Neural Communication

- Nerve cells are specialized for generating and moving information around in the nervous system.
- These two simple functions are the origin of all our conscious experience and responses.
- The brain, the prime control center of the body, crouches within the bony shelter of the skull.
- Resembling in a way the underground war room beneath the Pentagon.
- Messages pour in from data-collecting outposts
  - Eyes
  - Ears
  - Skin
  - And elsewhere
- And commands are sent out to response units.

Neural Impulse

- Muscles
- And glands
- The brain, like, the commander in the windowless war room, has no direct connection with the outside world.
- By itself the brain is blind and deaf—totally insensitive.
- For knowledge of the environment, it is wholly dependent on messages in the form of nerve impulse patterns coming in along the nerves.
- Every stimulus to which the nervous system can react is first changed by a sensory receptor into the only language the can understand, nerve impulse patterns.
- Inside the brain itself, messages are sent from place to place as patterns of impulses in axons.
- The nerve impulse is a fundamental component of hearing, thinking, feeling, loving, hating and hurting.
- It underlies every conscious experience.

Nature of Nerve Impulses

- As students of the brain, we must understand what the impulse is and how it works.
- First, the nerve impulse is an electrical event within the axon of the nerve cell.
- It is a traveling event
- Starting at the cell body end of the axon and running down to the terminal buttons at the other end.
- Under normal conditions then, a nerve impulse is only conducted in a particular direction, towards the terminal buttons.
- This is the principle of one-way conduction.
- A second important principle of conduction is the all-or-none law.

Nature of Nerve Impulses (continued)

- When you walk into a dark room and turn on the light
- Nerve messages tell your brain that the light-intensity level has increased.
- How is this information about intensity conveyed?
- Does a more intense light create bigger nerve impulses?
- The answer to that question is to be found in the all-or-none law that states:
- If an axon fires at all, it will fire at full strength.
- Each axon has only one size of nerve impulse.
- Stronger stimuli simply produce more frequent impulses.

Bioelectricity

- The nerve impulse involves a different kind of current than the one traveling in a length of lamp cord.
- A current is a flow of charged particles, and that definition holds no matter where the current is found.
- And that definition holds no matter where the current is found
- However, the particles that make up a current in a nerve impulse are quite different from those in a house wire.
- Before we can learn about the specific particles involved, we need a little background information.
- Solid matter is composed of particles called molecules.
- Which in turn are made up of atoms.
- A molecule of table salt, for example, is composed of:
  - Sodium atom (Na)
  - And a chlorine atom (Cl)
  - And is called sodium chloride (NaCl).
Bioelectricity (continued)

- Atoms themselves consist of two parts:
  - Solid centers called nuclei composed of:
    - Protons
    - Neutrons
  - And negatively charged particles called:
    - Electrons
  Atomic nuclei carry a positive charge and electrons carry a negative charge.
- A basic law of physics states:
  - That positively charged particles are attracted to negatively charged particles
  - This attraction of unlike charges holds together the two parts of the atom.

Bioelectricity (continued)

- Because the negatively charged electrons cancel the positive charges of the nucleus:
  - The atom as a whole is neutral
  - All positive charges with the atom is balanced by negative charges
- In some situations, however, the balance is lost when an atom acquires or loses one or two electrons.
  - In either case, the resulting unbalanced (charged) particle is called an ion.
    - An ion has a positive charge when it has too few electrons
    - And a negative charge when it has too many electrons.

Bioelectricity (continued)

- Earlier we said that currents in the nerve impulse were different from those in a wire.
- Now we can find out why that is so.
  - The current in a house wire is the flow of electrons jumping between the metal atoms that make up the wire.
  - Nerve impulse involve currents in which the charged particle are ions flowing through fluid.
  - Two types of ion that flow in your brain, whenever you think, act, feel or see:
    - Sodium ions
    - Chloride ions
  - You eat salt because it tastes good, but the reason that it tastes good is that your whole conscious experience depends on it.

Bioelectricity (continued)

- Tasting “good” means that your brain contains circuits whose vital function is to make you find and consume salt.
- Other ions are also involved in the current that make up the nerve impulse.
  - But the basics of bioelectricity can be illustrated with sodium and chloride.

Resting Potential

- Let’s conduct an imaginary experiment.
  - A glass of water divided into two separate compartments by a partition running across the center.
  - We put sodium ions in one of the compartments
  - And chloride ions in the other.
  - The ions are strongly attracted to one another but are held apart by the dividing wall.
Resting Potential (continued)

- Now if a hole is created in the partition
- The mutual attraction produces a flow of sodium ions into chloride side
- And vice versa
- This flow of charged particle is an electric current
- And continues until every positive ion is closely associated with a negative ion.
- We have demonstrated that one can generate an ionic current if the opposite charges are first separated and then allowed to flow back together.

Creating the Resting Potential

- Creating a voltage across the cell membrane seems at first to be a simple thing:
- All that is needed is more positive ions on one side than on the other
- There are at least four factors that have a say in how ions will be distributed between the inside and the outside of a neuron:
  1) semipermeability
  2) sodium/potassium pump
  3) diffusion pressure
  4) electrostatic forces
- Attraction
- And repulsion

Resting Potential (continued)

- At the end of the first step in this procedure, when all sodium ions have been separated into one compartment
- And chloride ions into the other
- The current has not yet occurred
- But the potential for a current flow is there
- Potential is a technical term here and refers:
  1. To the separation of charges between two places
  2. The positive charges are in one place
  3. And the negative charges in another
- Axons function like biological batteries,
  1. The cell membrane acts just like the partition in our water glass
  2. It keeps positive on one side from reaching negatives on the other.

Resting Potential (continued)

- However, unlike charges provide enough attraction to keep the ions lined up along the inside and outside of the membrane.
- The axon employs several types of negative and positive ions:
  1. Sodium ions (Na⁺)
  2. Chloride ions (Cl⁻)
  3. Potassium ions (K⁺)
  4. And protein anions (A⁻)
Creating the Resting Potential (continued)

- It is easier to understand how the four forces work if we imagine a hypothetical set of circumstances in which each force can occur by itself.
- Let us begin with diffusion pressure alone and then add in the other three, one at a time.
  - Diffusion is the tendency for identical particles in solution to move apart from one another so that they fill the available space with the greatest possible distance between each other.
  - Concentration gradient – like molecules move from greater concentration to less concentration.
- 'Semipermeable membrane' like those of a neuron allow some ions to diffuse through readily but not others.

Creating the Resting Potential (continued)

- Potassium and chloride are able to diffuse through easily.
- Sodium moves through only with difficulty.
- The protein anion is too big to fit through the membrane and is permanently trapped inside the cell.
- The ions that can move through the membrane do so by of large, cylindrical protein molecules called ion channels.
- Which create tubelike opening through the membrane at frequent intervals.

Creating the Resting Potential (continued)

- The inability of the protein anions to diffuse out of the axon creates a large electrostatic repulsion between them and chloride ions.
- Electrostatic repulsion is the tendency for particles with identical charges to repel one another.
- The repulsion pushes most of the chloride ions out of the axon.
- A few chloride ions remain inside because the electrostatic repulsion is countered in part by the diffusion pressure pushing the chloride ions inward.
- This leaves the inside of axon with slightly more negative ions than there is on the outside.
- The neuron is actually -70mV inside relative to the outside.

Creating the Resting Potential (continued)

- The force electrostatic repulsion is matched by electrostatic attraction.
- Unlike charges attract one another.
- This attraction pulls a few extra potassium ions inward but not enough of them to cancel the negativity there.
- The rest are held back by the strong diffusion pressure from the inside potassium ions.
- This pressure builds as more potassium ions are attracted inward.
- Finally, a point is reached at which the inward electrostatic attraction is balanced by the outward diffusion pressure.
  - This is called an equilibrium point.
  - It is reached before many potassium ions have entered.

Creating the Resting Potential (continued)

- The only remaining difference between our hypothetical axon and a real one are the equal distribution of sodium ions across membrane.
- And the size of the difference in potassium ion distribution.
- Diffusion pressure and electrostatic forces have had negligible effects on the sodium ions because the membrane is nearly impermeable to their passage.
- A set of chemical reactions, the sodium-potassium pump, works continually through the day (24/7) to move sodium ions to the outside of the membrane and the potassium ions to the inside.
- It must draw on the chemical energy supply of the neuron to do this because it must transport the sodium ions against the forces of diffusion and electrostatic repulsion.
Creating the Resting Potential (continued)

- Once some of the sodium ions have been moved to the outside, an equilibrium between all the opposing forces is reached.
- It is this combination of forces that is responsible for the **resting potential**.
- To summarize:
  - The resting potential develops because the protein anions are all held inside by the membrane
  - When some chloride ions are forced in by diffusion
  - The inside turns slightly negative

Creating the Resting Potential (continued)

- The sodium ions are unable to cancel out this resting potential because of the ion pump and membrane impermeability.
- There aren’t enough potassium ions inside to do the job because of the outward diffusion pressure.
- So, in its resting state, the cell membrane stays negative on the inside and positive on the outside.

Distribution of Ions

**The Concentration of Ions Inside and Outside the Neuron**

<table>
<thead>
<tr>
<th>Anion (—)</th>
<th>Inside of Cell</th>
<th>Outside of Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride (Cl⁻)</td>
<td>49</td>
<td>960</td>
</tr>
<tr>
<td>Potassium (K⁺)</td>
<td>345</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2-1: Relative concentrations of ions either inside or outside the nerve membrane. Numbers are expressed in millimoles per liter.

- Sodium is a 9:1 ratio outside to inside
- Potassium is a 40:1 ratio inside to outside
- Chloride is a 14:1 ratio outside to inside

Movement of Ions During the Nerve Impulse

- With a resting potential established, a nerve impulse becomes possible.
- As soon as the gates on the sodium channels open
- The membrane becomes completely permeable to sodium ions, and they flow inward.
- Creating an electric current by their movement.
- It has been estimated that each channel opening allows the passage of about 100 ions.
- They are attracted inward by excess of negative charges there
- And they are also pushed inward by diffusion pressure from overcrowding outside the axon

Movement of Ions During the Nerve Impulse (continued)

- If sodium ions move inward only because they were electrostatically attracted to the excess of negative ions there.
- The flow of sodium ions would stop as soon as all the negative charges had been balanced.
- Instead, the flow continues until the inside of the axon reaches a charge of +40 mV.
- It is the diffusion pressure of all the sodium ions on the outside that pushes the extra ions into the cell.
- As the extra sodium ions enter, however, they produce an overall positive charge inside the cell, which creates electrostatic repulsion for the sodium ions that are still outside.
- The entrance of extra sodium ions has left the outside of the cell with a slight excess of negative charges
- Which attract the remaining sodium ions
Movement of Ions During the Nerve Impulse

(continued)

- So, as more and more sodium ions enter the axon, the electrostatic forces that resist this flow becomes greater and greater.
- Finally a point is reached where the electrostatic forces that resist entrance of sodium are strong enough to balance the diffusion pressure sending them inward.
- The flow stops.
- The two forces have reached an equilibrium (electrostatic repulsion & diffusion pressure), and the voltage at this equilibrium point is +40 mV in the axons of mammal.
- Thus, a potential of +40 mV on the inside of the membrane is called the sodium equilibrium potential.
- It is this equilibrium that determines when the inflow of sodium ions will be cut off.

Movement of Ions During the Nerve Impulse

(continued)

- As the sodium current ends, the membrane once more becomes impermeable to sodium ions.
- At this point in the process, the axon is like a gun that has been fired.
- In order to get it to fire again it must be reloaded.
- In other word, the neuron must reestablish its resting potential.
- If there is to be another current flow.
- The problem is solved by an outward flow of potassium ions that begin as soon as the sodium current is slackening off.
- The potassium current continues until the negative charge on the outside of the membrane has been neutralized.

Movement of Ions During the Nerve Impulse

(continued)

- It continues beyond that point to establish a positive charge outside the membrane.
- The force that pushes out these potassium ions is diffusion pressure.
- The overcrowding of potassium ion inside the cell is overcoming the electrostatic repulsion of positive ions following into an area that already has a positive charge on it.
- But, once more, as more positive ions flow out, the electrostatic force resisting that flow automatically becomes greater.
- Finally, at +70 mV the force of electrostatic repulsion is strong enough to balance the diffusion pressure.
- And the outward flow of potassium ions stop.

Movement of Ions During the Nerve Impulse

(continued)

- The potassium equilibrium potential has been reached.
- This voltage is also the resting potential, which has now been established.
- The axon is once more laden and ready to be fired again.
- One problem remains.
- Every impulse draws more sodium inward and more potassium outward.
- The sodium-potassium pump works day and night (24/7) to restore the ions to their starting points.

Movement of Ions During the Nerve Impulse

(continued)

- The exchange of sodium and potassium across the membrane is the action potential of the axon.
- Action potential consists of two transmembrane currents, one flowing inward (Na+) and the other flowing outward (K+) at one point on the membrane.
- The nerve impulse consists of a sequence of such transmembrane currents progressing down the length of the axon from the soma to telodendria.
- Next we must find out how such a sequence of transmembrane current can come about.

Conduction of the impulse

- The area where the axon emerges from the cell body is called the axon hillock.
- It is the area that impulses are born.
- Currents from the cell body disturb the membrane of the hillock and cause the channels in this area to open.
- Sodium ions rush inward, drawn by the presence of the negative ions within the axon (electrostatic attraction).
- Consequently, channels in the neighboring membrane open and allow a current to flow there also.
- This current, in turn, disturbs the next area of membrane a bit further down the axon.
- Which responds by opening channels - and so on.
- Down the entire length of the axon.
Conduction of the Impulse (continued)

- Once this chain reaction is triggered by the current in the cell body, it then proceeds from the cell body to telodendria as automatically as knocking over a row of dominoes.
- This traveling wave of disturbances and transmembrane current is the nerve impulse (or action potential).\textsuperscript{55}

Electrotonic Currents

- The disturbance that opens the ion channels is a drop in the voltage across the membrane.
- What causes a voltage drop in the parts of the membrane?
- The answer is a process called an \textbf{electrotonic current}.
- This is a type of current that consists of a flow of electrons.
- Jumping from one ion to the next in much the same way that electrical wire move from one molecule of copper to the next.
- Whenever an ionic transmembrane current flows it generates an accompanying electrotonic current.
- That spreads out along the axon membrane in both direction.\textsuperscript{55}

Electrotonic Currents (continued)

- This current decreases the voltage in the regions adjacent to the area of membrane occupied by the transmembrane current.
- The voltage drops opens the ion channels, thus triggering a sodium current in the new region.
- The new transmembrane current also generates electrotonic currents that spread to unstimulated regions of the axon, decreasing the voltage there and triggering ionic currents.
- These ion channels are voltage regulated.\textsuperscript{56}

Electrotonic Currents (continued)

- The original transmembrane current started by the stimulus spreads down the entire length of the axon.
- As each region of membrane stimulates its neighbor with electrotonic currents.
- Another way of describing the nerve impulse is to say that an action potential at one end of the axon.
- Will set off a wave of action potential along the whole axon.
- Because the impulse at one point on the membrane triggers the impulse at the next point.
- Nerve impulses are said to be \textbf{self-propagating}.\textsuperscript{55}

Electrotonic Currents (continued)

- One result of self-propagation is that the strength of the nerve impulse does not weaken as it progressed down the axon.
- The size of the action potential in each segment of axon is determined by the diameter of the segment rather than by how far the impulse has already traveled.
- This characteristic of the impulse is frequently called \textbf{nondecremental conduction};
- That is, the impulse shows no decrement as it travels.
- The action potentials stand in sharp contrast to electrotonic current, which lose strength as the distance from the source increases.
- We shall see that the soma and dendrites are characterized by \textbf{decremental conduction}.
- Whereas nondecremental conduction is the rule in the axon.\textsuperscript{56}
Action Potential

Saltatory Conduction

- Fast-conducting axons are vital for responses requiring short reaction times.
- In the myelin sheath of the axon, evolution has provided vertebrates with a device for enhancing speed of conduction.
- Myelin provides an insulation for each axon that minimizes the degree to which electrotonic currents can reach the ion gates in the membrane.
- The bare spots between the glial cells are the nodes of Ranvier.
- They are the only places on a myelinated fiber where transmembrane currents can be elicited.

Saltatory Conduction (continued)

- In saltatory conduction, a transmembrane current occurring in the first segment of axon spreads its electrotonic current along the intervening myelin.
- When these currents reach the bare membrane at the first node of Ranvier, they open the ion gates there.
- And trigger another action potential.
- In myelinated axons the nerve impulse jumps from one node of Ranvier to the next like a stone skipping over the water.

Saltatory Conduction (continued)

Saltaory Conduction (continued)

Saltatory Conduction (continued)

Sallatory Conduction (continued)

Polarization

- In discussing nerve impulses, several concepts are almost always used.
- For example, a membrane with a resting potential across it is said to be polarized.
- This simply means that there is some separation of charges so that more positive charges are on one side and more negatives on the other.
- Depolarization would of course make the inside of the cell less negative relative to the outside of the cell.
- Hyperpolarization would make the inside of the cell more negative relative to the outside of the cell.
- Hyperpolarization occurs when the cell is more negative than resting potential.
Refractory Period

Absolute Refractory Period

- After the neuron has produced an action potential it takes a brief moment to recover.
- In fact, for about 1 ms, the neuron cannot produce an action potential no matter how much stimulation it receive.
- This short period of nonexcitability is called the absolute refractory period.
- At the ionic level, this simply means that the first impulse already has the membrane channels open.
- The stimulus cannot reopen something that is already open.

Refractory Period (continued)

Relative Refractory Period

- Immediately following the absolute refractory period comes the relative refractory period.
- During which it again becomes possible to obtain a nerve impulse.
- The axon does not have to repolarizes all the way to -70 mv for depolarization to be initiated.
- The duration of the relative refractory period is anywhere from 1 to 4 ms.
- There is a limit to the rate at which an axon can be fired.
- This rate is set by the duration of the absolute refractory period.

Refractory Period (continued)

Refractory Period

- If a stimulus increases in strength, if fires the neuron earlier and earlier in the relative refractory period.
- Eventually, it reaches the beginning of that period, and further increases can do nothing to make the cell fire faster.
- Because the absolute period is longer in some neurons than in other, some cells are capable of much faster rates of firing than are others.
- The record speed is 1,000 impulse per second.
- But a typical rate is around 500 per second.
- A moment of simple arithmetic would tell you that the typical absolute refractory period lasts about 2 ms.