Foundations of the brain

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Agenda

Describe structure and function of:

- Neuronal cells (microscopic level)
- Nervous system (macroscopic level)

In other words:

- **How do neurons communicate?** Structure and function of neurons
- **What do neurons communicate?** The type of information sent and received
- **Why do neurons communicate?** The higher-level functions that emerge from this communication

Why study the brain, neurons, etc?

A fundamental principle in Biology: "structure determines function"

Psychology studies mental "functions"

Useful for psychologists to understand (at the least at a basic level) the biological substrate to the mental functions.

Structure of a neuron

Neuron's three main structures:

- Soma
- Dendrites (neurite)
- Axon (neurite)

the three main neuronal structures:

- soma
- dendrites
- axon

Image: Drawing of a neuron and its main structures

The **soma**, or cell body, is the central part of a neuron that contains the *nucleus*, which houses the cell's genetic material (DNA). The soma is responsible for maintaining the neuron's health, regulating its metabolic functions, and synthesizing proteins necessary for the neuron's structure and signaling processes.

Neurites are projections from the soma and include both dendrites and the axon.

Dendrites are branched extensions that receive signals from other neurons and transmit them toward the soma.

The **axon** is a long, singular projection that transmits signals away from the soma to other neurons, muscles, or glands.

Dendrites

Image: Stellate neuron

Dendrites are specialized structures that **receive information*** from other neurons (axons).

Image of a stellate neuron, so called because of the shape of the dendrites

Each neuron typically has **many dendrites**, which are organized in a branching pattern known as the **dendritic tree**.

The **structure and shape** of dendrites vary across different types of neurons, enabling diverse functional roles in neural communication.

Axon

Image: Neuron structure showing axon

The **axon** is a singular, elongated projection that **transmits information** away from the soma to other neurons (dendrites or soma).

While each neuron has **only one axon**, it may branch into **collaterals** to communicate with multiple targets.

Many axons are **wrapped in myelin**, a fatty substance that enables **faster conduction** of electrical impulses by insulating the axon membrane.

Soma

Image: Neuron cell body (soma)

The soma, also known as the cell body, is the central part of a neuron. It contains the nucleus, which houses the cell's genetic material, and is responsible for regulating the neuron's activities, including protein synthesis and energy production.

The soma **integrates** incoming signals from the dendrites and determines whether to generate an action potential that travels down the axon.

review questions

Which part of the neuron *mainly* receives information from other neurons?

a) Axon
b) Soma

c) Myelin
d) Dendrites

Correct response: d

Note the emphasis on mainly in the question: the soma can also receive information but it's not its main function

True or false: Each neuron has multiple axons.

Correct response: false

Electrochemical Communication: post-synaptic potential

Image: Anatomy of neuron

When stimulated, the **dendrites** change their chemicals, generating an electrical **post-synaptic potential**.

This potential is conducted **passively** towards the soma and then to the **axon hillock**.

The potentials generated by many dendrites are **summed** (some positive, some negative). If the resulting potential is **large enough**, it triggers an **action potential** in the axon.

Electrochemical Communication: Action Potential

Image: Neuron with axon in foreground

The **action potential** is a rapid change in electrical potential that propagates along the axon and reaches the **synapse**, the interface (or junction) with another neuron.

Synapse (Pronounced *s n.æps*)

Image: Chemical synapse

The synapse is the junction between the **axon terminal** of one neuron and the **dendrite** (or soma) of another neuron.

When an action potential reaches the axon terminal, it triggers the release of **neurotransmitters** into the **synaptic cleft**.

These chemicals bind to receptors on the post-synaptic neuron, causing changes in its electrical state.

It is the site where **neurotransmitters** are released to allow communication between neurons.

Synapses can be **excitatory** or **inhibitory**, depending on the type of neurotransmitter and receptor involved. This process is essential for all forms of **neural communication**, including learning, memory, and reflexes.

The **presynaptic neuron** (sender) releases **neurotransmitters** from its axon terminal into the synaptic cleft, whereas the **postsynaptic neuron** receives and processes the signal.

This interaction can either **excite** or **inhibit** the postsynaptic neuron, depending on the type of neurotransmitter and receptor involved.

The summation of multiple post-synaptic potentials will determine whether that neuron will, in turn, generate its own action potential.

Neurotransmitters

Image: Synapse schematic

Neurotransmitters are molecules that play a crucial role in synaptic communication. They are released by the **presynaptic neuron** into the synaptic cleft in response to an action potential.

Once released, neurotransmitters bind to specific receptors on the **postsynaptic neuron**, triggering changes in its electrical or chemical state.

Neurotransmitters: types of functions

Neurotransmitter types:

- Excitatory
- Inhibitory
- Modulatory

Neurotransmittes can either:

- excite
- inhibit
- modulate

the post-synaptic neuron

Excitatory neurotransmitters (e.g., glutamate) increase the likelihood of the postsynaptic neuron firing an action potential.

Inhibitory neurotransmitters (e.g., GABA) decrease the likelihood of the postsynaptic neuron firing.

Modulatory neurotransmitters adjust properties (e.g., excitability) of neural circuits.

The **interplay** between inhibition and excitation ensures precise and regulated communication among neurons, enabling complex processes such as learning, memory, and motor control.

Review questions

What is the gap between two neurons called?

Explain the difference between pre-synaptic and post-synaptic neurons in synaptic communication.

Types of Neurons

Neurons can be classified based on several characteristics, including:

- number of dendrites
- shape of dendrites
- axon length
- type of neurotransmitter they release

This classification highlights the *diversity* of neurons and their *specialized* roles in the nervous system.

Classification by Number of Dendrites

- **Unipolar**: Single projection (one neurite) from the soma that branches into dendrites and an axon. Examples: Sensory neurons
- **Bipolar**: One axon and one dendrite (two neurites) extending from the soma. Examples: Retinal neurons
- **Multipolar**: One axon and multiple dendrites, the most common type of neuron. Examples: Motor neurons, interneurons

Classification by Number of Dendrites

Image: [Neuron shape classification]

Illustration of **unipolar**, **bipolar**, or **multipolar** neurons, depending on the number of projections extending from the soma.

Classification by Shape

- **Pyramidal**: Triangular-shaped soma with a long apical dendrite and multiple basal dendrites. Found in the cerebral cortex

- **Stellate**: Star-shaped neurons with radiating dendrites. Found in the cerebellum

Classification by Shape

Image: Pyramidal and stellate cells

Illustration of **pyramidal** and **stellate** neurons, highlighting their distinct shapes and structural features.

Classification by Axon Length

- **Golgi Type I**: Long axons that extend far from the soma. Examples: Motor neurons
- **Golgi Type II**: Short axons that remain close to the soma. Examples: Interneurons

Golgi **Type I** neurons, also known as **projecting neurons**, have long axons that extend to distant targets, enabling communication across different regions of the nervous system.

Golgi **Type II** neurons, also known as **local circuit neurons**, have short axons that remain close to the soma, facilitating communication within a localized area.

Classification by Neurotransmitter

In addition to **excitatory** (i.e., they activate the postsynaptic neuron and increase the likelihood of an action potential) and **inhibitory** (i.e., they suppress the activity of the postsynaptic neuron and reducing the likelihood of an action potential), some neurotransmitters are **modulatory**: they influence the overall activity of neural circuits by altering the strength or dynamics of synaptic communication.

For example, a modulatory neurotransmitter can influence the excitability of a postsynaptic neuron.

- **Excitatory**: Release neurotransmitters that increase the likelihood of action potentials in the postsynaptic neuron. Examples: Glutamatergic neurons
- **Inhibitory**: Release neurotransmitters that decrease the likelihood of action potentials in the postsynaptic neuron. Examples: GABAergic neurons
- **Modulatory**: Release neurotransmitters that modulate the activity of other neurons. Examples: Dopaminergic, serotonergic neurons

Dual Nature of Neural Information Communication

Dendrites receives information.

The soma receives and integrates information.

The axon sends information.

But what information are we talking about?

Electrico-chemical potentials

Electrico-chemical potentials

Neural Communication types:

- Electrical communication (within neuron)
- Chemical communication (between neurons)

Within a neuron, information is transmitted *electrically* (post-synaptic potentials, action potential).

Between neurons (in the synapse), information is transmitted *chemically* via neurotransmitters.

Neurons communicate information using both **electrical** and **chemical** mechanisms.

Spiking Rate and Neural Coding

The action potential is a all-or-nothing event (either sent or not sent): same voltage and same duration for each neuron under stable conditions.

So how do neurons communication different information?

Through **spiking rate**: the *number* of action potentials sent *per second*. The frequency at which action potentials are sent (i.e., how often they are sent) can vary.

The **spiking rate** encodes meaning in neuronal communication.

For example, a neuron may exhibit a high spiking rate during specific activities, such as processing auditory information during speech, indicating its **specialization** in that domain.

Neurons that respond to similar types of information are often spatially **grouped together**, reflecting **regional functional specialization**.

Review questions

Explain the dual nature of neural communication (electrical vs. chemical)

If all action potentials are the same, how do neurons communicate different types or intensities of information?

Not just neurons

Image: Types of neuroglia

Glial cells, or **glia** (pronounced *li .ə*), are *non-neuronal* cells in the nervous system that provide support, protection, and nourishment to neurons. They play a critical role in maintaining the homeostasis of the neural environment and facilitating efficient neural communication.

This illustration shows **different types of glial cells** and their roles.

Types of glia

Brief overview of some glial cells

- **Astrocytes**: Maintain the blood-brain barrier, regulate nutrient supply, and support synaptic function.
- **Oligodendrocytes**: Produce myelin sheaths that insulate axons in the CNS, enabling faster signal transmission.
- **Schwann Cells**: Produce myelin sheaths in the peripheral nervous system (PNS)
- **Microglia**: Act as immune cells in the CNS, clearing damaged cells and protecting against pathogens

Neurons and glia

Until recently, it was believed that the **ratio of neurons to glial cells** in the human brain was approximately **1:10**, meaning there were ten times as many glial cells as neurons. However, recent research has revised this estimate, suggesting a ratio closer to **1:1**.

This ratio is not uniform across the nervous system; different regions exhibit varying proportions of neurons and glial cells. For example:

- The **cerebral cortex** has a higher density of neurons relative to glial cells.
- The **white matter** contains more glial cells due to the abundance of myelinated axons.

White and gray matter

Image: Gray and white matter of the cerebrum

The brain is composed of **gray matter** and **white matter**, each playing distinct roles in neural function.

- **Gray matter** consists primarily of **neuronal cell bodies**, **dendrites**, and **glial cells**. It is involved in processing and integrating information.
- **White matter** is made up of **myelinated axons**, which facilitate the rapid transmission of signals between different brain regions.

Interim summary

End of the brief "microscopic" view of the brain

Video to watch in your own time, summarizing some of the content covered so far.

Video: 2-Minute Neuroscience: The Neuron - https://youtube.com/watch?v=6qS83wD29PY

Nervous system

Nervous System structure:

- Central Nervous System: Brain (Cerebrum, Cerebellum, Brainstem) and Spinal Cord
- Peripheral Nervous System: Somatic (Sensory Afferent, Motor Efferent) and Autonomic (Sympathetic, Parasympathetic, Enteric)

The central nervous system includes the brain and the spinal cord.

The cerebrum

Cerebrum structure:

- Cerebral Cortex: Frontal, Parietal, Temporal, Occipital Lobes

- Subcortical Structures: Basal Ganglia, Thalamus, Hypothalamus

The cerebrum includes multiple structures

The cerebral cortex

The outermost layer of the brain, responsible for cognitive functions such as **perception**, **decision-making**, **language**, and **conscious thought**. It is divided into four lobes:

Image: Lobes of cerebral cortex

- **Frontal Lobe**: Involved in reasoning, planning, and voluntary movement.
- **Parietal Lobe**: Processes sensory information like touch and spatial awareness.
- **Temporal Lobe**: Handles auditory processing and memory.
- **Occipital Lobe**: Dedicated to visual processing.

Cerebral cortex and cognitive functions

The cerebral cortex enable complex **cognitive functions** such as:

- **Perception**: processing sensory input from various modalities (e.g., hearing, vision, touch, taste) to create a coherent representation of the environment.
- **Attention**: it allows to select relevant stimuli while filtering out distractions
- **Memory**: encoding, storing, and retrieving ot memories.
- **Language**: speech production and comprehension.
- **Decision-Making**: reasoning, problem-solving, and planning, which are essential for making informed decisions.
- **Conscious Thought**: self-awareness and the ability to reflect on one's thoughts and actions.

Frontal lobe

The **frontal lobe** is the largest of the brain's lobes and is responsible for a wide range of functions, including:

- **Executive Functions**: Planning, decision-making, problem-solving, and goal-setting.
- **Motor Control**: Houses the **primary motor cortex**, which controls voluntary movements.
- **Language Production**: Includes Broca's area, essential for speech production.
- **Attention and Focus**: Regulates concentration and the ability to shift focus between tasks.
- **Emotional Regulation**: Plays a role in managing emotions and social behavior.
- **Working Memory**: Supports short-term memory and the manipulation of information.
- **Personality**: Influences traits such as self-awareness, motivation, and social interactions.

Temporal lobe

The **temporal lobe** is located on the sides of the brain, near the ears, is responsible for functions including:

- **Auditory Processing**: Houses the **primary auditory cortex**, which processes sounds and enables hearing.
- **Language Comprehension**: Includes Wernicke's area, essential for understanding spoken and written language.
- **Memory Formation**: Plays a key role in forming and retrieving long-term memories, particularly through the **hippocampus**.
- **Emotional Processing**: Involved in interpreting emotions and social cues, with contributions from the **amygdala**.
- **Object Recognition**: Helps identify and categorize objects and faces through visual processing pathways.
- **Learning**: Supports the acquisition of new information and skills.

Parietal lobe

The **parietal lobe** is located near the top and back of the brain and is involved in various sensory and integrative functions:

- **Sensory Processing**: Interprets sensory information such as touch, temperature, pain, and pressure.
- **Spatial Awareness**: Helps in understanding spatial relationships and navigating the environment.
- **Proprioception**: Processes information about the position and movement of the body.
- **Integration of Sensory Input**: Combines information from different senses to create a coherent perception of the world.
- **Attention and Focus**: Plays a role in directing attention to relevant stimuli.
- **Mathematical and Logical Reasoning**: Supports numerical processing and problem-solving tasks.

Occipital lobe

The **occipital lobe** is located at the back of the brain and is primarily responsible for visual processing. Its functions include:

- **Visual Perception**: Processes visual information received from the eyes.
- **Color Recognition**: Interprets and distinguishes different colors.
- **Motion Detection**: Identifies and tracks movement within the visual field.
- **Spatial Processing**: Helps in understanding spatial relationships and depth perception.
- **Object Recognition**: Assists in identifying shapes, patterns, and objects.
- **Visual Memory**: Stores and retrieves visual information for future reference.

Review question

An athlete suffers a concussion affecting the frontal lobe. Based on the functions of this lobe, what cognitive or motor difficulties might they experience?

Layers of the cerebral cortex

The cerebral cortex is highly **folded**, increasing its surface area and enabling complex neural processing.

Image: Structure of the cerebellar cortex

The cerebral cortex is organized into **six distinct layers**, each with unique types of neurons and connections.

These layers vary in thickness and composition across different parts (structural specialization), reflecting the functional specialization of each region.

Brodmann areas

Image: Brodmann areas

The cerebral cortex is divided into distinct zones based on differences in cytoarchitecture. These zones, known as **Brodmann areas**, identified in the early 20th century by Korbinian Brodmann.

Generally, each area is associated with specific functions, such as sensory processing, motor control, or higher cognitive tasks.

For example:

- **Primary motor cortex (Brodmann area 4)**: Contains large pyramidal neurons critical for voluntary *movement*.
- **Broca's area (Brodmann areas 44 and 45)**: Located in the frontal lobe, it is critical for speech *production* and language processing.

Optional: Exploration of the brain

Interactive 3D brain explorer (online only):

https://www.brainfacts.org/3d-brain#intro=false&focus=Brain