Fundamentals of Neuroscience

Nimish Singh
Westwood High School

Abstract: It cannot be expected that any network of fields will be more interrelated than neuroscience, which evolved over centuries, drawing on historic milestones and improving technological innovations. This essay follows the comprehensive history of the neuroscience field from Ancient Civilizations through the Renaissance, 17th and 18th centuries into the 19th and 20th centuries—all about pivotal experiments and key figures. It describes the structure and function of the nervous system, explaining the role of the central and peripheral nervous systems and going into the details of the forebrain, midbrain, and hindbrain. The basic constituents of the brain are neurons, and how they communicate is explained in a way that shows how they allow sensory input, motor commands, and neural integration. The essay also allows one to realize neuroplasticity: how the plasticity of the brain, in layman's terms, underlies learning and memory and fosters recovery from injury. Knowing the history and core concepts of neuroscience allows us a greater understanding of the inner intricacies of the brain and the development of scientific thought that has brought us thus far to enable future innovations within this diverse discipline.

HISTORICAL OVERVIEW

Understanding the basic principles of neuroscience is but one small domain of the story. Appreciation for the historical context in which the principles have been developed is also important. The history of neuroscience illustrates the transition and development of ideas in science, in general, while understanding how the scientific built-up knowledge and technology of the past affect what we now know and how research is done. By learning about these pioneering experiments and innovative theories (and the geniuses behind them) we gain an appreciation for the complexities of the brain and the advancement of scientific inquiry. This historical perspective will deepen understanding, yes, but it will also inspire further innovation, grasping more of the journey that discovery is in neuroscience.

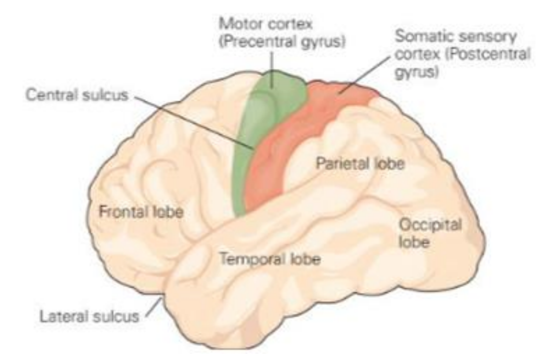
The investigation into the nervous system is not a new inquiry: it began with the observations and theories of ancient peoples. Medical writings from ancient Egypt, circa 1700 BCE, described symptoms of and treatments for injuries to the head and spinal column, which implied the early conviction that the brain and spinal cord were significant (Minagar). In a similar vein, early Greek physicians Hippocrates and Galen postulated on the function of the brain concerning sensation and movement to establish theoretical foundations for later neurological inquiry.

In the Renaissance, such anatomists as Andreas Vesalius rekindled the interest in general anatomy, describing, due to careful dissections, the brain and features of the nervous system with great detail with his published work *Tabulae Anatomicae* (Milestones). The Renaissance was marking the time of re-emergence of the systematical study of the nervous system, with evidence of physiological experiments that would be built up in the coming centuries.

Pivotal developments in neuroanatomy and physiology took place in the 17th and 18th centuries. Thomas Willis provided seminal work, *Cerebri anatome*, detailing the most complete and accurate diagram of the nervous system at the date, even describing the Circle of Willis and the eleventh cranial nerve of Willis (Bulletin). That work provided very important basic steps for future neuroscientific development.

In the 19th century, the "classical period" of experimental neuroscience began. Advances such as microscopes equipped scientists with tools, they could use to study the cellular-level organization of the nervous system. Santiago Ramón y Cajal discovered the structure and function of neurons and founded the neuron doctrine, which underlies our theories of neural communication (Milestones). To this day, his detailed histological studies and drawings are the cornerstone of modern neuroscience.

This was further advanced by technological development in the 20th century. These included the use of tools like EEG and PET scanning, which made it possible to record existing brain activity in real-time and map functional regions. Otto Loewi and Henry Dale went on to discover neurotransmitters that would elucidate the chemical basis of neural communication (Milestone), while Donald Hebb's theory of synaptic plasticity gave insight into the experience of learning-driven formation of neural connections (Langille).



Source: Principles of Neural

Today, neuroscience has morphed into an interdisciplinary field; genetics, molecular biology, and computational modeling are some of the fields of which it consists. Projects such as the Human Connectome Project aspire to map the networks within the human brain, thus allowing new insight into its organization and function.

Neuroimaging techniques that will enable non-invasive testing of brain structure and brain activity, from the level of individual neurons and ensembles to global networks, have been developed.

NERVOUS SYSTEM

As we venture into minute details of neuroscience, understanding the structure and functioning of the nervous system becomes the most basic requirement. A web of mechanisms that underlie every activity of human behavior and thought processes and feelings, this makes up the nervous system. It comprises the central nervous system (CNS), which includes the brain and spinal cord, and the peripheral nervous system (PNS), including nerves extending all over the body. Specific roles and functions are associated with each portion of the nervous system, from processing sensory information to the control of motor actions, as well as regulation of autonomic functions. We can now examine the various parts that make up the nervous system and how these complex structures interrelate to accomplish the myriad functions that bring meaning to life. Even though we won't be drilling into the spinal cord itself, these will lay a good foundation upon which to discuss the four major branches of neuroscience: cellular and molecular neuroscience, systems neuroscience, cognitive and behavioral neuroscience, and computational neuroscience.

The human brain, perhaps one of the most gifted pieces of biological engineering, essentially consists of three parts: forebrain, midbrain, and hindbrain. All parts participate crucially in our neurological functions, and comprehension of these components enables us to understand how our brains work.

FOREBRAIN

The forebrain is the largest and most complex portion of the brain, containing structures critical for complex behaviors, emotions, and cognition. Contained within the forebrain is the cerebrum, divided into two hemispheres connected by the corpus callosum. The cerebrum represents the higher brain functions responsible for thought, action, and emotion. Each hemisphere is further divided into four lobes: the frontal lobe, parietal lobe, temporal lobe, and occipital lobe.

- Frontal Lobe: The frontal lobe, located in the very anterior end of the brain, is responsible for various executive functions like decision-making, problem-solving, planning, and regulation of behavior and emotion. In the frontal lobe, the prefrontal cortex is important in personality and social behavior development (Anatomy).
- Parietal Lobe: The parietal lobe sits above the occipital lobe and at the back of the frontal lobe; it deals with sensory information received from the outside world. This mainly concerns spatial sense and navigation (proprioception) with some information on touch and temperature (Anatomy).
- Temporal Lobe: The temporal lobe is located under the lateral fissure in both cerebral hemispheres and has a primary function associated with processing auditory information; however, it also participates in encoding memory.

It contains the hippocampus and has close connections in establishing long-term memory (Anatomy).

- Occipital Lobe: Situated at the back of the brain, the occipital lobe serves as the primary center for visual processing. It interprets visual stimuli and information obtained from the eyes (Anatomy).

It also contains the thalamus, a relay station where information is passed from the spinal cord to the cerebral cortex. It functions in the processing and transmission of sensory information and is involved in the maintenance of consciousness, sleep, and alertness (Martin). Lying next to the thalamus is the hypothalamus—a small organ but of critical significance in maintaining homeostasis. It controls such vital body functions as temperature, hunger, thirst, and circadian rhythms and the endocrine system through the pituitary gland (Anatomy). Another important structure of the forebrain is the hippocampus, which plays a significant role in the formation of memories. It assists in the formation of long-term from short-term memories in spatial navigation and, therefore, is a very crucial part of learning and memory (Anatomy).

MIDBRAIN

The midbrain is the small portion of the brain lying below the cerebral cortex and above the hindbrain. It plays a key role in motor movement and auditory/visual processing. The midbrain houses structures such as the tectum and tegmentum, which participate in sensory processing and motor control (Anatomy).

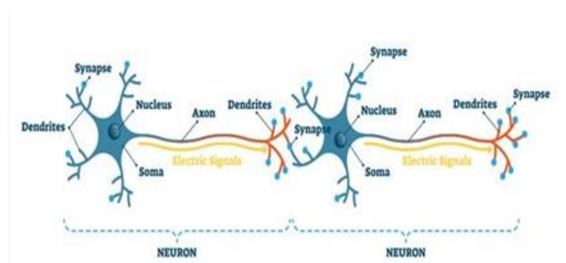
HINDBRAIN

The hindbrain is located at the lower part of the brain, consisting of the cerebellum, pons, and medulla oblongata. These structures are highly implicated in the coordination of movement and maintaining basic life functions.

- Cerebellum: Located at the back of the brain, it coordinates voluntary movements, balance, and posture. The cerebellum is responsible for smooth coordination in the activity of muscles while it also participates in motor learning (Anatomy).
- Pons: The pons is situated above the medulla and below the midbrain, interconnecting parts of the nervous system. It participates in motor control and sensory analysis and is involved in regulating sleep and respiratory functions (Anatomy).
- Medulla Oblongata: The medulla is the lowest portion of the brainstem and controls all the autonomic functions related to breathing, heart rate, and blood pressure. It assists in reflexes like swallowing, coughing, and vomiting (Anatomy).

NEURAL STRUCTURE

Neurons are the most basic functional units of the brain and nervous system. They receive sensory input, send motor commands for muscular activity, and transform and conduct electrical signals. The following is the structure of a neuron:



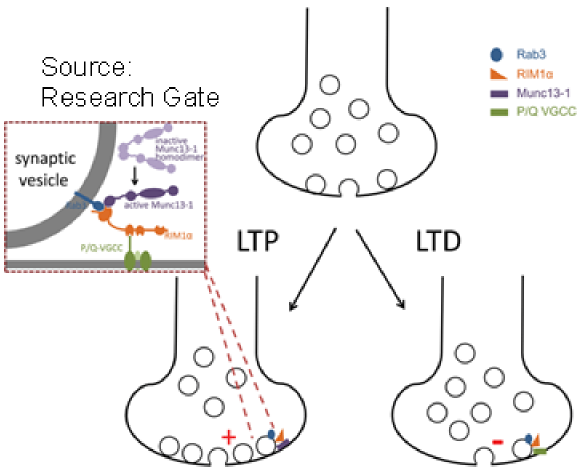
Source: Guy-Evans, Olivia. "Neurons (Nerve Cells): Structure, Function & Types."

- Cell Body (Soma): Equipped with a nucleus and cytoplasm and maintains the life activity of the neuron (Ludwig).
- Dendrites: Branch-like structure responsible for receiving messages from other neurons and conveying the information to the cell body (Ludwig).
- Axon: Long, thin extension that carries electrical impulses away from the cell body to other neurons, muscles, or glands (Ludwig).
- Myelin Sheath: A fatty layer that insulates the axon, increasing the speed of transmission of electrical impulses (Guy-Evans).
- Nodes of Ranvier: Gaps in the myelin sheath facilitate the rapid conduction of the nerve impulse (Guy-Evans).

- Axon Terminals: Endpoint of an axon where the release of neurotransmitters enables communication with other neurons (Ludwig).

NEUROTRANSMITTERS

The synapse is where an axon terminal of one neuron meets a dendrite of another, providing for communication between the neurons. Neurotransmitters are the means of sending the signal across the synaptic gap. The following are the most notable ones:



- Acetylcholine: Regulates muscle control and is essential for voluntary movement. It plays a key role in transmitting nerve impulses to muscles, enabling physical actions (Picciotto).
- Endorphins: Acts as a natural pain reliever by binding to opioid receptors in the brain, reducing the perception of pain and promoting a sense of well-being (Chaudhry).
- Dopamine: Involved in regulating motor functions and reward pathways (Sheffler).
- Norepinephrine/Noradrenaline: Prepares the body for action by increasing heart rate, blood pressure, and blood sugar levels, thus enhancing the body's response to stressful or dangerous situations (Sheffler).
- Serotonin: Influences emotional arousal, mood regulation, and sleep patterns. It is crucial for maintaining a stable mood and a healthy sleep cycle (Sheffler).
- GABA (Gamma-Aminobutyric Acid): Serves as the main inhibitory neurotransmitter in the brain, helping to reduce neuronal excitability and maintain a balance between excitation and inhibition in the central nervous system (Sheffler).

These highly complex processes of synaptic transmission and neural integration underlie neural communication, giving rise to the full gamut of complex behaviors and high-order cognitive functions that define human experience.

NEUROPLASTICITY AND LEARNING

One of the most exciting things about the brain is its ability to change and adapt; this is neuroplasticity. Neuroplasticity refers to the ability of the brain to reorganize itself by forming new neural connections all through life. This adaptability, therefore, underlies learning, memory, and recovery from brain injuries (Stanton).

Learning is accomplished by strengthened pre-existing synapses and the formation of new synapses, which in turn are supported by LTP and LTD. The LTP is a long-term increase in the strength of transmission between two neurons excited simultaneously, while LTD is a long-lasting decrease in synaptic strength (Stanton). These mechanisms are crucial for synaptic plasticity, the process whereby synapses change in strength as a function of their previous activity over time (Stanton).

CONCLUSION

The journey through the historical and structural facets of neuroscience reveals how deep the evolution of our understanding of the brain and nervous system has been. Each breakthrough—from ancient times through modern technological advancements - contributed to a growingly detailed, complex understanding of neural functions and behaviors. The central and peripheral nervous systems, in their inter-structured complexity and operations, reflect just how sophisticated we are as biological organisms. Research into neurons and their communication mechanisms reveals very complex processes underlying even simple sensory inputs, motor controls, and cognitive functions. Moreover, the concept of neuroplasticity underscores the brain's amazing capability for adaptation and change, one of the underlying requirements for learning and recovery. This historical depth does much to enhance our appreciation not only for the nature of past discoveries but also for laying a foundation for future innovations in continued exploration and understanding of the vast complexities of the brain. It is these insights of history, in their integration with modern research, that build an unsurpassed pathway leading toward continued breakthroughs in the unraveling of the mysteries of the human brain and furthering general knowledge of neuroscience.

REFERENCES

[1] Minagar, Alireza et al. "The Edwin Smith surgical papyrus: description and analysis of the earliest case of aphasia." *Journal of medical biography* vol. 11,2 (2003): 114-7. doi:10.1177/096777200301100214

[2] "Milestones in Neuroscience Research." *History of Neuroscience*, faculty.washington. edu/ chudler/hist.html. Accessed 19 July 2024.

[3] Bulletin of the Royal College of Surgeons of England. "Thomas Willis - Cerebri Anatome - 1664." *Royal College of Surgeons*, 21 May 2024, www.rcseng.ac.uk/library-and-publications/library/blog/thomas-willis-cerebri-anatome-1664/.

[4] Langille, Jesse J, and Richard E Brown. "The Synaptic Theory of Memory: A Historical Survey and Reconciliation of Recent Opposition." *Frontiers in systems neuroscience* vol. 12 52. 26 Oct. 2018, doi:10.3389/fnsys.2018.00052

[5] Martin, John H. "Organization of the Central Nervous System." *Neuroanatomy: Text and Atlas*, 5e Ed. McGraw Hill, 2021, https://accessmedicine.mhmedical.com/content.aspx?bookid=2945&sectionid=248249761.

[6] Ludwig, Parker E., et al. "Neuroanatomy, Neurons." *U.S. National Library of Medicine*, 24 July 2023, www.ncbi.nlm.nih.gov/books/NBK441977/#

[7] Guy-Evans, Olivia. "Neurons (Nerve Cells): Structure, Function & Types." *Simply Psychology*, 16 Jan. 2024, www.simplypsychology.org/neuron.html.

[8] Sheffler, Zachary M. "Physiology, Neurotransmitters." *U.S. National Library of Medicine*, 1 May 2023, www.ncbi.nlm.nih.gov/books/NBK539894/.

[9] Stanton, P K. "LTD, LTP, and the sliding threshold for long-term synaptic plasticity." *Hippocampus* vol. 6,1 (1996): 35-42. doi:10.1002/(SICI)1098-1063(1996)6:1<35::AID-HIPO7>3.0.CO;2-6

[10] Picciotto, Marina R et al. "Acetylcholine as a neuromodulator: cholinergic signaling shapes nervous system function and behavior." *Neuron* vol. 76,1 (2012): 116-29. doi:10.1016/j.neuron.2012.08.036

[11] Chaudhry, Shazia R. "Biochemistry, Endorphin." StatPearls [Internet]., *U.S. National Library of Medicine*, 3 Apr. 2023, ww.ncbi.nlm.nih.gov/books/NBK470306/.