Electroencephalogram (EEG)

Authored by

mohammad looti

September 26, 2025

RECOMMENDED CITATION

mohammad looti (2025). *Electroencephalogram (EEG)*. PSYCHOLOGICAL SCALES. Retrieved from https://scales.arabpsychology.com/?p=29021

Electroencephalogram (EEG)

Primary Disciplinary Field(s): Neuroscience, Clinical Neurology, Psychology, Cognitive Science, Sleep Medicine

1. Core Definition

An **electroencephalogram** (EEG) is a neurophysiological measurement technique that records the electrical activity generated by the brain, primarily from the cerebral cortex, as observed from the scalp surface. This method involves placing multiple electrodes at specific locations across a person's scalp, which are typically prepped with a conductive gel or paste to ensure optimal electrical contact. These electrodes detect voltage fluctuations resulting from the ionic current flows within the neurons of the brain, specifically the summed excitatory and inhibitory postsynaptic potentials of large populations of cortical neurons.

The minute electrical signals picked up by the electrodes are then transmitted to a recording device, where they are significantly amplified--often by tens of thousands of times--to make them visible and interpretable. This amplified signal is typically displayed as a series of oscillating waveforms, which represent the synchronized activity of neuronal ensembles. The resulting EEG recording provides a direct measure of brain function, offering insights into various states of consciousness, cognitive processes, and neurological conditions, distinguished by different frequency bands and morphological patterns of brain waves.

The non-invasive nature and high temporal resolution of EEG make it a uniquely valuable tool for capturing the dynamic electrical events occurring in the brain in real-time. Unlike imaging techniques that measure metabolic activity (e.g., fMRI) or structural changes (e.g., MRI), EEG directly reflects neural firing patterns, providing an immediate window into brain activity with millisecond precision. This direct measurement of electrical activity underpins its utility in both clinical diagnostics and fundamental neuroscience research, allowing for the study of brain functions such as sleep, attention, memory, and various psychological and neurological disorders.

2. Etymology and Historical Development

The term **electroencephalogram** derives from Greek roots: "elektron" (amber, referring to electricity), "enkephalos" (brain), and "gramma" (a written record). The earliest foundational work on animal electricity was conducted in the late 18th century by Luigi Galvani, but the first definitive observation of electrical brain activity was made in 1875 by British physician Richard Caton, who reported rhythmic electrical potentials from the exposed cerebral cortex of rabbits and monkeys. However, his findings did not immediately lead to clinical application in humans.

The true pioneer in human EEG was the German psychiatrist **Hans Berger**, who, starting in 1924, successfully recorded the first human electroencephalogram from the scalp. Berger's meticulous experiments and observations, published in 1929, demonstrated the existence of rhythmic electrical activity in the human brain that could be detected non-invasively. Initially, his findings were met with considerable skepticism within the scientific community, primarily due to the subtlety of the signals and the technical challenges of recording them.

Despite the initial doubt, Berger persisted, identifying key waveforms such as the "alpha wave" (Berger's wave) and "beta waves," and observing changes in these patterns corresponding to different mental states, such as alertness, relaxation, and sleep. It was not until the mid-1930s, when scientists like Edgar Adrian and Bryan Matthews independently replicated Berger's work using more advanced equipment, that the scientific world fully acknowledged the significance of EEG. This validation cemented EEG's place as a legitimate scientific and clinical tool, paving the way for its rapid development and widespread adoption in neurology and psychiatry.

3. Key Characteristics

Non-Invasiveness: EEG is a completely non-invasive procedure, involving only the placement of electrodes on the scalp, making it safe and suitable for repeated measurements across all age groups, including infants and the elderly. This characteristic distinguishes it from invasive brain recording techniques such as electrocorticography (ECoG).

High Temporal Resolution: One of EEG's most significant advantages is its ability to measure brain activity with exceptional temporal precision, typically on the order of milliseconds. This allows researchers and clinicians to capture the rapid neural dynamics associated with cognitive processes, sensory perception, and motor commands, providing a real-time window into brain function.

Measurement of Postsynaptic Potentials: EEG primarily records the synchronized activity of large populations of pyramidal neurons in the cerebral cortex, specifically the extracellular current flows generated by their postsynaptic potentials. It does not directly measure action potentials, which are too brief and spatially localized to be detected effectively from the scalp.

Sensitivity to Cortical Activity: Due to the physical properties of volume conduction, EEG signals are predominantly generated by activity in the superficial layers of the cerebral cortex. Electrical activity from deeper brain structures is heavily attenuated and distorted by the skull, cerebrospinal fluid, and scalp, making it challenging to localize deep sources precisely.

Different Brain Wave Types: EEG waveforms are characterized by different frequency bands, each associated with distinct brain states and functions. These include **Delta** (0.5-4 Hz, deep sleep), **Theta** (4-8 Hz, light sleep, drowsiness, memory tasks), **Alpha** (8-13 Hz, relaxed wakefulness with eyes closed), **Beta** (13-30 Hz, active thinking, alertness, concentration), and

Gamma (30-100+ Hz, higher-order cognitive processing, attention, perception).

4. Significance and Impact

The impact of the electroencephalogram on medicine and neuroscience has been profound, establishing itself as an indispensable diagnostic and research tool. Clinically, EEG is the primary method for diagnosing and classifying **epilepsy**, a neurological disorder characterized by recurrent seizures. The unique electrical signatures of epileptic activity, such as interictal spikes and sharp waves, or generalized spike-and-wave discharges during seizures, are readily detectable by EEG, guiding treatment decisions and prognosis. Its role extends to the diagnosis of other conditions, including sleep disorders, encephalopathies, and brain death confirmation.

Beyond diagnostics, EEG has revolutionized our understanding of brain function in both healthy and diseased states. In cognitive neuroscience, **event-related potentials** (ERPs), which are specific EEG changes time-locked to sensory, motor, or cognitive events, have provided critical insights into processes like attention, memory, language, and decision-making. Researchers can dissect the temporal sequence of neural events underlying various cognitive functions, offering a unique perspective that complements spatial information from other neuroimaging techniques.

Furthermore, EEG has paved the way for emerging technologies and therapeutic applications. It is central to the development of **Brain-Computer Interfaces** (BCIs), which allow individuals to control external devices or communicate directly using their brain signals, offering new hope for those with severe motor impairments. Similarly, neurofeedback, a therapeutic technique that uses real-time EEG feedback to help individuals learn to self-regulate their brain activity, has shown promise in managing conditions like ADHD, anxiety, and chronic pain, highlighting the continuing evolution and versatility of EEG technology.

5. Debates and Criticisms

Despite its widespread utility, EEG is not without its limitations and areas of ongoing debate. A primary criticism centers on its relatively poor **spatial resolution**. While EEG excels at capturing the timing of brain activity, accurately localizing the precise source of that activity within the brain is challenging due to the phenomenon of **volume conduction**. Electrical signals generated by neural sources spread through the brain tissue, cerebrospinal fluid, skull, and scalp, becoming blurred and attenuated by the time they reach the electrodes. This "inverse problem" - determining the intracranial sources from scalp potentials - is mathematically ill-posed and requires complex computational modeling, which always involves certain assumptions and approximations.

Another significant challenge in EEG recording and interpretation is the susceptibility to various **artifacts**. These are electrical signals originating from non-cerebral sources that can contaminate the EEG trace and obscure genuine brain activity. Common physiological artifacts include electromyographic (EMG) activity from scalp or facial muscles, electrooculographic (EOG) activity from eye movements and blinks, and electrocardiographic (ECG) activity from the heart. Environmental artifacts, such as electrical interference from power lines (line noise) or nearby electronic devices, can also degrade signal quality. Effective artifact identification and removal are crucial for accurate EEG analysis, often requiring sophisticated signal processing techniques or careful experimental design.

Furthermore, EEG primarily measures activity from the superficial cortex, with signals from deeper brain structures being significantly attenuated. This inherent limitation means that activity in subcortical regions, which are critical for many neurological functions, is largely inaccessible with standard scalp EEG. While advanced techniques like high-density EEG and source localization algorithms attempt to mitigate these issues, they still face fundamental biophysical constraints. Debates also persist regarding the standardization of recording protocols, interpretation criteria, and the clinical utility of advanced quantitative EEG (qEEG) metrics in certain psychiatric conditions, where findings can sometimes be less robust or specific than in neurological disorders.

6. Methodology and Instrumentation

The standard procedure for conducting an EEG involves several critical steps to ensure accurate and reliable data collection. First, a predetermined number of electrodes, typically ranging from 19 to 256, are placed on the participant's scalp according to an international standard system, most commonly the **10-20 system** (or its denser variants like the 10-10 or 10-5 system). This system ensures consistent electrode placement across individuals, facilitating comparison of recordings. Each electrode site is usually prepared by gently abrading the skin to reduce impedance and applying a conductive gel or paste, which minimizes resistance between the electrode and the scalp, ensuring optimal signal transmission.

Once electrodes are securely in place and impedances are checked to be sufficiently low (typically below 5 kOhms), the electrodes are connected to an EEG amplifier. This device performs several crucial functions: it amplifies the extremely small biological signals (microvolts) to a measurable level, filters out unwanted noise (e.g., high-frequency muscle noise, low-frequency drift), and converts the analog electrical signals into digital data. The digital data is then sampled at a high rate (e.g., 250 Hz to 2000 Hz) to preserve the temporal detail of the brain waves. Modern EEG systems are often integrated with video recording capabilities, particularly in clinical settings, to correlate observed patient behavior with concurrent electrical brain activity.

The recording environment is also critical. Efforts are made to minimize electrical interference from external sources by conducting recordings in shielded rooms or using specialized amplifiers that effectively reject common mode noise. Throughout the recording, clinicians or researchers monitor the raw EEG data for artifacts and ensure the participant remains as still and relaxed as possible, as movement or muscle tension can significantly distort the brain signals. The careful execution of this methodology ensures the integrity of the collected EEG data, which is paramount for both accurate clinical diagnosis and robust scientific research.

7. EEG Waveforms and Clinical States

EEG waveforms are typically categorized into distinct frequency bands, each reflecting different physiological states and levels of brain activity. The slowest brain waves, **Delta waves** (0.5-4 Hz), are predominantly observed during deep, dreamless sleep (Stage N3 sleep) and are often indicative of a comatose state or severe brain pathology when present in awake adults. Slightly faster are **Theta waves** (4-8 Hz), which are associated with drowsiness, light sleep (Stage N1 and N2), and certain states of meditation or memory processing. Their sustained presence in an awake, alert adult, particularly over certain cortical regions, can sometimes suggest abnormal brain function.

The **Alpha rhythm** (8-13 Hz) is a characteristic rhythm of relaxed wakefulness, particularly when the eyes are closed. It is typically most prominent over the posterior regions of the brain and attenuates or "blocks" with eye opening or mental effort. This rhythm is often the first to be identified and studied by Hans Berger. Above alpha are **Beta waves** (13-30 Hz), which are associated with alert wakefulness, active concentration, mental engagement, and problem-solving. They are typically seen over frontal and central areas and can also be enhanced by certain medications, such as benzodiazepines.

The fastest brain waves are **Gamma waves** (30-100+ Hz), which are thought to be involved in higher-order cognitive processing, sensory binding, attention, and conscious perception. While often difficult to reliably detect and interpret due to their low amplitude and susceptibility to muscle artifact, gamma oscillations are increasingly recognized for their role in complex neural networks and cognitive integration. Pathological EEG patterns, conversely, can include abnormal slowing (excess delta or theta activity in awake states), sharp waves, spikes, spike-and-wave complexes (characteristic of epilepsy), or patterns indicative of brain damage like burst suppression or generalized periodic discharges, all providing crucial diagnostic information.

8. Clinical Applications

The **clinical utility of EEG** is extensive, making it a cornerstone diagnostic tool in neurology. Its most well-established application is in the diagnosis and management of **epilepsy**. EEG can capture both interictal (between seizures) and ictal (during seizures) epileptic activity. Interictal discharges, such as spikes, sharp waves, and spike-and-wave complexes, provide crucial information about the type of epilepsy, the seizure focus, and guide therapeutic decisions. During an actual seizure, EEG records the characteristic changes in brain activity, allowing for accurate classification of seizure type (e.g., focal vs. generalized) and differentiation from non-epileptic events.

EEG is also indispensable in **sleep medicine**, where it is a core component of **polysomnography** (PSG). By recording brain waves alongside other physiological parameters (e.g., EOG, EMG, ECG, respiratory effort), EEG allows for accurate sleep staging, identifying different sleep stages (N1, N2, N3, REM) crucial for diagnosing sleep disorders such as insomnia, narcolepsy, and sleep apnea. Abnormal patterns like periodic limb movements or central apneas are often correlated with specific EEG changes, providing a comprehensive assessment of sleep architecture and quality.

Furthermore, EEG plays a critical role in assessing altered states of consciousness, including coma, encephalopathy, and brain death. In comatose patients, EEG patterns can help determine the severity of brain dysfunction and monitor prognosis. Specific patterns like triphasic waves are indicative of certain metabolic encephalopathies, while burst suppression or complete electrocerebral inactivity (isoelectric EEG) can be crucial in confirming brain death. In the operating room, EEG is used for **intraoperative monitoring** to assess the depth of anesthesia and to detect signs of brain ischemia during cerebrovascular or cardiac surgery, thereby minimizing neurological complications.

9. Research and Emerging Applications

Beyond its clinical diagnostic roles, EEG remains a powerful tool in fundamental neuroscience research, particularly in the field of **cognitive neuroscience**. The high temporal resolution of EEG makes it ideal for studying the precise timing of neural events associated with cognitive processes through **Event-Related Potentials (ERPs)**. ERPs are averaged EEG responses time-locked to specific stimuli or events, revealing distinct components (e.g., P300, N400, Contingent Negative Variation) that reflect various stages of information processing, from sensory encoding to decision-making and motor preparation. This allows researchers to dissect the neural correlates of attention, memory, language comprehension, and executive functions.

EEG is also at the forefront of developing **Brain-Computer Interfaces (BCIs)**. BCIs utilize EEG signals to translate brain activity into commands that can control external devices, offering communication and control for individuals with severe motor disabilities. Users can learn to modulate specific EEG rhythms (e.g., mu rhythm) or use evoked potentials (e.g., P300 speller) to type, move a cursor, or operate prosthetic limbs. The portability and relatively low cost of EEG-based BCIs make them a promising avenue for assistive technologies and human-computer interaction.

Emerging applications include **Neurofeedback**, a form of biofeedback that uses real-time EEG displays to help individuals learn to voluntarily regulate their own brainwave patterns. This technique is being explored as a non-pharmacological intervention for various conditions, including

Attention-Deficit/Hyperactivity Disorder (ADHD), anxiety disorders, depression, and chronic pain, by training individuals to enhance or suppress specific brainwave frequencies. Additionally, advanced analytical techniques like **quantitative EEG (qEEG)** and connectivity analysis are being developed to extract more nuanced information from EEG data, allowing for the study of brain networks and functional connectivity in both healthy and pathological states, further expanding the research potential of this versatile neurophysiological tool.

Further Reading

Electroencephalography - Wikipedia
Electroencephalography (EEG) - National Institute of Neurological Disorders and Stroke (NINDS)
Electroencephalography - ScienceDirect Topics
Electroencephalography - Britannica