Activity 48.1 How do ion concentrations affect neuron function?

Much of our understanding of neuron function was based on studies of the squid giant axon. Squid move through the water by contracting the muscles of the mantle. This compresses water inside the mantle that is forced out the siphon. Squid can change the direction of movement by directing the flow from the siphon either forward or backward (relative to the head or anterior end).

1. In which direction would the squid move if water flow from the siphon was directed toward the head end of the organism?

2. When squid are startled or in danger, they can simultaneously contract all muscles of the mantle to jet water forcefully out of the siphon and escape rapidly. Assume the mantle of the squid is 30 cm in length (about 12 inches). The brain sends a signal to major nerve ganglia in the mantle, which relay the signals to axons innervating the mantle muscles. For all muscles of the mantle to contract simultaneously, all nerve signals sent along these axons must reach all parts of the mantle at the same time.

   a. On the diagram of the squid above, draw and number three neurons. Assume all are simultaneously stimulated by a single motor neuron from the brain. Neuron 1 innervates the mantle muscles nearest the brain. Neuron 2 innervates the muscles in the midregion of the mantle. Neuron 3 innervates the muscles at the tail end of the mantle.

   b. In invertebrates like the squid, how must the nervous system be structured to allow both the muscles nearest the brain and those farthest from it to contract simultaneously? In your drawing, indicate any differences in the size or structure of the three neurons that would be required. Explain your reasoning.
3. Researchers discovered that they could remove the giant axons of the squid. With some skill, the axons could be maintained outside the body if held in ion solutions of the same concentrations as the squid's extracellular fluids. If stimulated with a microelectrode, these isolated axons would generate action potentials. By recording the potential difference between an electrode in the axon versus one in the fluid bathing the axon, the scientists could also record the potential difference at rest and any change in potential difference that occurred as a nerve impulse, or action potential, was generated.

The ion concentrations the researchers recorded for the squid giant axon are listed in the table below.

<table>
<thead>
<tr>
<th>Ion concentrations (mM) for intra- and extracellular fluids of the squid axon</th>
<th>Intracellular (mM)</th>
<th>Extracellular (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium (K⁺)</td>
<td>400</td>
<td>20</td>
</tr>
<tr>
<td>Sodium (Na⁺)</td>
<td>50</td>
<td>440</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>40 – 150</td>
<td>560</td>
</tr>
<tr>
<td>Calcium (Ca²⁺)</td>
<td>$1 \times 10^{-4}$</td>
<td>10</td>
</tr>
</tbody>
</table>

Some of these ion concentrations for the human are listed in the table below.

<table>
<thead>
<tr>
<th>Ion concentrations (mM) for intra- and extracellular fluids of the human axon</th>
<th>Intracellular (mM)</th>
<th>Extracellular (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>
</tbody>
</table>

Using the Nernst equation, your textbook calculates that in humans the equilibrium potential for potassium is $-90$ mV and that for sodium is $+62$ mV.

What are the equilibrium potentials for potassium and sodium for the squid?

The Nernst Equation $E_{ion} = \frac{62mV}{z} \log \frac{[ion]_{out}}{[ion]_{in}}$  
(e.g., Na = +1, Cl = -1)

$E_{K} = \frac{62mV}{z} \log \frac{K_{out}}{K_{in}}$  
$E_{Na} = \frac{62mV}{z} \log \frac{Na_{out}}{Na_{in}}$

4. In a typical neuron, which ion has the greatest influence on the membrane potential at rest? In other words, flux of which ion contributes the most to the resting membrane potential? Explain why this occurs.
5. In calculating the resting and action potentials of the axon, we generally don’t worry about the concentration differences of calcium or chloride ions. Explain.

6. What effects would the following changes in extracellular $K^+$ concentration be likely to have on the resting membrane potential of neurons in a human?

   a. Change extracellular $K$ from 5 mM to 2 mM

      $E_{K^+} =$

   b. Change extracellular $K$ from 5 mM to 10 mM

      $E_{K^+} =$
Activity 48.2 How do neurons function to transmit information?

Working in groups of three or four, construct a dynamic (claymation-type) model of the transmission of an action potential along a neuron and then across a synapse to generate an action potential in a postsynaptic neuron.

When developing and explaining your model, be sure to include definitions or descriptions of the following terms and structures.

### Neurons or Parts of Neurons
- dendrite
- axon
- cell body
- synaptic vesicles
- presynaptic neuron
- postsynaptic neuron

### Ions
- $K^+$
- $Na^+$
- negative organic ions
- $Ca^{++}$

### Gates
- voltage-gated ion channels
- $Na^+$ gates or channels
- $K^+$ gates or channels
- $Ca^{++}$ gates or channels

### Building the Model

- Using chalk on a tabletop or a marker on a large sheet of paper, draw the membranes of two neurons and the synaptic region between them. Each neuron should each be at least 4 inches across and a foot or more in length.
- Identify the axon, cell body, and dendrite(s) on your drawing.
- Make the ions and gates from playdough or cutout pieces of paper. Indicate the placement of gates in the membranes and ions inside the membrane versus outside the membranes.
- Include a key for your model that indicates how ions and gates are differentiated from each other. You may use color coding for the ions and gates.
- Start the model by “initiating” an action potential in the axon hillock.
- Indicate how this action potential is propagated along the axon and how it can lead to production of an action potential in the postsynaptic neuron.
- When you have completed your model, explain it to another student or to your instructor.
Use your understanding of how action potentials are generated and propagated to answer the questions.

1. All cells maintain an ionic (and therefore electrical) potential difference across their membranes. In most cells, this potential difference is between -50 and -100 mV. That is, the inside of the cells is more negative than the outside by 50 to 100 mV. Although all cells in the body maintain this potential difference across their membranes, only certain cells (for example, neurons) are capable of generating action potentials.

   a. How is this potential difference across the cell membrane generated?

   b. What characteristics of membranes allow cells to concentrate or exclude ions?

   c. What is it about neurons (nerve cells) that makes their properties different from those of other cells? In other words, what enables nerve cells to produce action potentials?

   d. How is an action potential started and propagated?

   e. Is any direct or indirect energy input required to generate an action potential? If so, when and where is the energy used?
f. What happens in time and space (along the axon) once an action potential begins?

\[
\begin{array}{|c|c|}
\hline
\text{Time (milliseconds)} & \text{Distance (mm)} \\
\hline
0.2 & 1 \\
20 & 10 \\
100 & \\
5,8 & 0.0001 \\
\hline
\end{array}
\]

2. If an axon is stimulated in the middle of its length, nervous signals (action potentials) will move out from the point of stimulus in both directions. Normally, however, nerve signals move in only one direction along neurons. Explain.

3. Whether or not an action potential is generated in a postsynaptic neuron depends on a number of factors. What are they? What ultimately determines whether or not an action potential is generated in the postsynaptic neuron?
4. Diffusion is efficient over only very short distances. In fact, as you can see in this table, diffusion is efficient only for distances of about 1 to 100 µm.

<table>
<thead>
<tr>
<th>Diffusion distance (µm)</th>
<th>Time required for diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5 msec</td>
</tr>
<tr>
<td>10</td>
<td>50 msec</td>
</tr>
<tr>
<td>100</td>
<td>5 sec</td>
</tr>
<tr>
<td>1,000 (1 mm)</td>
<td>8.3 min</td>
</tr>
</tbody>
</table>

a. How wide is a synapse?

b. If a synapse were two times as wide, what effect would it have on the transmission of nerve signals from one neuron to the next? How would this change affect the response time of an organism?

5. If you examine neuron transmission within an organism, you discover that every action potential generated is stereotyped; for example, every action potential reaches the same maximum height and the same minimum height. In addition, the generation of action potentials is an all-or-none phenomenon. That is, once the potential difference across the membrane reaches threshold, an action potential will be generated. Given this, how does the nervous system signal differences in intensity of signal?
Activity 48.3  What would happen if you modified a particular aspect of neuron function?

In the following questions, test your understanding of the various parts of the nervous system by asking yourself what would happen if a certain part was damaged. What would the system still be able to do? What would it be unable to do?

1. Some nerve gases and insect poisons work by destroying acetylcholine esterase. Acetylcholine esterase is normally present in acetylcholine synapses and acts to degrade acetylcholine. What is likely to happen to nervous transmission in insects exposed to this type of insect poison?

2. The pufferfish (fugu) contains the poison tetrodotoxin. Some shellfish produce a paralytic poison called saxotoxin. Both of these poisons block the Na⁺ channels in neurons. What specific effects could these toxins have on neuron function?

3. A type of spider (the funnel-web spider) produces a toxin that blocks the Ca⁺ channels.

   a. Can a neuron exposed to this toxin fire an action potential? Explain.

   b. Can a neuron transmit a signal across the synapse using neurotransmitters? Explain.
4. You isolate a section of a squid giant axon and arrange an experiment so that you can change the solution bathing the axon. You insert an electrode into the axon and place another electrode outside the cell so that you can measure the potential across the cell membrane. With the axon bathed in normal extracellular fluid, you observe a resting potential of $-70 \text{ mV}$ and action potentials, when stimulated, that reach $+55 \text{ mV}$.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Normal concentrations</th>
<th>Experimental concentration in (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inside neuron</td>
<td>Outside neuron</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>50</td>
<td>440</td>
</tr>
<tr>
<td>K$^+$</td>
<td>400</td>
<td>20</td>
</tr>
</tbody>
</table>

a. You change the solution bathing the neuron by increasing the K$^+$ concentration to 40 mM. What effect will this have on the neuron? For example, will it depolarize the membrane and make it easier to start an action potential? Will it hyperpolarize the membrane and make it more resistant to starting an action potential? Or will it have no effect? Explain your answer.

b. What would happen if, instead of adding more K$^+$ to the outside, you added more Na$^+$ to the fluid bathing the neuron? Explain.