Overview of neuron structure and function

Introduction to neurons and glia. How the structure of a neuron allows it to receive and transmit information.

How do you know where you are right now?

Your ability to perceive your surroundings – to see hear, and smell what's around you – depends on your nervous system. So does your ability to recognize where you are and to remember if you've been there before. In fact, your very capacity to wonder how you know where you are depends on your nervous system!

If your perceptions indicate danger ("Oh no, the house is on fire!"), your ability to act on that information also depends on your nervous system. In addition to letting you consciously process the threat, your nervous system triggers involuntary responses, like an increase in heart rate and blood flow to your muscles intended to help you cope with danger.

All of these processes depend on the interconnected cells that make up your nervous system. Like the heart, lungs, and stomach, the nervous system is made up of specialized cells. These include nerve cells (or neurons) and glial cells (or glia). Neurons are the basic functional units of the nervous system, and they generate electrical signals called action potentials, which allow them to quickly transmit information over long distances. Glia are also essential to nervous system function, but they work mostly by supporting the neurons.

In this article, we'll take a closer look at neurons, glia and nervous systems. We'll see how the structure of neurons supports their function, and how they can be organized into circuits that process information and generate a response.

The human nervous system

In humans and other vertebrates, the nervous system can be broadly divided into two sections: the central nervous system and the peripheral nervous system. The central nervous system (CNS) consists of the brain and the spinal cord. It is in the CNS that all of the analysis of information takes place.

The peripheral nervous system (PNS), which consists of the neurons and parts of neurons found outside of the CNS, includes sensory neurons and motor neurons. Sensory neurons bring signals into the CNS, and motor neurons carry signals out of the CNS.

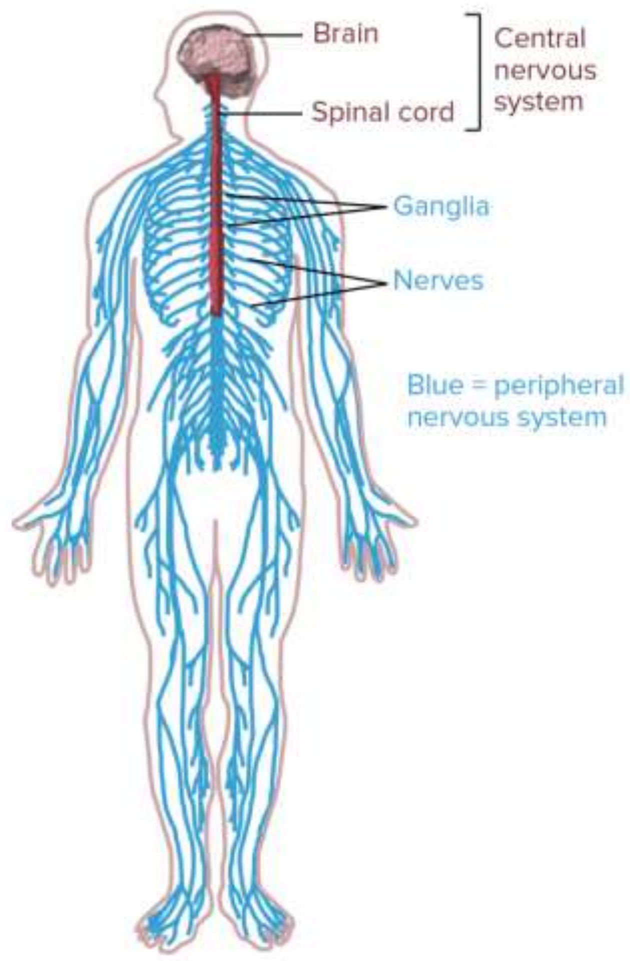

Image modified from "Nervous system diagram," by Medium69 (CC BY-SA 4.0).

The cell bodies of some PNS neurons, such as the motor neurons that control skeletal muscle (the type of muscle found in your arm or leg), are located in the CNS. These motor neurons have long extensions (axons) that run from the CNS all the way to the muscles they connect with (innervate). The cell bodies of other PNS neurons, such as the sensory neurons that provide information about touch, position, pain and temperature, are located outside of the CNS, where they are found in clusters known as ganglia. The axons of peripheral neurons that travel a common route are bundled together to form nerves.

Classes of neurons

Based on their roles, the neurons found in the human nervous system can be divided into three classes, sensory neurons, motor neurons, and interneurons.

Sensory neurons

Sensory neurons get information about what's going on inside and outside of the body and bring that information into the CNS so it can be processed. For instance, if you picked up a hot coal, sensory neurons with endings in your fingertips would convey the information to your CNS that it was really hot.

Motor neurons

Motor neurons get information from other neurons and convey commands to your muscles, organs and glands. For instance, if you picked up a hot coal, it motor neurons innervating the muscles in your fingers would cause your hand to let go.

Interneurons

Interneurons, which are found only in the CNS connect one neuron to another. They receive information from other neurons (either sensory neurons or interneurons) and transmit information to other neurons (either motor neurons or interneurons). For instance, if you picked up a hot coal, the signal from the sensory neurons in your fingertips would travel to interneurons in your spinal cord. Some of these interneurons would signal to the motor neurons controlling your finger muscles (causing you to let go) while others would transmit the signal up the spinal cord to neurons in the brain, where it would be perceived as pain.

Interneurons are the most numerous class of neurons and are involved in processing information, both in simple reflex circuits (like those triggered by hot objects) and in more complex circuits in the brain. It would be combinations of interneurons in your brain that would allow you to draw the conclusion that things that looked like hot coals weren't good to pick up, and, hopefully, retain that information for future reference.

The basic functions of a neuron

If you think about the roles of the three classes of neurons, you can make the generalization that all neurons have three basic functions. These are to:

1. Receive signals (or information).
2. Integrate incoming signals (to determine whether or not the information should be passed along).
3. Communicate signals to target cells (other neurons or muscles or glands).

These neuronal functions are reflected in the anatomy of the neuron.

Anatomy of a neuron

Neurons, like other cells, have a cell body (called the soma). The nucleus of the neuron is found in the soma. Neurons need to produce a lot of proteins, and most neuronal proteins are synthesized in the soma as well.

Various processes (appendages or protrusions) extend from the cell body. These include many short branching processes, known as dendrites, and a separate process that is typically longer than the dendrites, known as the axon.

Dendrites

The first two neuronal functions, receiving and processing incoming information, generally take place in the dendrites and cell body. Incoming signals can be either excitatory – which means they tend to make the neuron fire (generate an electrical impulse) – or inhibitory – which means that they tend to keep the neuron from firing.

Most neurons receive many input signals throughout their dendritic trees. A single neuron may have more than one set of dendrites, and may receive many thousands of input signals. Whether or not a neuron is excited into firing an impulse depends on the sum of all of the excitatory and inhibitory signals it receives. If the neuron does end up firing, the nerve impulse, or action potential, is conducted down the axon.

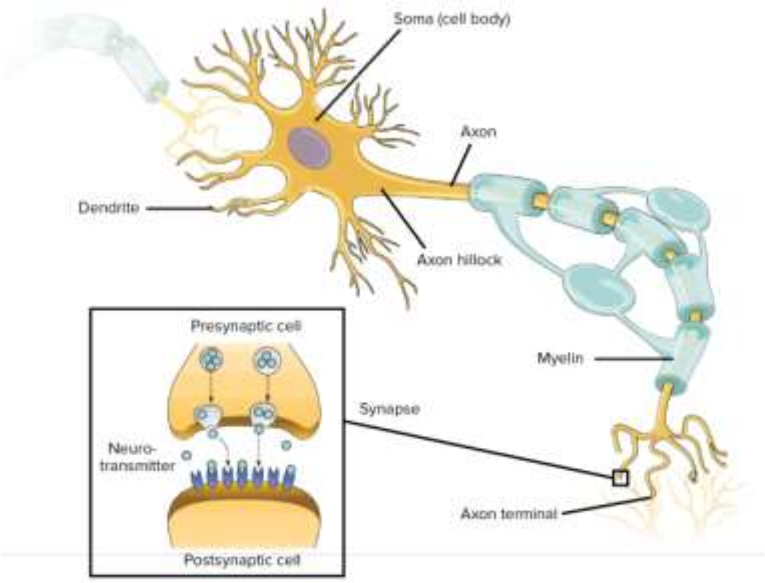

Image modified from "Neurons and glial cells: Figure 2" and "Synapse," by OpenStax College, Biology (CC BY 3.0).

Axons

Axons differ from dendrites in several ways. The dendrites tend to taper and are often covered with little bumps called spines. In contrast, the axon tends to stay the same diameter for most of its length and doesn't have spines.

The axon arises from the cell body at a specialized area called the axon hillock. In motor neurons and interneurons, it's at the axon hillock that the action potential is initiated.

Finally, many axons are covered with a special insulating substance called myelin, which helps them convey the nerve impulse rapidly. Myelin is never found on dendrites.

Towards its end, the axon splits up into many branches and develops bulbous swellings known as axon terminals (or nerve terminals). These axon terminals make connections on target cells.

Synapses

Neuron-to-neuron connections are made onto the dendrites and cell bodies of other neurons. These connections, known as synapses, are the sites at which information is carried from the first neuron, the presynaptic neuron, to the target neuron (the postsynaptic neuron). The synaptic connections between neurons and skeletal muscle cells are generally called neuromuscular junctions, and the connections between neurons and smooth muscle cells or glands are known as neuro-effector junctions. At most synapses and junctions, information is transmitted in the form of chemical messengers called neurotransmitters. When an action potential travels down an axon and reaches the axon terminal, it triggers the release of neurotransmitter from the presynaptic cell. Neurotransmitter molecules cross the synapse and bind to membrane receptors on the postsynaptic cell, conveying an excitatory or inhibitory signal.

Thus, the third basic neuronal function – communicating information to target cells – is carried out by the axon and the axon terminals. Just as a single neuron may receive inputs from many presynaptic neurons, it may also make synaptic connections on numerous postsynaptic neurons via different axon terminals.

Variations on the neuronal theme

Most neurons follow the same general structural plan, but the structure of individual neurons varies and is adapted to the specific function a given neuron (or class of neurons) needs to carry out. Different types of neurons show great diversity in size and shape, which makes sense given the tremendous complexity of the nervous system and the huge number of different tasks it performs.

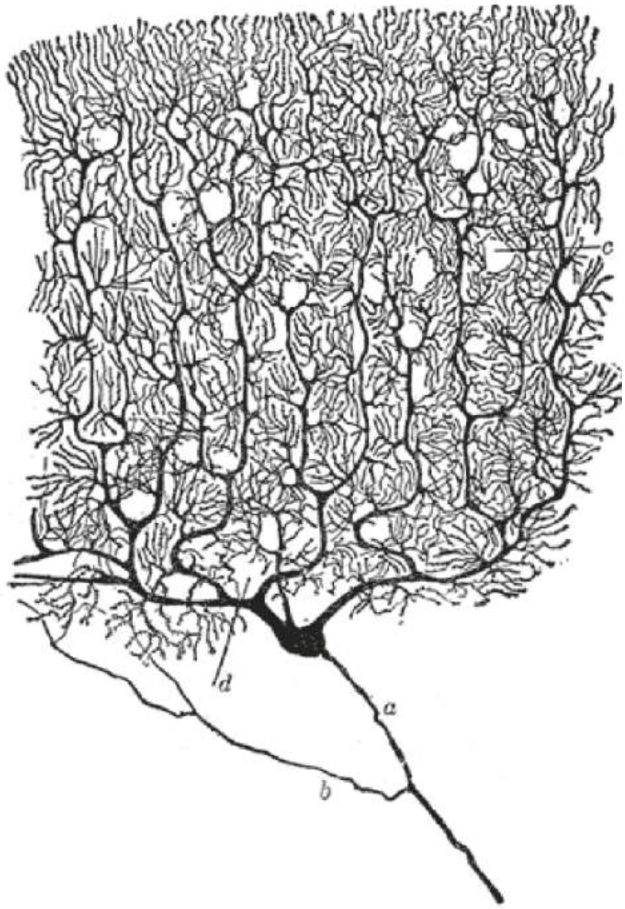

Image modified from "Purkinje cell," by Santiago Ramón y Cajal (public domain).

For instance, specialized neurons called Purkinje cells are found in a region of the brain known as the cerebellum. Purkinje cells have a highly complex dendritic tree that allows them to receive – and integrate – an enormous number of synaptic inputs, as shown above. Other types of neurons in the cerebellum can also be recognized by their distinctive shapes.

Similarly, neurons can vary greatly in length. While many neurons are tiny, the axons of the motor neurons that extend from the spinal cord to innervate your toes can be a meter long (or longer, in basketball players like Michael Jordan, LeBron James, or Yao Ming)! Another example of diversity in form comes from sensory neurons: in many sensory neurons, the morphological distinction between axon and dendrites is blurred. A single myelinated process leaves the cell body and splits in two, sending one branch to the spinal cord to communicate information and the second to sensory receptors in the periphery to receive information.

Neurons form networks

A single neuron can't do very much by itself, and nervous system function depends on groups of neurons that work together. Individual neurons connect to other neurons to stimulate or inhibit their activity, forming circuits that can process incoming information and carry out a response. Neuronal circuits can be very simple, and composed of only a few neurons, or they can involve more complex neuronal networks.

The knee-jerk reflex

The simplest neuronal circuits are those that underlie muscle stretch responses, such as the knee-jerk reflex that occurs when someone hits the tendon below your knee (the patellar tendon) with a hammer. Tapping on that tendon stretches the quadriceps muscle of the thigh, stimulating the sensory neurons that innervate it to fire.

Axons from these sensory neurons extend to the spinal cord, where they connect to the motor neurons that establish connections with (innervate) the quadriceps. The sensory neurons send an excitatory signal to the motor neurons, causing them to fire too. The motor neurons, in turn, stimulate the quadriceps to contract, straightening the knee. In the knee-jerk reflex, the sensory neurons from a particular muscle connect directly to the motor neurons that innervate that same muscle, causing it to contract after it has been stretched.

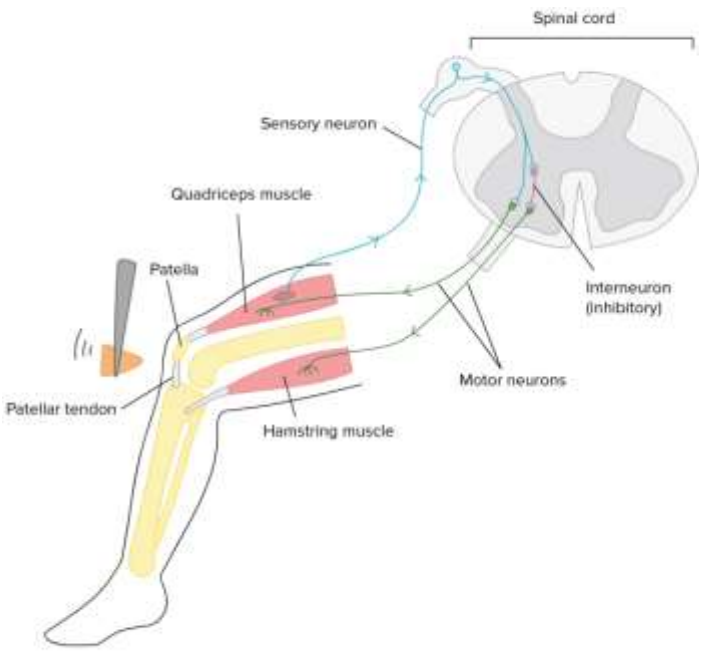

Image modified from "Patellar tendon reflex arc," by Amiya Sarkar (CC BY-SA 4.0). The modified image is licensed under a CC BY-SA 4.0 license.

Sensory neurons from the quadriceps are also part of a circuit that causes relaxation of the hamstring, the muscle that antagonizes (opposes) the quadriceps. It wouldn't make sense for the sensory neurons of the quadriceps to activate the motor neurons of the hamstring, because that would make the hamstring contract, making it harder for the quadriceps to contract. Instead, the sensory neurons of the quadriceps connect to the motor neurons of the hamstring indirectly, through an inhibitory interneuron. Activation of the interneuron causes inhibition of the motor neurons that innervate the hamstring, making the hamstring muscle relax.

The sensory neurons of the quadriceps don't just participate in this reflex circuit. Instead, they also send messages to the brain, letting you know that someone tapped your tendon with a hammer and perhaps causing a response. (“Why did you do that?”) Although spinal cord circuits can mediate very simple behaviours like the knee jerk reflex, the ability to consciously perceive sensory stimuli – along with all of the higher functions of the nervous system – depends on the more complex neuronal networks found in the brain.

Glial cells

At the beginning of this article, we said that the nervous system was made up of two types of cells, neurons and glia, with the neurons acting as the basic functional unit of the nervous system and the glia playing a supporting role. Just as the supporting actors are essential to the success of a movie, the glia are essential to nervous system function. Indeed, there are many more glial cells in the brain than there are neurons.

There are four main types of glial cells in the adult vertebrate nervous system. Three of these, astrocytes, oligodendrocytes, and microglia, are found only in the central nervous system (CNS). The fourth, the

Schwann cells, are found only in the peripheral nervous system (PNS).

Types of glia and their functions

Astrocytes are the most numerous type of glial cell. In fact, they are the most numerous cells in the brain! Astrocytes come in different types and have a variety of functions. They help regulate blood flow in the brain, maintain the composition of the fluid that surrounds neurons, and regulate communication between neurons at the synapse. During development, astrocytes help neurons find their way to their destinations and contribute to the formation of the blood-brain barrier, which helps isolate the brain from potentially toxic substances in the blood. Microglia are related to the macrophages of the immune system and act as scavengers to remove dead cells and other debris.

The oligodendrocytes of the CNS and the Schwann cells of the PNS share a similar function. Both of these types of glial cells produce myelin, the insulating substance that forms a sheath around the axons of many neurons. Myelin dramatically increases the speed with which an action potential travels down the axon, and it plays a crucial role in nervous system function.

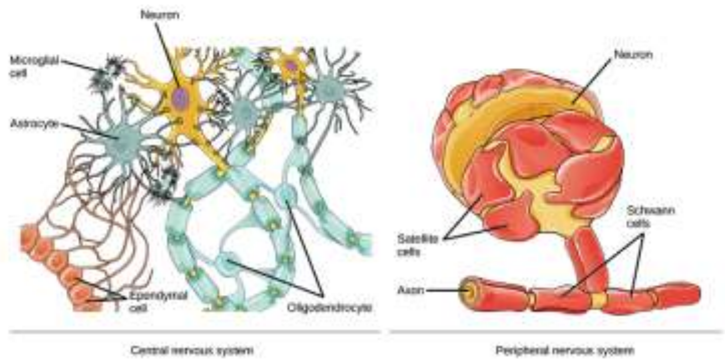

Image modified from "Neurons and glial cells," by OpenStax College, Biology (CC BY 4.0).

Other types of glia (in addition to the four main types) include satellite glial cells and ependymal cells. Satellite glial cells cover the cell bodies of neurons in PNS ganglia. Satellite glial cells are thought to support the function of the neurons and might act as a protective barrier, but their role is still not well understood. Ependymal cells, which line the ventricles of the brain and the central canal of the spinal cord, have hair like cilia that beat to promote circulation of the cerebrospinal fluid found inside the ventricles and spinal canal.