Mechanisms Involved in the Transmission Network of the Neuron

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As Dr. John Stewart, a physicist from the University of Arkansas, always elucidated in his lectures, human beings are vessels of salt. Concerning this salt, Dr. Stewart eludes to chemical ions, such as potassium and sodium, which help initiate electrical responses that stream through these salt vessels via cells called neurons. Human beings possess a very complex electrical circuitry that's intricately interwoven, but can be exemplified through the simplest of circuits in a physics laboratory. To further explore this topic, the physics and biological aspects of neurons will be examined to allow a better comprehension of the mechanisms involved in the transmission network of the neuron.

The electrical transmission network of the neuron doesn't originate specifically with neurons, but with the cell membrane that encompasses neurons. The cell membrane is composed of a phospholipid bilayer that is selectively permeable to the necessities of the cell. In an aqueous solution, the phospholipid bilayer distinguishes the hydrophilic heads of the phospholipid bilayer, which point outward towards the aqueous solution, from the hydrophilic tails of the phospholipid bilayer that point inward. Larger molecules are denied entrance through the phospholipid bilayer and require the machinery of a pump to relocate the molecule from outside the cell membrane into the inside of the cell.

The processes by which ions flow across the membranes of living cells are often classified as either passive or active mechanisms (Scott 1977). Passive transport is considered to be in response to a gradient of the electrochemical potential (Scott 1977). Each chemical species (for example, "water molecules", "sodium ions", "electrons", etc.) has an electrochemical potential (a quantity with units of energy) at any given location, which represents how easy or difficult it is to add more of that species to that location (Wikipedia 2012). In a biological environment, a chemical species will attempt to establish equilibrium on either side of the cell

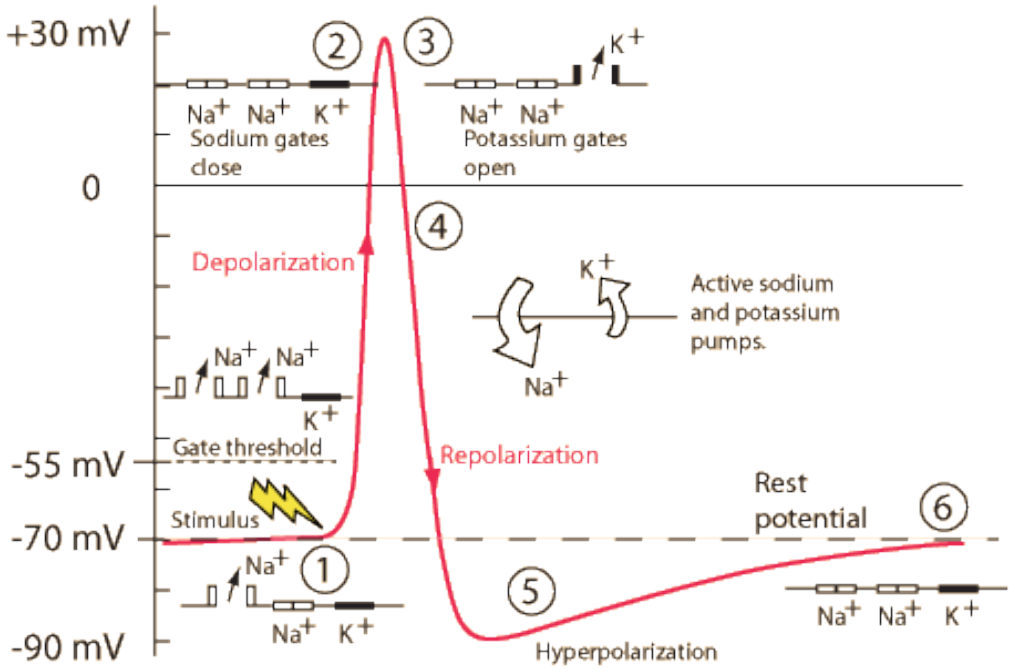
membrane by traveling from a higher electrochemical potential concentration gradient to a lower electrochemical potential concentration gradient.

As mentioned earlier by Scott, another process used by cells to move ions across cell membranes is active transport. Active transport involves the flow of ions against the electrochemical potential (Scott 1977). During active transport, energy must be released to force a chemical species to travel from a lower to a higher electrochemical potential concentration gradient. This is a directly conflicting mechanism compared to the objective of the neuron, where the goal of the neuron is to maximize its output of electrical impulses by minimizing its internal energy.

Electrical impulses in a neuron come into being in the cell membrane by two different kinds of membrane potential or transmembrane potential. These membrane potentials are not directly proportional to a cell membrane's electrochemical potential. They are known as a cell membrane's resting potential and action potential. Within a human cell, the resting potential is always negative, around -70 mV, and is obtained by chemical pumps and ion channels. One necessary pump is the sodium-potassium pump (Na^+K^+ATPase), a voltage-gated pump that opens and closes due to the voltage across the cell membrane. This pump uses ATP, Adenosine triphosphate, as the energy source to catalyze this ion transfer. Three sodium ions from inside the cell first bind to the transport protein (Biologymad 2004). Then a phosphate group is transferred from ATP to the transport protein causing it to change shape and release the sodium ions outside the cell (Biologymad 2004). Two potassium ions from outside the cell then bind to the transport protein and as the phosphate is removed, the protein assumes its original shape and releases the potassium ions inside the cell (Biologymad 2004). Ion channels are usually closed, allowing sodium and potassium ions to slowly leak into the cell. When ATP is not readily

available for the cell, however, these ion channels open and allow the sodium and potassium ions to flow freely into and out of the cell at no energy cost to the cell. With the cell constantly using pumps and ion channels, a natural imbalance of ions are procured on either side of the cell membrane, causing the potential difference of -70mV, which has come to be known as the membrane's resting potential.

To conduct electrical impulses, the neuron's cell membrane must procure an action potential, opposite that of the resting potential. This concept can be illustrated in the following diagram.



Before point #1 can be achieved, the cell membrane must become stable through its resting potential, as was mentioned in the previous paragraph. When an imbalance of the resting potential occurs, the transmembrane potential begins to reach its threshold value. It is at this point that the process of creating an electrical impulse is about to be begin at point #1. The cell membrane receives a stimulus through neurotransmitters, which are chemical messages transmitted across the gap, or synapse, of one neuron to an adjacent neuron. This signals the

opening of Na^+ voltage-gated pumps causing further imbalance of the resting potential. When the transmembrane potential reaches its threshold value, membrane conductivity itself becomes dependent on electric field strength (or transmembrane potential) (Nunez 1981), causing the opening of transmitter-gated Na^+ channels often start[ing] depolarization (Brodal 2004). To become depolarized, the cell membrane must first be polarized due to the electrochemical potential of Na^+ and K^+.

With the opening of a few Na^+ channels, Na^+ ions rush into the axon more rapidly than the passive transport system, initiating the buildup of a positive charge within the axon. As the charge becomes more positive within the axon, additional Na^+ channels open to allow more Na^+ ions to flow into the axon. The neuron's objective is to stay at its resting potential, using as little energy as possible. Since the axon has procured a positive charge far above its resting potential, the neuron must now counteract this positive charge to return to its electrochemical potential equilibrium. The buildup of Na^+ ions within the axon has now exceeded the neuron's capacity to hold this positive charge, forcing at point # 2, the closing of all voltage-gated Na^+ ion pumps and initiating the opening of K^+ voltage-gated pumps at point #3.

In the situation of a positive membrane potential, K^+ is driven out by both the concentration gradient and the membrane potential (electrical force) (Brodal 2004). Now the positive charge is being transferred to the outside of the axon, allowing the interior of the neuron's axon to return to a negative state. The K^+ ions and K^+ voltage-gated pumps follow the exact same route as the Na^+ ions and Na^+ voltage-gated pumps, except in the opposite direction. This process is known as repolarization, shown at point #4.

Depolarization and repolarization can be imagined through the description of a free flowing pendulum. A pendulum is a device that consists of a string and a weight that's attached

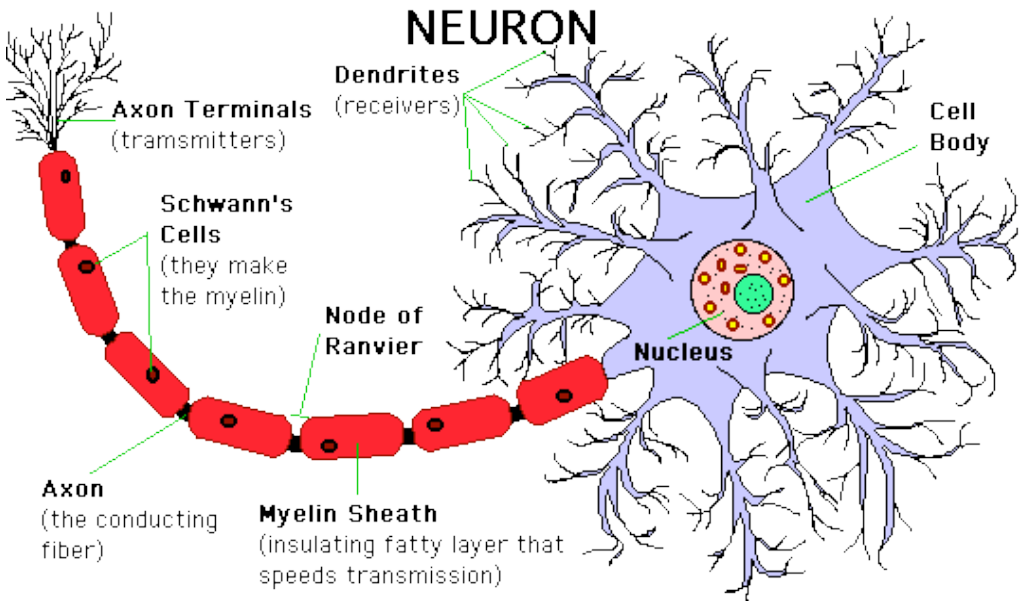
to the string. When the end of the string that is not attached to the weight is attached to a grounded location, such as a ceiling, the weight can swing back and forth freely when subjected to gravity and a sideways stimulus. At rest, the pendulum stays stationary at its equilibrium position or resting potential, due to gravity. When acted upon by a sideways force, the pendulum moves from its equilibrium position up to its maximum climax, synonymous to the process of depolarization. Due to the effect of gravity, the pendulum must swing back down through its equilibrium position, which corresponds to the process of repolarization. Eventually with the abnormal influx of K^+ ions, the cell's membrane potential will become more negative than the resting potential resulting in the process of hyperpolarization at point #5. Too many K^+ ions have been pumped out of the axon, similar to the pendulum going past its equilibrium position after being subjected to the fall of gravity from its maximum climax.

Now the neuron must return to its resting potential. This is achieved once again through the sodium-potassium pump (Na^+K^+ATPase). When equilibrium is reached at point #6, the neuron is ready to transmit another electrical impulse.

Altogether incredibly elaborate, the process of the action potential sequence occurs in a matter of a few milliseconds. Since an active axon may be surrounded by a conducting medium, [a myelinated sheath], that consists of an array of passive fibers (Nunez 1981), very little charge is lost in the transfer of these ions, consequently making this process very efficient. Between these myelinated sheaths, every so often there are nodes that are not myelinated, meaning that the axon isn't insulated at these points. At these nodes, this is where the voltage-gated pumps are located which allow the ions to generate points #1-#5. This allows the action potential to jump from node to node, until the action potential has reached the end of the axon. Once this

process begins, a chain reaction occurs from neuron to neuron, until the electrical impulse has reached its desired destination or is interrupted.

As with any cell, neurons are differentiated to complete certain tasks; specifically transmitting electrical impulses in this case. To better understand this function, one must inspect a neuron's structure for the reason that in all biological circumstances, structure precedes function.



A neuron encompasses all of the basic machinery of a eukaryotic human cell, but a crucial difference is the structures that proliferate out of the soma, or cell body of the neuron. Picture a tree. If the base of a tree represents the cell body of the neuron, then the branches represent appendages, known as dendrites, which extend out from the neuron. Dendrites receive the electrical impulses from neighboring neurons. To maximize the collection of energy from the sun, trees produce leaves on their branches which increase the collection surface area. Therefore the more leaves, the more energy that can be harvested from the sun. In the same approach, dendrites have small spikes that propagate outward, to not only increase the surface area of the neuron, but provide an opportunity for other neurons to attach and transport electrical signals.

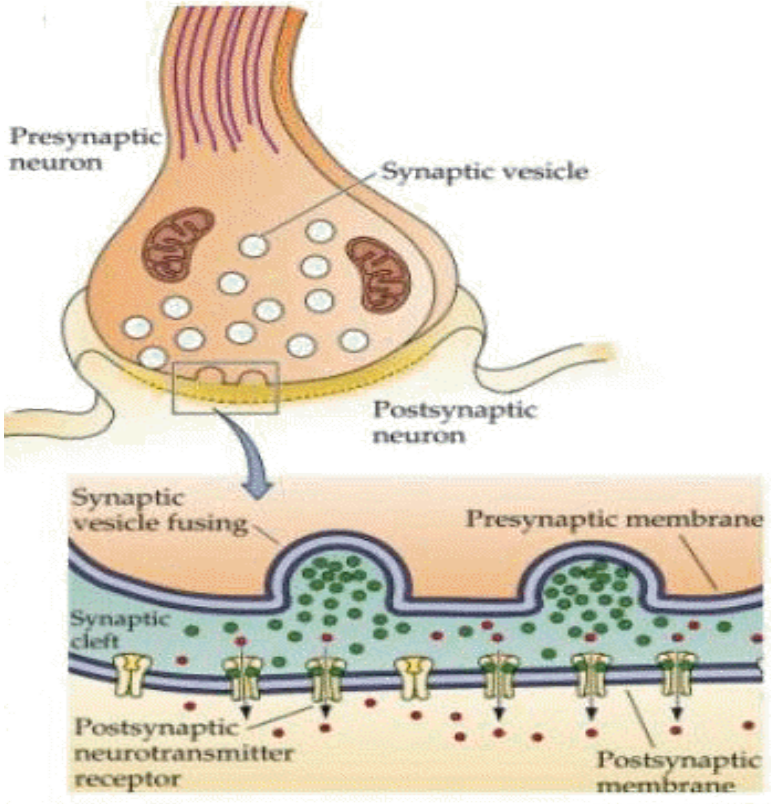
Going back to the tree analogy, underneath the base of the tree lays a dispersed network of roots. Pertaining to the neuron, there is only one "root" that protrudes from the soma, known as the axon or nerve fiber. Encased around the axon, cylindrically speaking, are Schwann cells, which provide an insulated myelin sheath around the axon. Ever so often, there is a fissure in the myelin sheath that isn't insulated and is identified as a node. Stemming from the central axon are side branches called axon collaterals, which assist in the amplification of the surface area of the neuron, while supplying nerve terminals, or boutons. Boutons are the tentacles of the neuron which will come in close contact with another neuron's cell membrane, usually a dendrite. Such a place of close contact between a bouton and another cell is called a synapse (Brodal 2004). The synapse is a very crucial component to the neuron, seeing that this focal point allows the direct transmission of the electrical impulse from one neuron to another. Compilations of these neurons collectively constitute a nerve.

Having discussed the neuron's biological structure and function, it's time to network these ideas and explore the actual mechanism of how neurons transmit electrical impulses to one another, since the origin of electrical impulses has already been touched upon.

As mentioned earlier, the synapse, the area between one neuron's axon and another neuron's dendrite, is a very crucial component of the neuron. To clarify this concept, a few more biological terms must be discussed. The end of the axon of one neuron, where the nerve terminals or boutons are located, comprises the presynaptic membrane. The tip of the dendrite of one neuron, where the spikes are located, consists of the postsynaptic membrane. Between the presynaptic membrane and the postsynaptic membrane exists the synaptic cleft. The axon and dendrite never come into direct physical contact with one another in the synaptic cleft region. Without the synapse and the processes that occur in it, neurons could only create electrical

impulses that traveled the length of the neuron. It is the bridge between neurons, the synapse, that allow electrical impulses to travel long distances throughout the body over many neurons. It's like having a piece of short rope. A short rope isn't long enough to reach the top of a three-story building, but if a lot of short ropes are knotted together, then this feat is achievable.

The direct transmission signals that tell the receiving neuron that the delivery neuron has undergone depolarization, repolarization and hyperpolarization are small chemical molecules known as neurotransmitters.



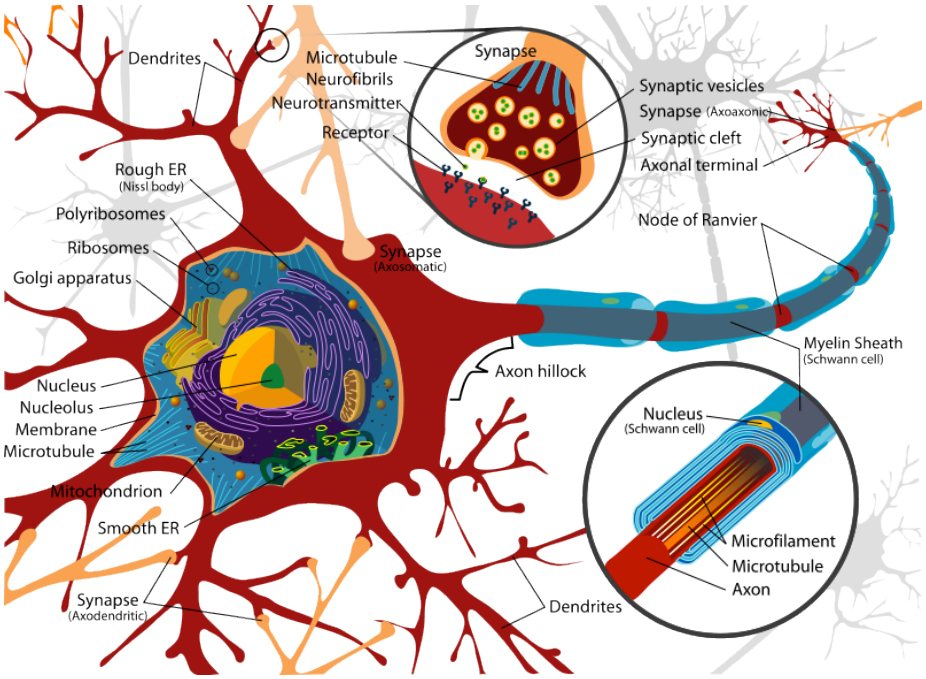
These molecules are the direct routes of communication between neurons. Neurotransmitters are synthesized in the cell body (the soma) and migrate down the axon to the presynaptic terminals (NeuroGenesis 2012). Upon preparing the neurotransmitters for transmission, the neuron houses these chemical molecules in synaptic vesicles. The end bulb of the axon stores a large quantity of synaptic vesicles containing chemical substances, with the

ability to selectively alter ionic permeability in the postsynaptic membrane (Scott 1977). The ionic permeability that Scott references refers to the processes of depolarization, repolarization and hyperpolarization.

Once the neuron has undergone depolarization, repolarization and hyperpolarization, the electrical impulses are ready to be transferred to the adjacent neuron. The signal is passed on, since the neuron has created a message, in the form of a neurotransmitter for the receiving neuron to obtain. When the action potential has been reached, the synaptic vesicles of the neurotransmitters fuse into the presynaptic membrane, allowing the chemical molecules that were encased by the synaptic vesicles to be released into the synaptic cleft. To allow a rapid transmission of the neurotransmitters from the presynaptic membrane to the postsynaptic membrane, the postsynaptic membrane has receptors on the outside of the membrane that grants passage to the neurotransmitters. There are many different neurotransmitters, which correspond to specific receptor sites. Neurotransmitters activate receptors by "sticking" to them and thus preventing other neurotransmitters from activating them (NeuroGenesis 2012). Upon finding the correct receptor, the neurotransmitter is then integrated into the neuron, releasing its message, and continuing the propagation of the electrical impulse.

Neurotransmitters are classified into two major types: excitatory neurotransmitters and inhibitory neurotransmitters. Neurotransmitters which propagate nerve impulses in the receiving neuron are called excitatory neurotransmitters (NeuroGenesis 2012). These neurotransmitters bring the postsynaptic membrane closer to the threshold of its action potential, allowing the receiving neuron to fire its own action potential. Concerning the physics of the neuron, excitatory neurotransmitters create a sink of current between the presynaptic and postsynaptic membranes. This current flows across the membrane, through the intracellular fluid, back across

the membrane at more distant locations, and finally back to the synapse to complete a closed loop (Nunez 1981). The total current that leaves the cell must equal the total current that enters the cell. The second kind of neurotransmitter, the inhibitory neurotransmitter, acts in the opposite way of an excitatory neurotransmitter, in that it inhibits electrical impulses. If the synapse is inhibitory, the resulting potential change (the inhibitory postsynaptic potential) acts in the opposite manner to the excitatory postsynaptic potential (but with generally different magnitude) and lessens the likelihood of an action potential in the postsynaptic neuron (Nunez 1981). Unlike the excitatory neurotransmitter, which provides a current sink between the presynaptic and postsynaptic membranes, the inhibitory neurotransmitter provides a local source of current at the synaptic membranes. The current sinks of the excitatory neurotransmitters, which are located across the presynaptic and postsynaptic membrane, demonstrate that excitatory and inhibitory neurotransmitters work hand in hand by countering this local source current.



The above image summarizes the transmission network of the neuron. From the structure of the neuron to the function of the neuron, every aspect has a purpose. Even the smallest

disturbance in the transmission network will interrupt the transmission of an electrical impulse. It is these electrical impulses that allow the vessels of salt, known as humans, to physically feel, move and interact with the surrounding environment. The neuron, so intricate and petite, is the foundation and lays down the basis to control the function of all the organs in humans. Without these electrical impulses, death would be imminent.

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