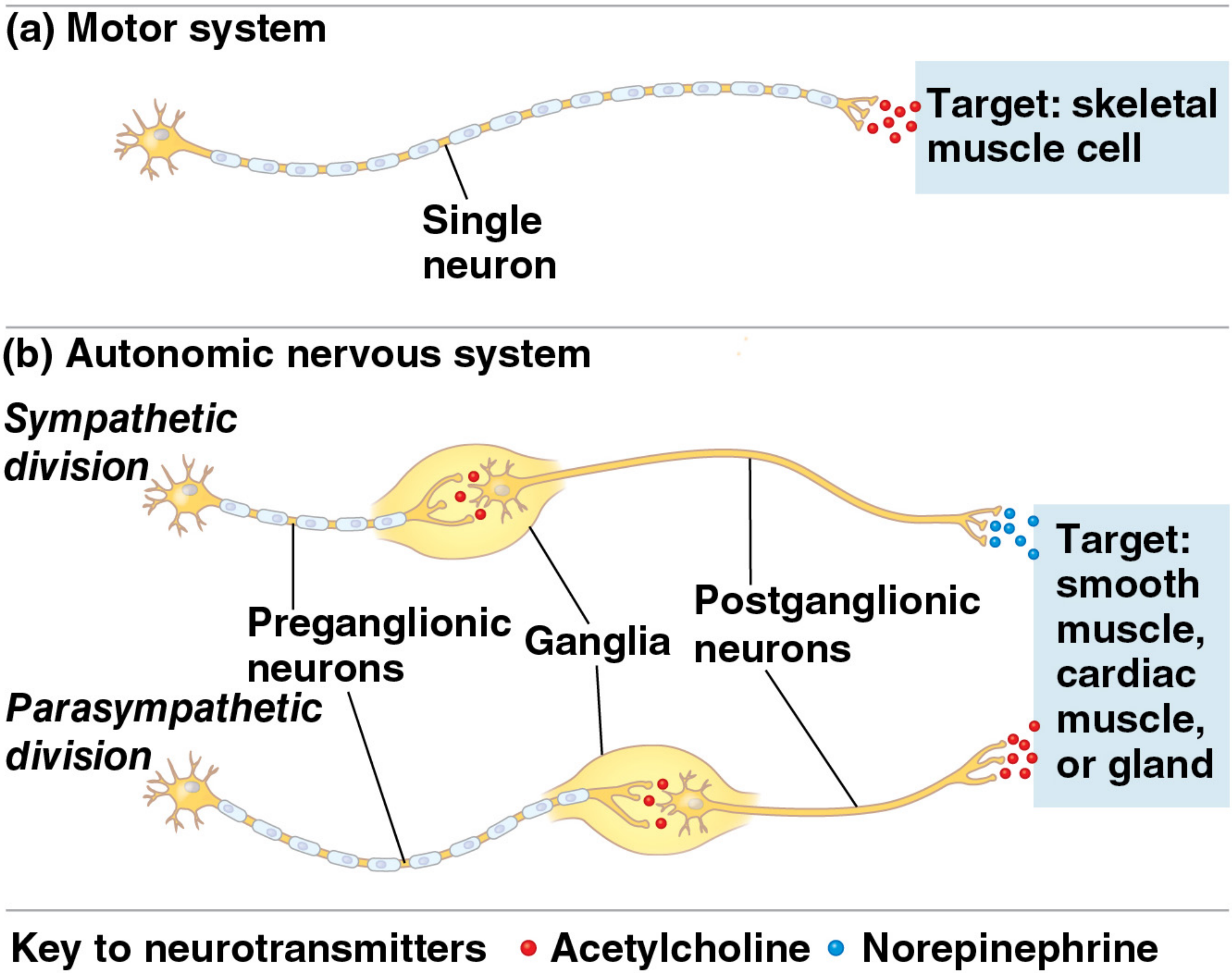
- The autonomic nervous system has sympathetic and parasympathetic divisions
- The **sympathetic division** regulates arousal and energy generation ("fight-or-flight" response)
- The **parasympathetic division** has antagonistic effects on target organs and promotes calming and a return to "rest-and-digest" functions

Figure 49.7


Parasympathetic division
Sympathetic division
Constricts pupil of eye
Stimulates salivary gland secretion
Constricts bronchi in lungs
Slows heart
Stimulates activity of stomach and intestines
Stimulates activity of pancreas
Stimulates gallbladder
Promotes emptying of bladder
Promotes erection of genitalia
Synapse
Cervical
Thoracic
Lumbar
Sacral
Sympathetic ganglia
Dilates pupil of eye
Inhibits salivary gland secretion
Relaxes bronchi in lungs
Accelerates heart
Inhibits activity of stomach and intestines
Inhibits activity of pancreas
Stimulates glucose release from liver; inhibits gallbladder
Stimulates adrenal medulla
Inhibits emptying of bladder
Promotes ejaculation and vaginal contractions

- In both sympathetic and parasympathetic systems, the pathway for information flow involves a preganglionic and postganglionic neuron
- Preganglionic neurons have cell bodies in the CNS and release acetylcholine as a neurotransmitter
- Postganglionic neurons of the parasympathetic division release acetylcholine
- Their counterparts in the sympathetic division release norepinephrine

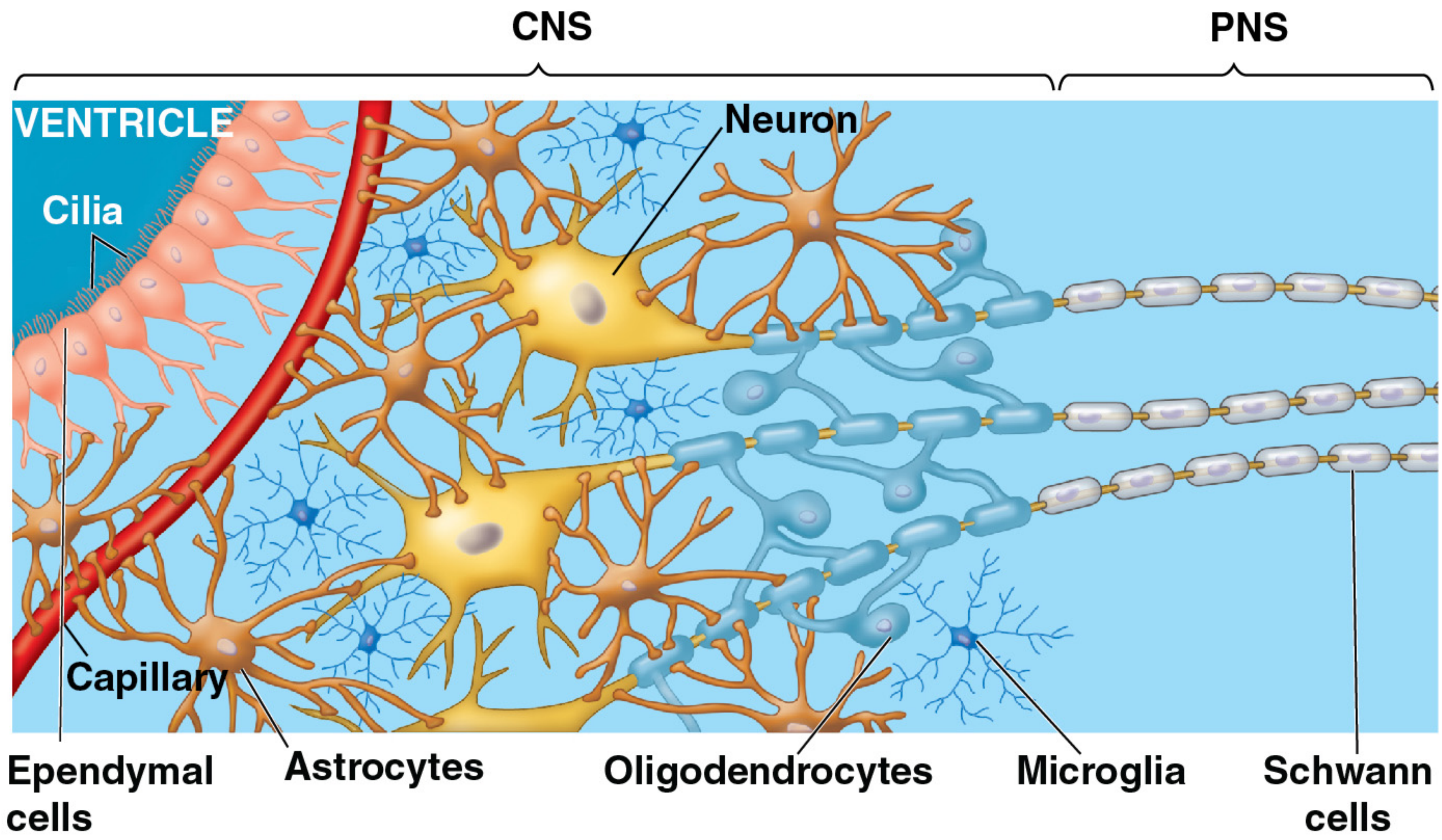
Figure 49.8


(a) Motor system
Target: skeletal muscle cell
Single neuron
(b) Autonomic nervous system
Sympathetic division
Preganglionic neurons
Ganglia
Postganglionic neurons
Target: smooth muscle, cardiac muscle, or gland
Parasympathetic division
Key to neurotransmitters
Acetylcholine
Norepinephrine

Glia

- The nervous systems of vertebrates and most invertebrates include glial cells in addition to neurons
- **Glial cells**, or **glia**, have numerous functions to nourish, support, and regulate neurons
  - Embryonic radial glia form tracks along which newly formed neurons migrate
  - Astrocytes participate in the formation of the blood-brain barrier, which restricts the entry of most substances into the brain

Figure 49.9


CNS
PNS
VENTRICLE
Cilia
Neuron
Capillary
Ependymal cells
Astrocytes
Oligodendrocytes
Microglia
Schwann cells

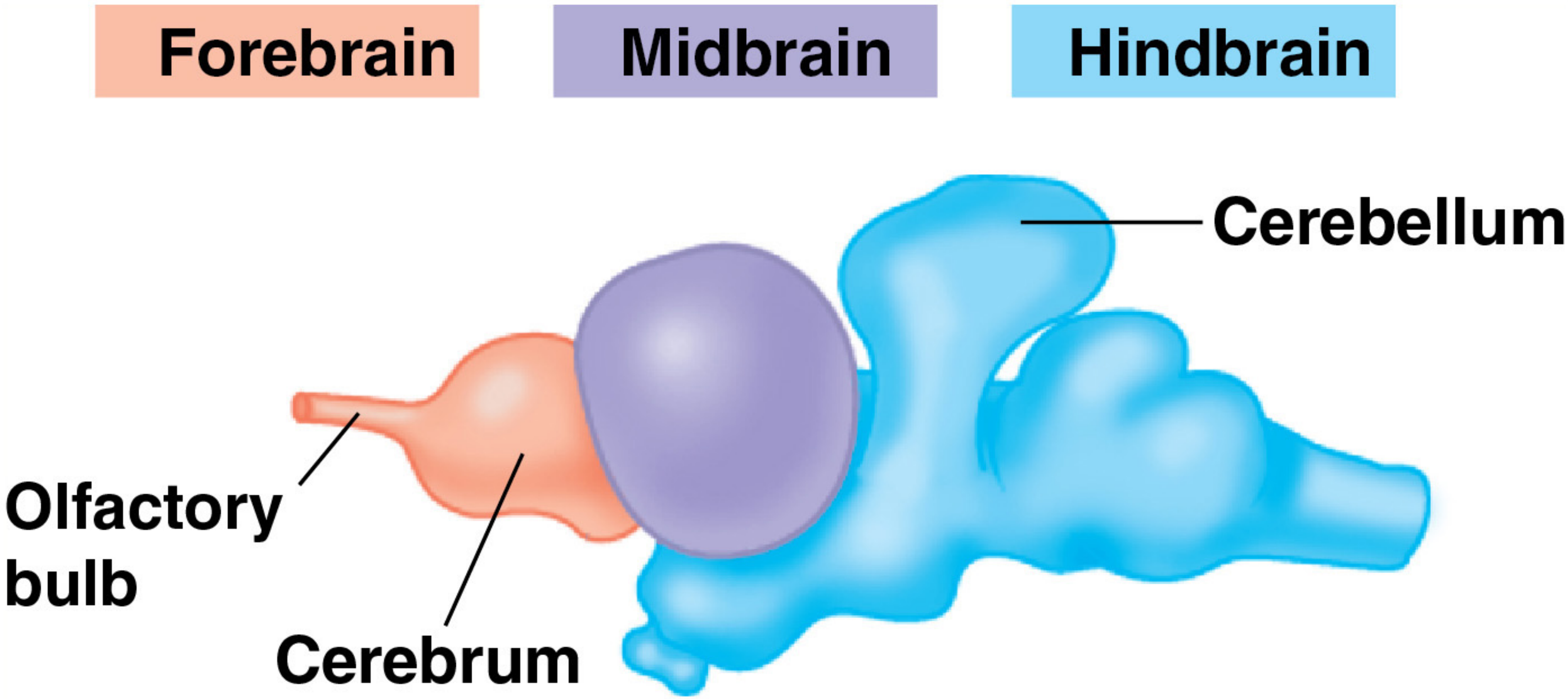
- Radial glial cells and astrocytes can both act as stem cells
- They undergo unlimited cell divisions to self-renew and to form more specialized cells

CONCEPT 49.2: The vertebrate brain is regionally specialized

- The vertebrate brain has three major regions: the forebrain, midbrain, and hindbrain
- Each region is specialized in function

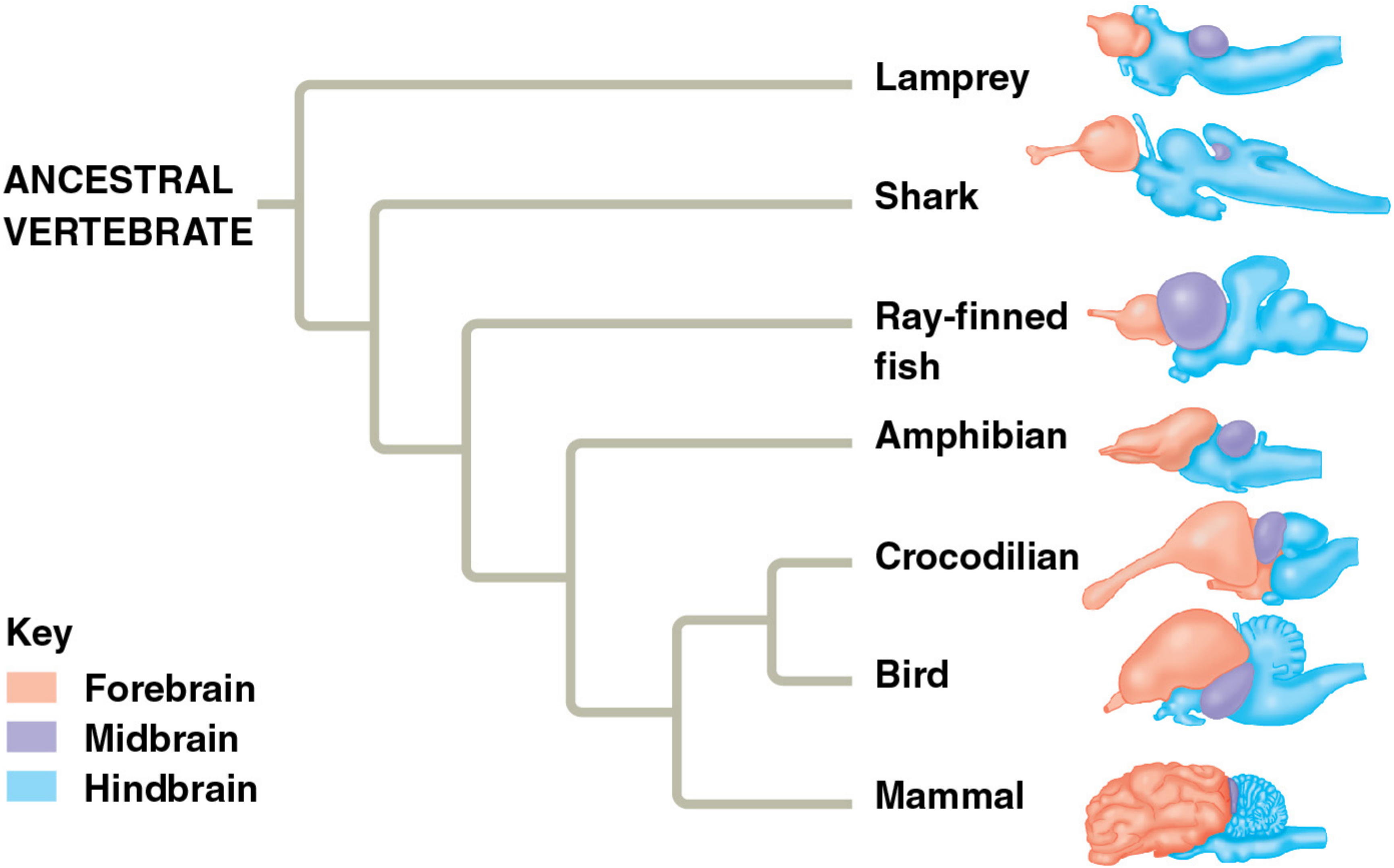
- The **forebrain** has activities including processing of olfactory input, regulation of sleep, learning, and any complex processing
- The **midbrain** coordinates routing of sensory input
- The **hindbrain** controls involuntary activities and coordinates motor activities

Figure 49.UN01



- Comparison of vertebrates shows that relative sizes of particular brain regions vary
- These size differences reflect the relative importance of the particular brain function
- Evolution has resulted in a close match between structure and function

Figure 49.10


ANCESTRAL VERTEBRATE
Lamprey
Shark
Ray-finned fish
Amphibian
Crocodilian
Bird
Mammal
Key
Forebrain
Midbrain
Hindbrain

- The human brain has 100 billion neurons, which make 100 trillion connections
- During embryonic development, the anterior neural tube gives rise to the forebrain, midbrain, and hindbrain

- The midbrain and part of the hindbrain form the **brainstem**, which joins with the spinal cord at the base of the brain
- The rest of the hindbrain gives rise to the **cerebellum**
- The forebrain divides into the diencephelon, which forms endocrine tissues in the brain, and the telencephalon, which becomes the **cerebrum**

Figure 49.11

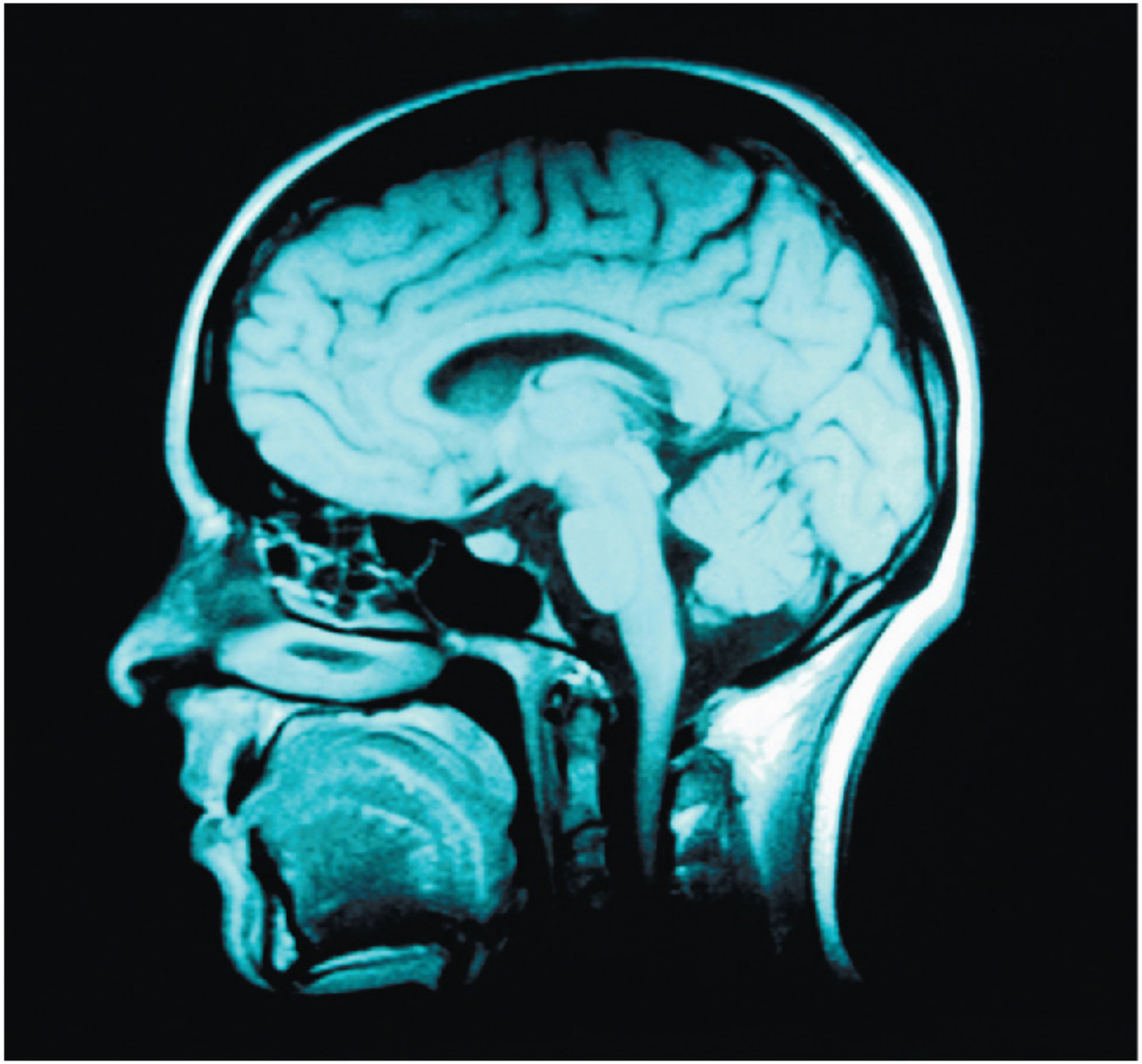
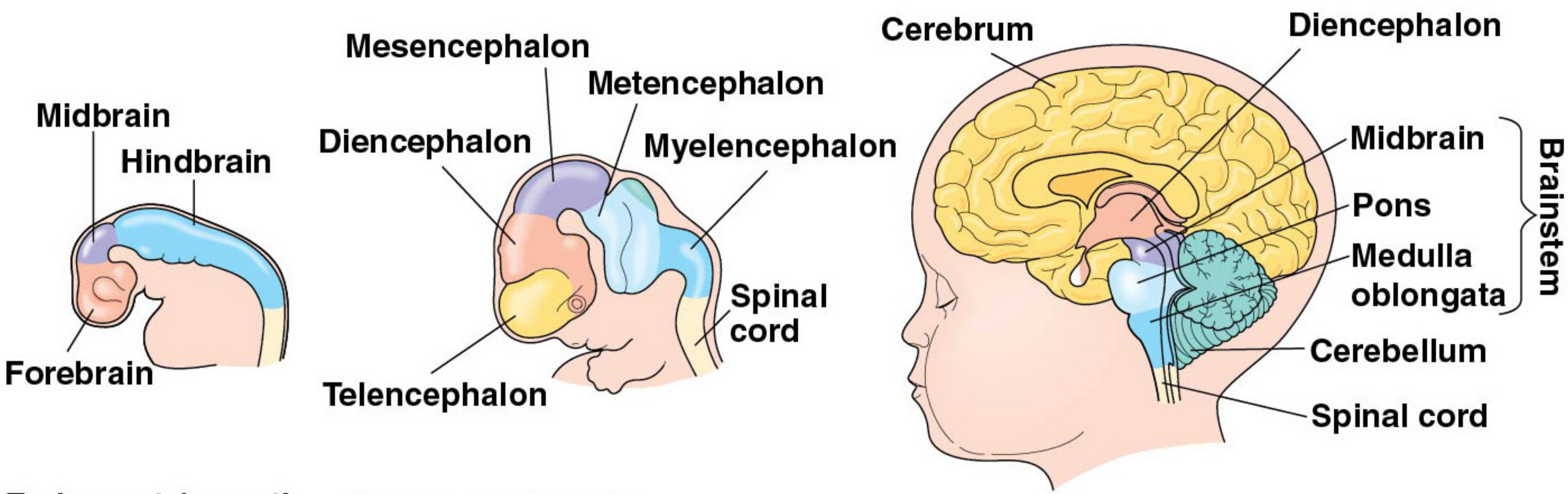


Figure 49.11

Embryonic brain regions		Brain structures in child and adult
Forebrain	Telencephalon	Cerebrum (includes cerebral cortex, basal nuclei)
	Diencephalon	Diencephalon (thalamus, hypothalamus, epithalamus)
Midbrain	Mesencephalon	Midbrain (part of brainstem)
Hindbrain	Metencephalon	Pons (part of brainstem), cerebellum
	Myelencephalon	Medulla oblongata (part of brainstem)



Embryo at 1 month

Embryo at 5 weeks

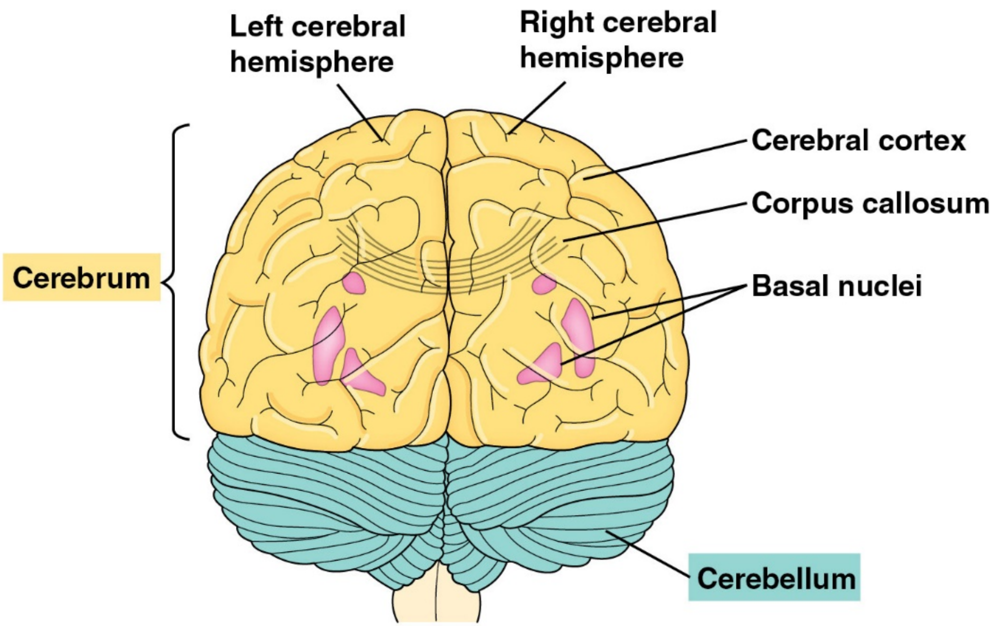
Child

- The cerebrum controls skeletal muscle contraction and is the center for learning, emotion, memory, and perception
- The outer layer of the cerebrum is called the **cerebral cortex** and is vital for perception, voluntary movement, and learning
- A thick band of axons called the **corpus callosum** enables the right and left cerebral cortices to communicate

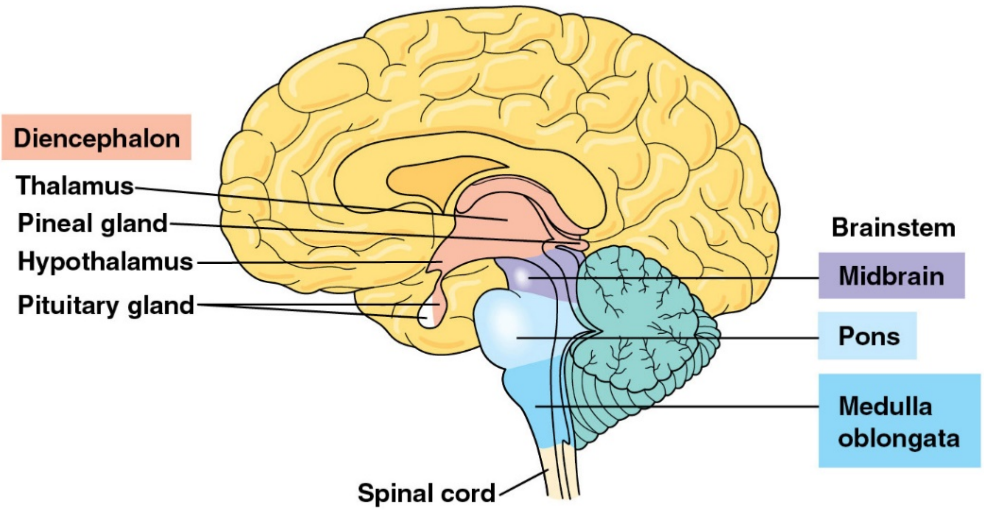
- The cerebellum coordinates movement and balance and helps in learning and remembering motor skills
- The diencephalon gives rise to the **thalamus**, **hypothalamus**, and epithalamus
- The hypothalamus constitutes a control center that includes the body's thermostat and central biological clock

- The brainstem consists of the midbrain, the **pons**, and the **medulla oblongata** (or medulla)
- The midbrain receives and integrates sensory information and sends it to specific regions of the brain
- A major function of the pons and medulla is to transfer information between the PNS and the midbrain and forebrain
- The medulla is also in control of several automatic functions such as breathing, heart and blood vessel activity, swallowing, vomiting, and digestion

Figure 49.11



Adult brain viewed from the rear



Arousal and Sleep

- The brainstem and cerebrum control arousal and sleep
- Arousal is a state of awareness of the external world
- Sleep is a state in which external stimuli are received but not consciously perceived
- Sleep is an active state for the brain
- Some animals have adaptations that allow for substantial activity during sleep

Figure 49.12

Location	Time: 0 hours	Time: 1 hour
Left hemisphere		
Right hemisphere		

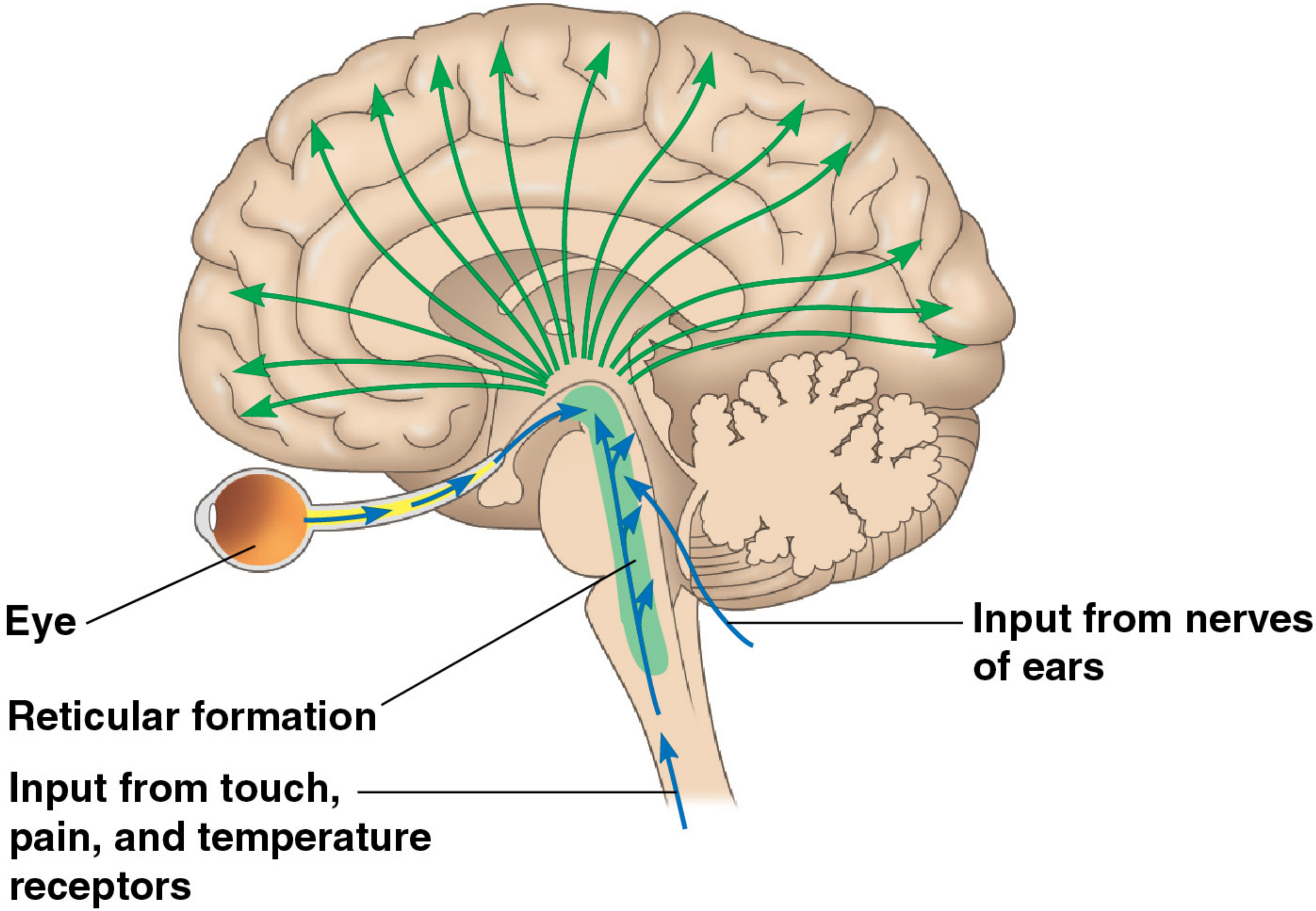
Key

 Low-frequency waves characteristic of sleep

 High-frequency waves characteristic of wakefulness

- Sleep is essential for survival and may play a role in the consolidation of learning and memory
- Arousal and sleep are controlled in part by the reticular formation, a network formed mainly of neurons in the midbrain and pons

Figure 49.13



Eye
Reticular formation
Input from touch, pain, and temperature receptors
Input from nerves of ears

- The neurons of the reticular formation control the timing of sleep periods characterized by rapid eye movements (REMs) and by vivid dreams
- Sleep is also regulated by the biological clock and regions of the forebrain that regulate intensity and duration

Biological Clock Regulation

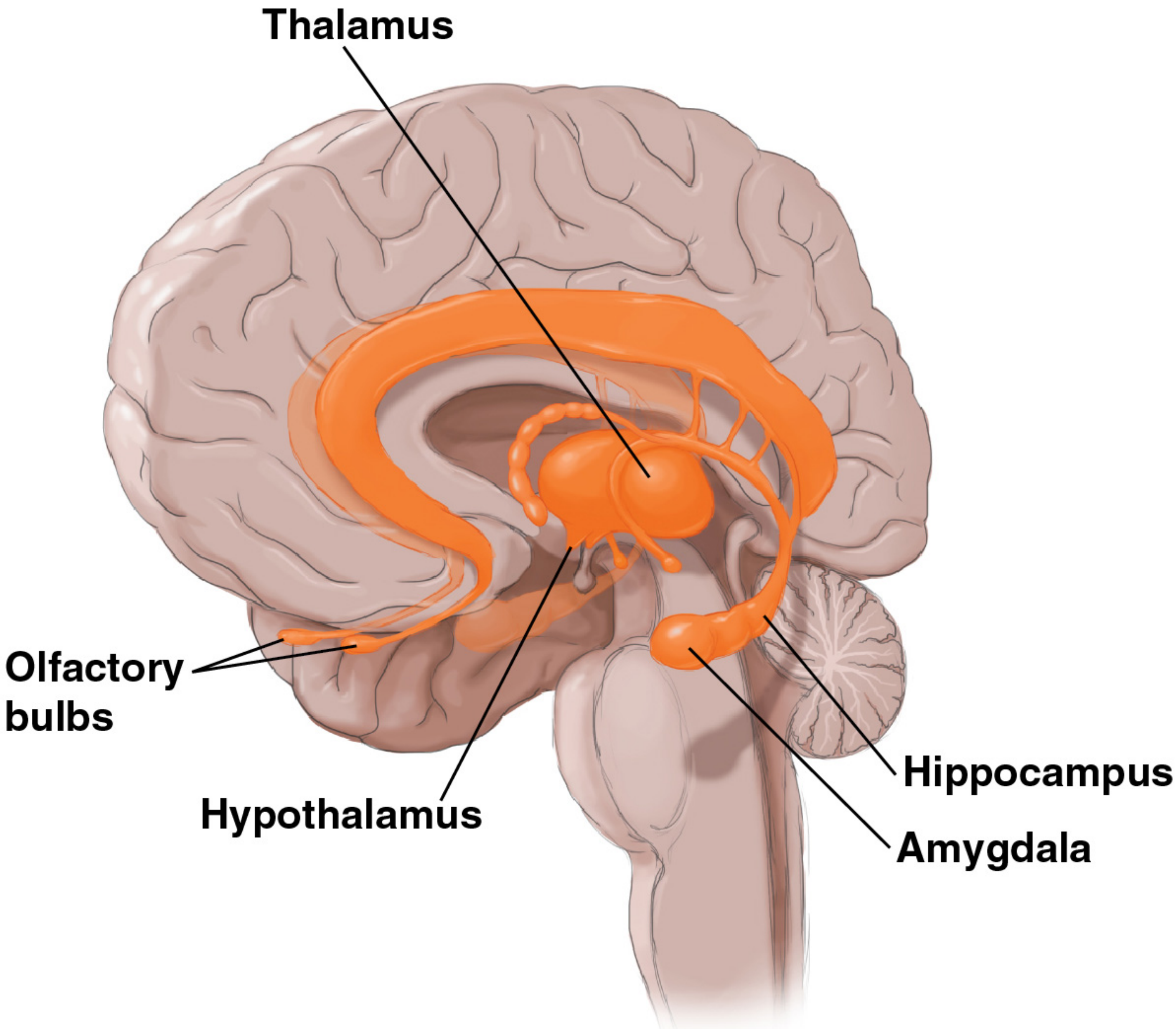
- Cycles of sleep and wakefulness are examples of circadian rhythms, daily cycles of biological activity
- Such cycles rely on a **biological clock**, a molecular mechanism that directs periodic gene expression and cellular activity
- Biological clocks are typically synchronized to light and dark cycles
- They maintain a roughly 24-hour cycle, even in the absence of environmental cues

- In mammals, circadian rhythms are coordinated by a clustered neurons in the hypothalamus called the **suprachiasmatic nucleus (SCN)**
- The SCN acts as a pacemaker, synchronizing the biological clock

Emotions

- Generation and experience of emotions involve many brain structures, including the amygdala, hippocampus, and parts of the thalamus
- These structures are grouped as the limbic system

Figure 49.14

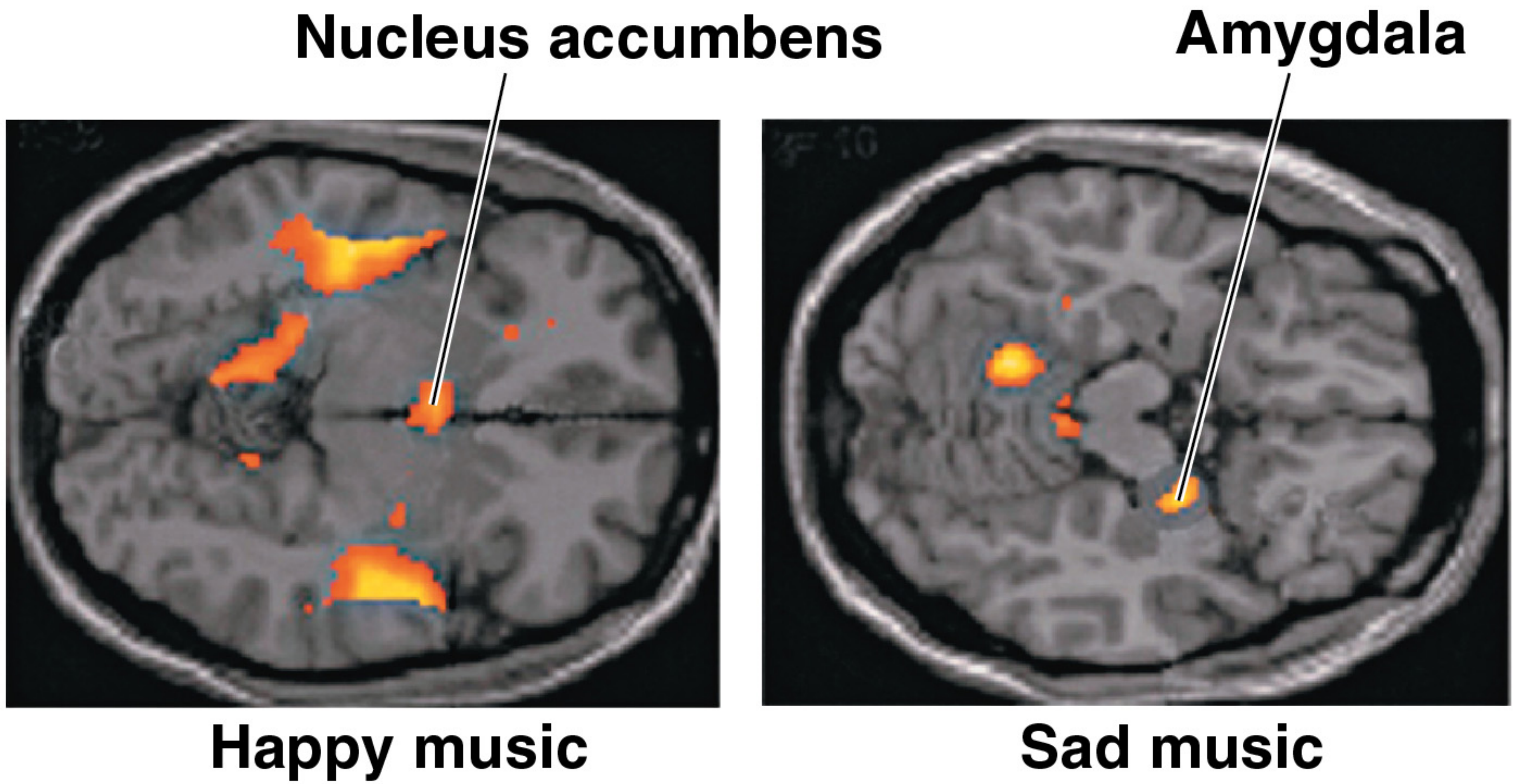

Thalamus
Olfactory bulbs
Hypothalamus
Hippocampus
Amygdala

- Storage and recall of emotional memory are dependent on the **amygdala**, an almond-shaped brain structure near the base of the cerebrum
- Generating and experiencing emotion often require interactions between different parts of the brain

Functional Imaging of the Brain

- Brain structures are studied with functional imaging techniques
- Positron-emission tomography (PET) enables a display of metabolic activity through injection of radioactive glucose
- Today, many studies rely on functional magnetic resonance imaging (fMRI), in which brain activity is detected through changes in local oxygen concentration

Figure 49.15

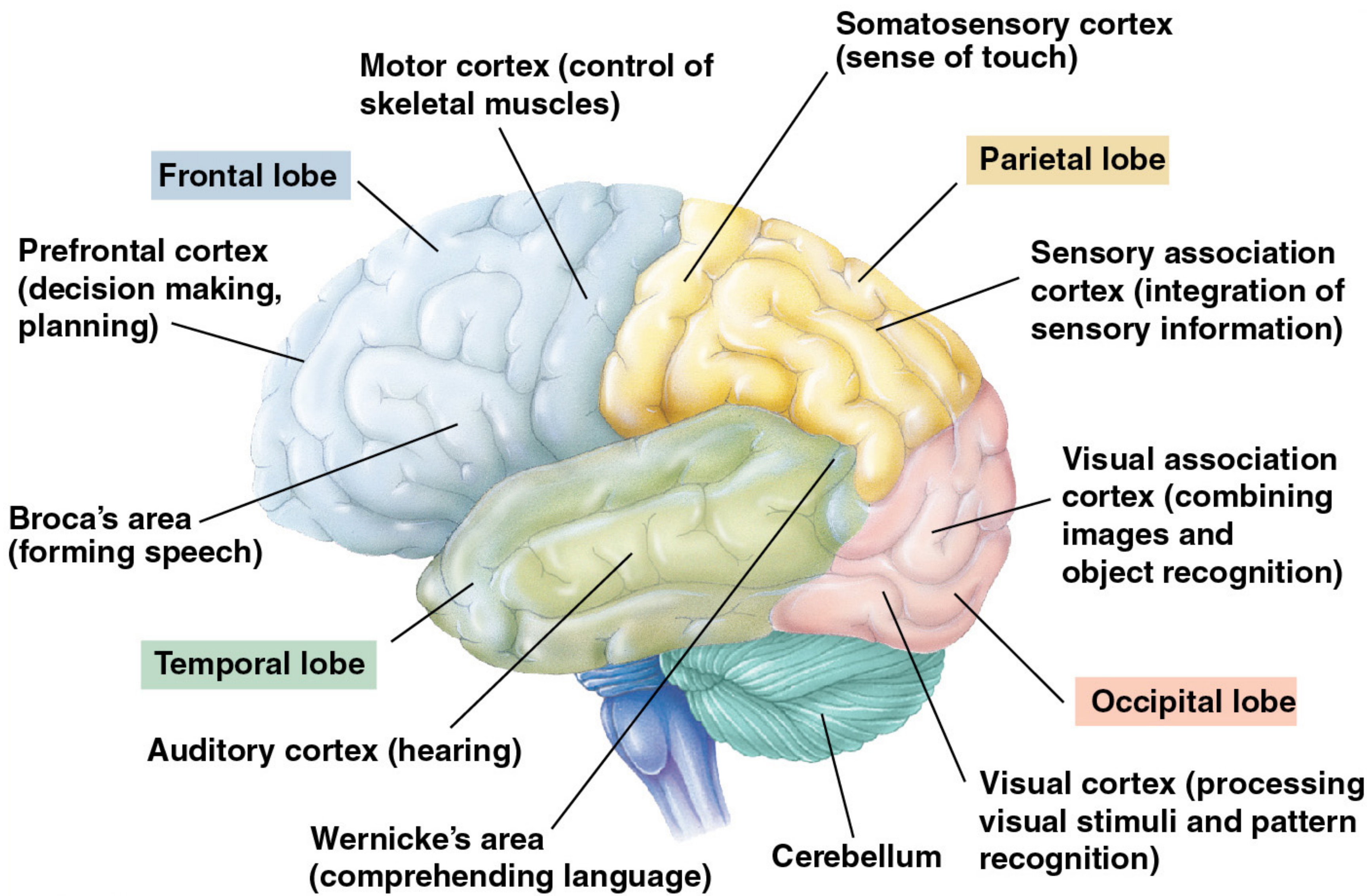


- The range of applications for fMRI include monitoring recovery from stroke, mapping abnormalities in migraine headaches, and increasing the effectiveness of brain surgery

CONCEPT 49.3: The cerebral cortex controls voluntary movement and cognitive functions

- The cerebrum, the largest structure in the human brain, is essential for language, cognition, memory, consciousness, and awareness of our surroundings
- Each lobe of the cerebral cortex (frontal, temporal, occipital, and parietal), is the focus of specific brain activities

Figure 49.16

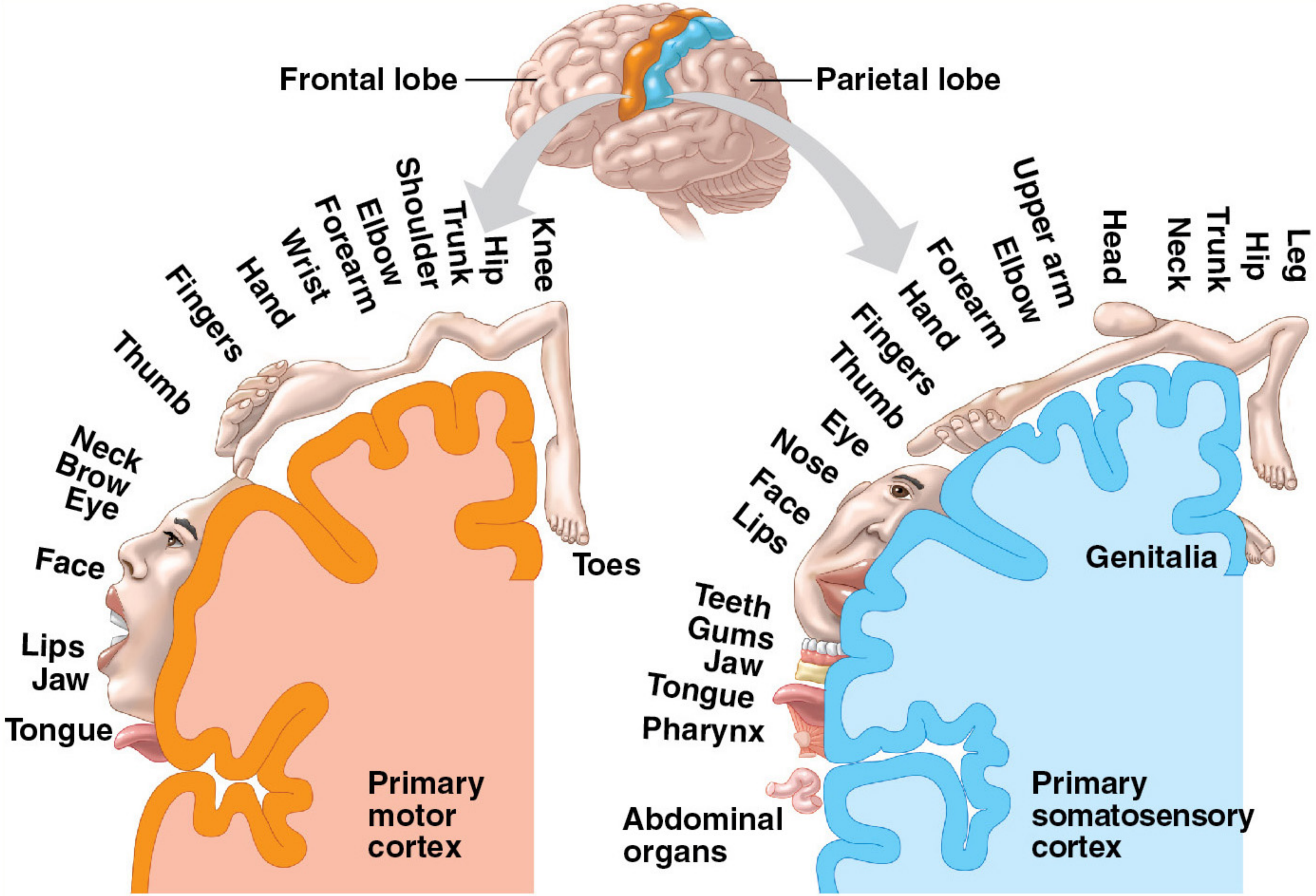

Somatosensory cortex (sense of touch)
Motor cortex (control of skeletal muscles)
Frontal lobe
Parietal lobe
Prefrontal cortex (decision making, planning)
Sensory association cortex (integration of sensory information)
Visual association cortex (combining images and object recognition)
Broca's area (forming speech)
Temporal lobe
Occipital lobe
Auditory cortex (hearing)
Visual cortex (processing visual stimuli and pattern recognition)
Wernicke's area (comprehending language)
Cerebellum

Information Processing

- The cerebral cortex receives input from sensory organs and somatosensory receptors
- Somatosensory receptors provide information about touch, pain, pressure, temperature, and the position of muscles and limbs
- The thalamus directs different types of input to distinct locations

- Information received at the primary sensory areas is passed to nearby association areas that process particular features in the input
- Integrated sensory information passes to the prefrontal cortex, which helps plan actions and movements
- In the somatosensory cortex and motor cortex, neurons are arranged according to the part of the body that generates input or receives commands

Figure 49.17

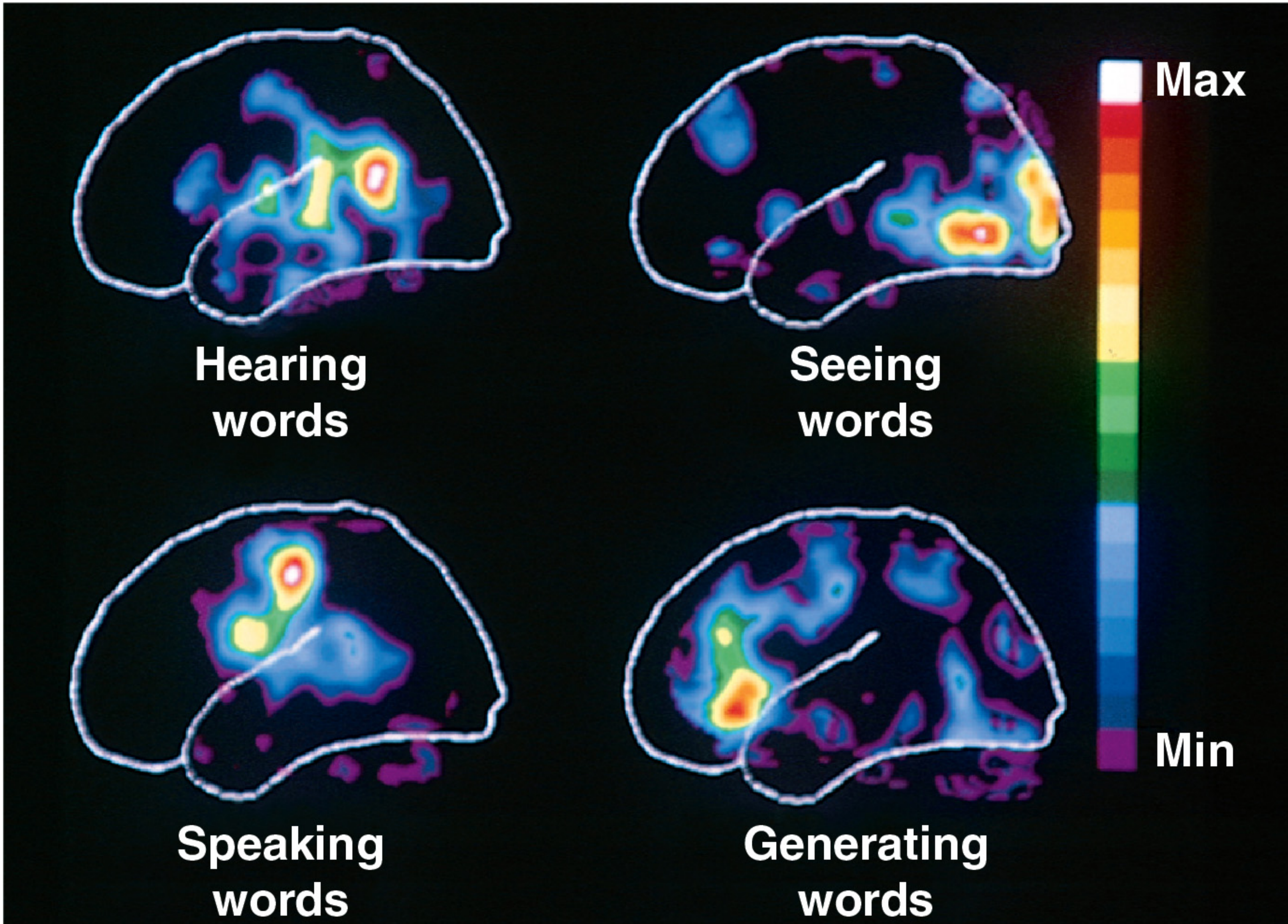


Frontal lobe
Parietal lobe
Knee
Hip
Trunk
Shoulder
Elbow
Forearm
Wrist
Hand
Fingers
Thumb
Neck
Brow
Eye
Face
Lips
Jaw
Tongue
Toes
Primary motor cortex
Leg
Hip
Trunk
Neck
Head
Upper arm
Elbow
Forearm
Hand
Fingers
Thumb
Eye
Nose
Face
Lips
Teeth
Gums
Jaw
Tongue
Pharynx
Abdominal organs
Genitalia
Primary somatosensory cortex

Language and Speech

- Mapping of cognitive functions within the cortex began in the 1800s
- Patients with damage in Broca's area in the frontal lobe can understand language but cannot speak
- Damage to Wernicke's area causes patients to be unable to understand language, though they can still speak
- PET studies confirm activity in Broca's area during speech generation and Wernicke's area when speech is heard

Figure 49.18


Max
Hearing words
Seeing words
Speaking words
Generating words
Min

Lateralization of Cortical Function

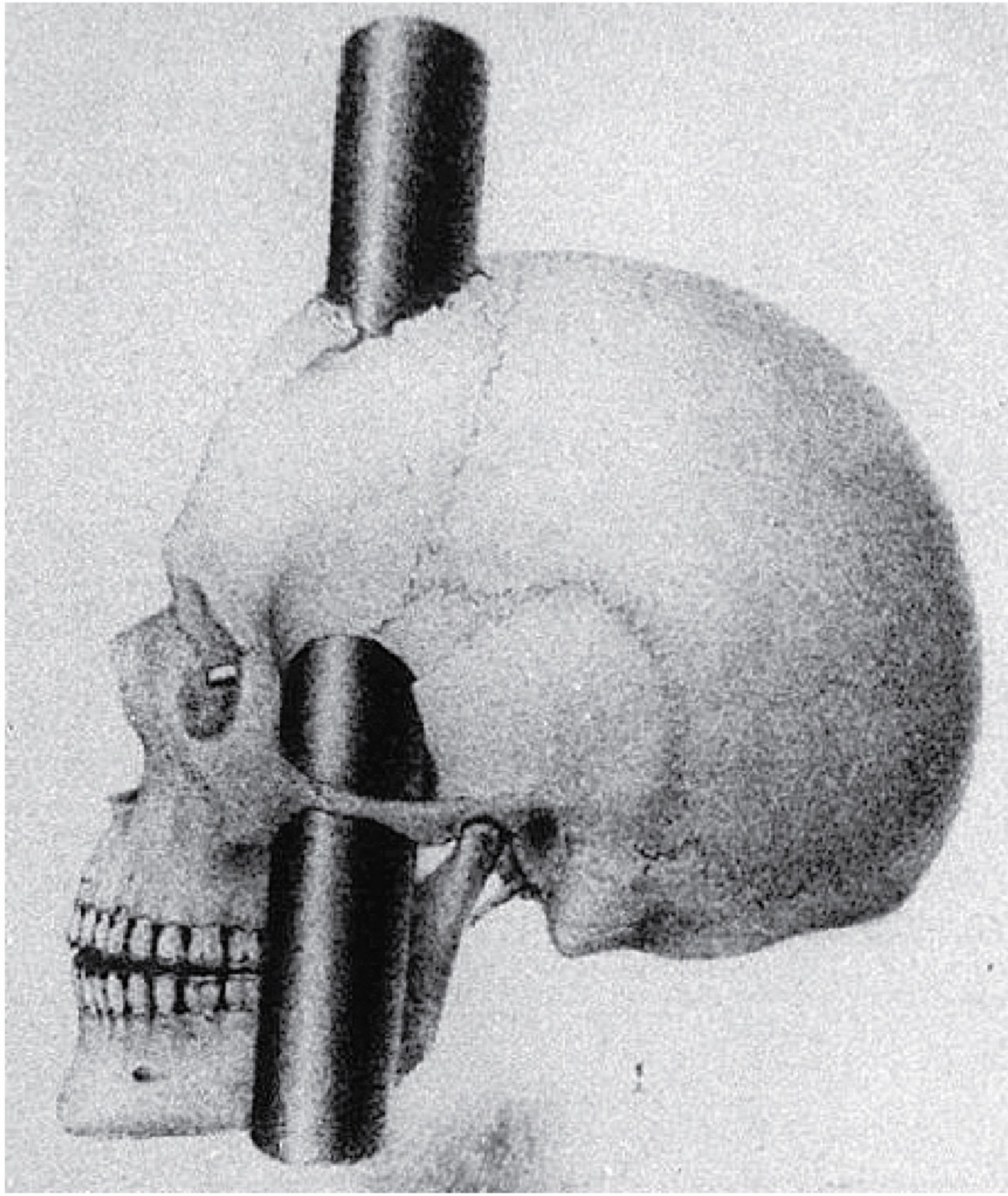
- The two hemispheres make distinct contributions to brain function
- The left hemisphere is more adept at language, math and logical operations
- The right hemisphere is stronger at facial and pattern recognition, spatial relations, and nonverbal thinking

- The difference in hemisphere function is called **lateralization**
- The two hemispheres work together by communicating through the fibers of the corpus callosum
- Severing the connection between hemispheres results in a “split-brain” effect

Frontal Lobe Function

- Frontal lobe damage may impair decision making and emotional responses but leave intellect and memory intact
- The frontal lobes have a substantial effect on “executive functions”

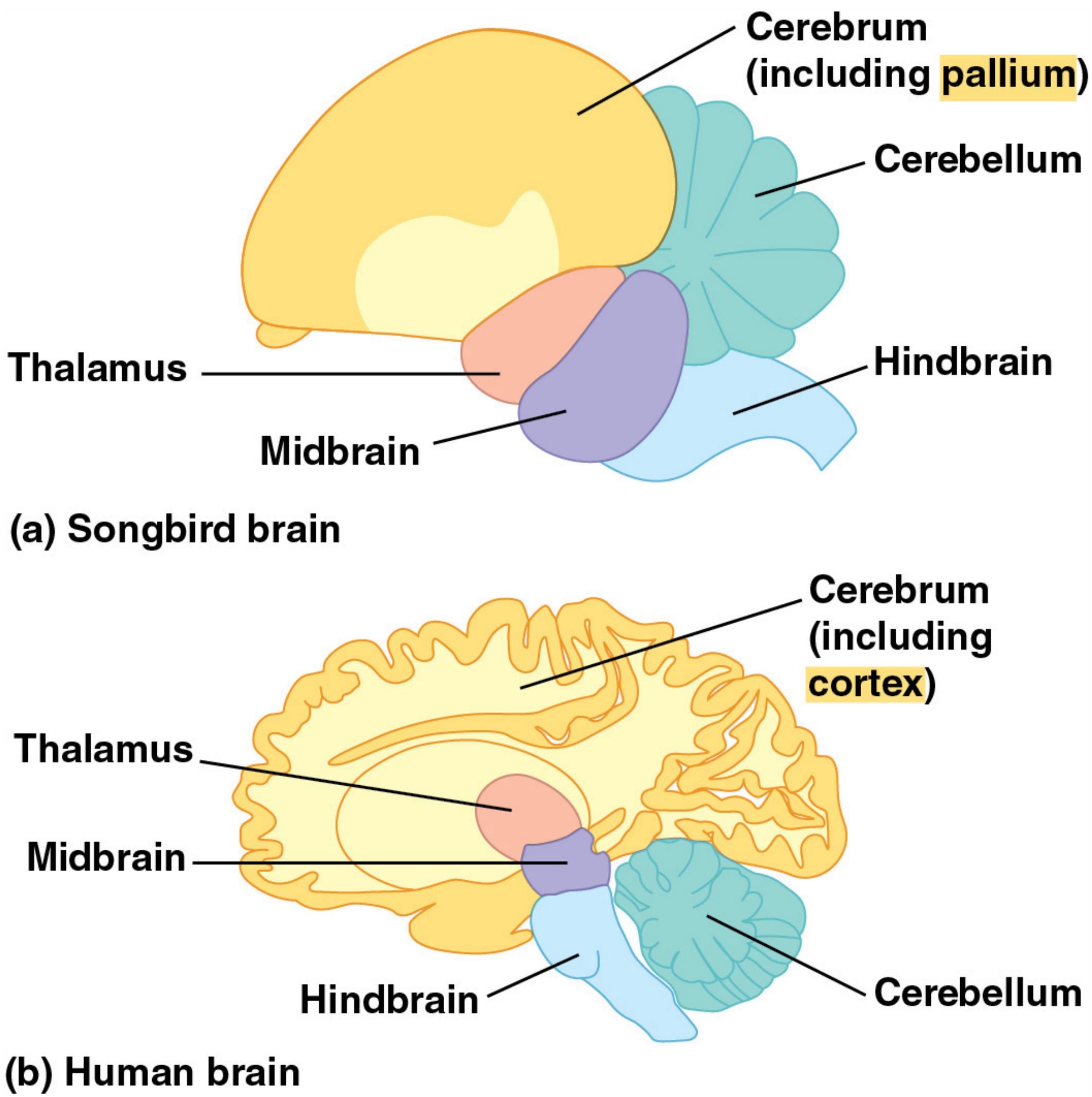
Figure 49.19



Evolution of Cognition in Vertebrates

- Previous ideas that a highly convoluted neocortex is required for advanced cognition may be incorrect
- The anatomical basis for sophisticated information processing in birds (without a highly convoluted neocortex) appears to be the clustering of nuclei in the top or outer portion of the brain (pallium)

Figure 49.20



Cerebrum
(including pallium)
Cerebellum
Thalamus
Hindbrain
Midbrain
(a) Songbird brain
Cerebrum
(including
cortex)
Thalamus
Midbrain
Hindbrain
Cerebellum
(b) Human brain

- The current consensus about how the pallium in birds and cerebral cortex in humans arose:
  - A common ancestor of birds and mammals had a pallium in which neurons were organized into nuclei
  - Early in mammalian evolution, this clustered organization was transformed into a layered one
  - Connectivity was maintained

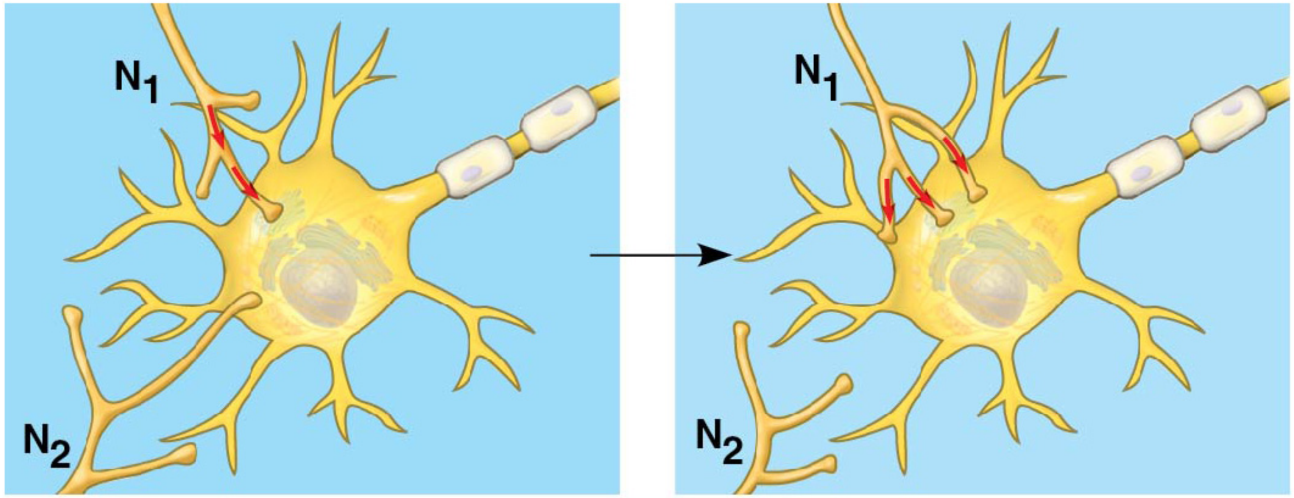
CONCEPT 49.4: Changes in synaptic connections underlie memory and learning

- Formation of the nervous system occurs in steps
  - Regulated gene expression and signal transduction determine where neurons form
  - Then neurons compete for growth-supporting factors in order to survive
  - Only half the synapses that form during embryo development survive into adulthood
  - In the final phase, synapse elimination occurs

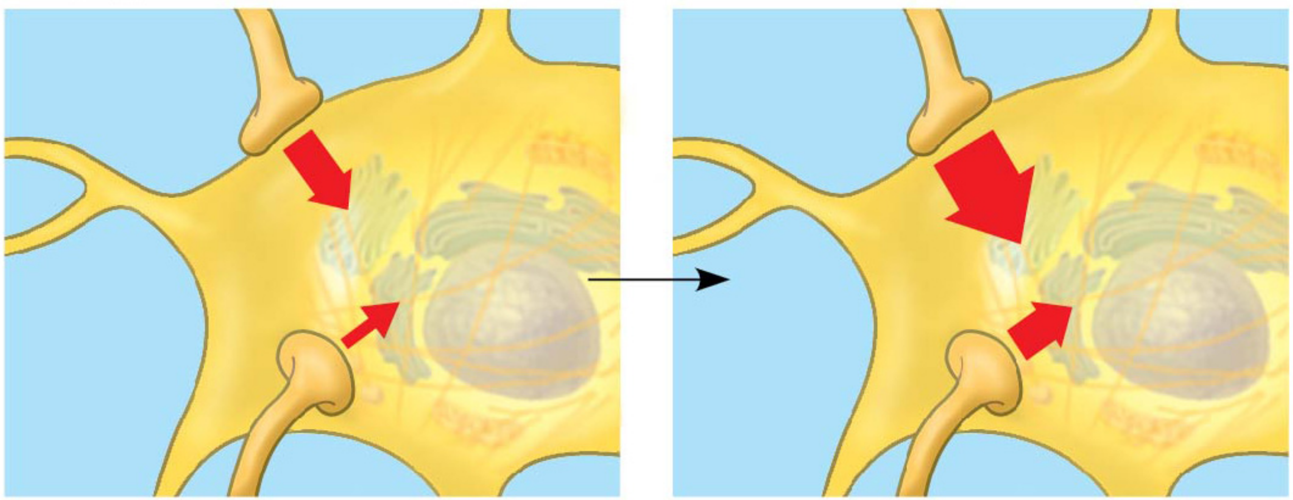
Neuronal Plasticity

- **Neuronal plasticity** describes the ability of the nervous system to be remodeled after birth
- Changes can strengthen or weaken signaling at a synapse
- A defect in neural plasticity may underlie autism spectrum disorder
- Children affected with autism display impaired communication and social interaction, as well as stereotyped, repetitive behaviors

Figure 49.21



(a) Connections between neurons are strengthened (N_1) or weakened (N_2) based on activity.



(b) If two synapses on a postsynaptic cell are often active at the same time, the strength of both responses may increase.

- There is evidence that autism spectrum disorder involves a disruption of activity-dependent remodeling at synapses
- Extensive research rules out any link to vaccine preservatives
- There is a strong genetic contribution to this and related disorders

Memory and Learning

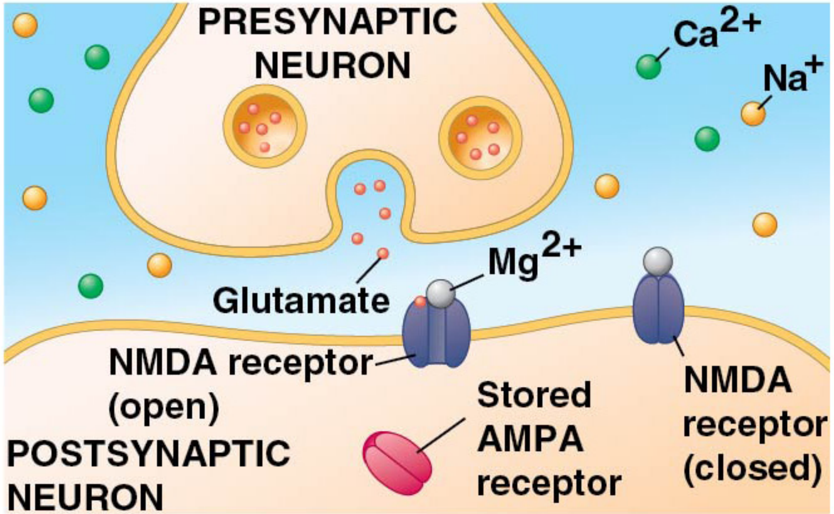
- Neuronal plasticity is essential to the formation of memories
- **Short-term memory** is accessed via temporary links formed in the hippocampus
- In **long-term memory**, the links in the hippocampus are replaced by connections in the cerebral cortex
- Some consolidation of memory is thought to occur during sleep

- Individuals who suffer damage to the hippocampus are unable to from new lasting memories but can freely recall events from before their injury
- Hippocampal damage and memory loss are common in the early stages of Alzheimer’s disease

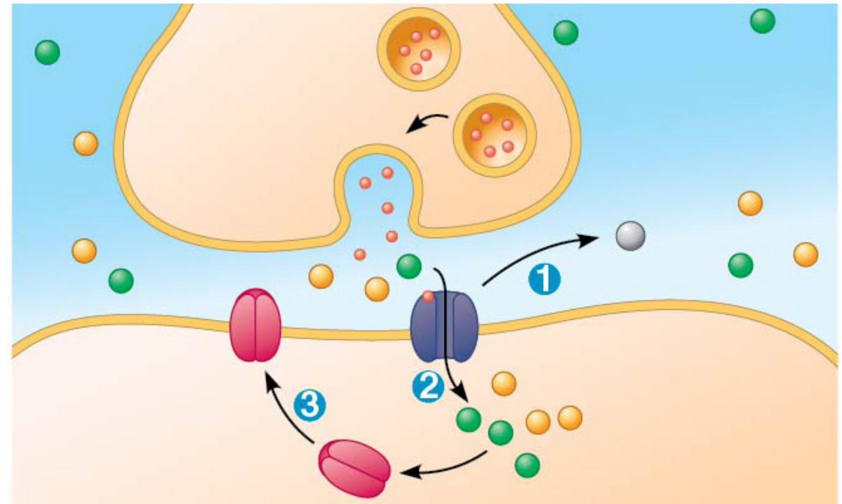
Long-Term Potentiation

- In the vertebrate brain, **long-term potentiation (LTP)** involves a lasting increase in the strength of synaptic transmission
- LTP involves a presynaptic neuron that releases the neurotransmitter glutamate
- LTP involves two types of glutamate receptors on the receiving cell
- The receptors on the postsynaptic membrane change in response to a stimulus

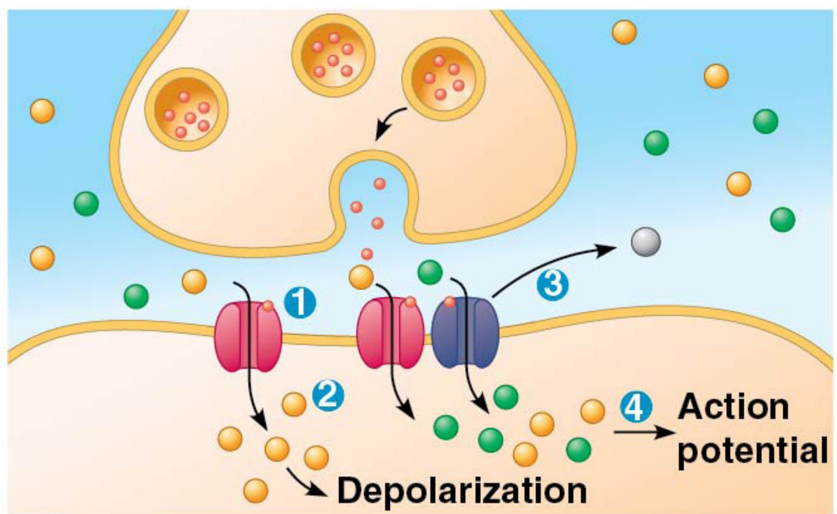
Figure 49.22



(a) Synapse prior to long-term potentiation (LTP).



(b) Establishing LTP.



(c) Synapse exhibiting LTP.

CONCEPT 49.5: Many nervous system disorders can now be explained in molecular terms

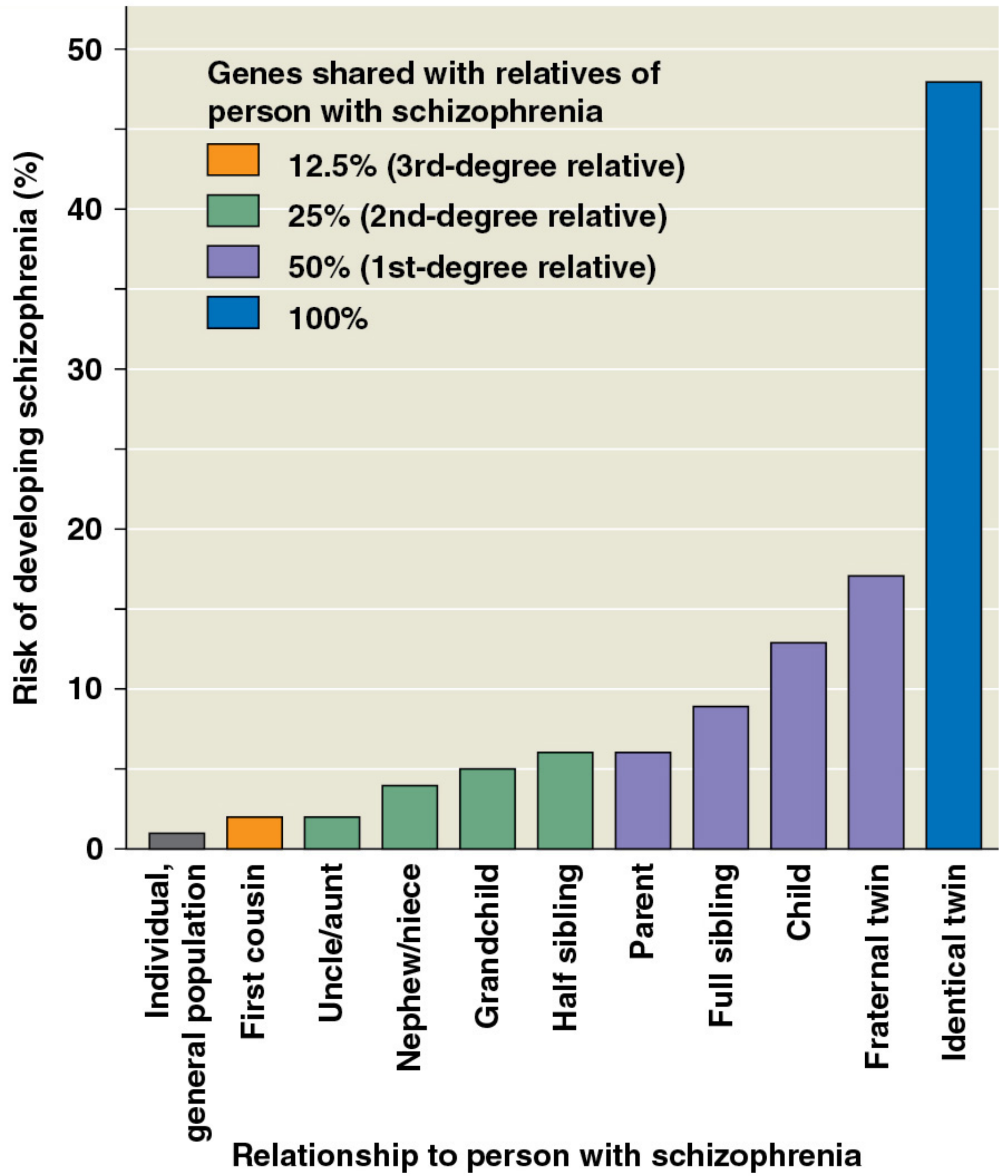
- Disorders of the nervous system include schizophrenia, depression, drug addiction, Alzheimer’s disease, and Parkinson’s disease
- Genetic and environmental factors contribute to diseases of the nervous system
- To distinguish between genetic and environmental variables, scientists often carry out family studies

Schizophrenia

- About 1% of the world’s population suffers from **schizophrenia**
- Schizophrenia is typically characterized by hallucinations and delusions
- There is a very strong genetic component to schizophrenia
- However, there is also a strong environmental influence

- An individual who shares 100% of their genes with a twin with schizophrenia has only a 48% chance of developing the disorder
- Research suggests that schizophrenia affects neuronal pathways that use dopamine as a neurotransmitter
- Many drugs that alleviate the symptoms of schizophrenia block dopamine receptors

Figure 49.23



Genes shared with relatives of person with schizophrenia
12.5% (3rd-degree relative)
25% (2nd-degree relative)
50% (1st-degree relative)
100%
Risk of developing schizophrenia (%)
50
40
30
20
10
0
Individual, general population
First cousin
Uncle/aunt
Nephew/niece
Grandchild
Half sibling
Parent
Full sibling
Child
Fraternal twin
Identical twin
Relationship to person with schizophrenia

Depression

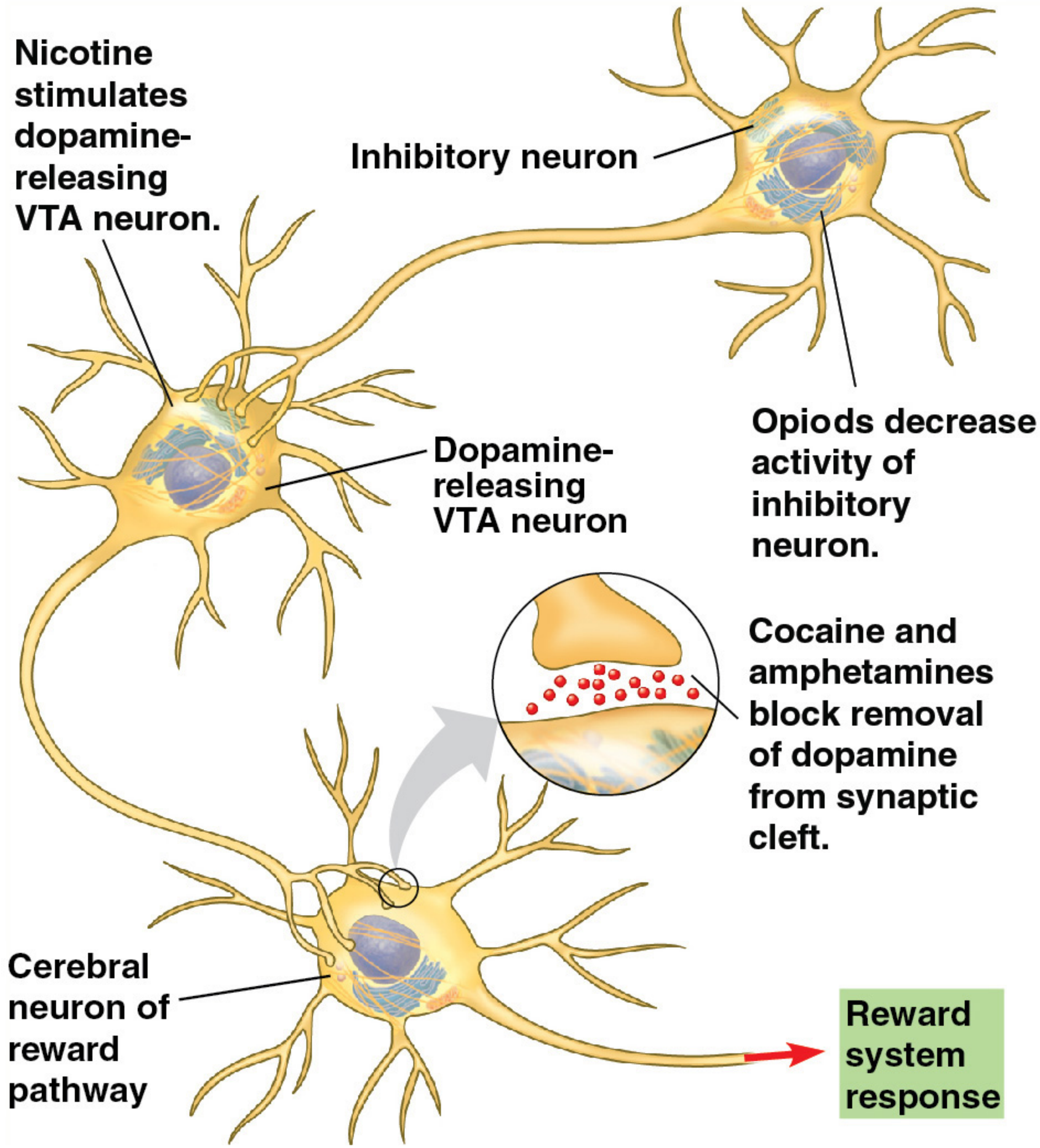
- Two broad forms of depressive illness are known
- In **major depressive disorder**, patients have a persistent lack of interest or pleasure in most activities
- **Bipolar disorder** is characterized by manic (high-mood) and depressive (low-mood) phases
- Treatments for these types of depression include drugs that increase the activity of biogenic amines in the brain

The Brain’s Reward System and Drug Addiction

- The brain’s reward system rewards motivation with pleasure
- The neurotransmitter, dopamine, is associated with the reward system
- Some drugs are addictive because they increase activity of the brain’s reward system
- These drugs include cocaine, amphetamine, heroin, alcohol, and tobacco

- Drug addiction is characterized by compulsive consumption and an inability to control intake
- Addictive drugs enhance the activity of the dopamine pathway
- Drug addiction leads to long-lasting changes in the reward circuitry that cause a craving for the drug
- It is hoped that insights gained by research in this field will lead to better prevention and treatment of drug addiction

Figure 49.24



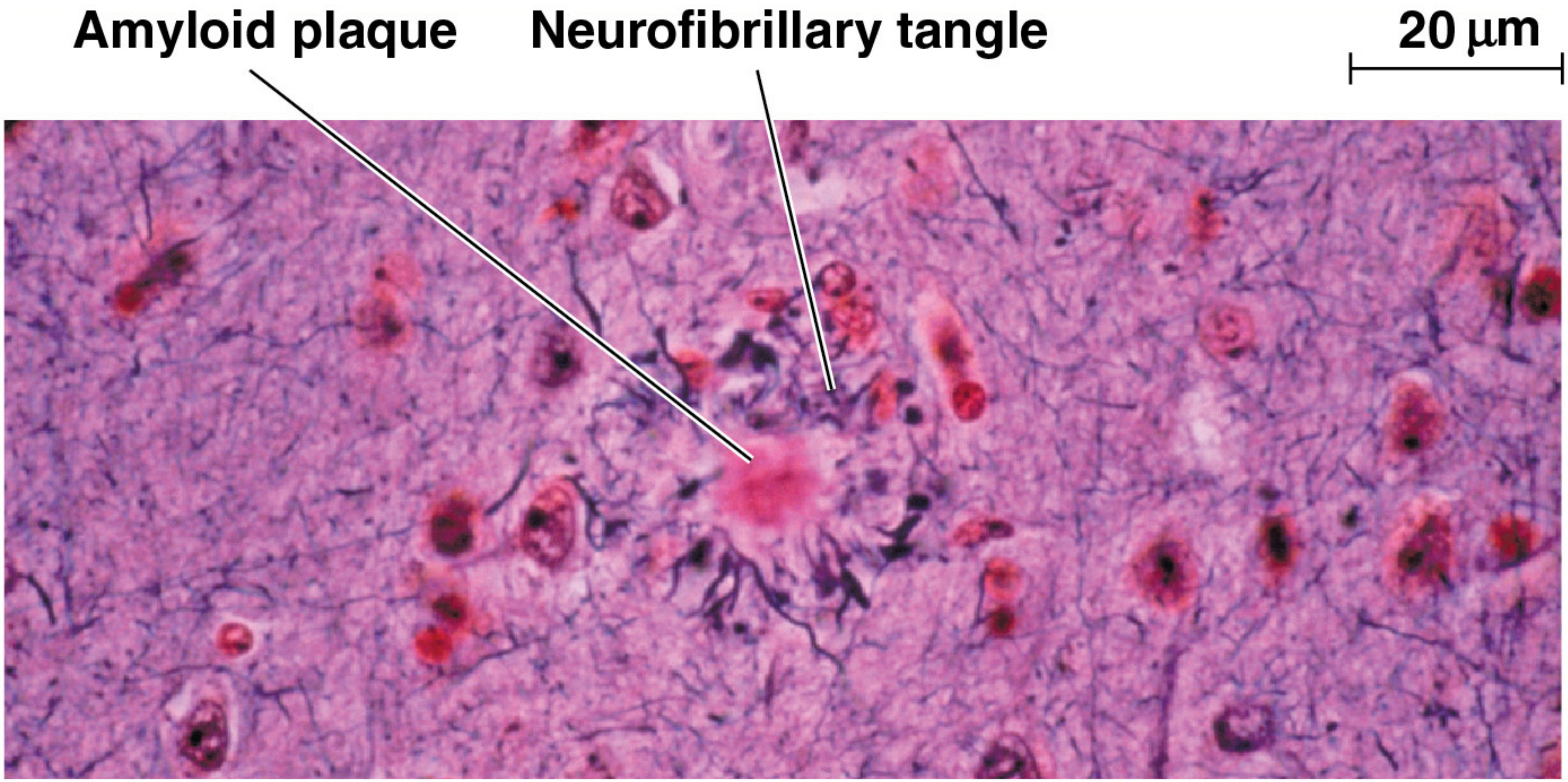
Nicotine stimulates dopamine-releasing VTA neuron.
Inhibitory neuron
Dopamine-releasing VTA neuron
Opiods decrease activity of inhibitory neuron.
Cocaine and amphetamines block removal of dopamine from synaptic cleft.
Cerebral neuron of reward pathway
Reward system response

Alzheimer’s Disease

- **Alzheimer’s disease** is a mental deterioration (dementia) characterized by confusion and memory loss
- The incidence of Alzheimer’s disease increases with age
- It is associated with formation of amyloid plaques and neurofibrillary tangles in the brain
- There is also massive shrinkage of brain tissue, reflecting the death of neurons in many areas of the brain

- The neurofibrillary tangles observed in Alzheimer’s disease are primarily made up of tau protein
- There is no cure for this disease, though some drugs are effective at relieving symptoms
- Tau protein accumulation is also characteristic of a degenerative brain disease found in athletes, military veterans, and others with a history of concussion
- This disease is known as chronic traumatic encephalopathy (CTE)

Figure 49.25



Parkinson's Disease

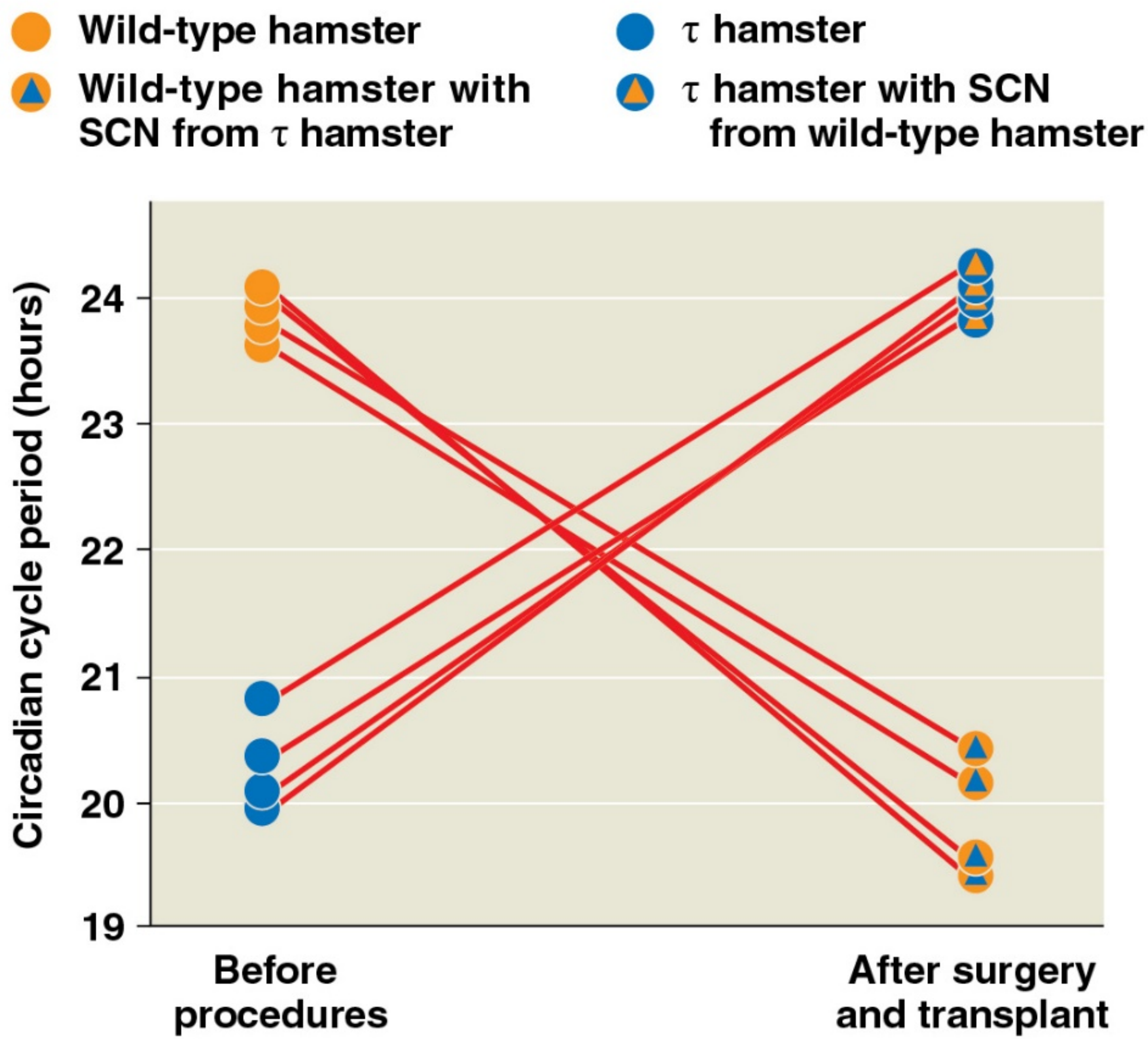
- **Parkinson's disease** is a motor disorder caused by death of dopamine-secreting neurons in the midbrain
- It is characterized by muscle tremors, flexed posture, and a shuffling gait
- The incidence increases with advancing age
- Most cases of Parkinson's disease lack an identifiable cause, although one form is known to have a genetic basis

- Parkinson’s disease can be treated but not cured
- A dopamine-related drug called L-dopa can reduce the severity of Parkinson’s disease symptoms

Figure 49.UN02

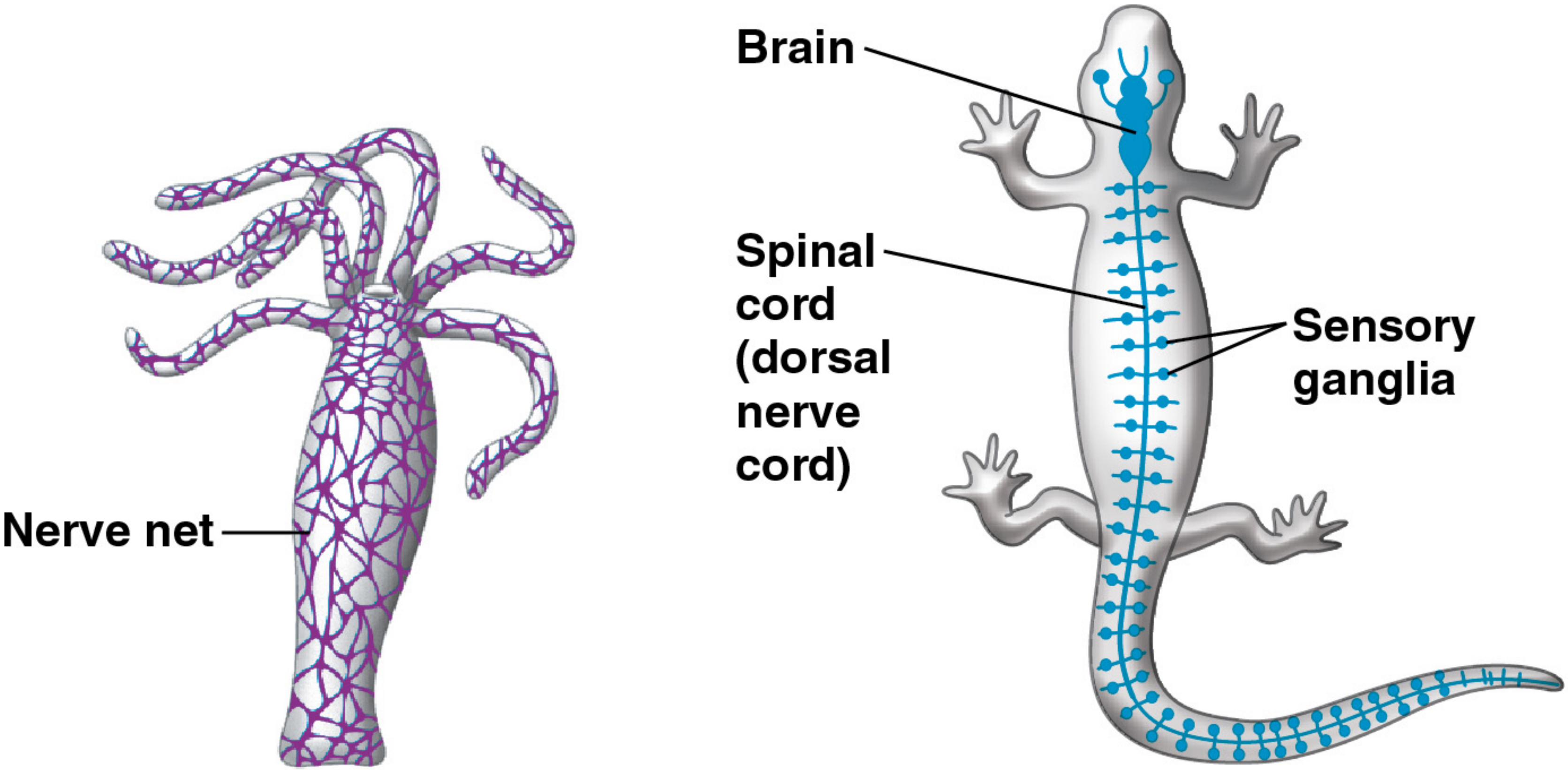
Future Directions in Brain Research

- In 2014, the National Institutes of Health and other U.S. government agencies launched a 12-year project, called BRAIN (Brain Research through Advancing Innovative Neurotechnologies)
- The objective is to:
  - Map brain circuits
  - Measure activity within those circuits
  - Understand how this activity is translated into thought and behavior



Data from M. R. Ralph et al., Transplanted suprachiasmatic nucleus determines circadian period, *Science* 247:975–978 (1990).

Figure 49.UN04



Hydra (cnidarian) Salamander (vertebrate)

Figure 49.UN05

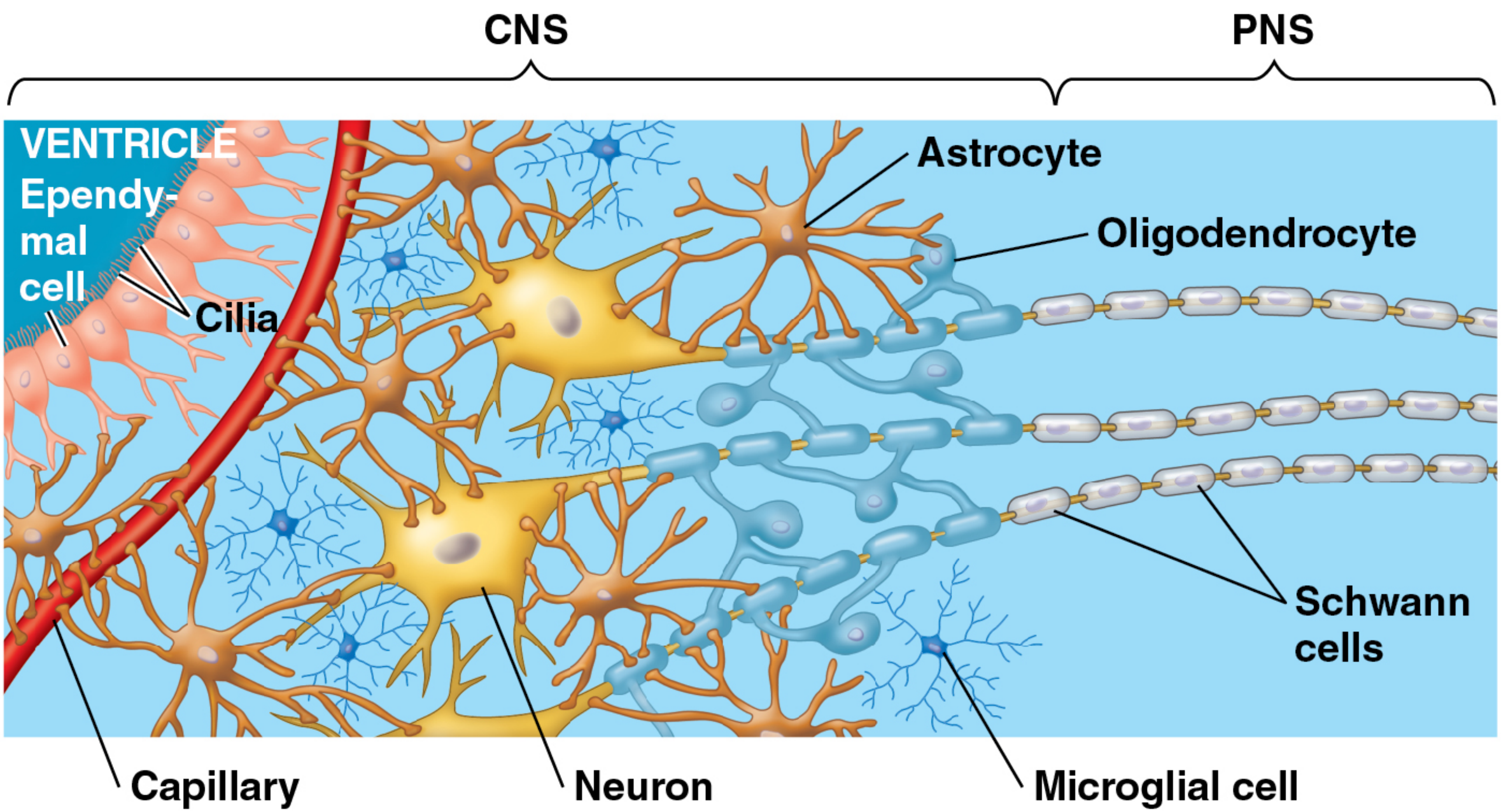


Figure 49.UN06

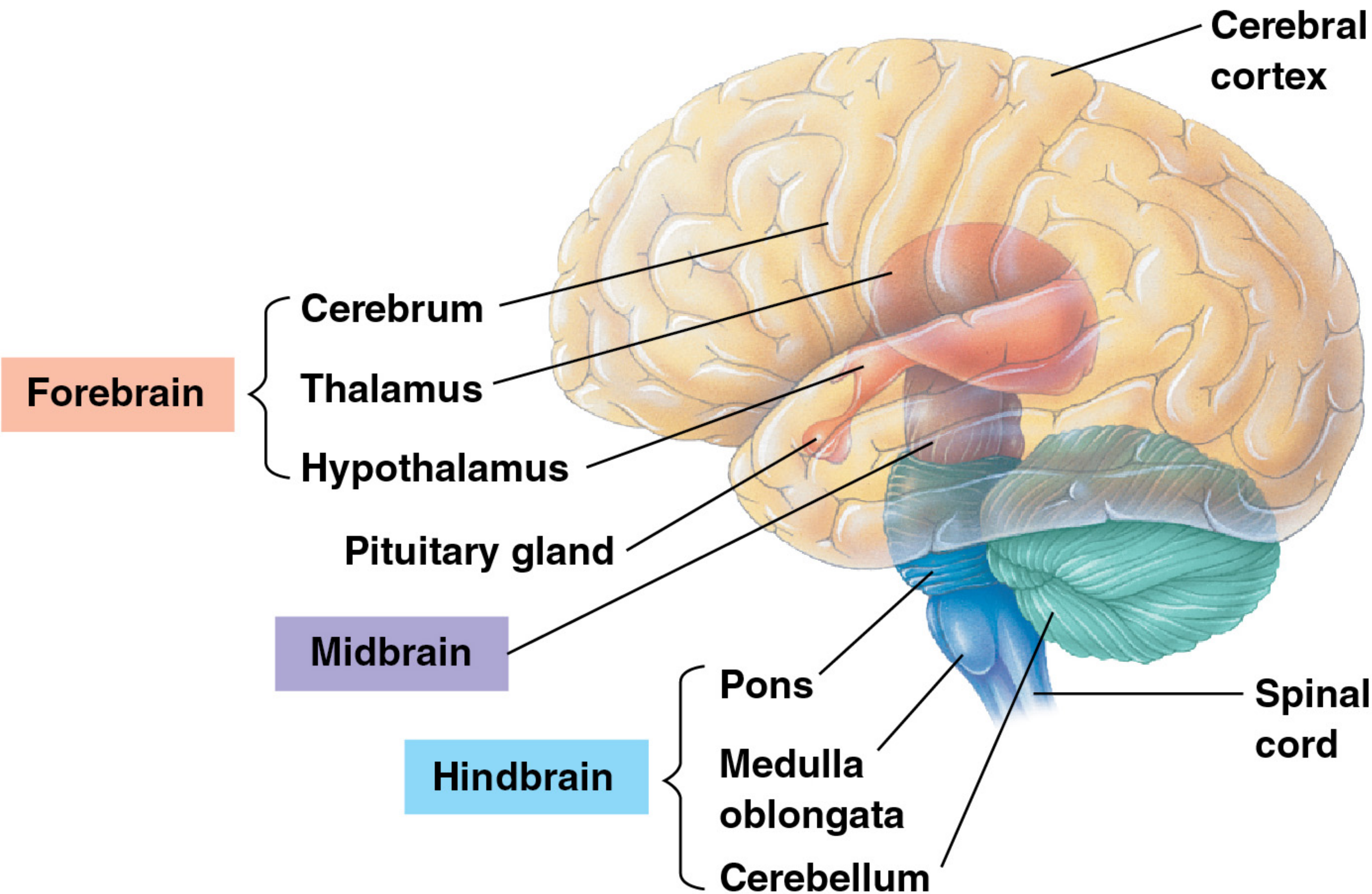


Figure 49.UN07