

Cognition and Neuroscience

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Acronyms

AP action potential

CNS central nervous system

EPSP excitatory postsynaptic potential

IPSP inhibitory postsynaptic potential

PNS peripheral nervous system

PSP postsynaptic potential

1 Introduction

1.1 Definitions

Neuroscience Study of the nervous system (structure aspects) on various levels of detail: Neuroscience

Molecular Proteins and molecular signaling of the nervous system.

Cellular Morphological and physiological properties of neurons.

Neural system Creation and functioning of networks of neurons.

Cognition Mental processes (function aspects) that react to inputs. It involves processes regarding the acquisition, storage, manipulation, and retrieval of information. Cognition

Perception Information from the environment.

Attention Focus on a specific stimulus in the environment.

Learning Merging new information with prior knowledge.

Memory Encoding, storing, and retrieving information.

Action Interact with the environment using perceived information.

Language Understanding and producing spoken or written thoughts.

Higher reasoning Decision-making and problem-solving.

Biomimicry Solving problems by taking inspiration from elements of nature.

Biomimicry

As proof of general intelligence¹, the human brain is taken as the model for artificial intelligence. Moreover, a successful brain-inspired AI application can provide a possibly plausible explanation of the functioning of the brain.

However, a brain differs from a computer in many aspects:

- Hardware and software are distinct while mind and brain are not.
- Machines learn by exploiting the capability of using a large memory while brains have limited capacity but high generalization ability.
- Brains produce both electrical and biochemical signals and have feedforward, feedback, and recurrent connections while machines typically only employ feed-forward connections.

Structure emulation Mimic or reverse engineer the structure of the brain (e.g. Blue Brain Project).

Function emulation Mimic a neural system on the algorithmic level (e.g. Deep Mind).

Cognitive neuroscience Study of the relationship between the physical brain and the intangible mind (thoughts, ideas). In other words, it studies the relationship between structure and function.

Cognitive
neuroscience

¹  Doubt

Example (Severed Corpus Callosum²). Normally, the right and left hemispheres of the brain can communicate. Moreover, the left visual field is sent to the right hemisphere and the right visual field is sent to the left hemisphere.

In patients where the hemispheres are split, a text shown on the right visual side is recognized as the speech capabilities are located in the left hemisphere, while a text shown on the left visual side does not trigger any speech reaction.

1.2 Neuroscience history

Two main schools of thought emerged and are still the subject of ongoing debates:

Localizationism Specific regions of the brain are responsible for particular faculties.

Localizationism

Assuming localizationism, 52 distinct regions with different neurons can be identified.

Aggregate field theory The brain works as a whole for mental functions.

Aggregate field theory

1.2.1 Neuron doctrine

The nervous system is made of a discrete amount of individual neurons (and not a continuous tissue).

Neuron doctrine

Principle of dynamic polarization Electrical signals in a neuron flow only in a single direction.

Principle of connectional specificity Neurons do not connect randomly but make specific connections at particular contact points.

Synapse Point of contact of two neurons. A synapse can be chemical or electrical.

Synapse

1.3 Cognitive science history

Rationalism All knowledge can be derived through reasoning, without sensory experiences.

Rationalism

Empiricism The brain starts as a blank slate and knowledge is added through sensory experiences.

Empiricism

Associationism Inspired by empiricism. Learning happens by correlating individual experiences (e.g. actions followed by a reward will be repeated).

Associationism

Behaviorism Inspired by empiricism. Everyone has the same neural basis that is improved through learning. Learning only involves observable behaviors.

Behaviorism

Remark. Associationism and behaviorism are not able to explain all types of learning (e.g. language).

Cognitivism The psychological and biological levels of an individual cannot be separated. Learning is based on the biology of the neurons.

Cognitivism

²<https://www.youtube.com/watch?v=lfGwsAdS9Dc>

2 Nervous system anatomy and physiology

Central nervous system Brain and spinal cord.

Peripheral nervous system Nerves that branch off from the brain and the spine.

2.1 Individual cells

2.1.1 Glia cells / Neuroglia

Cells that support neurons. There are 2 to 10 times more glia cells than neurons.

Glia cells/Neuroglia

Microglia Immune system cells located in the central nervous system. They intervene in response to toxic agents or to clear dead cells.

Microglia

- Responsible for antigen presentation (determine the type of external agent).
- Become phagocytes (cells that ingest harmful agents) during injuries, infections, or degenerative diseases.



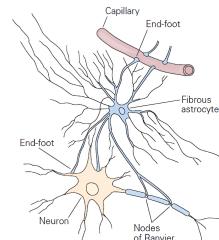
Remark. In patients affected by Alzheimer's disease, microglia may become hyperactive and damage neurons.

Astrocytes Star-shaped cells located in the central nervous system.

Astrocytes

They surround neurons and are in contact with the brain's vasculature.

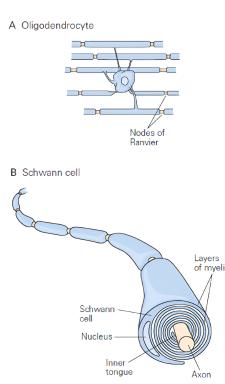
- Provide nourishment to neurons.
- Regulate the concentration of ions and neurotransmitters in the extracellular space.
- Communicate with the neurons to modulate synaptic signaling.
- Maintain the blood-brain barrier that separates the tissues of the central nervous system and the blood.



Oligodendrocytes and Schwann cells Oligodendrocytes are located in the central nervous system, while Schwann cells are located in the peripheral nervous system.

Oligodendrocytes
Schwann cells

- Produce thin sheets of myelin that wrap concentrically around the axon of the neurons. This insulating material allows the rapid conduction of electrical signals along the axon.



Remark. Myelin is white, giving the name to the white matter.

Remark. In multiple sclerosis, the immune system attacks the oligodendrocytes, slowing or disrupting messages traveling along the nerves.

2.1.2 Neurons / Nerve cells

A nervous system has around 100 billion neurons. There are 100 distinct types of neurons varying in form, location, and interconnectivity.

Generally, a neuron does the following:

1. Receives some information.
2. Makes a decision.
3. Passes it to other neurons.

Eukaryotic cell A neuron is an eukaryotic cell. Therefore, it has:

Neurons/Nerve cells

Eukaryotic cell

Cell membrane Membrane that separates the intracellular and extracellular space.

Cytoplasm Intracellular fluid mainly made of proteins and ions of potassium, sodium, chloride, and calcium.

Extracellular fluid Fluid in which the neuron sits. Similar composition of the cytoplasm.

Cell body/soma Metabolic center of the cell.

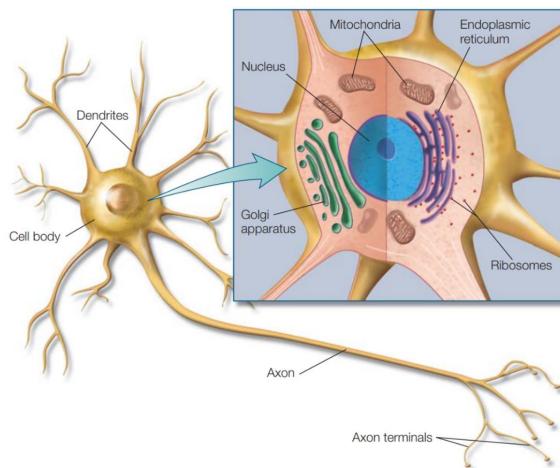


Figure 2.1: Neuron as an eukaryotic cell

Neuron-specific components

Dendrites Receives the outputs of other neurons. A neuron has multiple dendrites with different shapes depending on the type and location of the neuron.

Dendrites

Axon Transmitting zone of the neuron that carries electrical signals from the dendrites to the synapses (from 0.1mm to 2m). A neuron has a single axon.

Axon

Synapses Represents the output zone of the neuron from where electrical or chemical signals can be transmitted to other cells. A neuron has multiple synapses.

Synapses

Presynaptic cell Cell transmitting a signal.

Postsynaptic cell Cell receiving a signal.

Synaptic cleft Narrow space separating presynaptic and postsynaptic cells (i.e. the space separating two neurons).

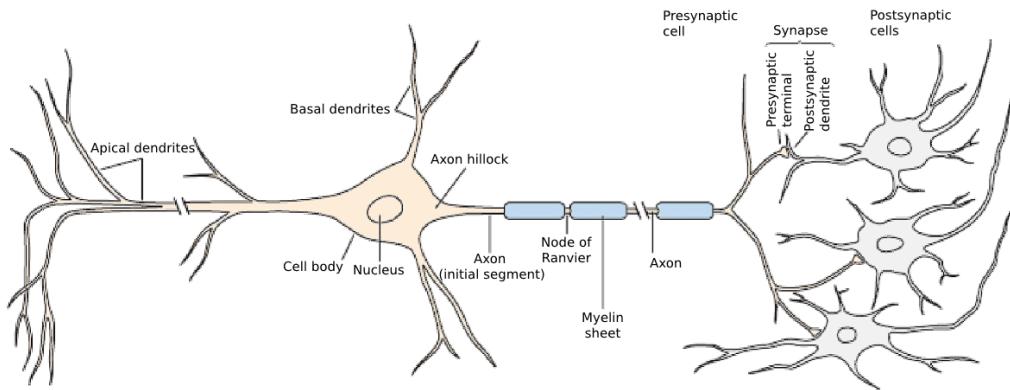
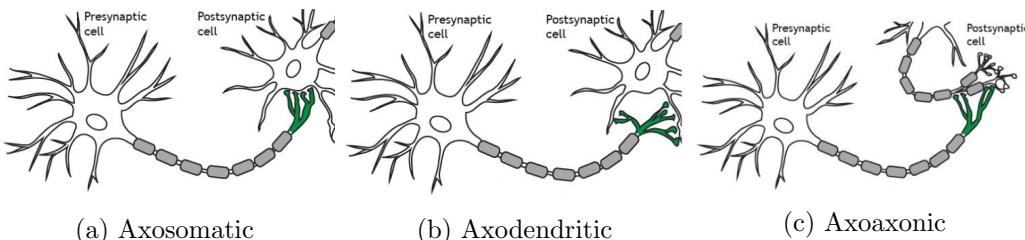


Figure 2.2: Neuron-specific components

There are three types of synapses:

- | | |
|---|--------------|
| Axosomatic Synapses that a neuron makes onto the cell body (soma) of another neuron. | Axosomatic |
| Axodendritic Synapses that a neuron makes onto the dendrites of another neuron. | Axodendritic |
| Axoaxonic Synapses that a neuron makes onto the synapses of another neuron. In this case, the transmitting neuron can be seen as a signal modulator of the receiving neuron. | Axoaxonic |



Neurons are divided into three functional categories:

- | | |
|---|---------------------------------------|
| Sensory neurons Carry information from the body's peripheral sensors into the nervous system. Provides both perception and motor coordination. | Sensory neurons |
| Motor neurons Carry commands from the brain or the spinal cord to muscles and glands. | Motor neurons |
| Interneurons Intermediate neurons between sensory and motor neurons. | Interneurons |
| Principle of connectional specificity Neurons do not connect randomly but rather make specific connections at particular contact points. | Principle of connectional specificity |

2.2 Information transfer within a neuron

2.2.1 Neuron functional regions

In a neuron, there are four regions that handle signals:

- | | |
|---|------------|
| Input zone Dendrites collect information from different sources in the form of postsynaptic potentials (PSPs). | Input zone |
|---|------------|

Integration/trigger zone PSPs are summed at the axon hillock and an action potential (AP) is generated if a threshold (-55mV) has been exceeded.

Conductive zone The AP is propagated through the axon.

Output zone Synapses transfer information to other cells.

Chemical synapses The frequency of APs determines the amount of neurotransmitters released.

Electrical synapses The AP is directly transmitted to the next neurons.

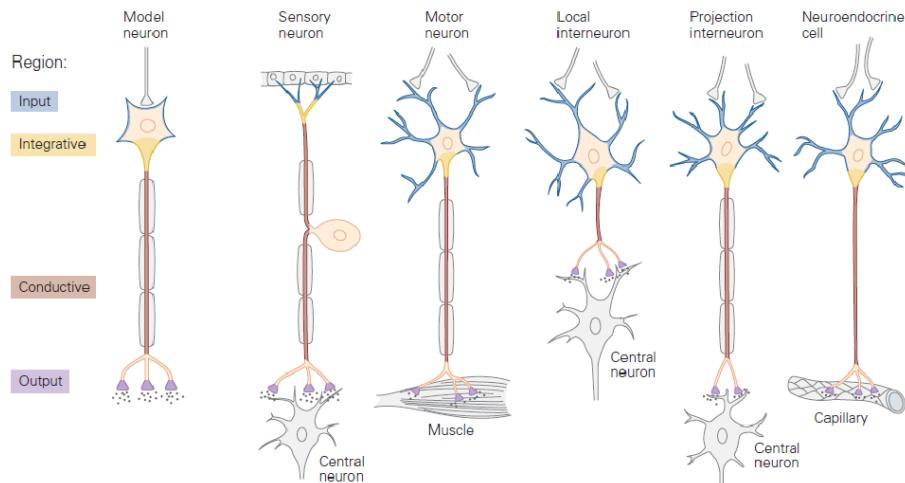


Figure 2.4: Transmitting regions of different types of neurons

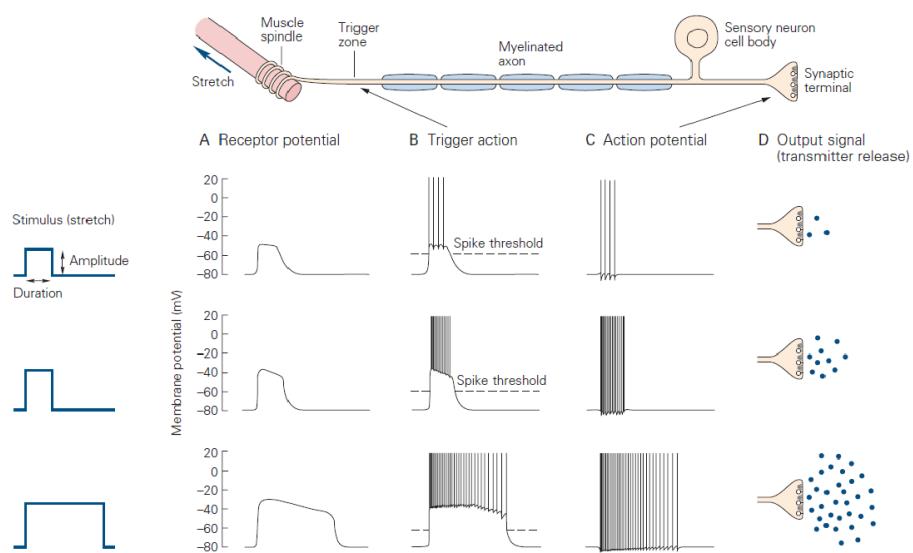


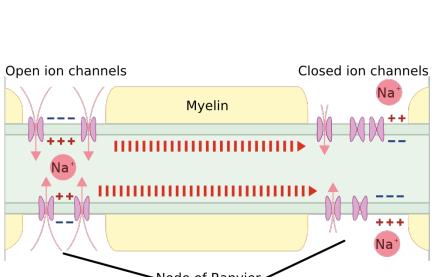
Figure 2.5: Signal from the input to the output zones

2.2.2 Neuron transmission signals

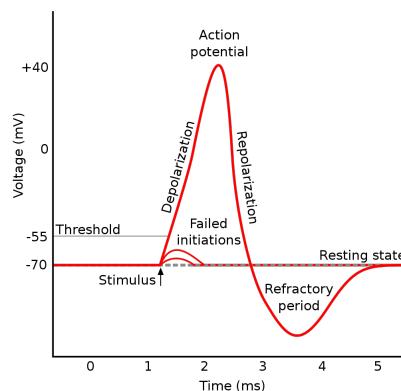
Resting membrane potential In a resting neuron, the voltage inside the cell is more negative (-70mV) than the outside. This allows the creation of an electrical signal when needed.

Resting membrane potential

Postsynaptic potential (PSP)	Small change in the membrane potential that alters the resting voltage of the cell.	Postsynaptic potential (PSP)
A PSP can be:		
Excitatory PSP (EPSP)	Has a depolarizing role: produces a decrease in the membrane potential (i.e. increases voltage inside the cell), therefore enhancing the ability to generate an AP.	Excitatory PSP
Inhibitory PSP (IPSP)	Has a hyperpolarizing role: produces an increase in the membrane potential (i.e. reduces voltage inside the cell), therefore reducing the ability to generate an AP.	Inhibitory PSP
A PSP has the following properties:		
<ul style="list-style-type: none"> The amplitude and duration of the signal are determined by the size of the stimulus that caused it. Overall, the amplitude is small. The signal is passively conducted through the cytoplasm, therefore it decays with distance and is able to travel 1mm at most. A single EPSP is not enough to fire a neuron. Multiple PSPs are summed at the axon hillock. There are two types of summation: <ul style="list-style-type: none"> Spatial summation Sum of the PSPs received at the same time. Temporal summation Sum of the PSPs received at different time points. 		
Remark.	The fact that a single EPSP is not enough to fire a neuron prevents a response to every single stimulus.	
Action potential (AP)	Signal generated when the sum of EPSPs exceeds a fixed threshold of -55mV (all-or-none).	Action potential (AP)
Saltatory conduction	Mechanism that allows a fast propagation on long distances of APs.	Saltatory conduction
	<ol style="list-style-type: none"> Depolarization causes the sodium ion (Na^+) channels located in the nodes of Ranvier of the axon to gradually open. Na^+ flows into the neuron and further depolarizes it until the Na^+ equilibrium potential is reached. With Na^+ equilibrium, Na^+ channels close and potassium ion (K^+) channels open. K^+ flows into the neuron and restores the membrane potential until the K^+ equilibrium potential is reached. With K^+ equilibrium, K^+ channels close and the membrane potential of the neuron is more negative than the resting potential (hyperpolarization). It will gradually return to its resting potential. 	
Remark.	During hyperpolarization, Na^+ channels cannot open (refractory period). This has two implications:	
	<ul style="list-style-type: none"> It limits the number of times a neuron can fire in a given time. Guarantees a unidirectional electrical current flow (Principle of dynamic polarization). 	Principle of dynamic polarization



(a) Ion channels along the axon



(b) Triggering of an action potential

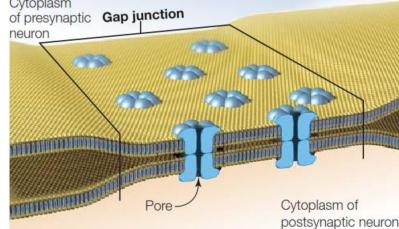
Remark. As the signal is constantly regenerated, APs have similar amplitude and duration in all neurons, regardless of the characteristics of the input PSPs. Therefore, the only way an AP has to carry information is by varying frequency and firing duration, making it a binary signal.

Example. Seizures are caused by misfiring neurons.

2.3 Information transfer between two neurons

2.3.1 Electrical synapse

Structure The neuronal membranes of the presynaptic and postsynaptic neurons are in contact at **gap junctions** and the cytoplasm of the two neurons is virtually continuous through connecting **pores**.



Electrical synapse

Functioning The two neurons are **isopotential** (i.e. they have the same membrane potential) and the ions of the presynaptic neurons are instantaneously transmitted to the postsynaptic neuron.

Properties

- Fast transmission.
- Allows for synchronous operations involving groups of neurons.
- The strength of the signal cannot be modulated.

2.3.2 Chemical synapse

Structure The synaptic cleft separates the presynaptic and postsynaptic neurons.

Chemical synapse

Neurotransmitter Chemical substance received by the receptors of the postsynaptic neuron.

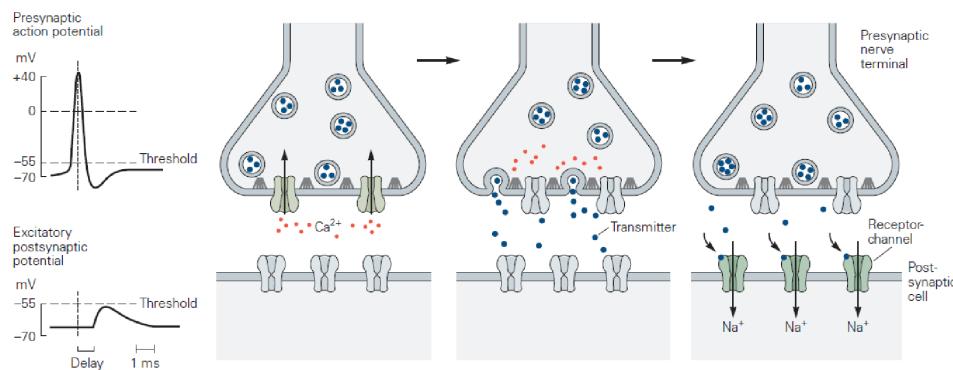
The effect of a neurotransmitter is decided by the receiving receptor and not by the cell transmitting it.

Presynaptic terminals Swellings at the end of the axon that contain synaptic vesicles.

Synaptic vesicles Vesicles containing neurotransmitter molecules.

Functioning The release of neurotransmitter molecules is based on the following steps:

1. An action potential arriving at the terminal of a presynaptic axon causes the calcium ion (Ca^{2+}) voltage-gates to open.
2. Ca^{2+} flow into the cell and cause the synaptic vesicles to bind to the cell membrane to release neurotransmitters into the synaptic cleft.
3. Neurotransmitters cross the synaptic cleft and bind to the receptors of the postsynaptic neuron. Depending on the neurotransmitter and the receiving receptor, there might be a generation of EPSP or IPSP.



When a receptor recognizes the neurotransmitter, it is released back into the synaptic cleft. To avoid a constant stimulation of the receptors, neurotransmitters are inactivated:

- The synaptic terminal can reuptake neurotransmitters through transporter proteins.
- Neurotransmitters might degenerate or be broken down by special enzymes.
- Neurotransmitters can be released far away from the site of the receptors.

Properties

- Slow transmission.
- The signal can be modulated.
- Has specific effects depending on the neurotransmitter and the receptors.

2.4 Neural circuit

Neural circuit Group of interconnected neurons that process a specific kind of information.

Neural circuit

Remark. The behavioral function of each neuron is determined by its connections.

Types of neurons

Sensory neuron Carry information from the peripheral sensors to the nervous system for both perception and motor coordination.

Sensory neuron

Motor neuron Carry information from the nervous system to muscles and glands.

Motor neuron

Interneuron Intermediate neurons between sensory and motor neurons.

Interneuron

Remark. In vertebrates, a stimulus causes multiple neural pathways to simultaneously encode different information. This allows for parallel processing to increase both the speed and reliability of the information transfer.

Neural pathways types

Divergent pathway One neuron activates many target cells. Typically happens at the input stages of the nervous system to ensure that a single neuron has a wide and diverse influence.

Divergent pathway

Convergent pathway Many neurons activate a single target cell. Typically happens at the output stages of the nervous system to ensure that a motor neuron is activated only when a sufficient number of neurons are firing.

Convergent pathway

Neuron firing types

Excitatory neuron Neurons that produce signals that increase the probability of firing of the postsynaptic neurons.

Excitatory neuron

Inhibitory neuron Neurons that produce signals that decrease the probability of firing of the postsynaptic neurons.

Inhibitory neuron

Feed-forward inhibition Excitatory neurons connected to inhibitory interneurons to block other downstream neurons. Allows to enhance the active pathway and to block other antagonist actions.

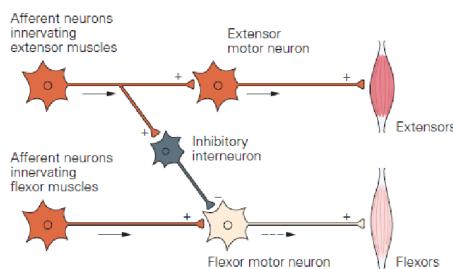


Figure 2.7: Example of feed-forward inhibition

Feed-back inhibition Excitatory neurons connected to inhibitory interneurons that return to the same neurons to inhibit them. Prevents the overload of neurons or muscles.

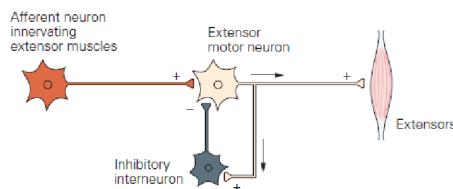
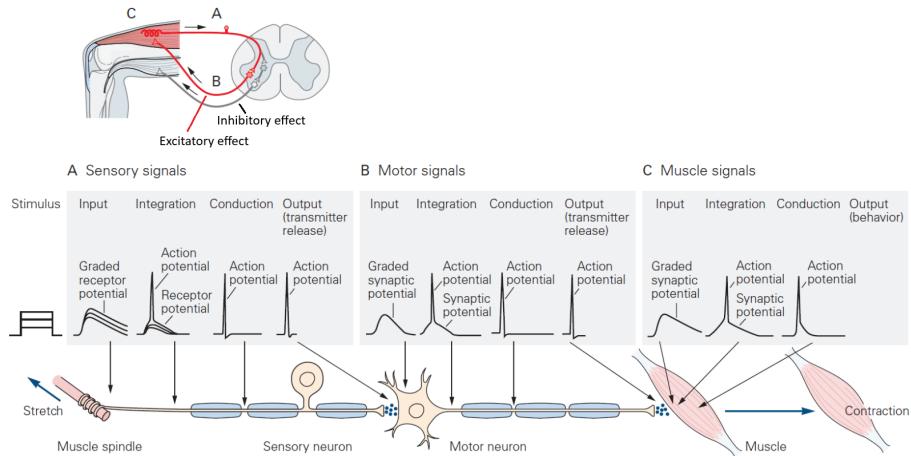


Figure 2.8: Example of feed-back inhibition

Example (Knee-jerk reflex). By tapping the patellar tendon (below the kneecap), the following happens:

1. The sensory information is conveyed from the muscle to the spinal cord (central nervous system).
2. The nervous system issues motor commands to the muscles which results in the knee jerk.
3. Inhibitory commands are issued to stop antagonist muscles.



2.5 Neural system

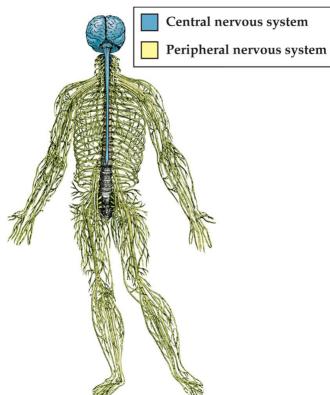


Figure 2.9: Composition of the nervous system

2.5.1 Peripheral nervous system (PNS)

The peripheral nervous system is composed of:

Nerves Groups of axons and glia.

Nerves

Ganglia Groups of neuron bodies outside the central nervous system

Ganglia

The PNS has the following functions:

- Delivers sensory information to the central nervous system.
- Carries commands from the central nervous system to the muscles.

- Supplies the central nervous system with information regarding both the external and internal environment.

The PNS has the following divisions:

Somatic nervous system

- Sensory neurons that receive information from the skin, muscles, and joints.
- Converts perceived spatial and physical information into electrical signals for the central nervous system to process.
- Controls the voluntary muscles.

Somatic nervous system

Autonomic nervous system

- Controls internal organs (viscera), the vascular system, and involuntary muscles and glands.
- Divided into three systems:

Autonomic nervous system

Sympathetic system Operates antagonistically against the parasympathetic system. Handles the body's response to stress (using norepinephrine).

Sympathetic system

Physically, the sympathetic system originates from the spinal cord. Its ganglia are closer to the spinal cord, therefore the axons from the central nervous system to the ganglia are shorter than the axons from the ganglia to the organs.

Example. Stimulates adrenal glands to prepare the body for action (fight or flight), increases heart rate, diverts the blood from the digestive tract to the somatic musculature, ...

Parasympathetic system Operates antagonistically against the sympathetic system. Acts to preserve the body's resources and restore homeostasis (using acetylcholine).

Parasympathetic system

Physically, the parasympathetic system originates from the base of the brain and from the sacral spinal cord. Its ganglia are outside the spinal cord, sometimes inside the affected organs, therefore the axons from the central nervous system to the ganglia are longer than the axons from the ganglia to the organs.

Example. Slows heart rate, stimulates digestion, ...

Enteric system Controls the involuntary muscles of the gut.

Enteric system

2.5.2 Central nervous system (CNS)

Meninges Three layers of membrane protecting the brain and the spinal cord.

Meninges

Dura mater The outermost and thickest layer.

Arachnoid mater The middle layer.

Pia mater The innermost and most delicate layer. It adheres to the brain's surface.

Cerebrospinal fluid Fluid that allows the brain to float and prevents it from simply sitting on the skull surface. It also reduces the shock to the brain and the spinal cord in case of rapid accelerations/decelerations.

Cerebrospinal fluid

The fluid is located in:

- The space between the arachnoid mater and the pia mater.
- The brain ventricles.
- Cisterns and sulci.
- The central canal of the spinal cord.

Blood-brain barrier Barrier between the brain's capillaries and the brain's tissue. It protects against pathogens and toxins. Blood-brain barrier

Remark. The effectiveness of the barrier also prevents drugs to treat mental and neurological disorders from passing through.

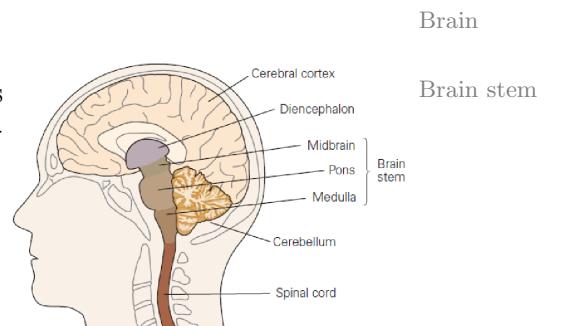
Spinal cord Acts as a relay for the information coming in and out of the brain. It is enclosed in the vertebral column. Spinal cord

Remark. Most pathways in the CNS are bilaterally symmetrical: the sensory and motor activities of one side of the body are handled by the cerebral hemisphere on the opposite side.

Brain

Brain stem Regulates basic life functions such as blood pressure, respiration, and sleep/wakefulness. It is divided into three sections:

- Medulla.
- Pons.
- Midbrain.



Cerebellum Contains lots of neurons and is responsible for:

- Maintaining posture.
- Coordinating head, eye, and arm movement.
- Regulating motor control (i.e. adjustments to the movement).
- Learning motor skills.

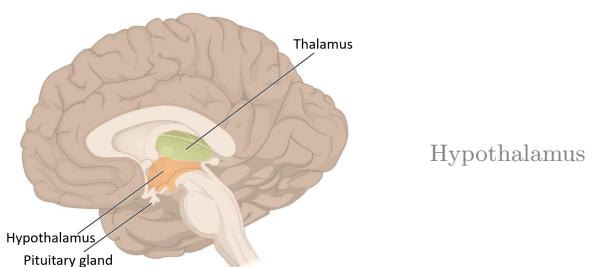
Cerebellum

Diencephalon

Thalamus Sorts incoming sensory information (except the sense of smell) of the peripheral nervous system and sends them to the sensory regions of the cerebral hemispheres.

Diencephalon
Thalamus

Hypothalamus Regulates the autonomic nervous system and homeostasis through the pituitary gland (which releases hormones). Handles the motivation system of the brain by favoring behaviors the organism finds rewarding.



Telencephalon/Cerebral hemispheres Consists of:

Cerebral cortex Made of gray matter (body of neurons).

Telencephalon/Cerebral hemispheres

White matter (axons and glial cells).

Basal ganglia Receive inputs from sensory and motor areas and mostly send them through the thalamus to the frontal lobe. Basal ganglia

They have a crucial role in motor control and reinforcement learning. This happens through two pathways:

Direct pathway When active, it causes the disinhibition of the thalamus and has the consequence of initializing movement.

Indirect pathway When active, it causes the inhibition of the thalamus and consequently inhibits movement.

To activate the direct pathway and inhibit the indirect pathway, the substantia nigra pars compacta (SNc) releases the neurotransmitter dopamine.

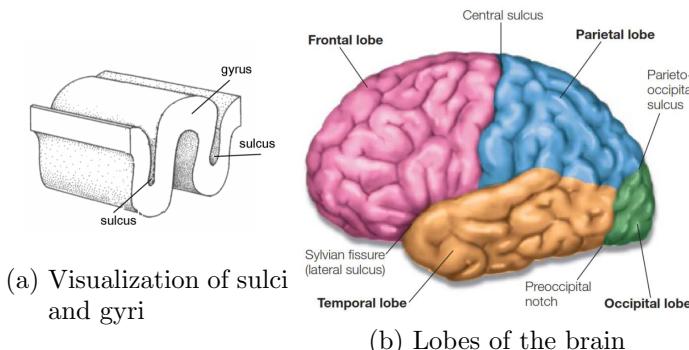
Example (Parkinson's disease). In patients affected by Parkinson's disease, the dopamine-related neurons in the SNc are lost causing an overactivation of the indirect pathway that inhibits movement.

Amygdala Responsible for recognizing a stimulus and reacting to it. Involved in attention, perception, value representation, decision-making, learning, memory, ... Amygdala

Hippocampus Responsible for long-term memory and spatial memory. Hippocampus

Cerebral cortex Surface of the brain which covers around 2.2m^2 to 2.4m^2 . To cover more surface, the cortex has infoldings (sulci and gyri) which also allow to connect neurons with shorter axons. Cerebral cortex

There are two symmetrical hemispheres connected through the corpus callosum and four different lobes.



Frontal lobe

Frontal lobe

Motor cortex

- Planning and execution of movement.
- Contains neurons that directly activate somatic movement neurons in the spinal cord.

Prefrontal cortex

- Long-term planning.
- Decision making.
- Motivation and value.

Parietal lobe	Receives and integrates information from the outside world, the body, and memory.	Parietal lobe
Somatosensory cortex	Receives information regarding touch, pain, temperature, and limb position.	
Remark.	Neurons responsible for a specific part of the body are clustered together.	
Occipital lobe		Occipital lobe
Visual cortex	Responsible for vision. Encodes features like luminance, spatial frequency, orientation, motion, ...	
Remark.	Neurons responsible for processing a specific feature are clustered together.	
Temporal lobe		Temporal lobe
Auditory cortex	Responsible for processing sound.	
Remark.	Neurons responsible for processing a specific sound frequency are clustered together.	
Association cortex	Portion of the cortex that has neither sensory nor motor responsibility. Receives and integrates inputs from many cortical areas.	Association cortex
Multisensory neuron	Cell activated by multiple sensory modalities.	