Chapter 48

Neurons, Synapses, and Signaling

Lectures by Erin Barley
Kathleen Fitzpatrick
Overview: Lines of Communication

• The cone snail kills prey with venom that disables neurons
• **Neurons** are nerve cells that transfer information within the body
• Neurons use two types of signals to communicate: electrical signals (long-distance) and chemical signals (short-distance)
• Interpreting signals in the nervous system involves sorting a complex set of paths and connections
• Processing of information takes place in simple clusters of neurons called *ganglia* or a more complex organization of neurons called a *brain*
Introduction to Information Processing

- Nervous systems process information in three stages: sensory input, integration, and motor output
Figure 48.2

- **Ganglia**
- **Brain**
- **Arm**
- **Eye**
- **Mantle**
- **Nerve**

Nerves with giant axons
• Sensors detect external stimuli and internal conditions and transmit information along sensory neurons

• Sensory information is sent to the brain or ganglia, where interneurons integrate the information

• Motor output leaves the brain or ganglia via motor neurons, which trigger muscle or gland activity
Many animals have a complex nervous system that consists of

- A **central nervous system (CNS)** where integration takes place; this includes the brain and a nerve cord
- A **peripheral nervous system (PNS)**, which carries information into and out of the CNS
- The neurons of the PNS, when bundled together, form **nerves**
Neuron Structure and Function

- Most of a neuron’s organelles are in the **cell body**
- Most neurons have **dendrites**, highly branched extensions that *receive* signals from other neurons
- The **axon** is typically a much longer extension that transmits signals to other cells at synapses
- The cone-shaped base of an axon is called the **axon hillock**
Figure 48.4

- Nucleus
- Dendrites
- Stimulus
- Axon hillock
- Cell body
- Presynaptic cell
- Axon
- Synapse
- Signal direction
- Synaptic terminals
- Postsynaptic cell
- Neurotransmitter
• The **synaptic terminal** of one axon passes information across the synapse in the form of chemical messengers called **neurotransmitters**.

• A **synapse** is a junction between an axon and another cell.
• Information is transmitted from a **presynaptic cell** (a neuron) to a **postsynaptic cell** (a neuron, muscle, or gland cell)

• Most neurons are nourished or insulated by cells called **glia**
Figure 48.5

- Sensory neuron
- Interneurons
- Motor neuron

- Dendrites
- Axon
- Cell body

- Portion of axon
Concept 48.2: Ion pumps and ion channels establish the resting potential of a neuron

- Every cell has a voltage (difference in electrical charge) across its plasma membrane called a membrane potential.
- The resting potential is the membrane potential of a neuron not sending signals.
- Changes in membrane potential act as signals, transmitting and processing information.
Formation of the Resting Potential

• In a mammalian neuron at resting potential, the concentration of $K^+$ is highest inside the cell, while the concentration of $Na^+$ is highest outside the cell.

• Sodium-potassium pumps use the energy of ATP to maintain these $K^+$ and $Na^+$ gradients across the plasma membrane.

• These concentration gradients represent chemical potential energy.
<table>
<thead>
<tr>
<th>Ion</th>
<th>Intracellular Concentration (mM)</th>
<th>Extracellular Concentration (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium ($K^+$)</td>
<td>140</td>
<td>5</td>
</tr>
<tr>
<td>Sodium ($Na^+$)</td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>Chloride ($Cl^-$)</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>Large anions ($A^-$) inside cell, such as proteins</td>
<td>100</td>
<td>(not applicable)</td>
</tr>
</tbody>
</table>
Concept 48.3: Action potentials are the signals conducted by axons

- Changes in membrane potential occur because neurons contain \textbf{gated ion channels} that open or close in response to stimuli.
Figure 48.10

(a) Graded hyperpolarizations produced by two stimuli that increase membrane permeability to K⁺

(b) Graded hyperpolarizations produced by two stimuli that increase membrane permeability to Na⁺

(c) Action potential triggered by a depolarization that reaches the threshold
• If a depolarization shifts the membrane potential sufficiently, it results in a massive change in membrane voltage called an action potential.
• Action potentials have a constant magnitude, are all-or-none, and transmit signals over long distances.
• They arise because some ion channels are voltage-gated, opening or closing when the membrane potential passes a certain level.
Generation of Action Potentials: A Closer Look

• An action potential can be considered as a series of stages
• At resting potential
  1. Most voltage-gated sodium (Na\(^+\)) channels are closed; most of the voltage-gated potassium (K\(^+\)) channels are also closed
Figure 48.11-1

Key
- Na⁺
- K⁺

[Diagram showing the resting state of a cell with sodium and potassium channels, and an inactivation loop. The membrane potential ranges from -100 mV to +50 mV. The threshold potential is marked, and the resting potential is shown.]
• When an action potential is generated
  2. Voltage-gated Na\(^+\) channels open first and Na\(^+\) flows into the cell
  3. During the *rising phase*, the threshold is crossed, and the membrane potential increases
  4. During the *falling phase*, voltage-gated Na\(^+\) channels become inactivated; voltage-gated K\(^+\) channels open, and K\(^+\) flows out of the cell
5. During the *undershoot*, membrane permeability to \( K^+ \) is at first higher than at rest, then voltage-gated \( K^+ \) channels close and resting potential is restored.
Figure 48.11-5

1 Resting state

2 Depolarization

3 Rising phase of the action potential

4 Falling phase of the action potential

5 Undershoot

OUTSIDE OF CELL

INSIDE OF CELL

Sodium channel
Potassium channel

Inactivation loop

Membrane potential (mV)

Time

Threshold

Resting potential

Action potential

Key

Orange circle: Na⁺

Orange diamond: K⁺
• During the **refractory period** after an action potential, a second action potential cannot be initiated.

• The refractory period is a result of a temporary inactivation of the Na\(^+\) channels.
Figure 48.12-3

Action potential

Axon

Plasma membrane

Cytosol

1

Na⁺

Action potential

2

K⁺

Action potential

3

K⁺

Na⁺

K⁺
Evolutionary Adaptation of Axon Structure

- The speed of an action potential increases with the axon’s diameter
- In vertebrates, axons are insulated by a myelin sheath, which causes an action potential’s speed to increase
- Myelin sheaths are made by glia—oligodendrocytes in the CNS and Schwann cells in the PNS
Figure 48.13

- Axon
- Myelin sheath
- Schwann cell
- Nodes of Ranvier
- Node of Ranvier
- Layers of myelin
- Axon
- Schwann cell
- Nucleus of Schwann cell

0.1 μm
• Action potentials are formed only at **nodes of Ranvier**, gaps in the myelin sheath where voltage-gated Na\(^+\) channels are found

• Action potentials in myelinated axons jump between the nodes of Ranvier in a process called **saltatory conduction**
Concept 48.4: Neurons communicate with other cells at synapses

- At electrical synapses, the electrical current flows from one neuron to another.
- At chemical synapses, a chemical neurotransmitter carries information across the gap junction.
- Most synapses are chemical synapses.
• The presynaptic neuron synthesizes and packages the neurotransmitter in **synaptic vesicles** located in the synaptic terminal
• The action potential causes the release of the neurotransmitter
• The neurotransmitter diffuses across the **synaptic cleft** and is received by the postsynaptic cell
Figure 48.15

Presynaptic cell

Postsynaptic cell

Axon

Synaptic vesicle containing neurotransmitter

Postsynaptic membrane

Presynaptic membrane

Voltage-gated Ca\(^{2+}\) channel

Ligand-gated ion channels

Ca\(^{2+}\)

K\(^+\)

Na\(^+\)
Generation of Postsynaptic Potentials

• Direct synaptic transmission involves binding of neurotransmitters to **ligand-gated ion channels** in the postsynaptic cell

• Neurotransmitter binding causes ion channels to open, generating a postsynaptic potential
• Postsynaptic potentials fall into two categories
  – **Excitatory postsynaptic potentials (EPSPs)** are depolarizations that bring the membrane potential toward threshold
  – **Inhibitory postsynaptic potentials (IPSPs)** are hyperpolarizations that move the membrane potential farther from threshold
• After release, the neurotransmitter
  – May diffuse out of the synaptic cleft
  – May be taken up by surrounding cells
  – May be degraded by enzymes
Neurotransmitters

• There are more than 100 neurotransmitters, belonging to five groups: acetylcholine, biogenic amines, amino acids, neuropeptides, and gases.

• A single neurotransmitter may have more than a dozen different receptors.
<table>
<thead>
<tr>
<th>Table 48.2 Major Neurotransmitters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neurotransmitter</strong></td>
</tr>
<tr>
<td>Acetylcholine</td>
</tr>
<tr>
<td>Amino Acids</td>
</tr>
<tr>
<td>GABA (gamma-aminobutyric acid)</td>
</tr>
<tr>
<td>Glutamate</td>
</tr>
<tr>
<td>Glycine</td>
</tr>
<tr>
<td>Biogenic Amines</td>
</tr>
<tr>
<td>Norepinephrine</td>
</tr>
<tr>
<td>Dopamine</td>
</tr>
<tr>
<td>Serotonin</td>
</tr>
<tr>
<td>Neuropeptides (a very diverse group, only two of which are shown)</td>
</tr>
<tr>
<td>Substance P</td>
</tr>
<tr>
<td>Met-enkephalin (an endorphin)</td>
</tr>
<tr>
<td>Gases</td>
</tr>
<tr>
<td>Nitric oxide</td>
</tr>
</tbody>
</table>
Acetylcholine

• **Acetylcholine** is a common neurotransmitter in vertebrates and invertebrates
• It is involved in muscle stimulation, memory formation, and learning
• Vertebrates have two major classes of acetylcholine receptor, one that is ligand gated and one that is metabotropic
Amino Acids

- Amino acid neurotransmitters are active in the CNS and PNS
- Known to function in the CNS are
  - Glutamate
  - Gamma-aminobutyric acid (GABA)
  - Glycine
Biogenic Amines

• Biogenic amines include
  – Epinephrine
  – Norepinephrine
  – Dopamine
  – Serotonin

• They are active in the CNS and PNS
Neuropeptides

- Several **neuropeptides**, relatively short chains of amino acids, also function as neurotransmitters.
- Neuropeptides include substance P and **endorphins**, which both affect our perception of pain.
- Opiates bind to the same receptors as endorphins and can be used as painkillers.
Chapter 49

Nervous Systems
Concept 49.2: The vertebrate brain is regionally specialized

- Specific brain structures are particularly specialized for diverse functions
- These structures arise during embryonic development
Embryonic brain regions

- Forebrain
  - Telencephalon
  - Diencephalon
- Midbrain
  - Mesencephalon
- Hindbrain
  - Metencephalon
  - Myelencephalon

Brain structures in child and adult

- Cerebrum (includes cerebral cortex, white matter, basal nuclei)
- Diencephalon (thalamus, hypothalamus, epithalamus)
- Midbrain (part of brainstem)
- Pons (part of brainstem), cerebellum
- Medulla oblongata (part of brainstem)

Embryo at 5 weeks

Embryo at 1 month

Child
Adult brain viewed from the rear
Arousal and Sleep

- The brainstem and cerebrum control arousal and sleep
- The core of the brainstem has a diffuse network of neurons called the reticular formation
- This regulates the amount and type of information that reaches the cerebral cortex and affects alertness
- The hormone melatonin is released by the pineal gland and plays a role in bird and mammal sleep cycles
Figure 49.10

Eye

Reticular formation

Input from touch, pain, and temperature receptors

Input from nerves of ears

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• Sleep is essential and may play a role in the consolidation of learning and memory

• Dolphins sleep with one brain hemisphere at a time and are therefore able to swim while “asleep”
Figure 49.11

Key

- Low-frequency waves characteristic of sleep
- High-frequency waves characteristic of wakefulness

<table>
<thead>
<tr>
<th>Location</th>
<th>Time: 0 hours</th>
<th>Time: 1 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left hemisphere</td>
<td></td>
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<td>![Waveform]</td>
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<td>Right hemisphere</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>![Waveform]</td>
<td>![Waveform]</td>
</tr>
</tbody>
</table>
Biological Clock Regulation

• Cycles of sleep and wakefulness are examples of circadian rhythms, daily cycles of biological activity
• Mammalian circadian rhythms rely on a **biological clock**, molecular mechanism that directs periodic gene expression
• Biological clocks are typically synchronized to light and dark cycles
• In mammals, circadian rhythms are coordinated by a group of 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 involves many brain structures including the amygdala, hippocampus, and parts of the thalamus.
• These structures are grouped as the limbic system.
• The limbic system also functions in motivation, olfaction, behavior, and memory.
Figure 49.13

Hypothalamus

Thalamus

Olfactory bulb

Amygdala

Hippocampus
• Generation and experience of emotion also require interaction between the limbic system and sensory areas of the cerebrum

• The structure most important to the storage of emotion in the memory is the **amygdala**, a mass of nuclei near the base of the cerebrum