

ELECTRICAL ACTIVITY OF THE BRAIN

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ELECTRICAL ACTIVITY OF THE BRAIN

The study of the **electrical activity of the brain** forms the foundation of modern neuroscience, providing crucial insights into cognitive processes, sensory perception, and neurological function. This activity, manifesting as fluctuating voltage potentials, is the direct consequence of ionic currents flowing across neuronal membranes, reflecting the immediate communication between billions of interconnected cells. The observable macroscopic patterns of this activity are commonly referred to as **brain waves** or brain rhythms, encompassing both spontaneous, internally generated oscillations and evoked changes resulting from external stimuli. Understanding these potentials allows researchers and clinicians to map the functional architecture of the central nervous system in real-time, distinguishing between states of consciousness, sleep stages, and pathological conditions.

While the underlying biochemical processes are microscopic, the resulting electrical field changes propagate through the brain tissue, cerebrospinal fluid, skull, and scalp, allowing for non-invasive detection. The very first measurements of these potentials in humans, pioneered by Hans Berger in the late 1920s, established electroencephalography (EEG) as a vital tool. Berger demonstrated that the brain is continuously active, displaying characteristic rhythms that change systematically depending on the individual's state, such as transitioning from alert wakefulness to relaxed repose. These **evoked and spontaneous changes in brain potentials** are the primary focus of electrophysiology, serving as a dynamic index of neural network engagement and disengagement across the cortex and deeper structures.

It is crucial to differentiate between the rapid, transient electrical signals responsible for transmitting information within a single neuron, known as **action potentials**, and the slower, summated electrical fields measurable externally. The signals detected by scalp electrodes are overwhelmingly generated by the synchronized postsynaptic potentials (PSPs) occurring in large populations of pyramidal neurons, specifically those oriented perpendicular to the cortical surface. When thousands of these neurons receive input simultaneously, the collective ionic flow creates a measurable dipole field. Therefore, the brain's electrical activity observable through non-invasive means represents the collective processing power of vast neuronal assemblies rather than the individual firing events of isolated cells, providing a window into large-scale network dynamics.

The Cellular and Synaptic Mechanisms

The generation of macroscopic electrical signals relies fundamentally on the principles of neurophysiology, particularly the movement of ions across the cell membrane following synaptic transmission. When a neuron releases neurotransmitters into the synaptic cleft, these chemicals bind to receptors on the postsynaptic neuron, leading to the opening or closing of ion channels. This action causes a rapid shift in the membrane potential, resulting in either an excitatory

postsynaptic potential (EPSP) or an inhibitory postsynaptic potential (IPSP). These local changes are sustained and relatively slow compared to the action potential, making them ideal candidates for summation across spatially distributed neurons. The resulting current flows create the electrical potential difference detectable on the scalp.

For these potentials to be measurable through volume conduction, two conditions must be met: first, the simultaneous activation, or **synchronization**, of a large number of neurons is necessary to amplify the signal above the background noise; and second, the neurons must be geometrically aligned, or possess a **closed-field organization**, typically found in the pyramidal cells of the cortex. Pyramidal cells are oriented in parallel columns, meaning their dendrites and cell bodies are positioned such that the resulting current dipoles add constructively rather than canceling each other out. This coherent alignment ensures that the collective dendritic currents generate an electrical field strong enough to penetrate the meninges, skull, and scalp, reaching the external electrodes where they are recorded as brain waves.

The efficiency of **volume conduction** dictates the fidelity with which surface electrodes can reflect underlying neural events. Current flows originating from deep subcortical structures, such as the thalamus or basal ganglia, are often attenuated and smeared by the time they reach the scalp, making direct localization challenging. Conversely, cortical activity, particularly that arising from the gyral crowns, is most robustly represented. Furthermore, the type of postsynaptic potential influences the observed polarity: EPSPs typically generate a current sink near the apical dendrites, resulting in a negative potential measured on the surface, while IPSPs result in current sources that may contribute to positive surface potentials. This complex interplay of excitatory and inhibitory signals shapes the frequency and amplitude characteristics that define the various brain rhythms.

Non-Invasive Measurement Techniques

The primary method for observing the electrical activity of the brain is **Electroencephalography (EEG)**. EEG is a non-invasive procedure that involves placing numerous small electrodes, typically according to the standardized 10-20 system, onto the scalp. These electrodes record the voltage fluctuations resulting from the summed postsynaptic potentials of cortical neurons over time. EEG boasts unparalleled temporal resolution, capable of capturing neural events on the order of milliseconds, making it indispensable for studying the precise timing of cognitive processes. However, its spatial resolution is inherently poor because the electrical signal is distorted and spread by the intervening tissues, a phenomenon known as the "inverse problem," where determining the exact source location is mathematically ambiguous.

A complementary technique is **Magnetoencephalography (MEG)**, which measures the magnetic fields associated with the same electrical currents detected by EEG. According to electromagnetic principles, any electrical current generates an orthogonal magnetic field. MEG utilizes highly

sensitive superconducting quantum interference devices (SQUIDs) housed within a magnetically shielded room to detect these extremely weak magnetic fields. Unlike electrical fields, magnetic fields are less distorted by the skull and scalp, offering significantly better spatial localization than EEG. Therefore, MEG excels at identifying the anatomical sources of cortical activity, making it highly valuable for pre-surgical mapping and understanding the spatial organization of neural networks during tasks.

While EEG measures potential differences and MEG measures magnetic flux, both provide essential, non-redundant information about the dynamics of the brain's electrical activity. Often, these two techniques are utilized in conjunction, a practice known as **EEG-MEG co-registration**, to leverage the high temporal precision of EEG and the superior spatial resolution of MEG. Additionally, advancements in computational modeling, such as source localization algorithms (e.g., LORETA or sLORETA), attempt to solve the inverse problem by mathematically estimating the intracranial sources of the scalp-recorded electrical potentials. These sophisticated tools transform raw EEG data into functional maps that approximate the location of the neural generators, thereby bridging the gap between temporal and spatial accuracy.

Spontaneous Activity: The Brain Wave Spectrum

Spontaneous electrical activity is characterized by continuous, rhythmic oscillations, or **brain waves**, which are categorized based on their frequency range, measured in Hertz (Hz). These rhythms reflect the synchronization of large populations of neurons oscillating at particular rates, and they correlate strongly with various states of consciousness and cognitive engagement. The major frequency bands provide a fundamental framework for interpreting EEG data, moving systematically from the slowest oscillations associated with deep sleep to the fastest associated with intense cognitive processing. Analyzing the power and coherence within these bands is a primary method for characterizing the functional state of the brain.

The slowest rhythms include **Delta waves** (0.5-4 Hz), which are predominantly observed during deep, non-rapid eye movement (NREM) sleep stages and are crucial for processes such as memory consolidation and physiological restoration. Slightly faster are **Theta waves** (4-8 Hz), typically associated with drowsiness, the transition to sleep, and specific forms of memory processing, particularly spatial navigation and working memory tasks, often originating from the hippocampus and adjacent structures. When an individual is awake but highly relaxed, such as meditating or resting with eyes closed, **Alpha waves** (8-13 Hz) dominate the posterior regions of the scalp. The classic Alpha rhythm is often described as an idling rhythm, reflecting a state of functional disengagement or inhibited processing in the visual cortex.

As cognitive demands increase and the brain shifts toward active processing, faster frequencies become more prominent. **Beta waves** (13-30 Hz) are characteristic of alertness, active

concentration, logical thinking, and the maintenance of motor control, such as planning a movement. A common phenomenon known as the Beta increase reflects enhanced vigilance or internal mental effort. The fastest established rhythms are **Gamma waves** (30-100+ Hz), which are hypothesized to play a critical role in 'binding' disparate sensory information into a coherent perception, selective attention, and high-level cognitive integration. The presence and power of Gamma oscillations are often seen as indicators of intense local processing and inter-regional communication, essential for complex tasks like object recognition or language comprehension.

Evoked Potentials and Event-Related Potentials (ERPs)

In contrast to spontaneous activity, **Evoked Potentials (EPs)** and **Event-Related Potentials (ERPs)** are small, transient voltage fluctuations that are temporally locked to a specific sensory, motor, or cognitive event. Because the electrical signal generated by a single stimulus presentation is usually minuscule and buried within the large background noise of the spontaneous EEG, researchers employ a signal averaging technique. By presenting the stimulus multiple times (often hundreds or thousands) and averaging the recorded EEG segments aligned to the onset of the stimulus, the random background activity cancels out, revealing the consistent, event-locked neural response.

ERPs are characterized by a sequence of positive and negative voltage deflections, or components, which are labeled according to their polarity (P for positive, N for negative) and either their typical latency in milliseconds (e.g., N100, P300) or their ordinal position (e.g., N1, P2). These components reflect distinct stages of neural information processing. Early components, occurring within the first 100 milliseconds, are primarily related to sensory processing, such as the auditory brainstem response or the visual N1 component, which reflects the initial registration of sensory input. These early waves are generally exogenous, meaning they are determined almost entirely by the physical characteristics of the stimulus.

Later ERP components, typically occurring after 100 milliseconds, are considered more **endogenous**, reflecting cognitive operations that are dependent on the task context, attention, and meaning assigned to the stimulus. For instance, the **P300** (or P3b), a large positive deflection peaking around 300-600 ms, is a classic marker of cognitive closure, context updating, and decision-making regarding task-relevant stimuli. Another crucial endogenous component is the **Mismatch Negativity (MMN)**, an automatic negative deflection elicited when an auditory stimulus violates an established pattern, serving as an index of pre-attentive change detection. The analysis of ERP component latency and amplitude allows psychologists to precisely track the time course of attention, memory retrieval, language processing, and conflict monitoring in the human brain.

Clinical Applications of Electrophysiology

The measurement of the brain's electrical activity is an invaluable diagnostic tool in clinical neurology and psychiatry, offering functional insights that anatomical imaging techniques cannot provide. The most classic and widespread clinical application of EEG is in the diagnosis and management of **epilepsy**. Epileptic seizures are fundamentally defined by abnormal, excessive, or hypersynchronous neuronal activity. EEG recordings can capture characteristic interictal (between seizures) patterns, such as sharp waves, spikes, and **spike-and-wave discharges**, which are pathognomonic markers of an underlying seizure disorder. Localizing the focus of these abnormal discharges is critical for determining the type of epilepsy and guiding treatment, including surgical planning.

Beyond epilepsy, EEG is the gold standard for monitoring and classifying **sleep disorders**. Polysomnography (PSG), which incorporates EEG alongside other physiological measurements, allows clinicians to accurately stage sleep into wakefulness, NREM sleep (Stages N1, N2, N3), and REM sleep based entirely on the characteristic frequency patterns. Deviations from normal sleep architecture, such as a lack of Delta waves or increased sleep spindle activity, can diagnose conditions like narcolepsy or insomnia. Furthermore, EEG is vital in critical care settings for monitoring cerebral function in patients with severe head trauma, stroke, or coma, where the presence of an **isoelectric line** (a flat EEG signal) is often used as a criterion for determining brain death, signifying the complete cessation of cortical electrical activity.

In psychiatry and cognitive neurology, electrophysiological techniques provide objective biomarkers for various conditions. Studies utilizing ERPs have revealed consistent abnormalities in components like the P300 and MMN in patients with **schizophrenia**, suggesting deficits in attention and information processing. Similarly, EEG microstate analysis, which examines the brief, quasi-stable patterns of electrical activity across the scalp, is being explored as a tool for understanding the underlying functional connectivity changes associated with conditions such as depression and Alzheimer's disease. These methods offer a non-invasive means to assess the integrity and dynamics of neural networks, aiding in differential diagnosis and monitoring treatment efficacy.

Neural Synchronization and Network Dynamics

A crucial realization in modern electrophysiology is that brain function is not simply about the presence of specific frequency bands, but rather the precise coordination and communication between different brain regions, a process known as **neural synchronization**. Synchronization occurs when two or more spatially distinct neuronal groups oscillate together with a consistent phase relationship, suggesting they are communicating or sharing information effectively. This coherence between regions is thought to be the mechanism by which sensory inputs are integrated and complex cognitive tasks are executed.

The study of synchronization often involves calculating metrics of **coherence** or phase-locking value (PLV) between electrodes situated over different cortical areas. For instance, increased synchronization in the Gamma band between visual and parietal cortices during object recognition tasks suggests that these regions are momentarily coupling their activity to bind visual features with spatial location. Disruptions in these synchronization patterns, particularly involving long-range connections, are increasingly implicated in neurological disorders. For example, reduced long-range Alpha coherence is sometimes observed in individuals with Autism Spectrum Disorder, potentially reflecting inefficient global information transfer.

Furthermore, the brain utilizes complex interactions between different frequency bands, termed **cross-frequency coupling (CFC)**. A common form is phase-amplitude coupling (PAC), where the phase of a slower oscillation (e.g., Theta rhythm) modulates the amplitude of a faster oscillation (e.g., Gamma rhythm). This mechanism is hypothesized to organize neuronal activity into discrete, time-locked packets, potentially serving as a fundamental mechanism for chunking information during memory encoding and retrieval. The intricate coordination of these oscillatory rhythms underscores the fact that the brain's electrical activity is a highly organized, hierarchical system designed to manage the vast flow of information necessary for moment-to-moment survival and cognition.