Chapter 2: Structure and Functions of the Cells of the Nervous System

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**Textbook and lecture notes**

**Cells of the Nervous System**

- Behavior is the primary function of the nervous system
  - The brain makes useful movements to acclimate to its outside environment
- **Sensory neuron**: a neuron that detects changes in the external and/or internal environment and sends information about these changes to the central nervous system
  - Information is gathered from the environment from our 5 senses
  - Goes from soma to brain?
- **Motor neuron**: a neuron located within the central nervous system that controls the contraction of a muscle or the secretion of a gland
  - Goes from brain to muscles
- **Interneuron**: a neuron located entirely within the central nervous system
  - In between sensory neurons and motor neurons
  - **Local interneurons**: form circuits with nearby neurons and analyze small pieces of information
  - **Relay neurons**: connect circuits of local interneurons in one region of the brain with those in other regions
- The nervous system consists of two basic divisions:
  - Central nervous system (CNS): consists of the parts that are encased by the bones of the skull and spinal column
    - The brain and spinal cord
  - Peripheral nervous system (PNS): found outside the brain and spinal cord
    - Includes the nerves attached to the brain and spinal cord

**Basic Structure of Neurons**

- **Figure 2.1**: The principal parts of a multipolar neuron (most common type found in the CNS)
○ Figure 2.2: (a) bipolar neuron primarily found in sensory systems (i.e. vision and audition) and (b) a unipolar neuron found in somatosensory system (i.e. touch and pain, etc.)
  ○ There should only be one side that is an axon and the other is a dendrite

- The neuron (nerve cell) is the information-processing and information-transmitting element of the nervous system
- Most neurons, in one form or another, have:
  ○ Cell body/soma, dendrites, axon, and terminal buttons
- **Soma** (cell body): the cell body of a neuron, which contains the nucleus
  ○ Contains much of the machinery that provides for the cell’s life processes
  ○ Its shape varies considerably in different kinds of neurons
- **Dendrite**: a branched, treelike structure attached to the soma of a neuron; receives information from the terminal buttons of other neurons (there are spines on the dendrites)
  ○ The messages that pass from neuron to neuron are transmitted across the synapse
    - **Synapse**: a junction between the terminal buttons of the sending cell (how cells communicate with one another) - place not an object
  ○ Communication at the synapse proceeds in one direction: from the terminal button to the membrane of the other cell
    - Has its exceptions
- **Axon**: the long, thin cylindrical structure that conveys information from the soma of a neuron to its terminal buttons - usually covered by a myelin sheath
  ○ Carries information from the cell body to the terminal buttons
    - The basic message the axon carries is called an action potential (brief electrical/chemical event that starts on the end of the axon next to the cell body and travels toward the terminal buttons)
    - Action potential is like a brief pulse; in a given axon, the action potential is always of the same size and duration
    - When it reaches a point where the axon branches, it splits but does not diminish in size (received full-strength action potential)
  ○ Axons and their branches come in different shapes (just like dendrites) (how many branches are coming out of the cell body) -- the 3 principal types of neurons are classified by the way their axons and dendrites leave the soma
    - **Multipolar neuron** (1 branch): a neuron with one axon and many dendrites attached
to its soma (see Figure 2.1) - somatic membrane gives rise to one axon but to the trunks of many dendritic trees

- **Bipolar neurons** (2 branches): a neuron with one axon and one dendrite attached to its soma (Figure 2.2a) - axon and dendrite are on opposite ends of the soma
  - Usually sensory - dendrites detect events occurring in the environment and communicate information about these events to the central nervous system
- **Unipolar neuron** (many branches): a neuron with one axon attached to its soma; the axon divides, with one branch receiving sensory information and the other sending the information into the central nervous system (Figure 2.2b) - usually motor neurons
  - Transmits sensory information from the environment to the CNS - usually detects touch, temperature changes, and other sensory events that affect the skin
  - Other neurons detect events in our joints, muscles, and internal organs
    - **Terminal buttons**: the bud at the end of a branch of an axon; forms synapses with another neuron; sends information to that neuron
      - When an action potential traveling down the axon reaches them, they secrete a chemical called a neurotransmitter (there are many in the CNS)
      - **Neurotransmitter**: a chemical that is released by a terminal button; has an excitatory or inhibitory effect on another neuron - helps determine whether an action potential occurs in its axon
- An individual neuron receives information from the terminal buttons of axons on other neurons
- A neuron may receive information from dozens or hundreds of other neurons - each of which form a large number of synaptic connections with it

- **Figure 2.4**: An overview of the synaptic connections between the neurons (the arrows represent the directions of the flow of information)

**Internal Structure**
- **Figure 2.3**: Nerves - a nerve consists of a sheath of tissue that encases a bundle of individual nerve fibers (aka axons)
  - **Membrane**: the boundary of the cell; a structure consisting principally of lipid molecules that defines the outer boundaries of a cell; constitutes many of the cell organelles
    - Embedded in the membrane are variety of protein molecules that have special functions
    - These proteins control the exit and entrance of substances through the membrane
      - Other proteins also act as transporters (they are actively carrying certain molecules in or out of the cell)
    - These proteins are also important in the transmission of information
  - **Cytoplasm**: the viscous, semiliquid substance contained in the interior of a cell
    - Contains small specialized structures
  - **Mitochondria**: (inside/surrounded by cytoplasm) an organelle that is responsible for extracting energy from nutrients
    - Adenosine triphosphate (ATP): a chemical produced by the mitochondria that break down into energy for the body to utilize
  - **Nucleus**: a structure in the central region of the cell, containing chromosomes
    - **Chromosomes**: a strand of DNA, with associated proteins, found in the nucleus; carries genetic information
      - Contains the recipes for making proteins (in DNA)
      - **Gene**: the functional unit of the chromosome, which directs the synthesis of one or more proteins (contains the recipe for individual proteins)
  - **Cytoskeleton**: support structure formed of microtubules and other protein fibers that are linked to each other and form a cohesive mass that gives a cell its shape
    - Gives the neuron its shape and made of various kinds of protein strands linked together (gives the neuron shape)
  - **Enzymes**: a molecule that controls a chemical reaction, combining 2 substances or breaking a substance into 2 parts
    - Enzymes determine what gets made from raw materials contained in the cell
    - Enzymes also determine which molecules remain intact
  - **Axoplasmic transport**: an active process by which substances are propelled along microtubules that run the length of the axon
    - Necessary because terminal buttons need some items that can only be produced in the soma
    - Accomplished by long protein strands called microtubules
      - **Microtubule**: a long strand of bundles of protein filaments arranged around a hollow core; part of the cytoskeleton and involved in transporting substances from place to place within the cell
      - **Anterograde axoplasmic transport**: movement of substances from the soma to the
terminal buttons (fast at 500mm per day)
  ▪ **Retrograde axoplasmic transport**: substances being transported from the terminal buttons back to the soma (half as fast as anterograde)

**Supporting Cells**
  • Half of the volume of the CNS are neurons
    ◦ Rest consists of a variety of supporting cells
    ◦ Neurons have a high rate of metabolism but no means of storing nutrients
      ◦ They need to be constantly supplied with nutrients and oxygen or they will die quickly (need supporting cells)
    ○ **Figure 2.6**: Structure and location of astrocytes - the processes of astrocytes surround capillaries and neurons of the CNS
  
  ○ **Figure 2.7**: Oligodendrocyte - an oligodendrocyte forms the myelin that surrounds many axons in the CNS (each cell forms 1 segment of myelin for several adjacent axons)
- **Figure 2.8:** Formation of myelin - during development, a process of an oligodendrocyte or an entire Schwann cell tightly wraps itself many times around an individual axon and forms one segment of the myelin sheath (a) oligodendrocyte (b) Schwann cell

- **Glia:** the supporting cells of the CNS; "nerve glue" by gluing the CNS together
  - Constitutes about 85% of the cells of the brain
  - Neurons are buffered physically and chemically from the rest of the body through glial cells
    - Glial cells surround neurons and hold them in place
    - Controls the neuron’s supply of nutrients and some of the chemicals they need to exchange messages with other neurons
    - Also destroys and removes neurons that were killed by disease or injury
  - 3 most important types of glial cells:
    - **Astrocyte:** a glial cell that provides support for neurons of the nutrients and other substances, and regulates the chemical composition of the extracellular fluid and cleanup (shaped like a star) - active interface between blood vessels and neurons
      - Some of the astrocyte’s processes (the arms of the star) are wrapped around blood vessels and around other parts of neurons - so somatic and dendritic membranes of neurons are largely surrounded by astrocytes
      - Also serves as the matrix that holds neurons in place
      - These cells also surround and isolate synapses - limits the dispersion of neurotransmitters that are released by the terminal buttons
      - **Phagocytosis:** the process by which cells engulf and digest other cells or debris caused by cellular degeneration - astrocyte takes up task of cleaning away debris
    - **Oligodendrocytes:** a type of glial cell in the CNS that forms myelin sheaths
      - **Myelin sheath:** a sheath that surrounds axons and insulates them, preventing messages from spreading between adjacent neurons - very small axons are not myelinated and lack the sheath
      - Sheath is a series of segments on the axon - resembles a string of elongated beads
      - **Node of Ranvier:** a naked portion of a myelinated axon, between adjacent oligodendroglia or Schwann cells
      - During the production of myelin, the process wraps layers of myelin around the axon
    - **Microglia:** the smallest of glial cells; they act as phagocytes and protect the brain from invading microorganisms
      - Serve as a one of the representatives of the immune system and are primarily responsible for the inflammatory reaction in response to brain damage
• **Schwann cells**: a cell in the PNS that is wrapped around a myelinated axon, providing one segment of its myelin sheath
  ○ Each segment consists of 1 Schwann cell (wrapped many times around the axon)
  ○ There is a chemical difference in the compounds of the proteins produced between oligodendrocytes of the CNS and Schwann cells in PNS

**The Blood-Brain Barrier**

• **Blood-brain barrier**: a semipermeable (selectively permeable) barrier between the blood and the brain produced by the cells in the walls of the brains capillaries
  ○ There are not the only found gaps in the CNS (it does not automatically let certain substances permeate through the membrane)
  ○ Other substances must be actively transported through the capillary walls by special proteins

• The presence of the blood-brain barrier makes it easier to regulate the composition of extracellular fluid
  ○ Also prevents the interference of the transmission of information between neuron from chemicals (stops these chemicals from reaching/passing through the brain)

• The blood-brain barrier is not uniform throughout the nervous system
  ○ In several places the barrier is relatively permeable
  ○ **Area postrema**: a region of the medulla where the blood-brain barrier is weak; poisons can be detected there and can initiate vomiting

• In most capillaries, the body cells are not tightly packed together (there are small gaps) to allow for the free exchange of most substances between the blood plasma and fluid outside the capillaries
  ○ In the CNS, the capillaries lack this gap - many substances cannot leave the blood
    ▪ Therefore, the walls of the capillaries in the brain constitute the blood-brain barrier

• Other substances must be actively transported through the capillary walls by special proteins
  ○ I.e glucose transporters bring the brain glucose, where other transporters rid the brain of toxic waste products

**Measuring Electrical Potentials of Axons**

• Used the giant axon of a squid to test conduction and electrical charges
  ○ Used to see whether there is a response from the electrical charge

• **Electrode**: a conductive medium that can be used to apply electrical stimulation or to record electrical potentials
  ○ **Microelectrode**: a very fine electrode, generally used to record the activity individual neurons

• **Membrane potential**: the electrical charge across a cell membrane; the difference in electrical potential inside and outside the cell
  ○ Electrical energy is stored with the differing positive and negatively charged gradients inside and outside the cell

• The message that is conducted down the axon consists of a brief change in the membrane potential
  ○ Change occurs very rapidly

• **Resting potential**: the membrane potential of a neuron when it is not being altered by excitatory or inhibitory postsynaptic potentials; approximately -70mV in the giant squid axon
  ○ Inside of the axon is negative and outside of the cell is positive

• **Depolarization**: reduction (toward 0) of the membrane potential of a cell from its normal resting potential
  ○ Take away some electrical charge across the membrane (reduces membrane potential)
  ○ Creating a larger amount of positive ions in the cell
• **Hyperpolarization**: an increase in the membrane potential of a cell, relative to the normal resting potential
  ○ This happens when enough a negative charge is added inside the cell
  ○ Hyperpolarization first overshoots the resting potential for a short time before returning back to resting potential
• **Action potential**: the brief electrical impulse that provides the basis for conduction of information along an axon
  ○ This constitutes the message carried by the axon from the cell body to the terminal buttons
  ○ **Threshold of excitation**: the value of the membrane potential that must be reached to produce an action potential
    ▪ Only achieved by adding a large enough depolarization

**The Membrane Potential: Balance of 2 Forces**

- Figure 2.14: An action potential - these results would be seen on an oscilloscope screen if depolarizing stimuli of varying intensities were delivered to the axon

- The electrical charge (to cause the action potential) is a result of a balance between 2 different forces
  ○ Diffusion
  ○ Electrostatic pressure
- **The force of diffusion: 1 force that moves molecules**
  ○ **Diffusion**: movement from molecules from regions of high concentration to regions of low concentration
    ▪ Without the presence of barriers, molecules will diffuse from regions of high concentration to regions of low concentration (due to movement of molecules)
    ▪ Rate of movement of molecule is proportional to the temperature
- **The force of electrostatic pressure: 1 force that moves ions**
  ○ **Ion**: a charged molecule
    ▪ Cations are positive (+)
    ▪ Anions are negative (-)
  ○ **Electrostatic pressure**: the attractive force between atomic particles charged with opposite signs (+ and -) or the repulsive force between atomic particles charged with the same sign (+/+-)
    ▪ Electrostatic pressure also moves ions from place to place: cations are pushed away
from an excess of cations and anions are pushed away from excess anions

- Ions in the extracellular and intracellular fluid

**Figure 2.15:** Control of the Membrane Potential - The figure shows the relative concentration of some important ions inside and outside the cell

**Figure 2.16** A Sodium–Potassium Transporter. These transporters are found in the cell membrane.

- **Sodium-potassium transporter:** a protein found in the membrane of all cells that extrudes sodium ions from and transports potassium ions into the cell
- Pushes 3 sodium (Na) for every 2 potassium (K) ions
- These transporters effectively keep the intracellular concentration of Na low (continuously pump out Na)
- Uses a lot of energy

*The Action Potential*
• A drastic change of the concentration of ions inside the cell change the membrane potential
  - Causes the action potential
    ▪ A brief increase in the permeability of the membrane to Na
• Ion channel: a specialized protein molecule that permits specific ions to enter or leave cells
  - Can be a sodium channel

(1). As soon as the threshold of excitation is reached, the sodium channels in the membrane open and Na rushes in (through diffusion and electrostatic pressure)
  - The opening of the channels is triggered by reduction of the membrane potential (depolarization)
  - They open to the point at which an action potential begins: the threshold of excitation
(2). The membrane of the axon contains voltage-dependent potassium channels, but these
channels are less sensitive than voltage-dependent sodium channels
  - They require a greater level of depolarization before they begin to open (they begin to open later than the sodium channels)
  - (3). At about the time the action potential reaches its peak (in approximately 1msec), the sodium channels become refractory (the channels become blocked and cannot open again until the membrane reaches resting potential once more)
    - No more Na enters the cell
  - (4). Voltage-dependent potassium channels in the membrane are open (lets K ions move freely through the membrane)
    - At this point the inside of the axon is positively charged - so K is driven out of the cell through diffusion and electrostatic pressures
    - This outflow of cations causes the membrane potential to return toward its normal value (potassium channels begin to close again)
  - (5). Once the membrane potential returns, the sodium channels reset so that another depolarization can cause them to open again
  - (6). The membrane actually overshoots its resting value (-70 mV) and only gradually returns to normal as the potassium channels finally close
    - Eventually the sodium-potassium transporters remove the Na ions that leaked in and retrieve the K ions that leaked out

**End of 8/25 class notes**

Conduction of the Action Potential

- **All-or-none law**: the principle that once an action potential is triggered in an axon, it is propagated, without decrement, to the end of the fiber (opposite to attenuation - need to keep regenerating the signal)
  - An action potential either occurs or does not occur
  - Once triggered, it is transmitted down the axon to its end
- An action potential always remains the same size, without growing or diminishing
  - **Rate law**: the principle that variations in the intensity of a stimulus or other information being transmitted in an axon are represented by variations in the rate at which that axon fires
    - The size of the stimulus does not change, instead the axon fires more rapidly to produce a more intense response and vice versa
- All but the smallest axons in the mammalian nervous system are myelinated
  - Segments of axons are covered by a myelin sheath produced by:
    - Oligodendrocytes of the CNS or
    - Schwann cells of the PNS
  - These segments are separated by the nodes of Ranvier (naked portions of the axon)
- **Saltatory conduction**: conduction of action potentials by myelinated axons (regeneration/attenuation at nodes)
  - In myelinated areas there can be no inward flow of Na when the sodium channels open, because there is no extracellular sodium
  - The axon conducts a passive disturbance that gets smaller as it passes down the axon - but it is still large enough to trigger a new action potential to the next node of Ranvier (saltatory conduction)
    - Attenuation (regeneration) at each Node of Ranvier
  - The action potential appears to jump from one node of Ranvier to the next
- Saltatory conduction has 2 advantages:
  - Economic: myelinated axons expend much less energy to maintain their sodium balance
    - Na can only enter through nodes of Ranvier, while still having lots of sodium-potassium transporters along the axon (have much less sodium entering the cell)