Cortical system and electroencephalography

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Objectives

Being able to elaborate:

- biological source of the EEG signal
- metrics that can be obtained from the EEG signal

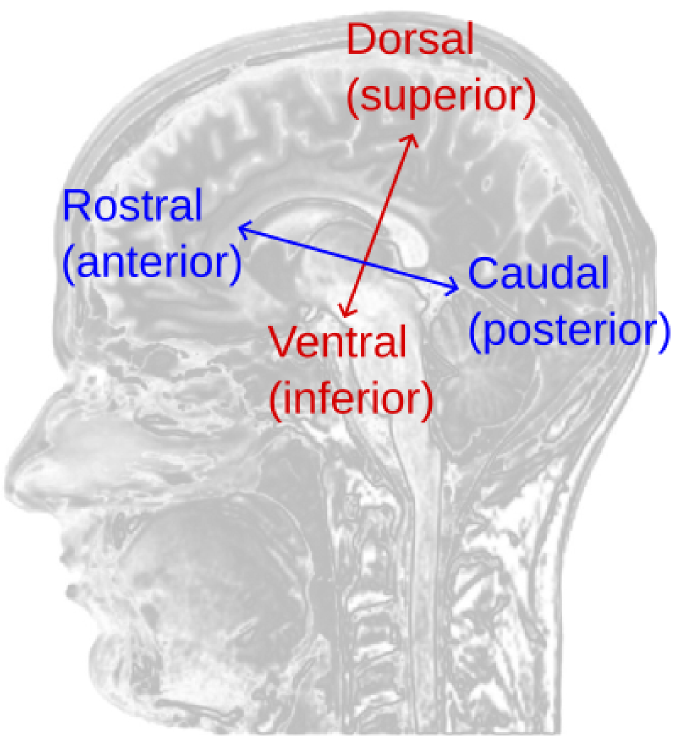
Why study brain activity

Studying brain activity is useful for several purposes:

- **Understanding** how different brain regions contribute to various cognitive and motor functions.
- **Sleep** staging to distinguish the different phases of sleep.
- **Diagnosing** and monitoring neurological conditions such as epilepsy, sleep disorders, and brain injuries.
- **Enable brain-computer interfaces** that allow direct control of machines and external devices by controlling brain activity.
- **Therapies** for mental health conditions such as anxiety, depression, and ADHD.

Anatomical directions

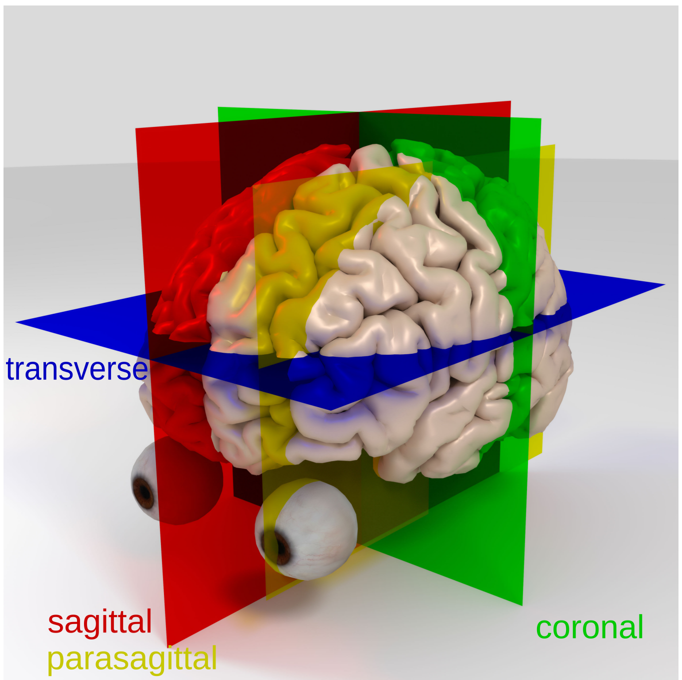
- **Anterior** (or rostral): towards the front (towards the face)
- **Posterior** (or caudal): towards the back (towards the tail)
- **Superior** (or dorsal): upwards
- **Inferior** (or ventral): downwards
- **Lateral**: towards the side
- **Medial**: towards the midline
- **Ipsilateral**: same side
- **Contralateral**: opposite side



Anatomical planes

Anatomical planes (useful to imagine as slices):

- **Sagittal** (midsagittal): vertical plane through the midline, dividing brain into left and right hemispheres
- **Parasagittal**: vertical plane parallel to the midline, dividing left and right but off-center
- **Coronal** (or frontal): vertical plane perpendicular to the midline, dividing anterior (rostral) and posterior (caudal)
- **Transverse** (or horizontal): horizontal plane dividing superior (dorsal) and inferior (ventral)



Key concepts about the brain

Key neuronal structures:

- **Dendrites**: Receive signals and generate postsynaptic potentials (PSPs)
- **Soma**: Integrates incoming PSPs from dendrites
- **Axon**: Transmits action potentials (AP) away from soma

Key potentials:

- **Postsynaptic potentials (PSP)**: Slower (hundreds of ms) and graded (their amplitude varies with input strength).
- **Action potentials (AP)**: Very fast (~1-2 ms duration) and all-or-none (same amplitude regardless of input strength).

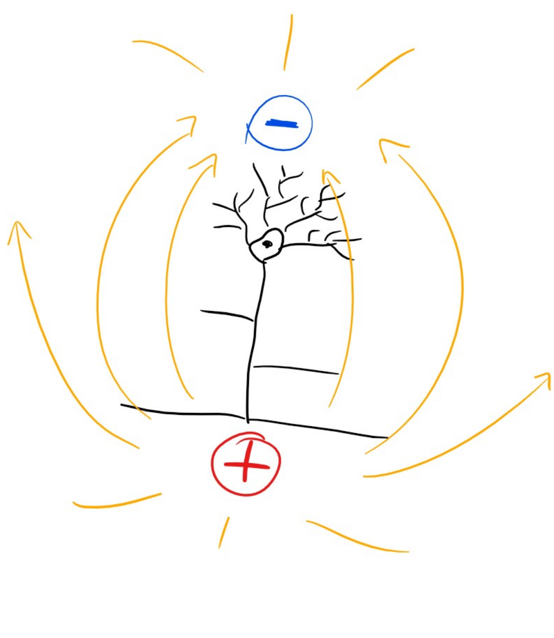
Key neuron type:

Pyramidal neurons: an important type of cortical neuron. They are the most abundant excitatory neurons in the cerebral cortex. Their connections reach across different layers of the cortex and to other brain regions. Their dendrites are aligned perpendicular to the cortical surface.

If you are not familiar with these concepts, I recommend reviewing the basics of neuroscience before proceeding. Check "Foundations of the Brain" on learning material

Dipoles in the brain

- Electrochemical activity in the dendrites generates electric fields.
- These fields create dipoles due to the separation of charges.



Summation of dipoles

Each neuronal activity generates a dipole. But most individual dipoles are too *small* to be detected from the scalp. However, when thousands of nearby neurons fire in synchronous, aligned activity, their individual dipoles **summate** into a bigger dipole and create a measurable electrical signal which is the foundation of EEG.

Summation in *time*:

- Dipoles must be active synchronously. Which type of potential (between PSPs and APs) is more likely to overlap in time? PSPs, because they are slower and can last hundreds of milliseconds, while APs are very brief (1-2 ms).
- Dipoles must be active for a sustained period. Brief, transient activity may not produce a strong enough signal to be detected at the scalp.

Summation in *space*:

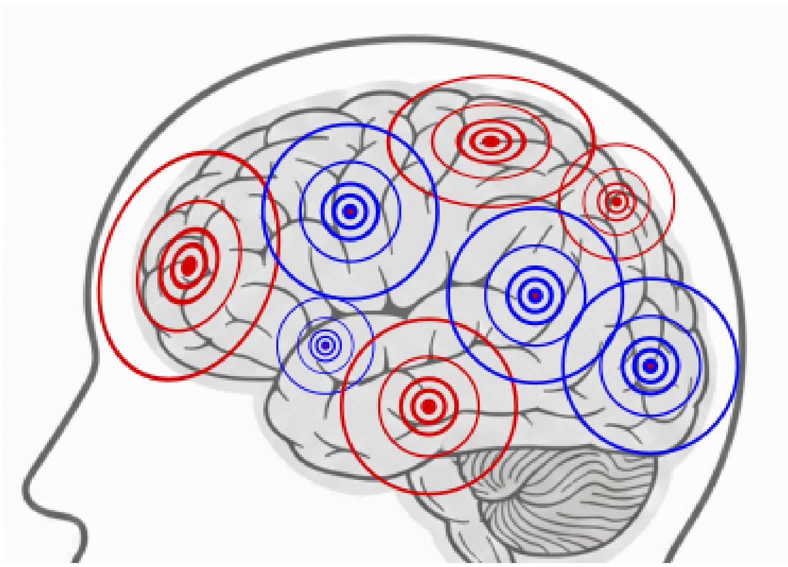
- Dipoles need to be aligned in the same direction. Dipoles that are not perfectly aligned but are close in orientation will summate less effectively. Dipoles that are oriented in opposite directions will cancel each other out.
- Dipoles need to be close enough to each other (local population) to summate effectively. Distant dipoles may not contribute significantly to the scalp signal due to spatial attenuation.

Detecting dipoles from the scalp

Electric fields propagate through the tissues (volume conduction), allowing us to detect the activity of neuronal populations from electrodes placed on the scalp.

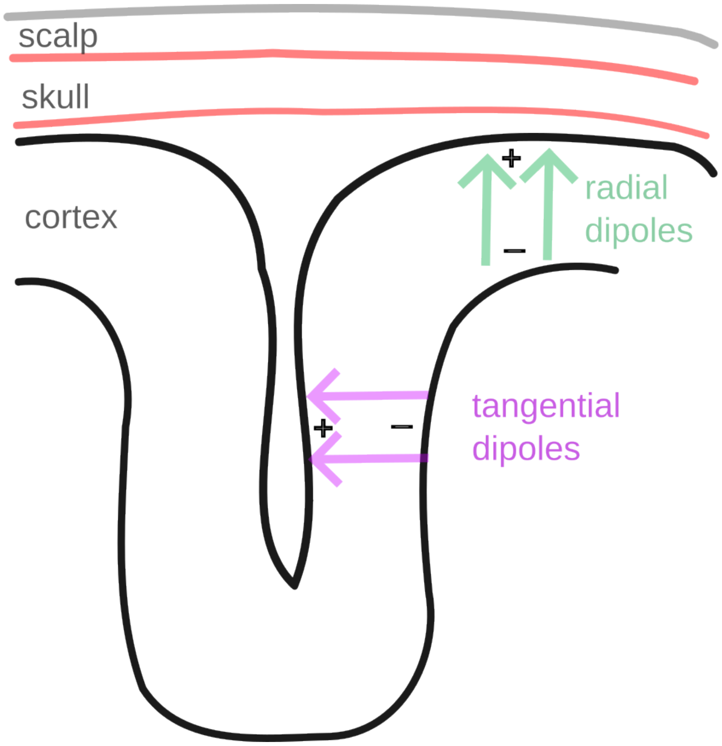
Several dipoles can be detected simultaneously.

We can observe scalp activity but it is challenging to determine the exact location of the underlying dipoles (so called, inverse problem).



Types of dipoles detectable from the scalp

- **Radial dipoles**: Oriented perpendicular to the cortical surface, often generated by pyramidal neurons in the gyri. These dipoles are more likely to be detected from electrodes on the scalp because their orientation aligns with the electrodes on the scalp.
- **Tangential dipoles**: Oriented parallel to the cortical surface, often found in the walls of the sulci. These dipoles are less likely to be detected by electrodes on the scalp as their orientation does not align well with the scalp.



- Both types of dipoles contribute to the overall EEG signal, but radial dipoles generally have a stronger influence due to their alignment with the scalp surface.

Electroencephalography (EEG)

MORPHEME	MEANING
Electro	= electrical activity
encephalo	= of the brain
graph	= measurement/recording

Characteristics of the EEG

Advantages:

- Noninvasive
- Portable (easy to set up and transport)

- High temporal resolution (captures fast neural dynamics)
- Measures neuronal activity
- Relatively low cost

Limitations:

- Poor spatial resolution (signals spread across scalp due to volume conduction)
- Inverse problem (difficulty in localizing sources of activity)
- Limited to cerebral cortex (not deeper structures)
- Susceptible to artifacts (e.g., eye movements, muscle activity)

Biological source of the EEG signal

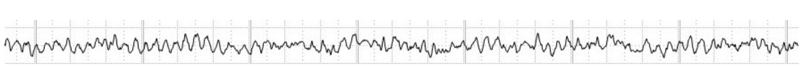
EEG signals comes mainly from *postsynaptic potentials (PSPs)* of *pyramidal neurons* in the cerebral cortex. This is because:

- PSPs are slower and can overlap in time, allowing for temporal summation.
- Pyramidal neurons are abundant and have an aligned architecture, which allows for spatial summation of their dipoles.

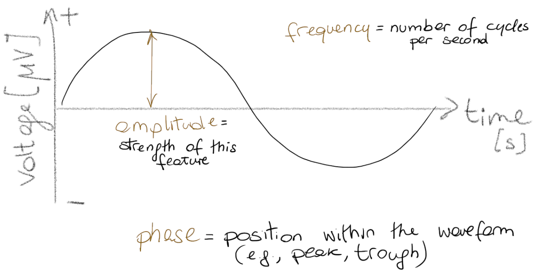
EEG captures rhythmic, coordinated brain activity and not isolated/localized neuronal firing.

EEG signal morphology

EEG signals appear like complex waveforms, consisting of multiple overlapping waveforms that vary in frequency, phase, and amplitude.



The three main parameters of waveforms



- **Frequency**: The number of cycles the waveform completes in a given time period, usually measured in Hertz (Hz). Higher frequency indicates more cycles per second.
- **Phase**: The position of a point in time on the waveform cycle, indicating the timing of the waveform relative to a reference point. Phase differences can affect how waveforms interact with each other.
- **Amplitude**: The height of the waveform, representing the strength or intensity of the signal. Higher amplitude indicates stronger signals.

Manipulating one parameter at a time

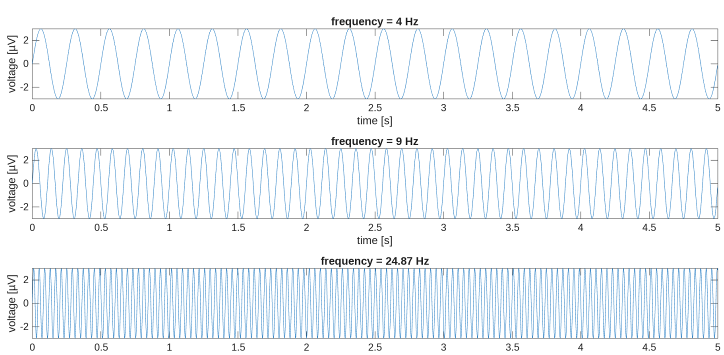


Figure 1: varying frequency

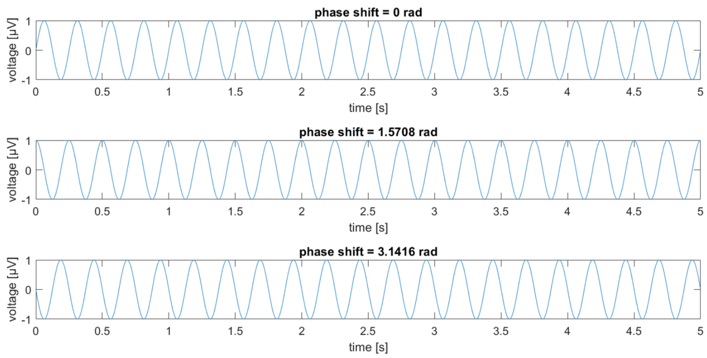


Figure 2: varying phase

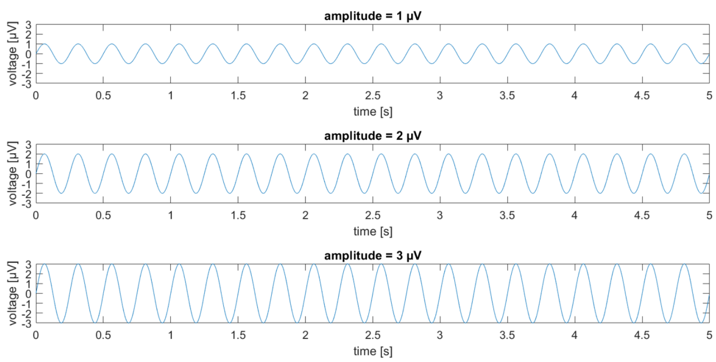


Figure 3: varying amplitude

Simulating EEG signal

Let's sum, time by time, three waves varying in frequency, phase, and amplitude.

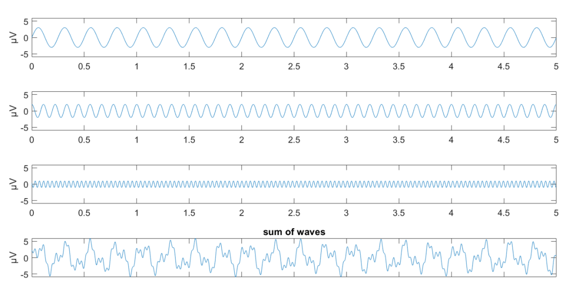


Figure 4: three simple waves and their sum

Simulating EEG signal with noise

Same as before but adding noise.

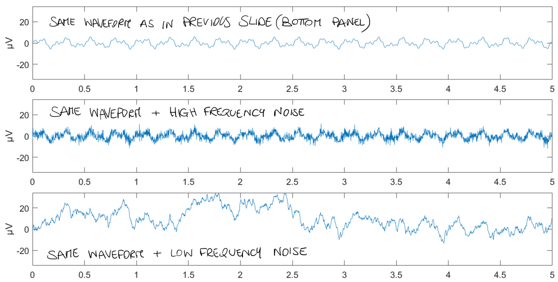
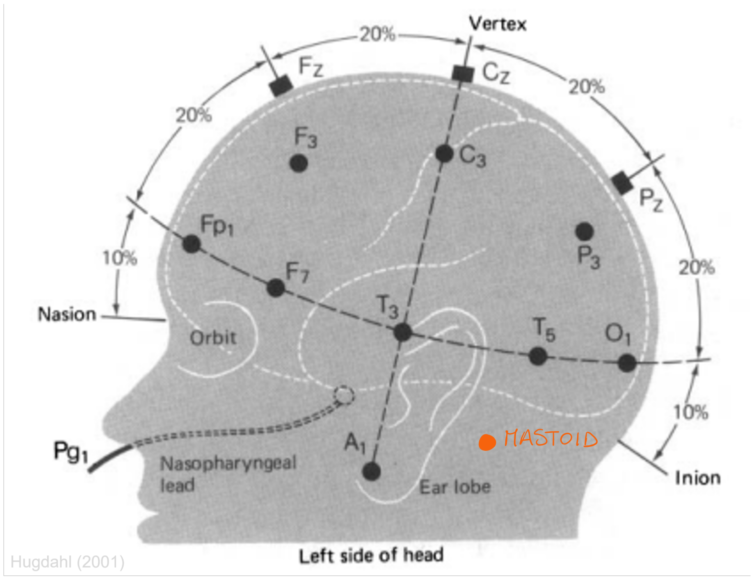


Figure 5: composite wave plus structured noise

10-20 system: main ideas

An internationally recognized method to describe the location of scalp electrodes.

- Electrodes are placed at intervals of 10% or 20% of the total distance between specified skull landmarks.
- Landmarks include the nasion (bridge of the nose), inion (bump at the back of the skull), and preauricular points (just in front of the ears).



10-20 system: labels

Electrode positions are labeled with letters and numbers, where letters correspond to brain regions (e.g., F for frontal, T for temporal) and numbers indicate the hemisphere (odd numbers for the left, even numbers for the right).

Letter	Region
F	Frontal
C	Central
P	Parietal
T	Temporal
O	Occipital
Fp	Frontopolar

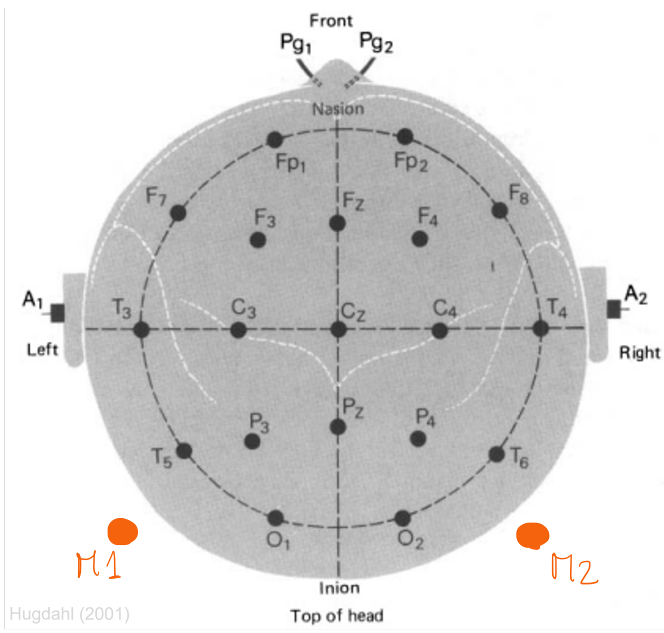
Second digit*	Lateral/medial position
z	on the midline
odd digit	lateral (left)
even digit	lateral (right)
smaller digit	closer to the midline

Second digit*	Lateral/medial position
larger digit	farther from the midline

** Note: z is used for midline electrodes, while odd and even digits indicate lateral positions.*

10-20 system examples

The 10-20 system can be expanded to include additional electrodes for higher resolution recordings, known as the 10-10 or 10-5 systems.



Some examples:

- Cz = central on the midline (aka vertex)
- P3 = parietal, lateral to the left
- P5 = parietal, even more lateral to the left (not in the figure)

Electrical reference

Reminder: voltage is difference in electrical potential between two points. Therefore, one electrode alone cannot measure anything. You need two electrodes to measure voltage.

- **Bipolar montage**:
  - Each electrode is referenced to an adjacent electrode.
  - Measures the voltage difference between pairs of electrodes.
  - Useful for detecting localized activity.
  - Commonly used in clinical settings to identify focal seizures (e.g., epilepsy).
- **Monopolar (or referential) montage**:
  - Each electrode is referenced to a common reference electrode.
  - Measures the voltage difference between each electrode and the reference.
  - Provides a broader view of brain activity.
  - Common reference points include the mastoids, earlobes, or an average of all electrodes.

EEG signals

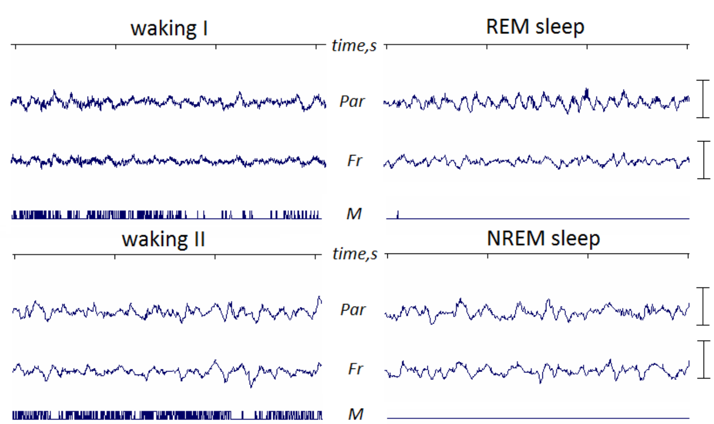
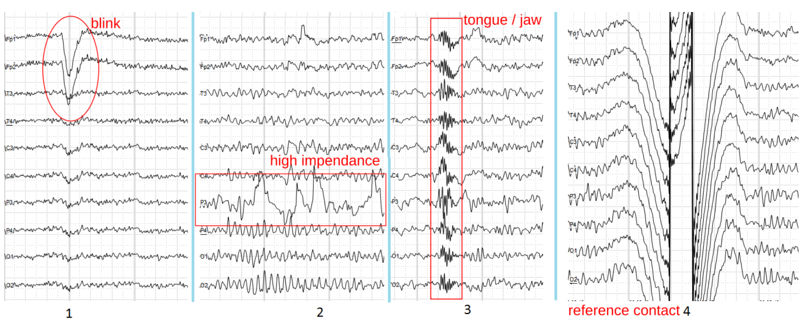


Figure 6: Recordings under different states of consciousness

Figure 7: Recordings from multiple channels

Sources of noise in the EEG signal



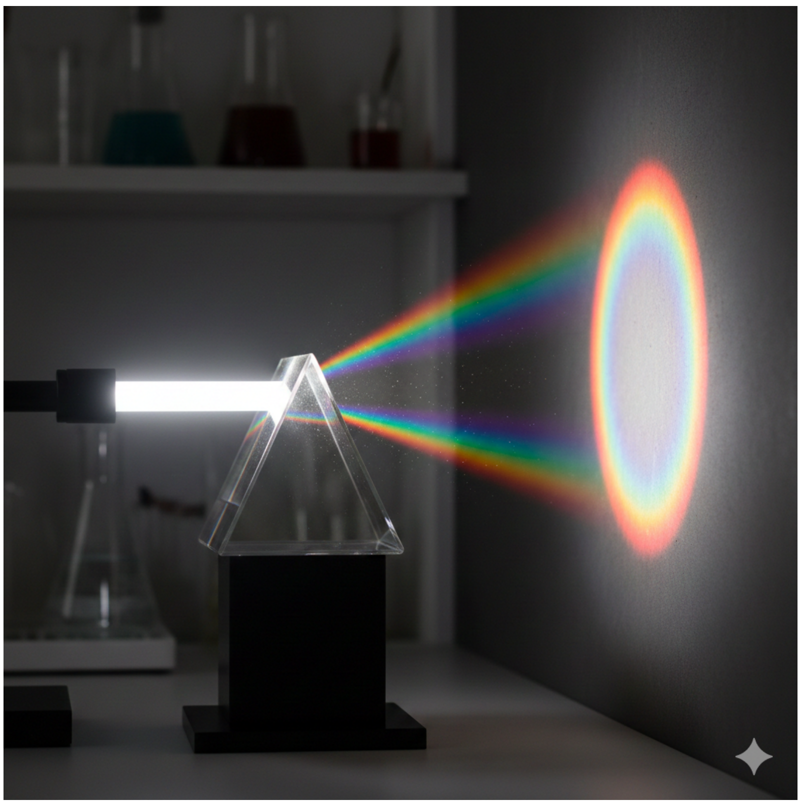
Commonly known as “artifacts”.

They are of non-neural origin and can contaminate the EEG signal and obscure the underlying brain activity.

- Eye movements: blinks and saccades, especially in the frontal region.
- Muscle activity: tension or movements in the scalp, neck, or face muscles can introduce high-frequency noise.
- Electrode movement: shifts in electrode position can cause sudden changes in the recorded signal.
- Sweat: changes in skin conductance can affect low-frequency characteristics.

- Heartbeats: electrical activity of the heart (e.g., R-waves, pulse waves).
- Environmental noise: electrical interference from nearby equipment or power lines can introduce 50/60 Hz noise.

Decomposing the EEG signal into its frequency components



A prism can break down white light into its component colors

Similarly, spectral decomposition techniques can break down the composite EEG waveforms into their component frequencies. Sometimes referred to as “brain rhythms”.

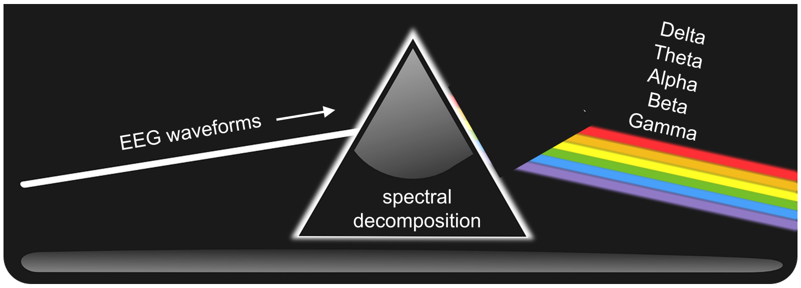


Figure 8: EEG spectral decomposition

Brain rhythms

- **Alpha waves (8-12 Hz)**: associated with neuronal suppression (e.g., cognitive activity, relaxation).
- **Beta waves (12-30 Hz)**: associated with alertness, concentration, and active thinking; can be increased by stress, anxiety, or mental effort.
- **Delta waves (0.5-4 Hz)**: predominantly seen during deep sleep.

- **Theta waves (4-8 Hz)**: associated with executive functions (inhibition, updating, shifting); more prominent in the frontal regions.
- **Gamma waves (30-100 Hz)**: associated with neuronal excitations.
- **Mu waves (8-13 Hz)**: similar to alpha waves but more localized to the sensorimotor cortex; associated with motor planning and execution.

Extractable metrics from EEG

Time domain metrics:

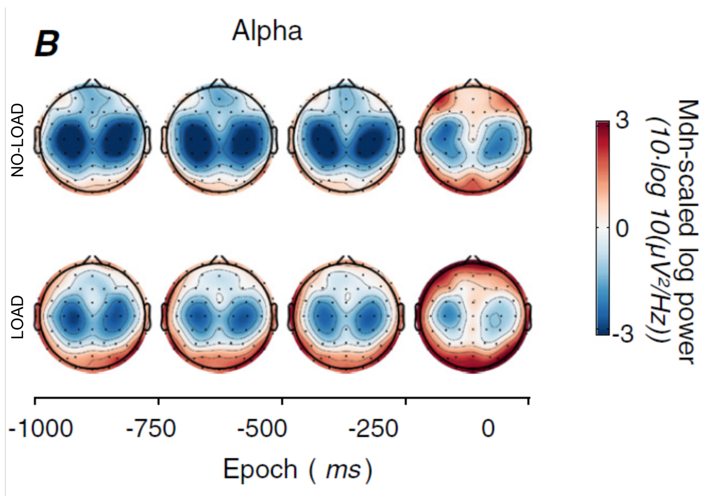
- **Event-Related Potentials (ERPs)**: Voltage changes time-locked to specific events or stimuli
- Measured as **amplitude** and **latency** of peaks/components
- High temporal precision (milliseconds)

- Reflect cognitive or motor processes related to specific events

Frequency domain metrics:

- **Spectral power**: Strength of oscillations at specific frequencies
- Measured across frequency bands (delta, theta, alpha, beta, gamma)
- Measured across multiple scalp locations (topographic patterns)
- Reflects underlying neural oscillations and brain states

Topographical mapping



- Visual representation of EEG data across the scalp.
- Helps identify spatial patterns of brain activity.
- Useful for detecting regional differences in brain function.
- Often used in clinical and research settings to analyze brain waves.
- Provides a comprehensive view of brain dynamics over time.

Uses of EEG in sport and exercise