



# **EEG Processing:**

## **An Entry to the World of Brain Waves**

Introduction to EEG, Its Characteristics and Applications

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## **What you are going to learn in this session?**

Welcome to the world of EEG! In this session, you'll dive into the basics of EEG, exploring its fascinating characteristics and wide-ranging applications. We'll start by understanding where EEG signals come from and how they are recorded. You'll discover the advantages of EEG over other imaging techniques like fMRI and PET, especially in terms of real-time monitoring. We'll walk through the components of an EEG system and the standardized 10-20 system for electrode placement, ensuring you get a clear picture of how EEG works. Additionally, you'll learn about different types of brain waves and the significant features of EEG signals. We'll also discuss the various clinical and research applications of EEG and address some common challenges and limitations, such as noise and spatial resolution issues. By the end of this session, you'll have a solid grasp of EEG technology and its crucial role in both neuroscience research and clinical practice.

- *Mohammadreza Shahsavari*

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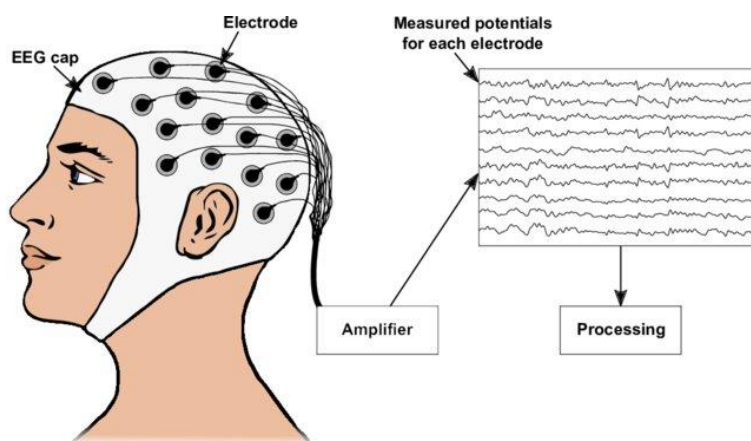
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## 1. What is EEG and Why it is Important? <sup>1, 2</sup>

Electroencephalography (EEG) is a non-invasive method used to record electrical activity of the brain. Electrodes placed on the scalp detect electrical signals produced by neuronal activity. This technique is critical in both clinical and research settings for several reasons:

- **Clinical Diagnosis:** EEG is essential for diagnosing neurological conditions such as epilepsy, sleep disorders, and brain tumors.
- **Monitoring Brain Activity:** It provides real-time monitoring of brain function, which is vital during surgeries and in intensive care units.
- **Research:** EEG helps researchers study brain functions, cognitive processes, and the effects of various interventions on brain activity.
- **Brain-Computer Interfaces (BCIs):** EEG is instrumental in developing BCIs, which allow for direct communication between the brain and external devices, aiding individuals with disabilities.

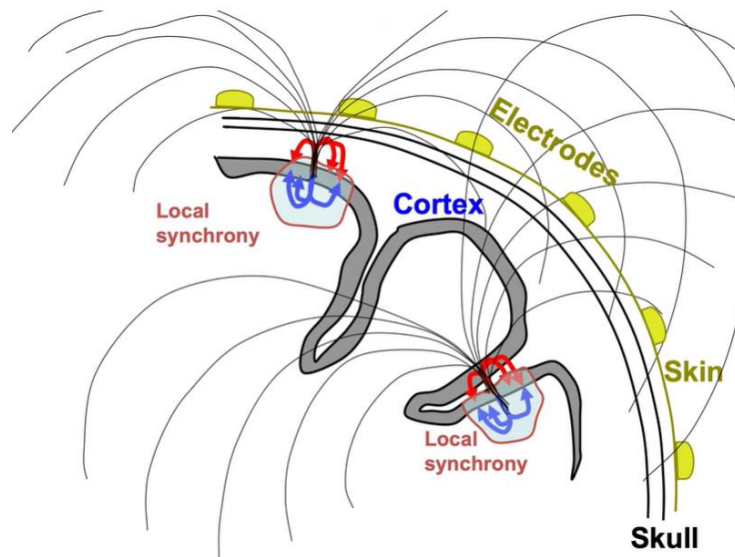
An EEG system does not record the activity of individual cells; instead, it captures the collective activity of many cells beneath each electrode, over time. Figure 2 illustrates how various local synchronies (local electrical sources) interact and combine to form the overall electrical field measured at the electrode positions.



*Fig 1.* EEG recording system, including the EEG cap, electrodes, amplifier, and the signals acquired from each electrode.

<sup>1</sup> [2-Minute Neuroscience: Electroencephalography \(EEG\)- YouTube](#)

<sup>2</sup> [EEGLAB introduction part 2: The origin of the EEG signal - YouTube](#)



*Fig 2.* Interaction of local synchronies (local electrical sources) shaping the overall electrical field at electrode positions.

## 2. EEG Recording and Electrode Placement<sup>3</sup>

### 2.1 Components of an EEG System

An EEG system comprises several key components:

- **Electrodes:** Sensors placed on the scalp to detect electrical activity.
- **Cables and Connectors:** Facilitate the transmission of signals from electrodes to the recording device.
- **Amplifier:** Boosts the weak electrical signals for analysis.
- **Computer/Recording Device:** Stores and processes the amplified signals.
- **Filters:** Remove unwanted noise and artifacts from the signals.
- **Display Device:** Visualizes the processed signals for real-time monitoring and interpretation.

<sup>3</sup> [10-20 International EEG Electrode Application Video - YouTube](#)

Signal flow starts with the electrodes placed on the scalp to detect electrical activity, which is transmitted through cables and connectors to the amplifier. The amplifier boosts the weak signals for better analysis. These amplified signals are then filtered to remove noise and artifacts. The cleaned signals are sent to the computer or recording device for digitization, storage, and further processing. Finally, the processed signals are visualized on a display device for real-time monitoring and interpretation, ensuring accurate and efficient capture of brain activity for diagnostic and research purposes.

## 2.2 Types of EEG Electrodes

### 1. Active (Main) Electrodes

Active electrodes are placed on specific locations on the scalp to detect the brain's electrical signals. They are positioned according to standardized systems like the International 10-20 system, which maps electrodes to specific anatomical landmarks. These electrodes pick up the voltage changes that result from neural activity in the brain.

#### Key Points:

- **Placement:** According to standardized mapping systems (e.g., International 10-20 system).
- **Function:** Detects electrical signals generated by neuronal activity.
- **Types:** Can be either passive (requiring an external amplifier to boost the signal) or active (containing a built-in preamplifier to boost the signal close to the scalp).

### 2. Reference Electrodes

Reference electrodes provide a stable voltage point against which the active electrodes' signals are compared. They are typically placed on parts of the body or scalp where minimal brain activity is expected to ensure that the signals from the active electrodes are accurately represented.

### Key Points:

- **Placement:** Common sites include the mastoid process (behind the ear) or on the earlobes.
- **Function:** Provides a reference point for comparing the electrical activity detected by the active electrodes.
- **Configuration:** There can be a single reference electrode or multiple reference electrodes, depending on the montage (configuration) used.

## 3. Ground Electrodes

The ground electrode serves to reduce electrical noise and artifacts in the EEG recording by providing a common ground for the electrical circuit. This helps to stabilize the overall signal and ensures more accurate readings by minimizing interference from external electrical sources.

### Key Points:

- **Placement:** Usually placed on a neutral site such as the forehead.
- **Function:** Reduces noise and electrical interference by grounding the system.
- **Importance:** Essential for obtaining clean and stable recordings.

## 2.3 EEG Recording Procedure

### 1. Preparation

The preparation stage is critical to ensure high-quality EEG recordings. The scalp is thoroughly cleaned with an alcohol solution to remove oils, sweat, and dead skin cells. This step enhances the conductivity between the scalp and the electrodes, minimizing impedance and improving signal quality. Sometimes, an abrasive gel is used to gently

exfoliate the skin, further ensuring good electrode contact. The subject's hair may also be parted and pinned if necessary to avoid interference with electrode placement.

## **2. Electrode Placement**

Electrodes are placed on the scalp using conductive paste or gel to secure them and ensure good electrical conductivity. The placement usually follows the standardized 10-20 system, where electrodes are positioned at specific intervals (10% or 20%) of the total front-back or left-right distance of the skull. This system ensures that the electrodes cover all major regions of the brain, allowing for comprehensive monitoring of brain activity. The correct placement is verified, often using measurements from anatomical landmarks like the nasion, inion, and preauricular points.

## **3. Calibration**

Calibration of the EEG system is essential to ensure accurate signal detection and amplification. This involves setting baseline values and checking each electrode's impedance to ensure it is within an acceptable range (typically below 10 k $\Omega$ ). Calibration helps in identifying any electrodes that may not be making proper contact or any potential issues with the equipment. Additionally, the amplifier settings are adjusted to optimize signal quality and reduce noise.

## **4. Recording**

During the recording phase, the subject is asked to relax in a comfortable position, minimizing movement and muscle tension to reduce artifacts in the EEG signals. Depending on the study or clinical evaluation, the subject may be asked to perform specific tasks, such as opening and closing their eyes, engaging in cognitive tasks, or responding to sensory stimuli. The duration of the recording can vary, ranging from a few minutes to several hours, depending on the objectives of the recording session.



## 5. Monitoring and Analysis

The recorded EEG signals are continuously monitored in real-time by a technician or researcher to ensure the quality and integrity of the data. Any noticeable artifacts, such as those caused by eye movements, muscle contractions, or external electrical interference, are noted and managed as much as possible during the recording. After the session, the recorded data is analyzed using specialized software, like EEGLAB, to identify specific patterns or abnormalities in brain activity. This analysis includes filtering the data to remove remaining artifacts (like eye movements, muscle activity, heartbeats, and electrode drift), segmenting the data into relevant epochs, and performing various signal processing techniques to extract meaningful information.<sup>4</sup>

The processed EEG data is then interpreted to understand brain function, diagnose neurological conditions, or investigate cognitive processes. The results can provide insights into the subject's brain activity patterns, help in diagnosing conditions such as epilepsy, sleep disorders, and other neurological issues, and contribute to research in cognitive neuroscience and other fields.<sup>5</sup>

### 2.4 Electrode Placement and 10-20 System

The 10-20 system is a standardized method used for placing electrodes on the scalp in electroencephalography (EEG) to ensure consistent and reproducible results. This system facilitates accurate comparison of EEG data across different studies and clinical settings.

- **Naming:** Electrodes in the 10-20 system are named according to their location on the scalp. The letter in each electrode name represents the corresponding brain region (e.g., F for frontal, P for parietal, T for temporal, and O for occipital), while

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<sup>4</sup> We will work with EEGLAB software during the 2nd and 3rd sessions and see these artifacts in real EEG data and learn methods for their removal.

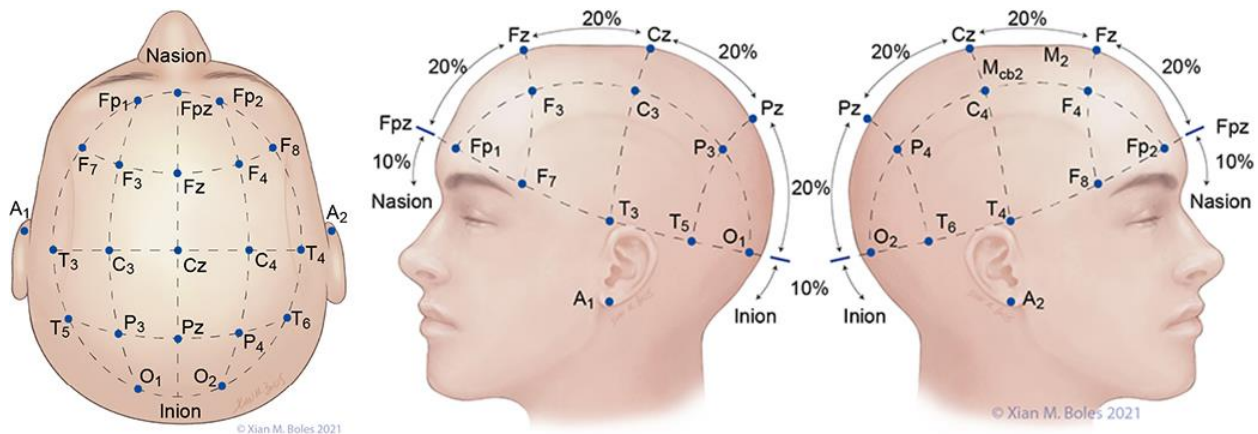
<sup>5</sup> The applications mentioned in this paragraph typically require advanced data processing techniques, such as machine learning and deep learning. These topics will be covered in future advanced courses.

the number indicates the position relative to the midline. Odd numbers (e.g., F3) are placed on the left hemisphere, even numbers (e.g., F4) on the right hemisphere, and 'z' (e.g., Pz) denotes a position on the midline (see Fig. 2).

- **Positions:** Electrodes are positioned at intervals of 10% or 20% of the total front-back or left-right distance of the skull. This means that the electrodes are spaced evenly and proportionally across the scalp. The '10-20' refers to these intervals: 10% or 20% of the distance from a reference point (nasion, inion, and preauricular points) to ensure that the electrode placement covers the entire scalp uniformly.
- **Usage:** The 10-20 system's standardization is crucial for the reproducibility and consistency of EEG recordings. It ensures that electrodes are placed in the same locations for every recording session, which is essential for comparing EEG data within a subject over time or across different subjects. This consistency is vital for both clinical diagnostics and research, as it allows for accurate localization of brain activity and reliable interpretation of the EEG data.

Figure 2 illustrates the naming and positions of the electrodes in the 10-20 EEG system.

This standardized placement method not only enhances the reliability of EEG results but also helps in identifying specific brain wave patterns associated with various cognitive functions and neurological conditions. By following the 10-20 system, clinicians and researchers can ensure that their EEG recordings are accurate, comparable, and interpretable across different contexts and studies.



**Fig 2.** Illustration of the 10-20 System of EEG Electrode Placement: This system is used to ensure standardized and reproducible positioning of electrodes on the scalp, enabling consistent recording of brain activity. The diagram shows the placement of electrodes from the front (nasion) to the back (inion) and the lateral aspects (left and right auricular points, A1 and A2), with distances measured as percentages of the total front-to-back or side-to-side distances.

## 3. Characteristics of EEG Signals

### 3.1 Comparison between EEG and other functional modalities

#### EEG vs. MEG:

It can be said that EEG is very similar to MEG data in many ways compared to other modalities like fMRI or PET.

- **Measurement:** Both EEG and MEG (Magnetoencephalography) capture brain activity with excellent temporal resolution. However, MEG measures the magnetic fields produced by neural activity, while EEG detects electrical potentials.
- **Spatial Resolution:** MEG often provides better spatial resolution than EEG because magnetic fields are less distorted by the scalp and skull compared to electrical signals. This allows for more precise localization of brain activity.

- **Applications:** MEG is particularly useful for source localization and mapping brain activity in response to sensory stimuli. EEG, on the other hand, is more accessible and widely used for a broad range of applications, including clinical diagnostics and cognitive research.

### EEG vs. fMRI:

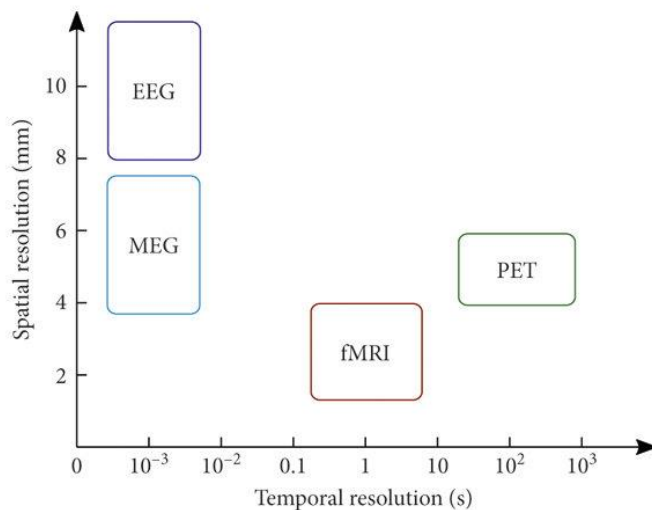
- **Temporal Resolution:** EEG excels in temporal resolution, capturing brain activity on a millisecond timescale. This high temporal resolution allows researchers to observe rapid changes in brain activity and understand the timing of neural processes.
- **Spatial Resolution:** In contrast, fMRI (Functional Magnetic Resonance Imaging) offers superior spatial resolution, providing detailed images of brain structures and pinpointing areas of brain activity with high accuracy. fMRI measures changes in blood oxygen levels (BOLD signals), which correlate with neural activity, but with a delay of a few seconds.
- **Applications:** EEG is preferred for studying the dynamics of brain activity, such as event-related potentials (ERPs) and neural oscillations, which require high temporal precision. fMRI is more suited for mapping brain functions and identifying active brain regions during specific tasks due to its high spatial resolution.

### EEG vs. PET:

- **Measurement:** PET (Positron Emission Tomography) measures metabolic activity in the brain by detecting gamma rays emitted from radioactive tracers injected into the bloodstream. This method reflects areas of high metabolic activity, which are associated with neural activity.
- **Spatial Resolution:** PET provides good spatial resolution, similar to fMRI, allowing for detailed images of brain metabolism and function.
- **Temporal Resolution:** PET has poor temporal resolution, typically in the range of minutes, making it unsuitable for capturing rapid changes in brain activity.

- **Invasiveness:** PET is more invasive than EEG because it involves the use of radioactive substances, which pose certain health risks and limit the frequency of use. EEG is non-invasive and can be used repeatedly without such risks.
- **Applications:** PET is often used in clinical settings to diagnose and monitor diseases like Alzheimer's and cancer, as well as to study brain metabolism and neurotransmitter systems. EEG is more suitable for continuous monitoring of brain activity and diagnosing conditions like epilepsy.

In summary, while EEG offers unparalleled temporal resolution, making it ideal for studying the timing of brain processes, other modalities like fMRI, MEG, and PET provide complementary strengths in spatial resolution and metabolic imaging. Each technique has its specific applications and advantages, making them valuable tools in the diverse field of brain research and clinical diagnostics.



*Fig 3.* Comparison of Spatial and Temporal Resolution of Different Functional Neuroimaging Techniques: EEG and MEG offer high temporal resolution but lower spatial resolution, whereas fMRI provides high spatial resolution but lower temporal resolution. PET has moderate spatial resolution and low temporal resolution.

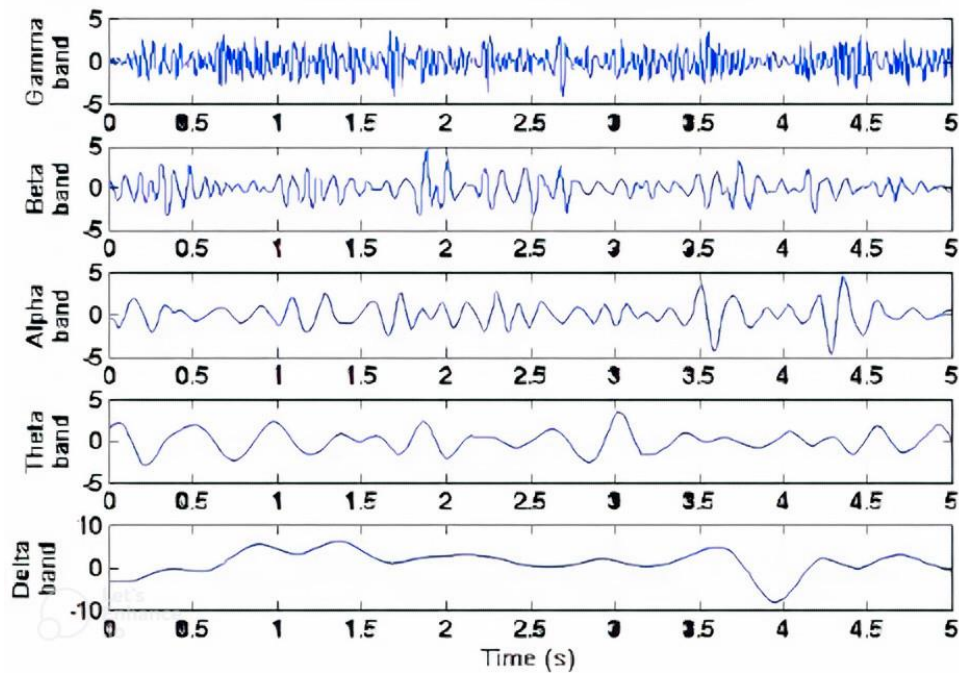
### 3.2 Important Features of EEG

- **Temporal Resolution:** EEG captures changes in brain activity on a millisecond scale, making it ideal for studying fast neural processes.
- **Cost and Portability:** EEG systems are generally less expensive and more portable than other neuroimaging techniques.
- **Direct Measurement of Neural Activity:** EEG directly measures electrical activity generated by neurons, providing a direct link to brain function.

## 4. Types of Brain Waves

*Table 1.* Overview of EEG Frequency Bands - Characteristics, Occurrence, and Significance

Name	Frequency Band	Characteristics	Occurrence and Significance
Delta	0.5 - 4 Hz	High amplitude, low frequency waves.	Predominant during deep sleep and in some abnormal brain conditions.
Theta	4 - 8 Hz	Medium amplitude and frequency.	Seen during light sleep, drowsiness, and in some cognitive tasks like memory encoding.
Alpha	8 - 13 Hz	Moderate amplitude and frequency.	Common in relaxed, awake states, especially with closed eyes.
Beta	13 - 30 Hz	Low amplitude, high frequency.	Associated with active thinking, focus, and alertness.
Gamma	30 - 100 Hz	Very high frequency, low amplitude.	Linked to high-level information processing, perception, and consciousness.



*Fig 4.* Time-domain representation of EEG signals across five frequency bands: Gamma (30-100 Hz), Beta (13-30 Hz), Alpha (8-13 Hz), Theta (4-8 Hz), and Delta (0.5-4 Hz). The x-axis shows time in seconds, and the y-axis shows amplitude in microvolts.

## 5. Applications of EEG

EEG applications can be broadly classified into clinical and research categories. Below, each section and its sub-sections are explained in detail.

### 5.1 Clinical Applications

#### 5.1.1 Diagnosis of Epilepsy

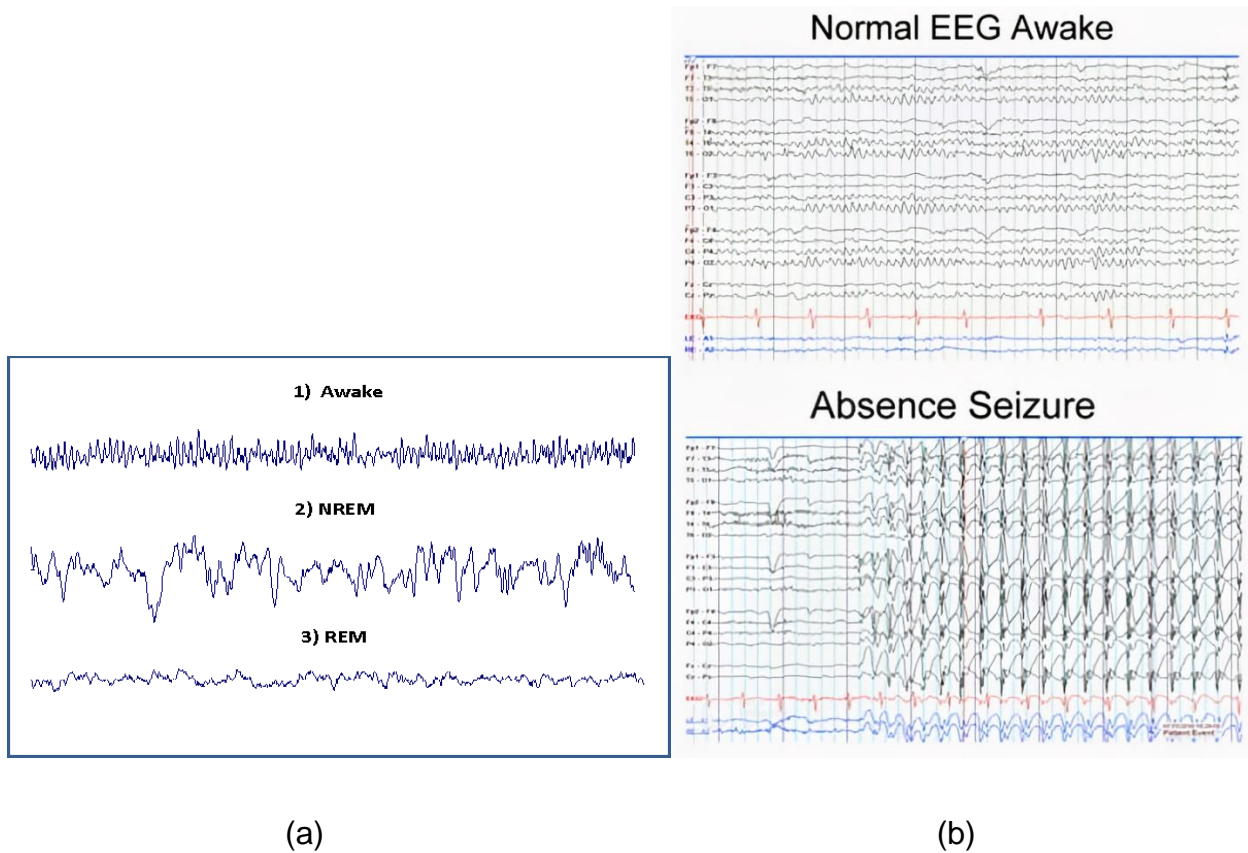
- EEG is crucial in diagnosing epilepsy because it can detect abnormal electrical discharges in the brain that are associated with seizures. By monitoring these electrical activities, healthcare professionals can identify patterns that are indicative of epilepsy.

- The specific abnormal electrical activities associated with epilepsy include:
  - **Spikes:** Sudden, sharp waves in the EEG signal.
  - **Sharp Waves:** Similar to spikes but typically broader.
  - **Spike-and-Wave Complexes:** Patterns of a spike followed by a slow wave, which are characteristic of certain types of epilepsy.

### 5.1.2 Sleep Monitoring

- EEG is extensively used in sleep research to analyze sleep patterns and diagnose sleep disorders. It provides valuable insights into the electrical activity of the brain during sleep.
- Sleep is divided into different stages, each characterized by unique EEG patterns:
  - **(Rapid Eye Movement) Sleep:** Associated with dreaming, showing low-amplitude, mixed-frequency waves similar to an awake state.
  - **NREM (Non-Rapid Eye Movement) Sleep:** Further divided into stages 1-3, with each stage showing progressively slower and higher amplitude brain waves.





**Fig 5.** Comparison of EEG Patterns in Different States and Conditions. (a) Comparison of EEG waveforms for normal awake state and absence seizure, highlighting distinct electrical activity patterns. (b) EEG patterns during different sleep stages (awake, NREM, and REM), showing characteristic waveforms for each state.

## 5.2 Research Applications

### 5.2.1 Cognitive Activity Studies

- EEG helps researchers explore how the brain processes various cognitive tasks such as attention, memory, and decision-making. It provides a real-time measure of brain activity.

- In cognitive research, specific tasks are designed to trigger certain cognitive responses. These responses can be measured using:
  - **Event-Related Potentials (ERPs):** These are brain responses that are directly the result of a specific sensory, cognitive, or motor event. ERPs are useful markers in understanding the timing and neural mechanisms underlying cognitive processes.

### 5.2.2 Brain-Computer Interfaces (BCIs)<sup>6</sup>

- Brain-Computer Interfaces are systems that enable direct communication between the brain and external devices. By using EEG signals, BCIs can translate brain activity into commands that control external devices.
- BCIs have various applications, including:
  - **Assistive Technologies:** Helping individuals with disabilities to control computers or prosthetic limbs.
  - **Neurorehabilitation:** Assisting in the recovery of brain functions after an injury by providing a means for patients to interact with their environment.
  - **Controlling External Devices:** Such as wheelchairs, drones, or other devices, providing greater autonomy to users.

## 6. Challenges and Limitations of EEG

EEG is a powerful tool for measuring brain activity, but it comes with several challenges and limitations. Understanding these issues is crucial for accurate data interpretation and effective application in research and clinical settings.

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<sup>6</sup> [Monkey MindPong - YouTube](#)

## 6.1 Noise and Artifacts

EEG signals are susceptible to various types of noise and artifacts that can obscure the true neural signals. Addressing these is essential for obtaining reliable data.

- **Types of Noise:**

- **Muscle Activity (EMG):** Electrical signals generated by muscle contractions can overlap with EEG signals, creating artifacts that can be misinterpreted as brain activity.
- **Eye Movements (EOG):** Movements of the eyes produce electrical activity that is picked up by EEG electrodes, especially those near the forehead and temples.
- **Environmental Interference:** External sources, such as power lines, electronic devices, and other electrical equipment, can introduce noise into EEG recordings, making it difficult to isolate the neural signals.

- **Artifact Reduction Techniques:**

- **Filtering:** Applying band-pass filters can help remove specific frequency ranges of noise, such as the 50-60 Hz range associated with power line interference.
- **Independent Component Analysis (ICA):** This statistical method separates mixed signals into independent components, allowing for the identification and removal of non-neural artifacts.
- **Careful Electrode Placement:** Strategically placing electrodes and ensuring proper contact with the scalp can minimize artifacts. Using conductive gel and adjusting electrode positions can improve signal quality.

## 6.2 Spatial and Temporal Limitations

EEG offers excellent temporal resolution, but its spatial resolution and ability to localize brain activity are limited compared to other neuroimaging techniques.

- **Spatial Resolution Challenges:**

- **Signal Diffusion:** Electrical signals from the brain diffuse as they pass through the skull and scalp, leading to a loss of spatial specificity. This makes it difficult to pinpoint the exact location of neural activity.
- **Compared to fMRI and MEG:** Functional Magnetic Resonance Imaging (fMRI) and Magnetoencephalography (MEG) provide higher spatial resolution. fMRI detects blood flow changes related to neural activity, and MEG measures magnetic fields generated by neural activity, both offering more precise localization.

- **Temporal Resolution Advantages and Limits:**

- **High Temporal Resolution:** EEG excels in capturing rapid changes in brain activity, with a temporal resolution on the order of milliseconds, which is crucial for studying dynamic neural processes.
- **Localization Limitations:** Despite its temporal advantages, EEG cannot accurately localize the source of neural activity. This limitation can be mitigated to some extent by combining EEG with other imaging techniques like fMRI or MEG.

## 6.3 Interferences and Environmental Factors

EEG recordings are vulnerable to interference from various environmental factors, which can degrade signal quality.

- **Electromagnetic Interference:**

- **External Electrical Sources:** Electrical devices, power lines, and other sources of electromagnetic fields can introduce noise into EEG recordings, complicating the interpretation of the data.

- **Solutions to Minimize Interference:**

- **Shielded Rooms:** Conducting EEG experiments in rooms designed to block external electromagnetic signals can significantly reduce interference.

- **High-Quality Cables:** Using cables with good shielding and low resistance can help maintain signal integrity.
- **Proper Grounding Techniques:** Ensuring that all equipment is properly grounded can minimize the introduction of unwanted electrical noise into the recordings.

By addressing these challenges and limitations through careful experimental design and advanced signal processing techniques, researchers and clinicians can maximize the utility of EEG for investigating brain function and diagnosing neurological conditions.