Chapter 11
Functional Organization of Nervous Tissue

Functions of the Nervous System

1. Sensory input. Monitor internal and external stimuli
2. Integration. Brain and spinal cord process sensory input and initiate responses
3. Controls of muscles and glands
4. Homeostasis. Regulate and coordinate physiology
5. Mental activity. Consciousness, thinking, memory, emotion

PNS
- Sensory receptors: ending of neurons or separate, specialized cells that detect such things as temperature, pain, touch, pressure, light, sound, odors
- Nerve: a bundle of axons and their sheaths that connects CNS to sensory receptors, muscles, and glands
  - Cranial nerves: originate from the brain; 12 pairs
  - Spinal nerves: originate from spinal cord; 31 pairs
- Ganglion: collection of neuron cell bodies outside CNS
- Plexus: extensive network of axons, and sometimes neuron cell bodies, located outside CNS
### Divisions of PNS

- **Sensory** (afferent): transmits action potentials from receptors to CNS.
- **Motor** (efferent): transmits action potentials from CNS to effectors (muscles, glands).

### Motor Division of PNS

- **Somatic nervous system**: from CNS to skeletal muscles.
  - Voluntary.
  - Single neuron system.
  - Synapse: junction of a nerve cell with another cell. E.g., neuromuscular junction is a synapse between a neuron and skeletal muscle cell.
- **Autonomic nervous system (ANS)**: from CNS to smooth muscle, cardiac muscle and certain glands.
  - Subconscious or involuntary control.
  - Two neuron system: first from CNS to ganglion; second from ganglion to effector.
- **Divisions of ANS**
  - Sympathetic: Prepares body for physical activity (ALERT)
  - Parasympathetic: Regulates resting or vegetative functions such as digesting food or emptying of the urinary bladder (Housekeeping)
  - Enteric plexuses within the wall of the digestive tract: Can control the digestive tract independently of the CNS, but still considered part of ANS because of the parasympathetic and sympathetic neurons that contribute to the plexi.
Cells of Nervous System

- **Glia** or neuroglia
  - Support and protect neurons
- **Neurons** or nerve cells receive stimuli and transmit action potentials
  - **Organization**
    - Cell body or soma
    - Dendrites: input
    - Axons: output

Parts of the Neuron—LAB

  - Nissl substance = chromatophilic substance = rough E.R. primary site of protein synthesis.
- Dendrites: short, often highly branched.
  - Dendritic spines: little protuberance where axons synapse with dendrite.
- Axons. Can branch to form collaterals.
  - Axon hillock
  - Initial segment: beginning of axon
  - Axoplasm
  - Axolemma
  - Presynaptic terminals (terminal boutons)
  - Synaptic vesicles
  - Trigger zone: site where action potentials are generated; axon hillock and part of axon nearest cell body

Axonic Transport Mechanisms

- Axoplasm moved **from cell body** toward terminals. Supply for growth, repair, renewal. Can move cytoskeletal proteins, organelles away from cell body toward axon terminals.
- Into cell body: damaged organelles, recycled plasma membrane, and substances taken in by endocytosis can be transported up axon to cell body. Rabies and herpes virus can enter axons in damaged skin and be transported to CNS.
Types of Neurons

- Functional classification
  - Sensory or afferent: action potentials toward CNS
  - Motor or efferent: action potentials away from CNS
  - Interneurons or association neurons: within CNS from one neuron to another

- Structural classification
  - Multipolar: most neurons in CNS; motor neurons
  - Bipolar: sensory in retina of the eye and nose
  - Unipolar: single process that divides into two branches. Part that extends to the periphery has dendrite-like sensory receptors

Glial Cells of the CNS: Astrocytes

- Processes form feet that cover the surfaces of neurons and blood vessels and the pia mater.
- Regulate what substances reach the CNS from the blood (blood-brain barrier). Lots of microfilaments for support.
- Produce chemicals that promote tight junctions to form blood-brain barrier
  - Blood-brain barrier: protects neurons from toxic substances, allows the exchange of nutrients and waste products between neurons and blood, prevents fluctuations in the composition of the blood from affecting the functions of the brain.
- Regulate extracellular brain fluid composition

Glial Cells of the CNS: Ependymal Cells

- Line brain ventricles and spinal cord central canal. Specialized versions of ependymal form choroid plexuses.
- Choroid plexus within certain regions of ventricles. Secrete cerebrospinal fluid. Cilia help move fluid thru the cavities of the brain. Have long processes on basal surface that extend within the brain tissue, may have astrocyte-like functions.
Glial Cells of the CNS: Microglia and Oligodendrocytes

- **Microglia**: specialized macrophages. Respond to inflammation, phagocytize necrotic tissue, microorganisms, and foreign substances that invade the CNS.
- **Oligodendrocytes**: form myelin sheaths if surrounding axon. Single oligodendrocytes can form myelin sheaths around portions of several axons. (In CNS)

Glial Cells of the PNS

- **Schwann cells** or neurolemmocytes: wrap around portion of only one axon to form myelin sheath. Wrap around many times. During development, as cells grow around axon, cytoplasm is squeezed out and multiple layers of cell membrane wrap the axon. Cell membrane primarily phospholipid.
- **Satellite cells**: surround neuron cell bodies in sensory ganglia, provide support and nutrients

Myelinated and Unmyelinated Axons

- **Myelinated axons**
  - Myelin protects and insulates axons from one another, speeds transmission, functions in repair of axons.
  - Not continuous
  - Nodes of Ranvier
  - Completion of development of myelin sheaths at 1 yr
  - Degeneration of myelin sheaths occurs in multiple sclerosis and some cases of diabetes mellitus.
- **Unmyelinated axons**: rest in invaginations of Schwann cells or oligodendrocytes. Not wrapped around the axon; gray matter.
Organization of Nervous Tissue

- **White matter**: myelinated axons. Nerve tracts propagate action potentials from one area in the CNS to another.
- **Gray matter**: unmyelinated axons, cell bodies, dendrites, neuroglia. Integrative functions.
  - In brain: gray is outer cortex as well as inner nuclei; white is deeper.
  - In spinal cord: white is outer, gray is deeper.

Electrical Signals

- Cells produce electrical signals called **action potentials**
- Transfer of information from one part of body to another
- Electrical properties result from ionic concentration differences across plasma membrane and permeability of membrane

Concentration Differences Across the Plasma Membrane

- These ion concentrations are a result of two processes: the Na/K pump and membrane permeability. Note high concentration of Na and Cl ions outside and high concentration of K and proteins on inside. Note steep concentration gradient of Na and K, but in opposite directions.
**Sodium-Potassium Exchange Pump**

![Diagram of Sodium-Potassium Exchange Pump]

**Permeability Characteristics of the Plasma Membrane**

- Proteins: synthesized inside cell; Large, don't dissolve in phospholipids of membrane. Proteins are negatively charged.
- $\text{Cl}^-$ are repelled by proteins and they exit thru always-open nongated $\text{Cl}^-$ channels.
- Gated ion channels open and close because of some sort of stimulus. When they open, they change the permeability of the cell membrane.
  - Ligand-gated: molecule that binds to a receptor; protein or glycoprotein

**Leak Channels**

- Many more of these for $\text{K}^+$ and $\text{Cl}^-$ than for $\text{Na}^+$.
  - So, at rest, more $\text{K}^+$ and $\text{Cl}^-$ are moving than $\text{Na}^+$.
  - How are they moving? Protein repels Cl, they move out. $\text{K}^+$ are in higher concentration on inside than out, they move out.
  - Always open and responsible for permeability when membrane is at rest.
  - Specific for one type of ion although not absolute.
**Gated Ion Channels**

- **Gated ion channels.** Gated ion channels open and close because of some sort of stimulus. When they open, they change the permeability of the cell membrane.
  - **Ligand-gated:** open or close in response to ligand such as ACh binding to receptor protein. Receptor proteins are usually glycoproteins, e.g., acetylcholine binds to acetylcholine receptor on a Na⁺ channel. Channel opens, Na⁺ enters the cell.

**Voltage Gated Ion Channels**

- **Voltage-gated:** open or close in response to small voltage changes across the cell membrane.
- At rest, membrane is negative on the inside relative to the outside.
- When cell is stimulated, that relative charge changes and voltage-gated ion channels either open or close. Most common voltage gated are Na⁺ and K⁺. In cardiac and smooth muscle, Ca²⁺ are important.

**Establishing the Resting Membrane Potential**

- Number of charged molecules and ions inside and outside cell nearly equal
- Concentration of K⁺ higher inside than outside cell, Na⁺ higher outside than inside
- Potential difference: unequal distribution of charge exists between the immediate inside and immediate outside of the plasma membrane: -70 to -90 mV
- The resting membrane potential
Establishing the Resting Potential

- At equilibrium there is very little movement of K⁺ or other ions across plasma membrane (Movement of K⁺ out through leakage channels = movement of ions is due to attraction to trapped proteins: N.B. leakage channels work in both directions. Movement of ions depends upon concentration gradient.)

- Na⁺, Cl⁻, and Cu²⁺ do not have a great affect on resting potential since there are very few leakage channels for these ions.

- If leakage channels alone were responsible for resting membrane potential, in time Na⁺ and K⁺ ion concentrations would eventually equalize.

- But they are maintained by the Na/K pump. For each ATP that is consumed, three Na moved out, two K⁺ moved in. Outside of plasma membrane slightly positive.

### Table 11.2 Characteristics Responsible for the Resting Membrane Potential

<table>
<thead>
<tr>
<th>No.</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The reaction of charged molecules and ions inside and outside the cell is nearly equal.</td>
</tr>
<tr>
<td>2.</td>
<td>The concentration of K⁺ is higher inside than outside the cell, and the concentration of Na⁺ is higher outside than inside the cell.</td>
</tr>
<tr>
<td>3.</td>
<td>The plasma membrane is 50 – 100 times more permeable to K⁺ than to other positively charged ions such as Na⁺.</td>
</tr>
<tr>
<td>4.</td>
<td>The plasma membrane is impermeable to large intracellular negatively charged molecules such as proteins.</td>
</tr>
<tr>
<td>5.</td>
<td>K⁺ tends to diffuse across the plasma membrane from the inside to the outside of the cell.</td>
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<tr>
<td>6.</td>
<td>Because negatively charged molecules cannot follow the positively charged K⁺, a small negative charge develops just inside the plasma membrane.</td>
</tr>
<tr>
<td>7.</td>
<td>The negative charge inside the cell is great enough to prevent additional K⁺ from diffusing out of the cell through the plasma membrane, an equilibrium is established.</td>
</tr>
<tr>
<td>8.</td>
<td>The change of voltage across the plasma membrane at equilibrium is reflected as a difference in potential, which is measured as millivolts.</td>
</tr>
<tr>
<td>9.</td>
<td>The resting membrane potential is proportional to the potential for K⁺ to diffuse out of the cell, but not to the actual rate of flow for K⁺.</td>
</tr>
<tr>
<td>10.</td>
<td>An equilibrium there is very little movement of K⁺ or other ions across the plasma membrane.</td>
</tr>
</tbody>
</table>

Changing the Resting Membrane Potential: K⁺

- **Depolarization**: Potential difference becomes smaller or less polar

- **Hyperpolarization**: Potential difference becomes greater or more polar

- K⁺ concentration gradient alterations
  - If extracellular concentration of K⁺ increases: less gradient between inside and outside: **Depolarization**
  - If extracellular ion concentration decreases: steeper gradient between inside and outside: **Hyperpolarization**

- K⁺ membrane permeability changes. In resting membrane. K⁺ in and out is equal through the leakage channels. But there are also gated K⁺ channels in the membrane. If they open, more K⁺ diffuses out but this is opposed by the negative charge that starts to develop as the K⁺ diffuses out.
Changes in Resting Membrane Potential: Ca$^{2+}$

- Voltage-gated Na$^+$ channels sensitive to changes in extracellular Ca$^{2+}$ concentrations
  - If extracellular Ca$^{2+}$ concentration decreases- Na$^+$ gates open and membrane depolarizes.
  - If extracellular concentration of Ca$^{2+}$ increases- gates close and membrane repolarizes or becomes hyperpolarized.

Local Potentials

- Result from:
  - Ligands binding to receptors
  - Changes in charge across membrane
  - Mechanical stimulation
  - Temperature changes
  - Spontaneous change in permeability
- Graded
  - Magnitude varies from small to large depending on stimulus strength or frequency
- Can summate or add onto each other
- Spread (are conducted) over the plasma membrane in a decremental fashion: rapidly decrease in magnitude as they spread over the surface of the plasma membrane.
- Can cause generation of action potentials

Table 11.3 Characteristics of Local Potentials

1. A stimulus causes ion channels to open, resulting in increased permeability of the membrane to Na$^+$, K$^+$, or Cl$^-$.
2. Increased permeability of the membrane to Na$^+$ results in depolarization, increased permeability of the membrane to K$^+$ or Cl$^-$ results in hyperpolarization.
3. Local potentials are graded; that is, the size of the local potential is proportional to the strength of the stimulus. Local potentials can also summate. Thus, a local potential produced in response to several stimuli is larger than one produced in response to a single stimulus.
4. Local potentials are conducted in a decremental fashion, meaning that their magnitude decreases as they spread over the plasma membrane. Local potentials cannot be measured a few millimeters from the point of stimulation.
5. A depolarizing local potential can cause an action potential.
Action Potentials

- Depolarization phase followed by repolarization phase.
  - **Depolarization**: more positive
  - **Repolarization**: more negative (may get afterpotential [slight hyperpolarization])
- Series of permeability changes when a graded potential causes depolarization of membrane. A large enough graded potential may cause the membrane to reach threshold. Then get action potential.
- **All-or-none principle.** No matter how strong the stimulus, as long as it is greater than threshold, then action potential will occur.

### Table 11.4 Characteristics of the Action Potential

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Action potentials are produced when a local potential reaches threshold.</td>
</tr>
<tr>
<td>2.</td>
<td>Action potentials are all-or-none.</td>
</tr>
<tr>
<td>3.</td>
<td>Depolarization is a result of increased membrane permeability to Na⁺ and movement of Na⁺ into the cell. Activation gates of the voltage-gated Na⁺ channels open.</td>
</tr>
<tr>
<td>4.</td>
<td>Repolarization is a result of decreased membrane permeability to Na⁺ and increased membrane permeability to K⁺, which stops Na⁺ movement into the cell and increased K⁺ movement out of the cell. The inactivation gates of the voltage-gated Na⁺ channels close, and the voltage-gated K⁺ channels open.</td>
</tr>
<tr>
<td>5.</td>
<td>No action potential is produced by a stimulus, no matter how strong, during the absolute refractory period. During the relative refractory period a stronger-than-threshold stimulus can produce an action potential.</td>
</tr>
<tr>
<td>6.</td>
<td>Action potentials are propagated, and for a given neuron or muscle fiber the magnitude of the action potential is constant.</td>
</tr>
<tr>
<td>7.</td>
<td>Stimulus strength determines the frequency of action potentials.</td>
</tr>
</tbody>
</table>

**Operation of Gates: Action Potential**

- **Resting membrane potential,** Voltage-gated Na⁺ channels are closed (the activation gates are closed and the inactivation gates are open), Voltage-gated K⁺ channels are closed.
- **Depolarization** Voltage-gated Na⁺ channels open because the activation gates open. As soon as the threshold depolarization is reached, many voltage-gated Na⁺ channels begin to open. Na⁺ diffuses in and this causes other Na⁺ channels to open—positive feedback—until all the Na⁺ channels are open. Voltage-gated K⁺ channels start to open. Depolarization results because the inward diffusion of Na⁺ is much greater than the outward diffusion of K⁺.
### Operation of Gates: Action Potential

- **Repolarization.** Voltage-gated Na\(^+\) channels are closed because the inactivation gates close. Voltage-gated K\(^+\) channels are now open. Na\(^+\) diffusion into the cell stops and K\(^+\) diffuse out of the cell causing repolarization.
- **End of repolarization and afterpotential.** Voltage-gated Na\(^+\) channels are closed. Closure of the activation gates and opening of the inactivation gates reestablish the resting condition for Na\(^+\) channels (see step 3). Diffusion of K\(^+\) through voltage-gated channels produces the afterpotential.
- **Resting membrane potential.** The resting membrane potential is reestablished after the voltage-gated K\(^+\) channels close.

### Refractory Period

- **Sensitivity of area to further stimulation decreases for a time**
- **Parts**
  - **Absolute**
    - Complete insensitivity exists to another stimulus.
    - From beginning of action potential until near end of repolarization. No matter how large the stimulus, a second action potential cannot be produced. Has consequences for function of muscle, particularly how often a.p.s can be produced.
  - **Relative**
    - A greater-than-threshold stimulus can initiate another action potential.

### Action Potential Frequency

- **Number of potentials produced per unit of time to a stimulus**
  - **Threshold stimulus:** causes a graded potential that is great enough to initiate an action potential.
  - **Subthreshold stimulus:** does not cause a graded potential that is great enough to initiate an action potential.
  - **Maximal stimulus:** just strong enough to produce a maximum frequency of action potentials.
  - **Submaximal stimulus:** all stimuli between threshold and the maximal stimulus strength.
  - **Supramaximal stimulus:** any stimulus stronger than a maximal stimulus. These stimuli cannot produce a greater frequency of action potentials than a maximal stimulus.
**Propagation of Action Potentials**

1. Action potential propagates down axon in the form of a traveling wave.
2. Ionic currents are activated by depolarizing the membrane potential to the threshold.
3. Depolarization of adjacent regions of the membrane results in a local depolarization wave propagating along the axon.
4. Local field potentials remain constant, allowing for the propagation of the action potential down the axon.

**Saltatory Conduction**

- **Nodes of Ranvier**: Nodes are separated by myelinated internodes.
- **Schwann cell**: Myelinated internodes are covered by Schwann cells.
- **Direction of action potential propagation**: Propagates through myelinated internodes and is blocked at nodes of Ranvier.

**Nerve Fiber Types**

- **Type A**: large-diameter, myelinated. Conduct at 15-120 m/s. Motor neurons supplying skeletal and most sensory neurons.
- **Type B**: medium-diameter, lightly myelinated. Conduct at 3-15 m/s. Part of ANS.
- **Type C**: small-diameter, unmyelinated. Conduct at 2 m/s or less. Part of ANS.
The Synapse

- Junction between two cells
- Site where action potentials in one cell cause action potentials in another cell
- Types of cells in synapse
  - Presynaptic
  - Postsynaptic

Electrical Synapses

- Gap junctions that allow graded current to flow between adjacent cells. **Connexons**: protein tubes in cell membrane.
- Found in cardiac muscle and many types of smooth muscle. Action potential of one cell causes action potential in next cell, almost as if the tissue were one cell.
- Important where contractile activity among a group of cells important.

Chemical Synapse

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Neurotransmitter Removal

- Method depends on neurotransmitter/synapse.
- ACh: acetylcholinesterase splits ACh into acetic acid and choline. Choline recycled within presynaptic neuron.
- Norepinephrine: recycled within presynaptic neuron or diffuses away from synapse. Enzyme monoamine oxidase (MAO). Absorbed into circulation, broken down in liver.

Removal of Neurotransmitter from Synaptic Cleft

Receptor Molecules and Neurotransmitters

- Neurotransmitter only "fits" in one receptor.
- Not all cells have receptors.
- Neurotransmitters are excitatory in some cells and inhibitory in others.
- Some neurotransmitters (norepinephrine) attach to the presynaptic terminal as well as postsynaptic and then inhibit the release of more neurotransmitter.
Neuromodulators

- Chemicals produced by neurons that facilitate action potentials. Some of these act by increasing or decreasing the amount of neurotransmitter released by the presynaptic neuron.
- Act in axoaxonic synapses. Axon of one neuron synapses with axon of second neuron. Second neuron is actually presynaptic. This type of connection leads to release of neuromodulators in the synapse that can alter the amount of neurotransmitter produced by the second neuron.

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Postsynaptic Potentials

- **Excitatory postsynaptic potential (EPSP)**
  - Depolarization occurs and response stimulatory
  - Depolarization might reach threshold producing an action potential and cell response

- **Inhibitory postsynaptic potential (IPSP)**
  - Hyperpolarization and response inhibitory
  - Decrease action potentials by moving membrane potential farther from threshold

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Presynaptic Inhibition and Facilitation

- **Axoaxonic synapses**: axon of one neuron synapses with the presynaptic terminal (axon) of another. Many of the synapses of CNS
- **Presynaptic inhibition**: reduction in amount of neurotransmitter released from presynaptic terminal. Endorphins can inhibit pain sensation
- **Presynaptic facilitation**: amount of neurotransmitter released from presynaptic terminal increases. Glutamate facilitating nitric oxide production
Neuronal Pathways and Circuits

- Organization of neurons in CNS varies in complexity
  - **Convergent pathways**: many converge and synapse with smaller number of neurons. E.g., synthesis of data in brain.
  - **Divergent pathways**: small number of presynaptic neurons synapse with large number of postsynaptic neurons. E.g., important information can be transmitted to many parts of the brain.
  - **Oscillating circuit**: outputs cause reciprocal activation.