EEG Data Processing Pipelines

See
https://www.fieldtriptoolbox.org/workshop/neurotecheu/
for the corresponding hands-on material

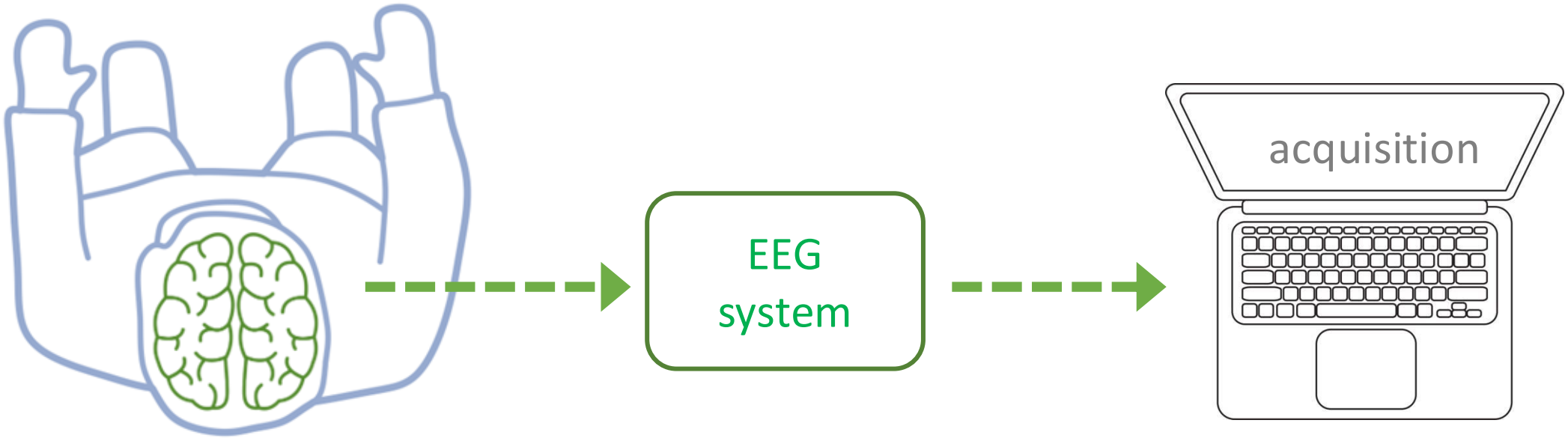
Robert Oostenveld

30 Oct 2026

NeurotechEU EEG/fNIRS hackathon

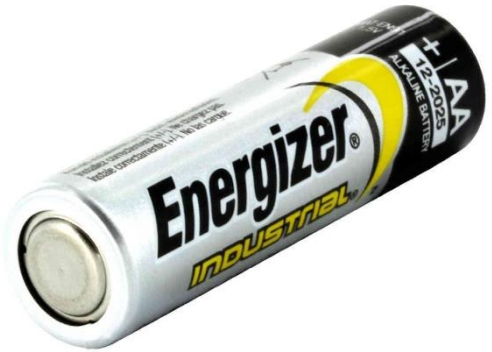
robert.oostenved@donders.ru.nl

How do we record the EEG?


EEG
system
acquisition

A common AA battery is 1.5 Volt



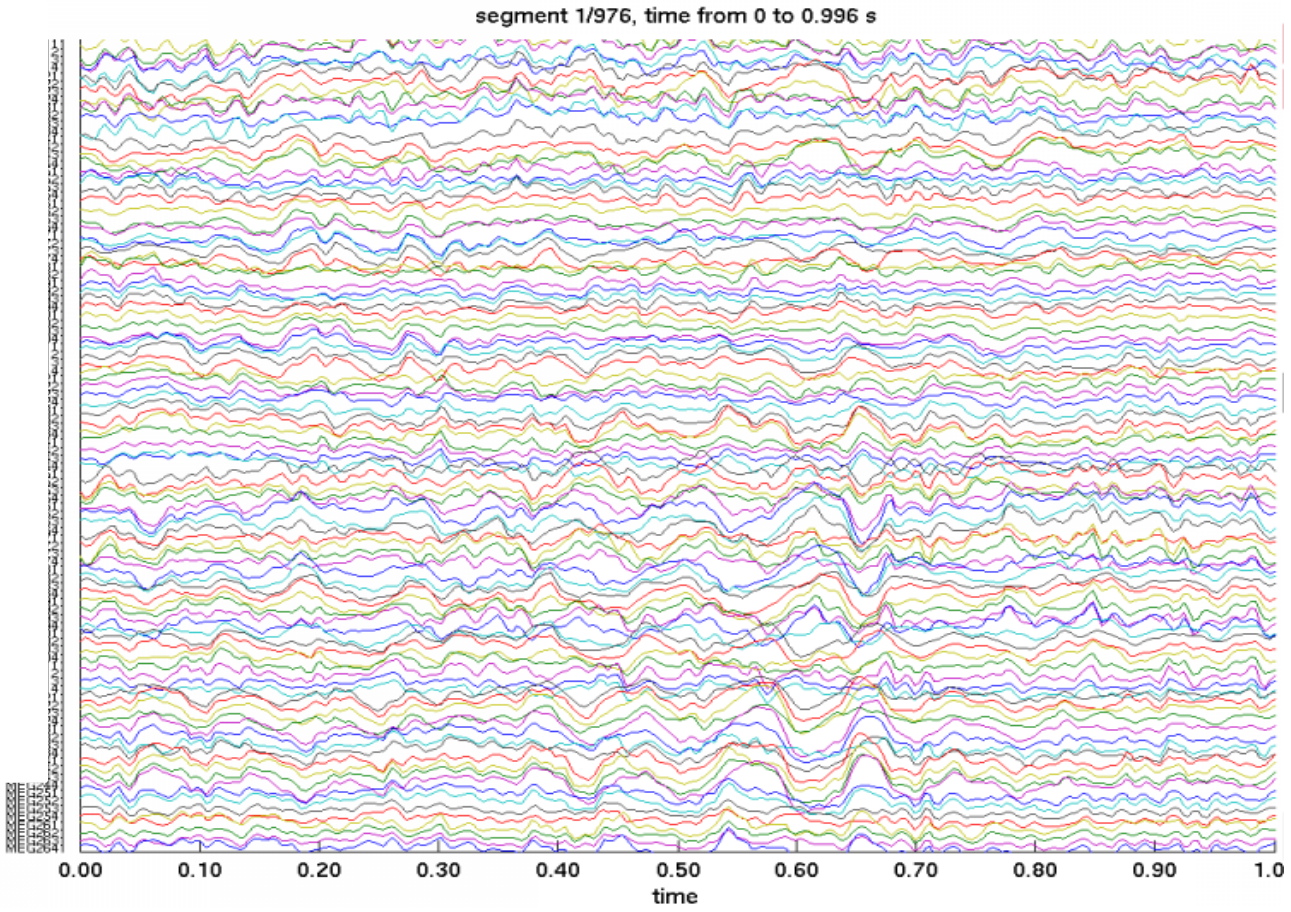


EEG signal also consists of voltages



Voltage between electrodes measured in microvolts (µV)

EEG channels

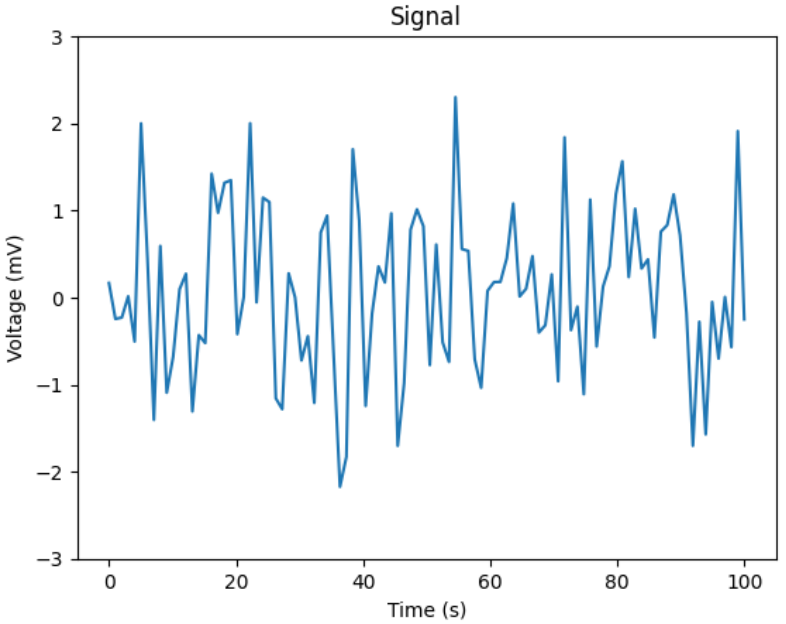


Time

Multiple microphones recording the sound in a ropom

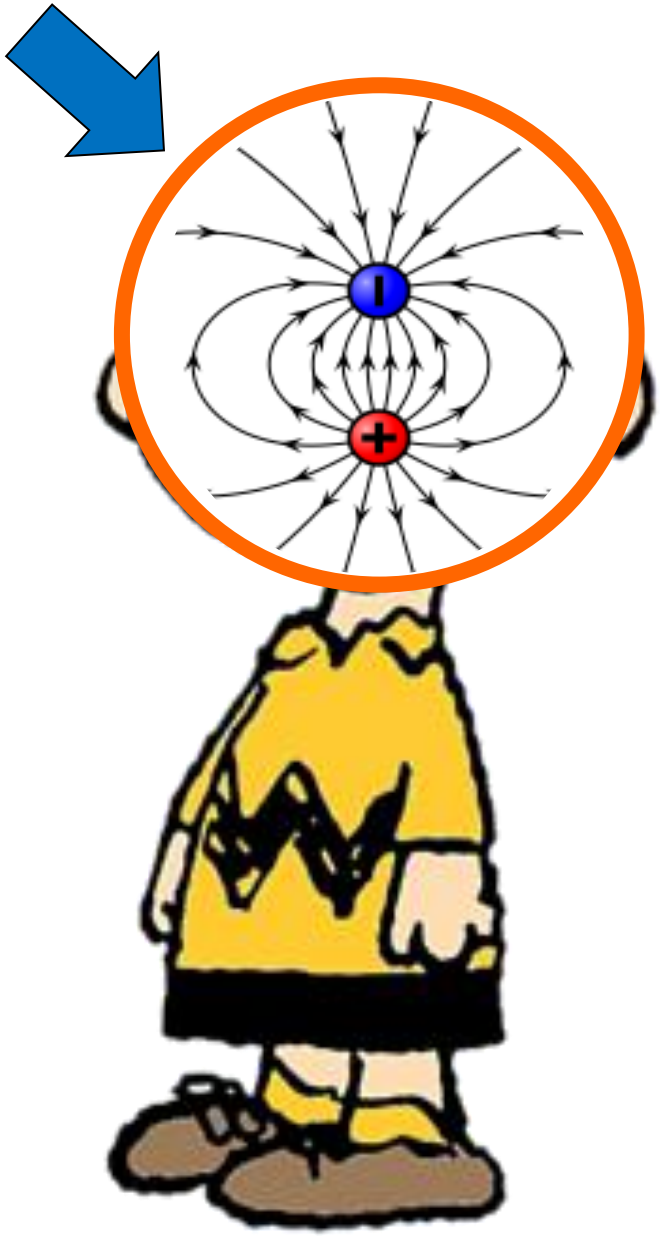




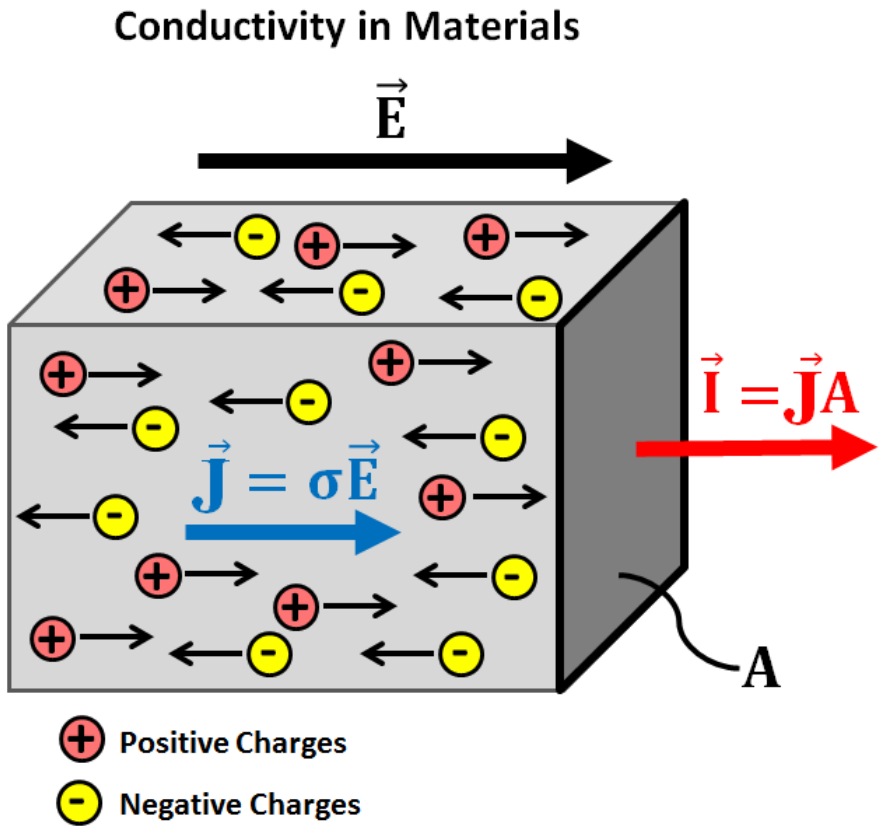


Electric currents in a volume

EEG measures the <u>electric field at the scalp</u>

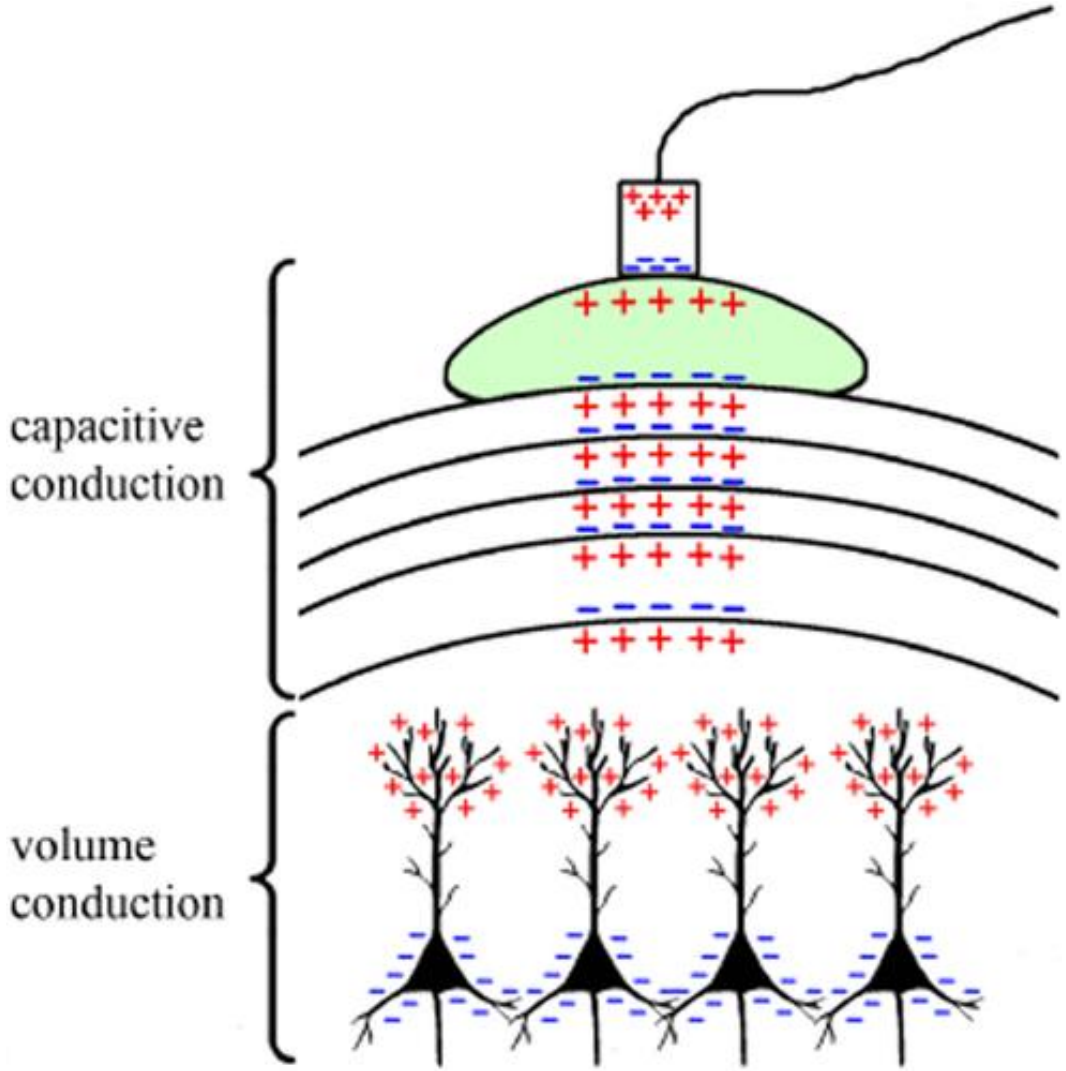


Electric currents in a volume



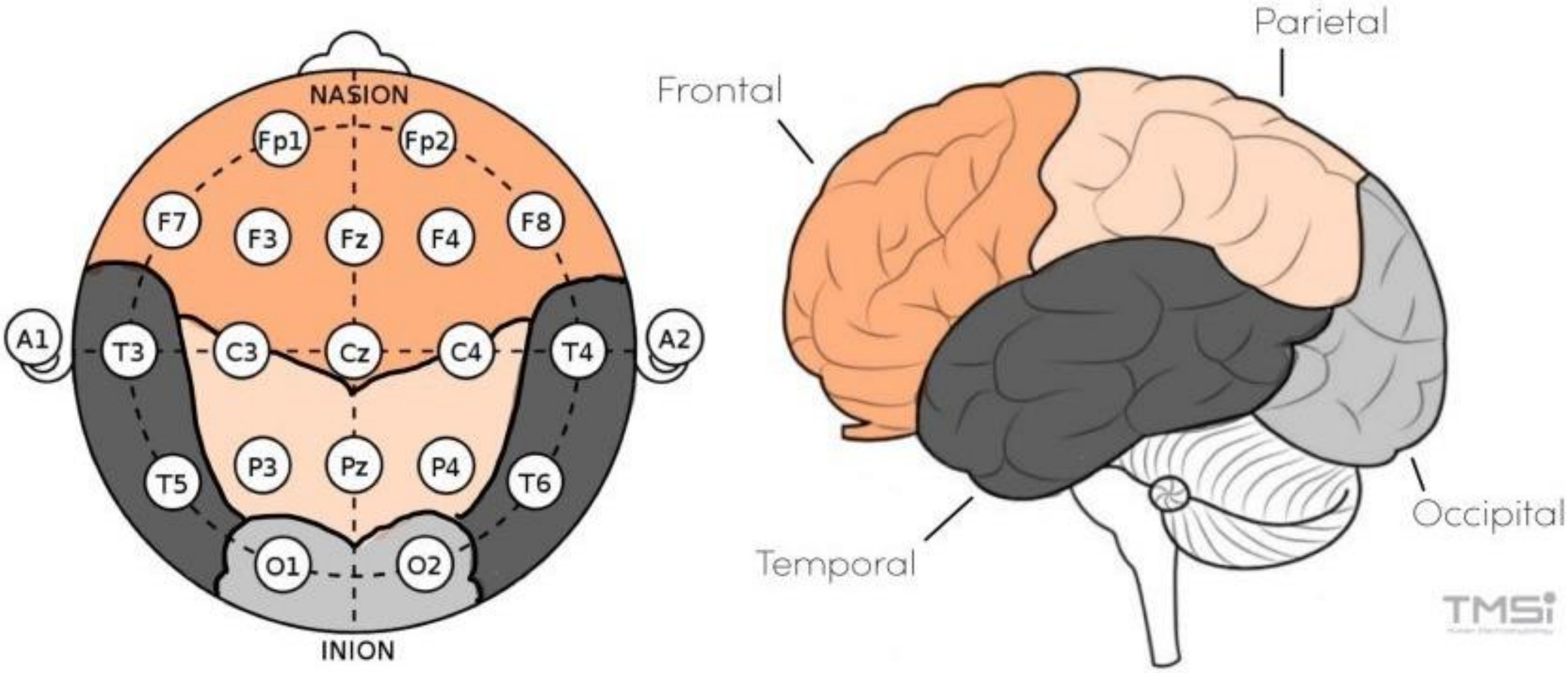
Resistivity

$$\rho = \frac{1}{\sigma}$$



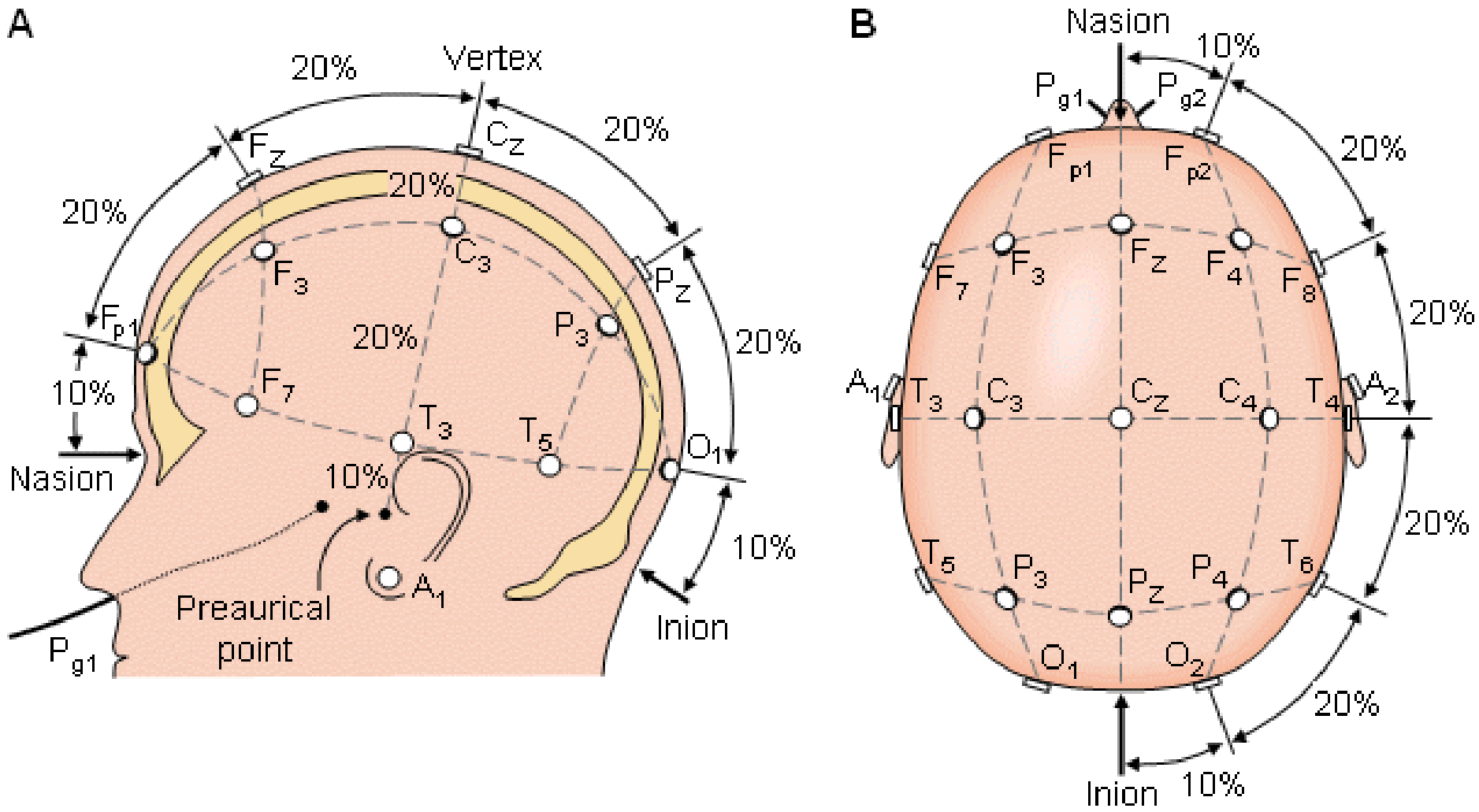
Jackson and Bolger (2014)

The 10-20 electrode placement system - naming

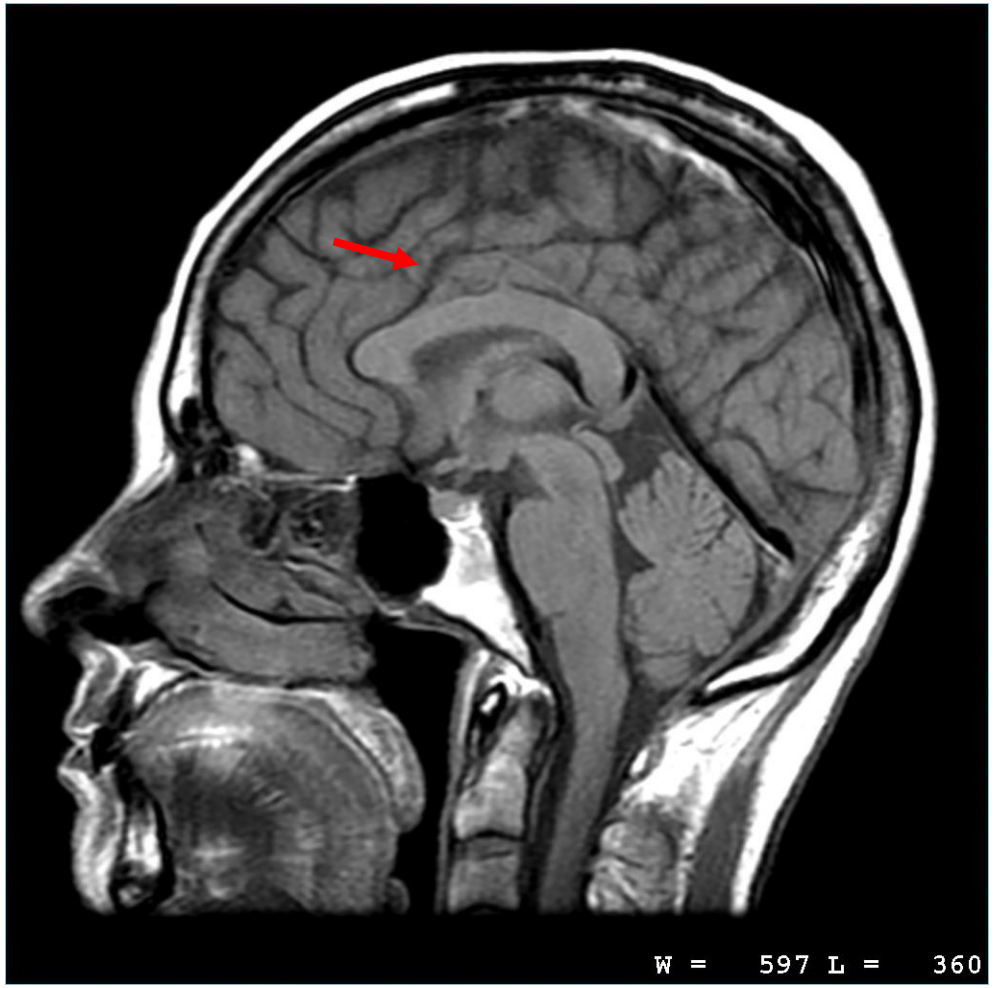


Electrodes T3/4 are nowadays mostly called C7/8, and T5/6 are called P7/8.
The ear lobes are called A1/2, the mastoids are called M1/2.

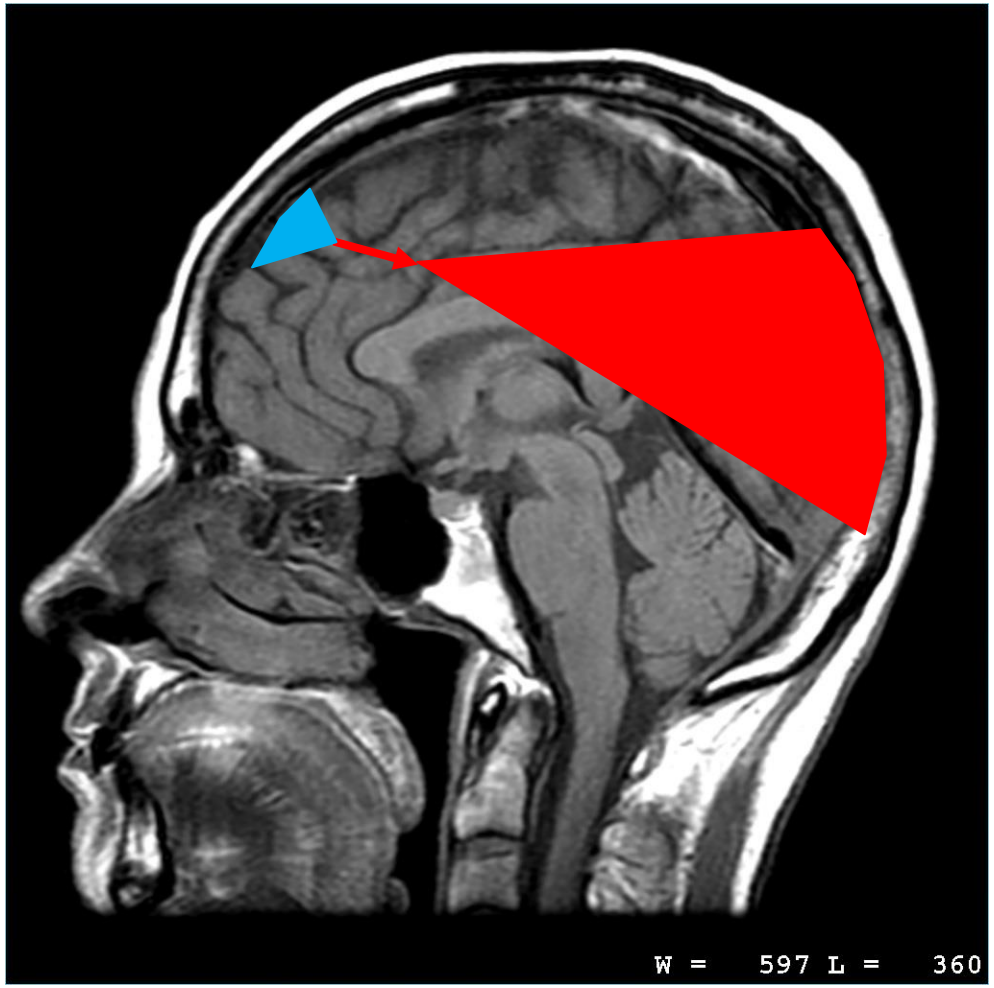
The 10-20 electrode placement system - placement



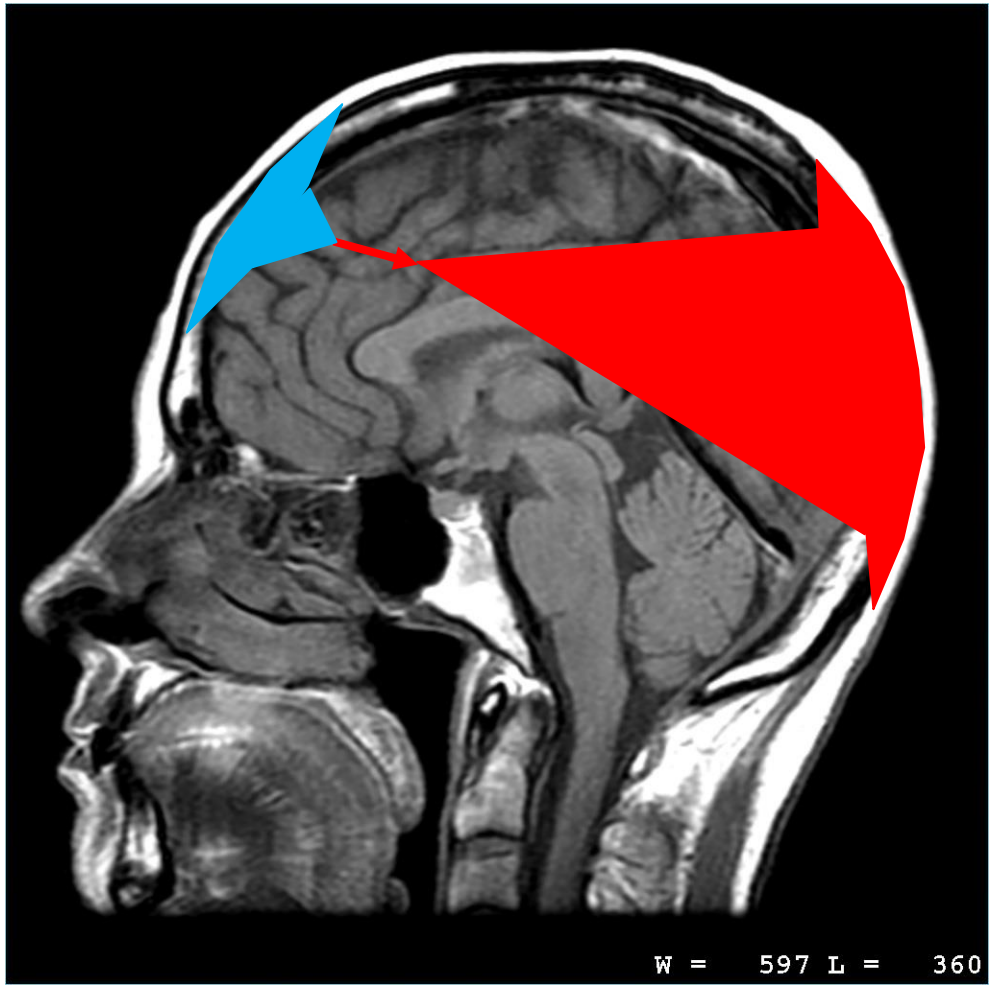
Volume conduction



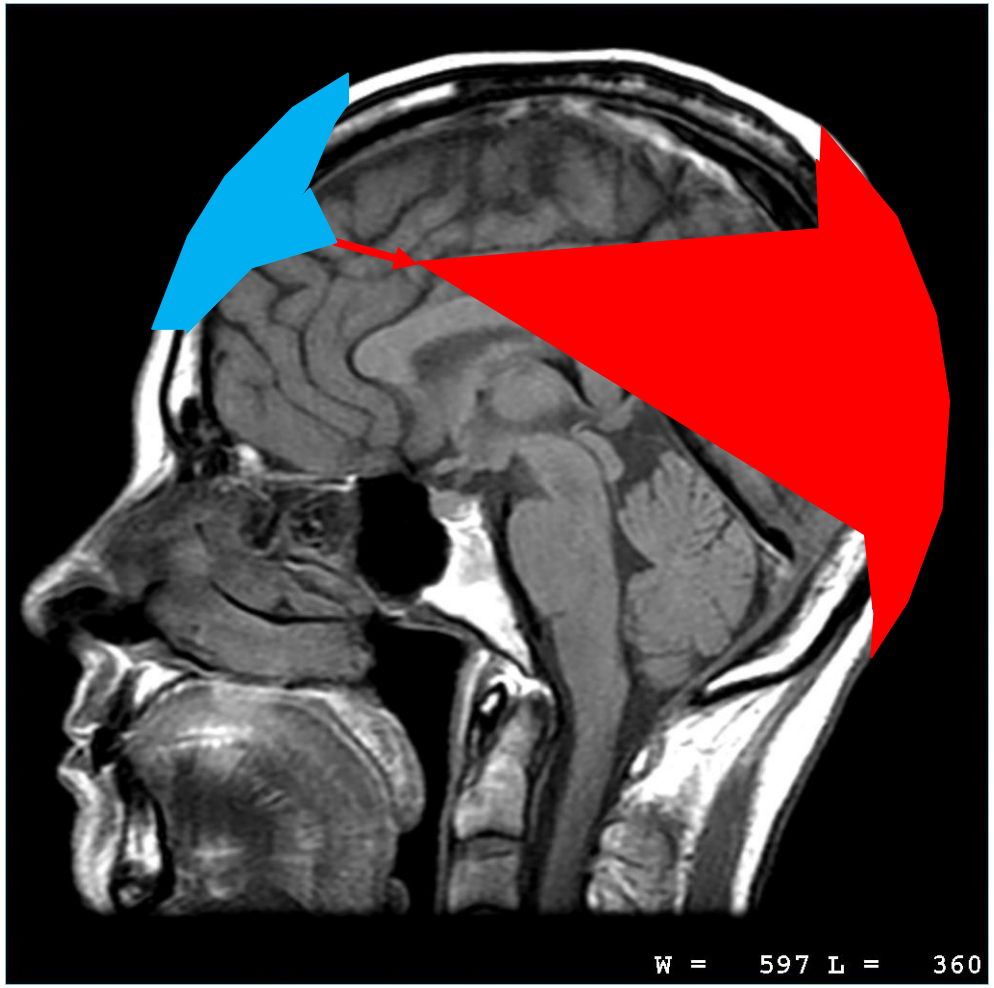
Volume conduction



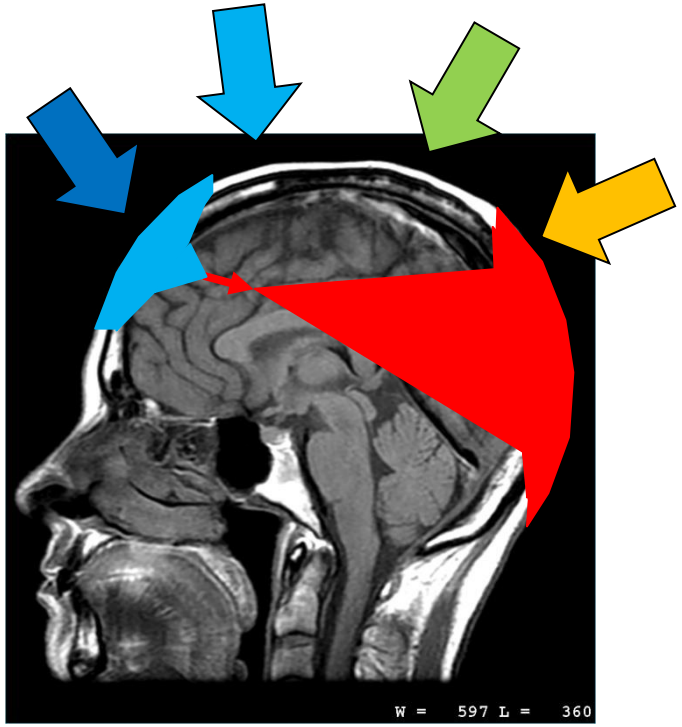
Volume conduction

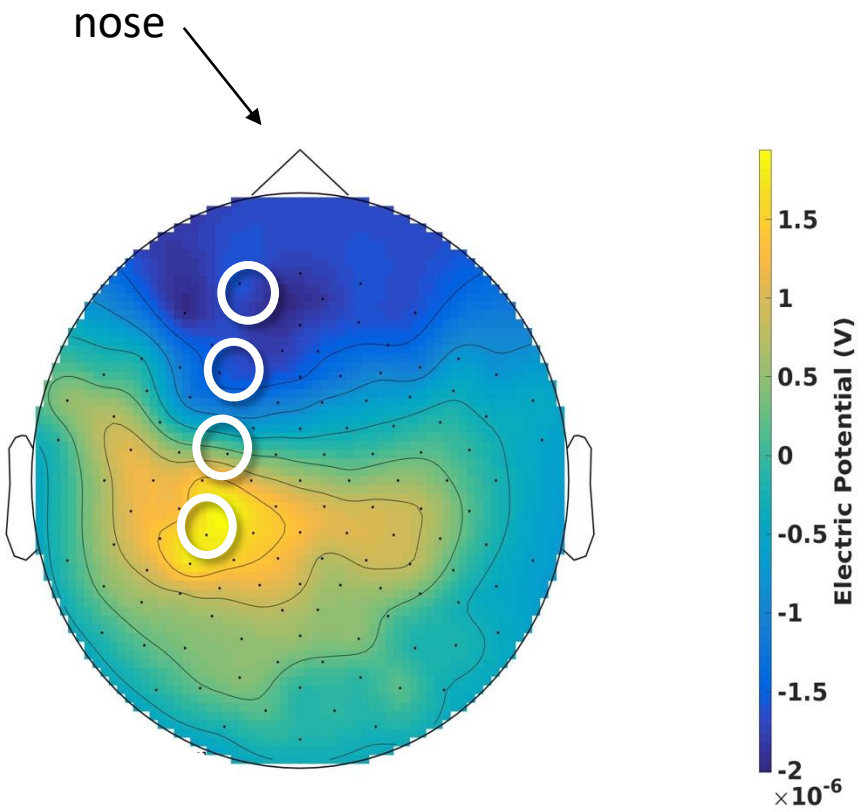


Volume conduction



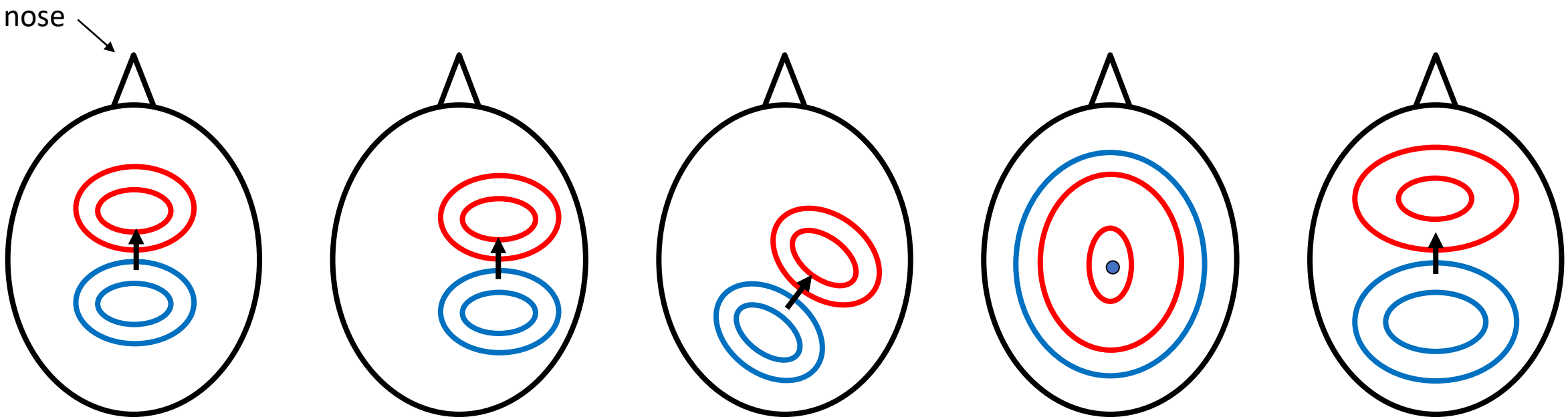
Spatial distribution of the voltage over the scalp





the head seen from the top

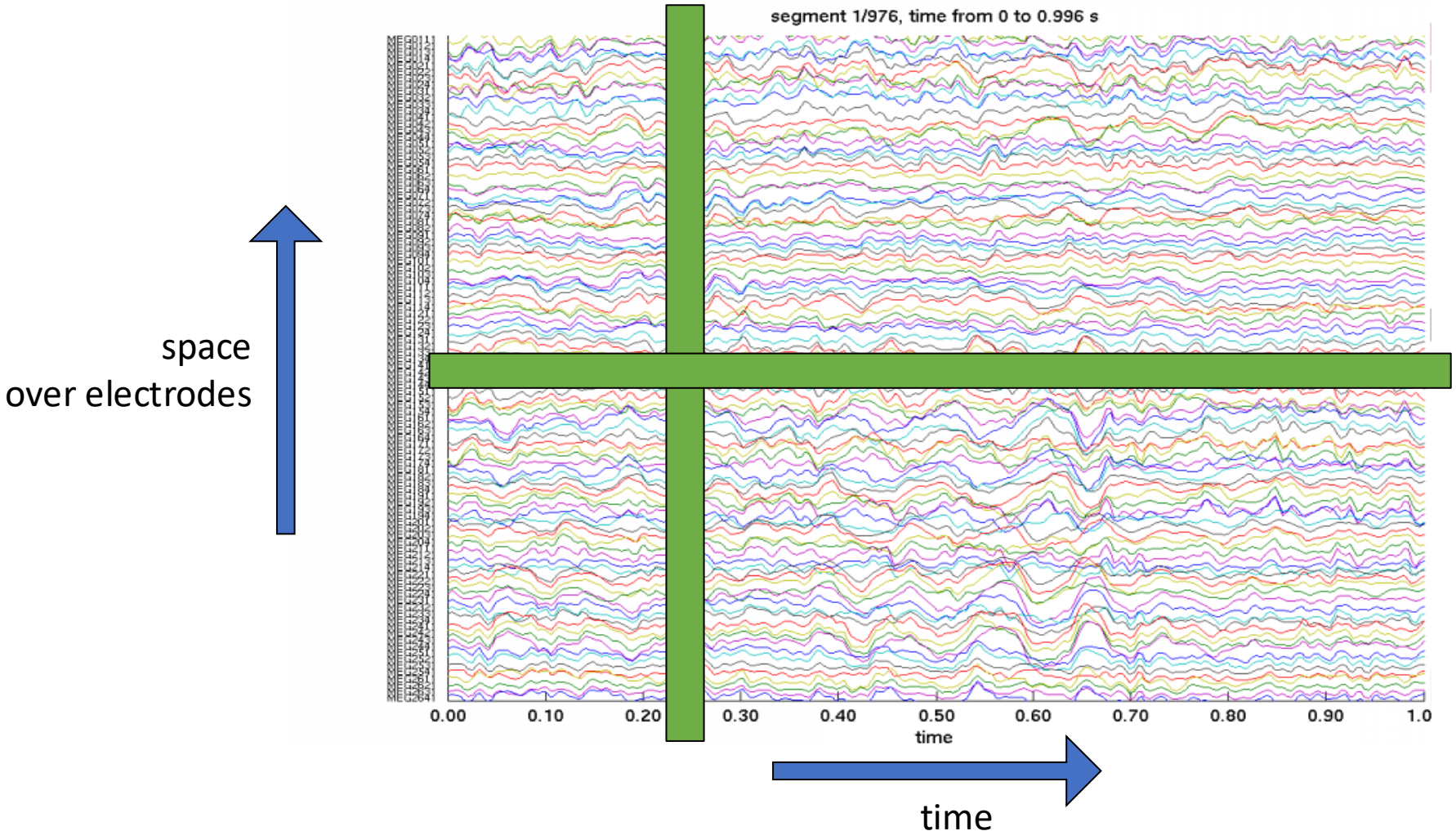
Spatial distribution for different generators



Spontaneous EEG is a mixture of many sources

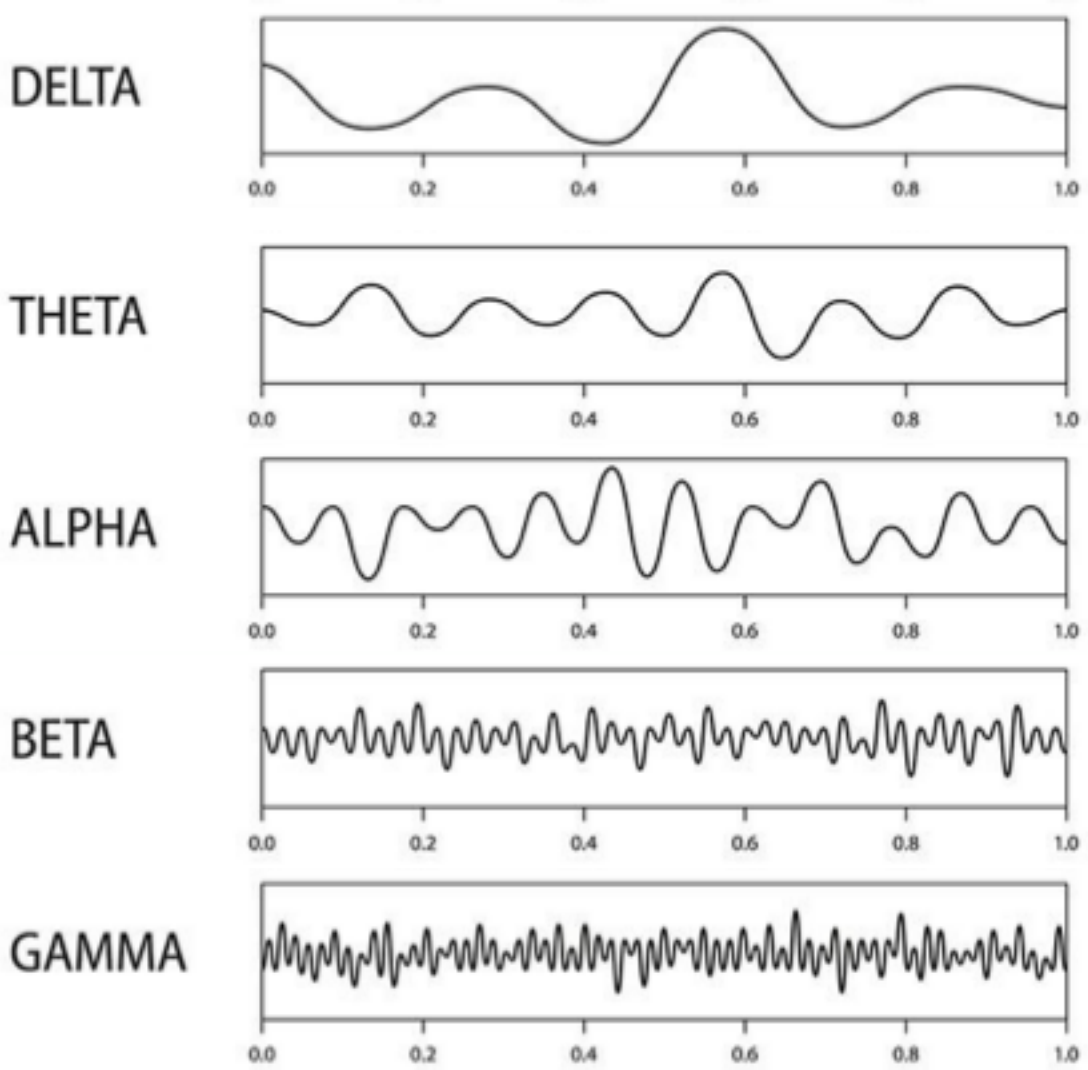
Many parts of the brain are active simulteneously.

The activity of each brain region fluctuates over time.

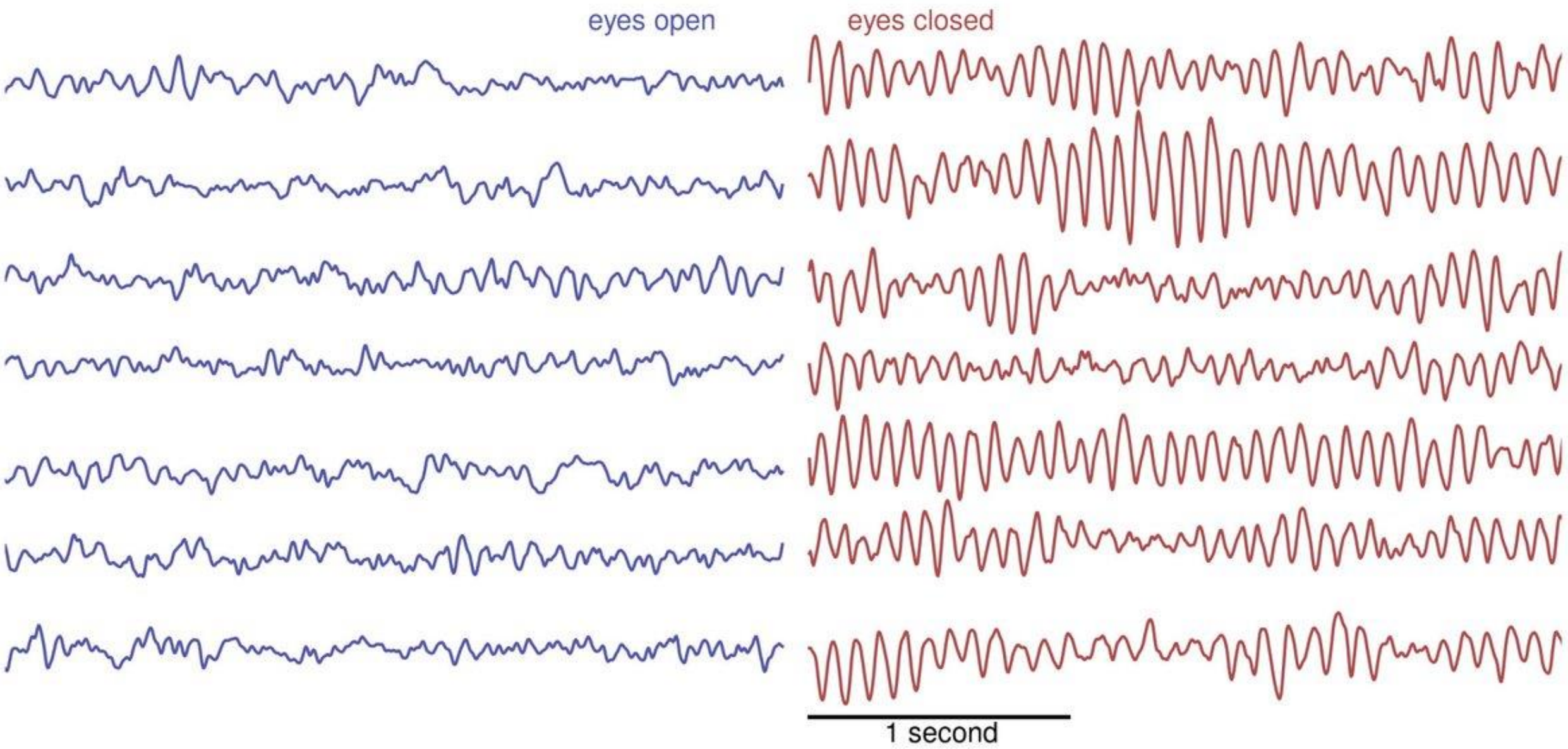


What does the EEG contain?

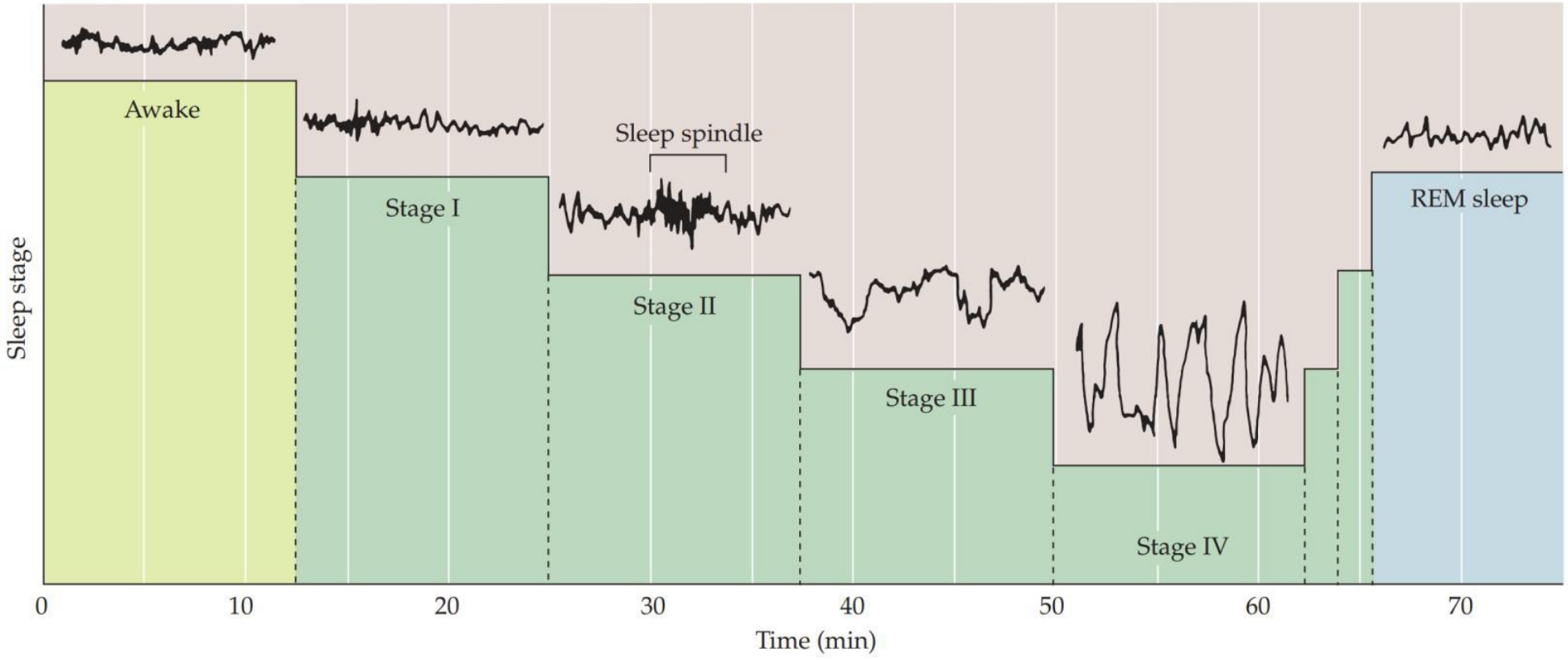
Spontaneous rhythms in the EEG, sorted by frequency



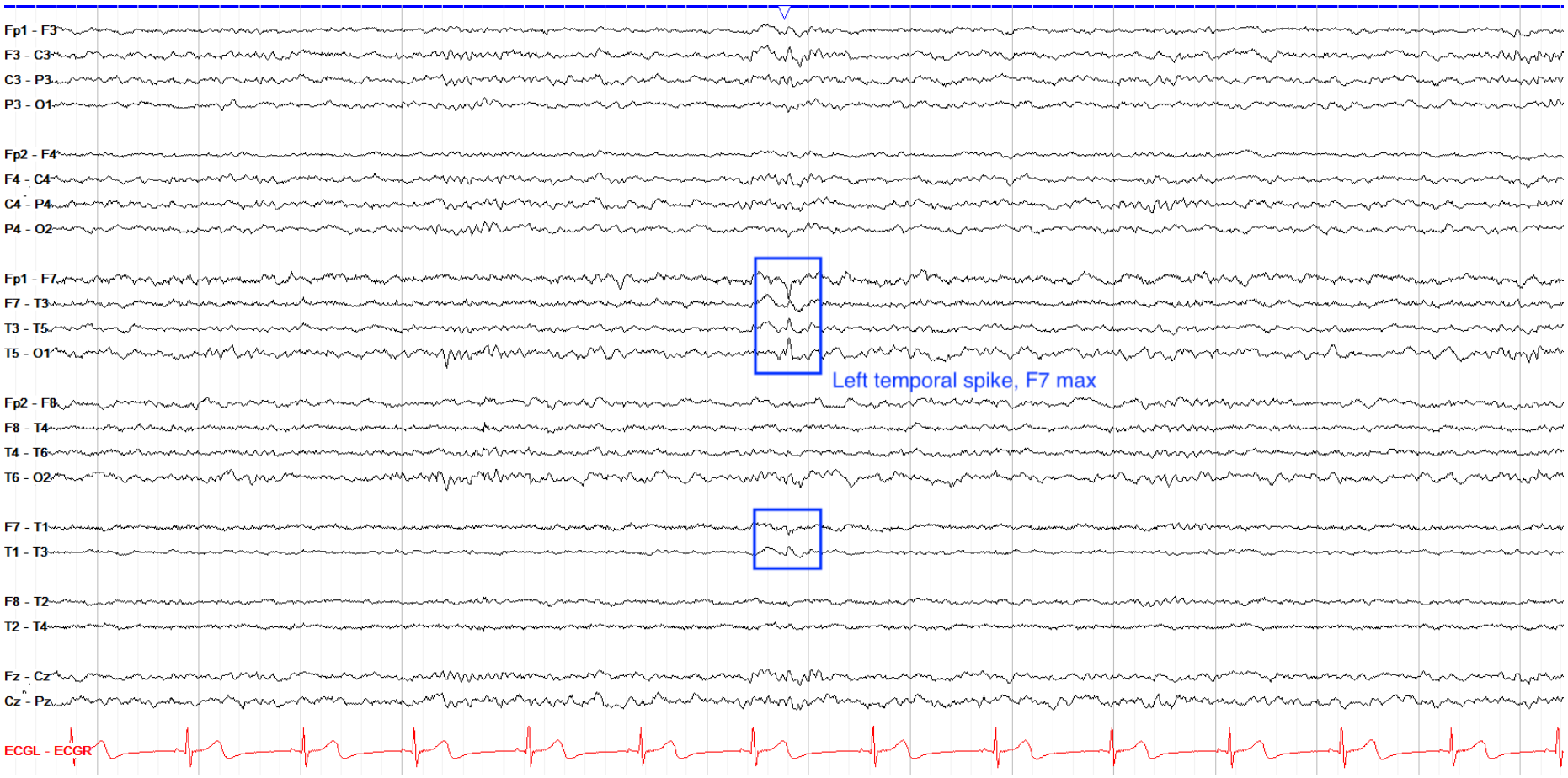
EEG when you close your eyes: occipital alpha



EEG during sleep: change in rhythms

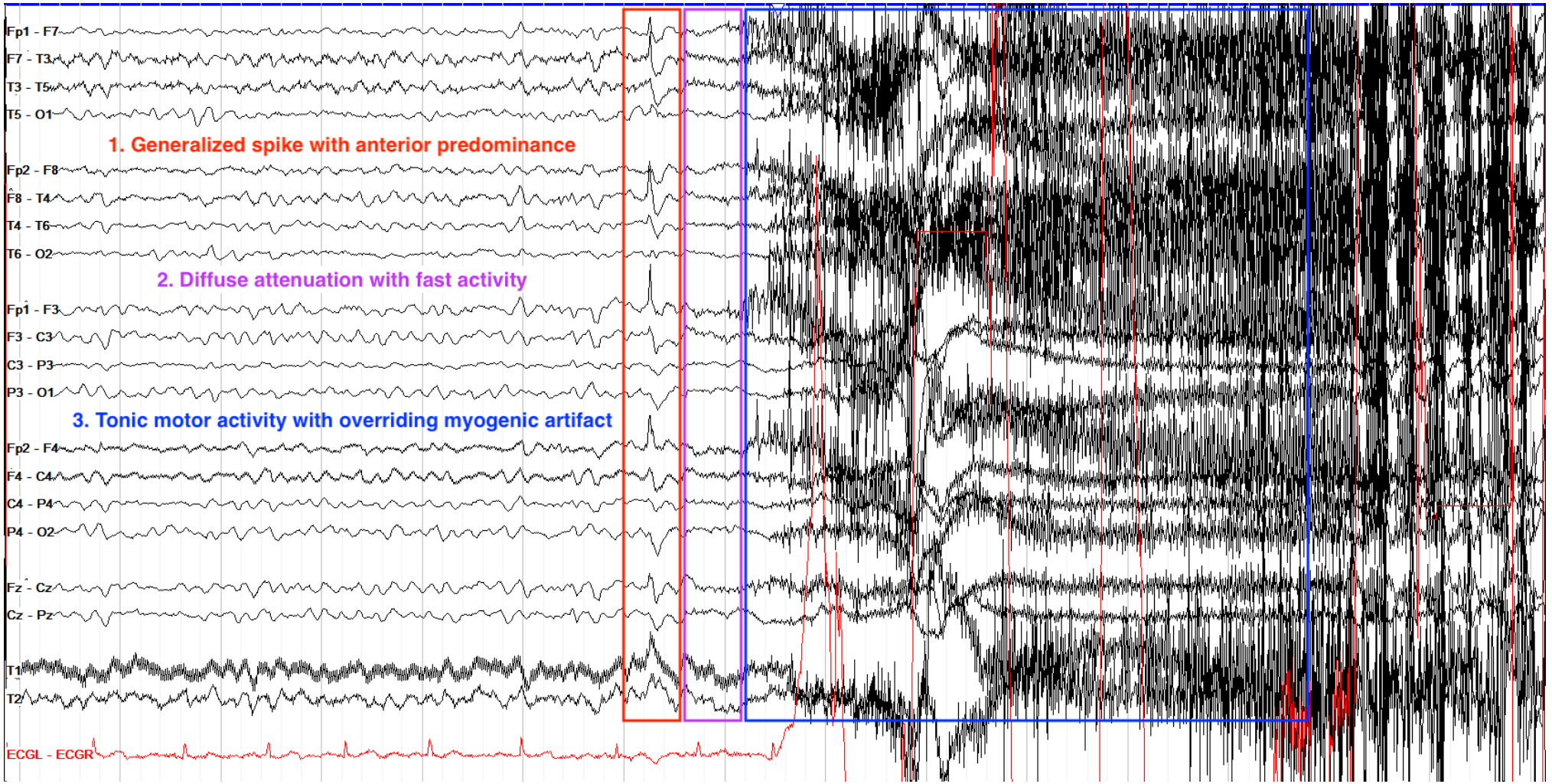


EEG in neurological disorders: epileptic spike



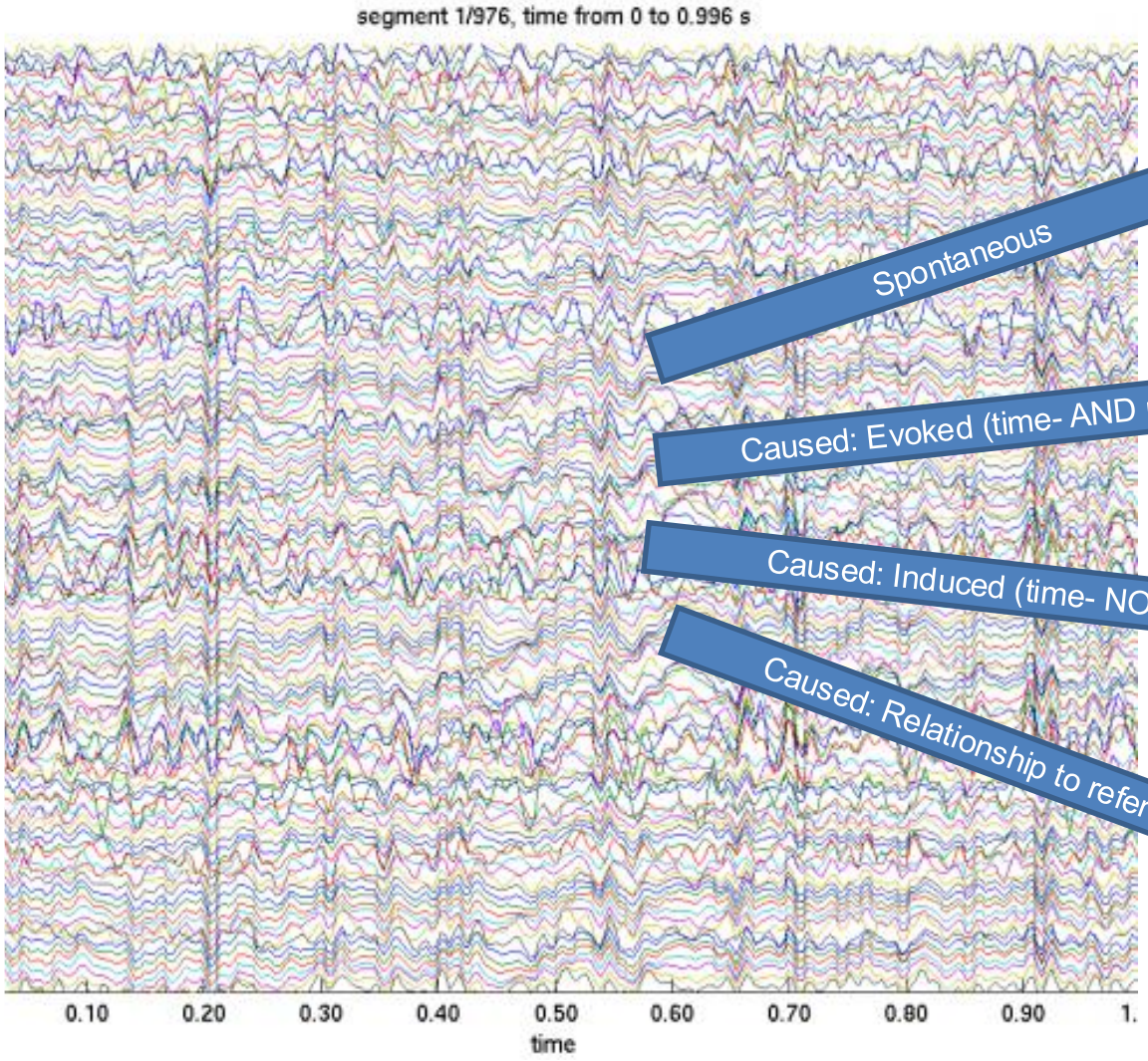
https://www.learningeeg.com/

EEG in neurological disorders: epileptic seizure



https://www.learningeeg.com/

EEG in the healthy brain, many features



Spontaneous

Caused: Evoked (time- AND phase- locked)

Caused: Induced (time- NOT phase-locked)

Caused: Relationship to reference signal

Spontaneous activity
- Oscillatory activity: Delta, Theta, Alpha, Beta, Gamma
- Broadband features
- ”Events”

Evoked responses
Event-related potentials (ERP)
All sensory modalities

Induced responses
Event-related modulation of oscillations
All sensory modalities
Brain stimulation

Frequency tagging
Coherence to motor / kinematics
Most sensory modalities

How do we analyze the EEG?

EEG data contains a lot of noise

Anything that causes **voltage changes** is picked up in the EEG signal

Bioelectricity

- from the brain
- from the muscles
- from the heart (also a muscle)
- from the eyes (retinal and muscular)

Line noise (50/60 Hz)

Electrode movements relative to the scalp

Slow changes in the electrode contact, for example due to sweat

Electrostatic potentials (e.g. rubbing your feet on the carpet)

EEG and timing



Knowing the precise timing of brain activity helps

- Stimulus presentation software sends triggers
- Cable (or network) between stimulus computer and EEG system

Knowing the (approximate) timing of the artifacts

- Telling the participant *when* to blink, or *when* to move

Alongside the EEG we record the experimental task timing and (some) behavior

- Button presses
- Eye tracker
- EOG signals
- Video of behavior and movement
- Motion capture system (with IMUs)

Stimulus presentation software

Can show text and images, play sounds and video.

Can record responses from the participant.

Keyboard, mouse, joystick, audio (speech), special button boxes, …

Writes the stimuli and responses (with timestamps) to a log file.

Specific for EEG: can send ”triggers” or “markers” for synchronization.

It allows you to “program” an experiment in the form of a script.
For MATLAB Psychtoolbox (PTB), for Python PsychoPy.

It handles the instructions, training trials, experimental trials with stimuli,
records the responses, provides feedback.

Recording EEG and triggers

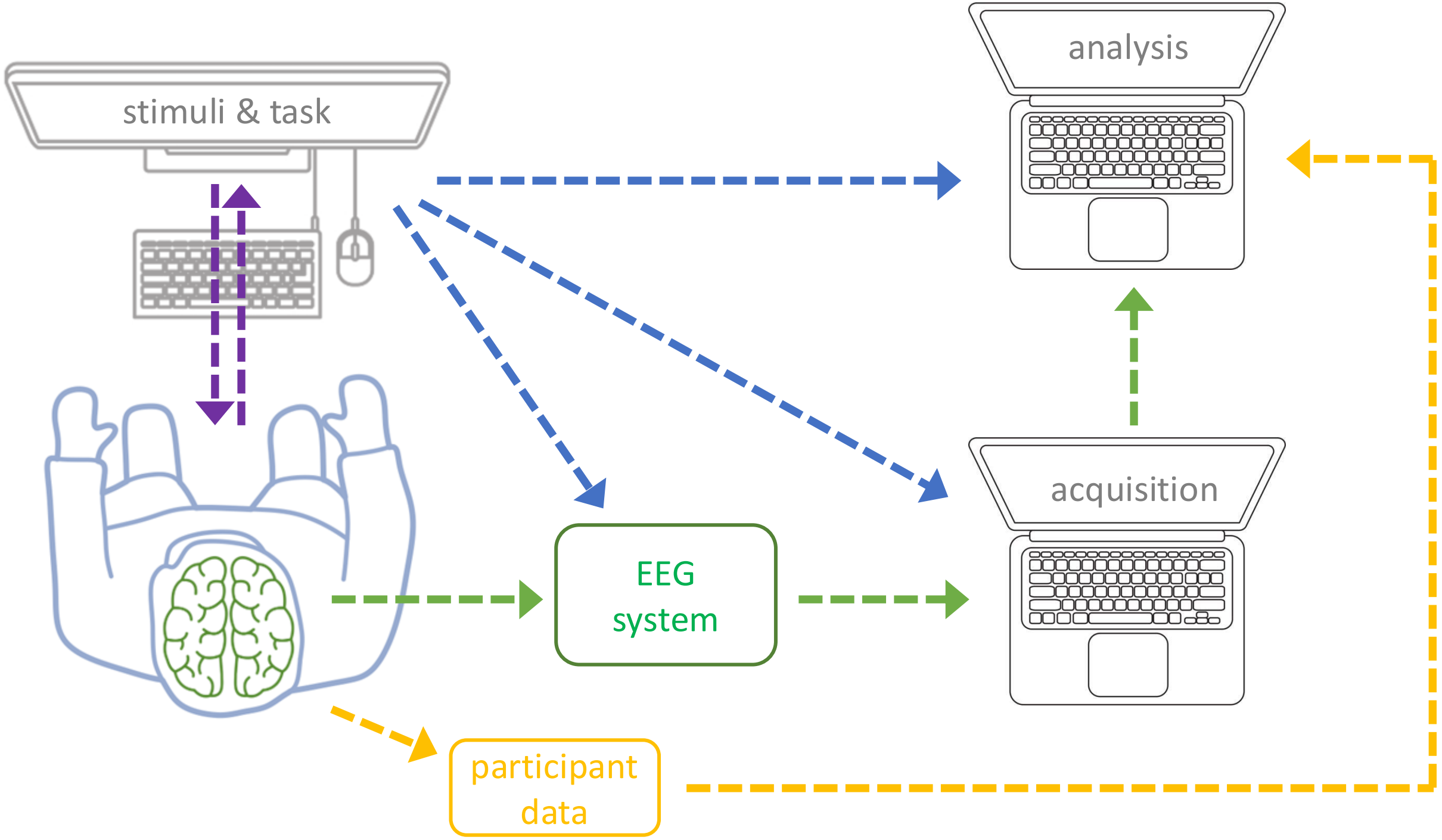
The stimulus presentation software sends a “trigger” or “marker” to the EEG system *exactly* at the moment that something happens.

We sample EEG usually at 250 or 500 Hz, which means that we have one sampe every 2 ms.

Computer displays often work at 60Hz: the screen is redrawn every 16.7 ms.

Sounds travel through air at 343 m/s: a distance of 1 meter takes ~3 ms.

Normally, computers do not have to be very precise in timing, as the brain is so good and flexible in auditory-visual integration.


stimuli & task
analysis
acquisition
EEG
system
participant
data

Spontaneous activity versus task-related activity

Spontaneous EEG has fluctuations of 10 to 100 µV (microvolt)

Event-related activity has fluctuations of 1-5 µV

Differences in event-related activity are even smaller with 0.1-0.5 µV

To be able to see the event-related activity, you have to average.

The background brain activity is considered noise for the purpose of the task.

Random noise averages out, and reduces with sqrt(Ntrials)

10 trials -> 3x lower noise

100 trials -> 10x lower noise

Averaging the EEG over trials and subjects

A typical experiment with a single participant has 100-500 trials, over the different conditions.

This allows to recognize the ERP (after averaging over trials) over the background spontaneous brain activity (noise).

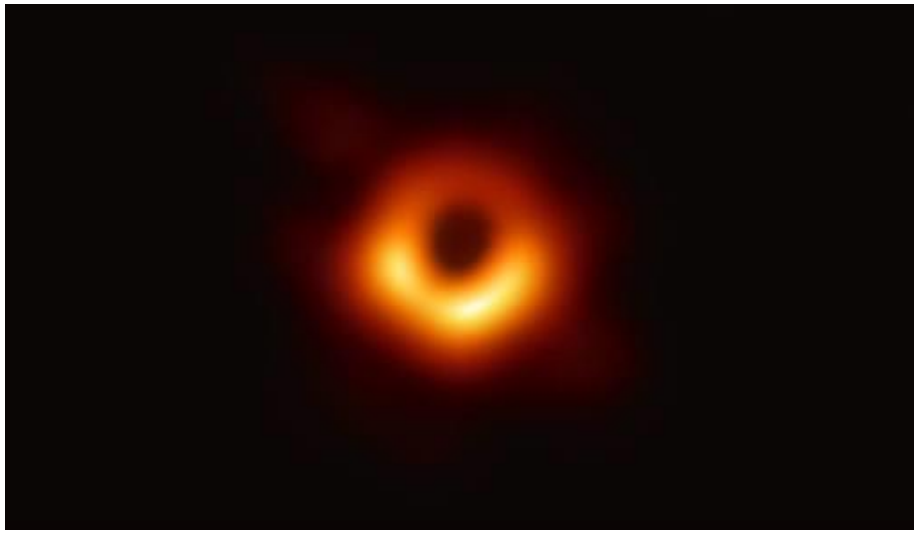
A typical study has 20-50 participants.

This allows to see subtle ERP differences between conditions, after averaging over the participants.

Brain-computer interfaces (BCIs) aims to detect brain activity in a single trial in a single participant.

Astrophysics - taking a photo of a black hole

For Sagittarius A* - the supermassive black hole at the center of our Milky Way - the final published image was produced by averaging together thousands of different computer-generated images created through various reconstruction methods.

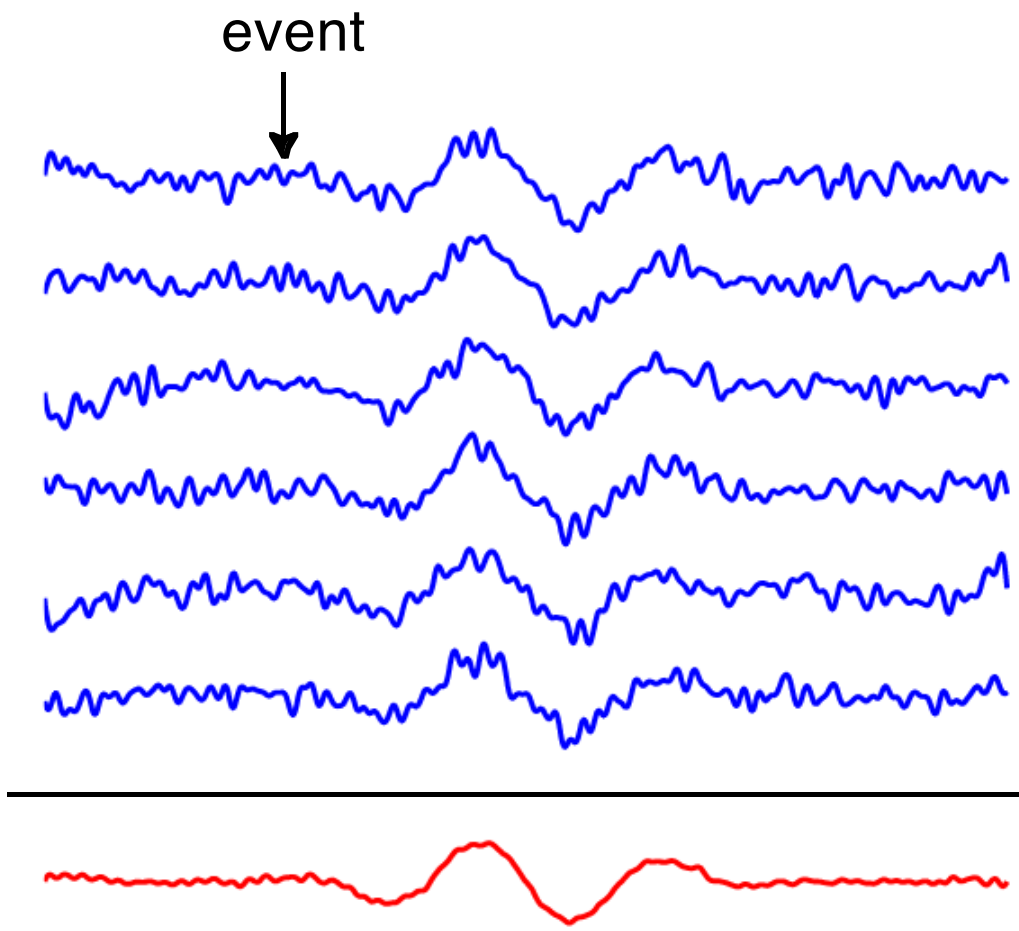


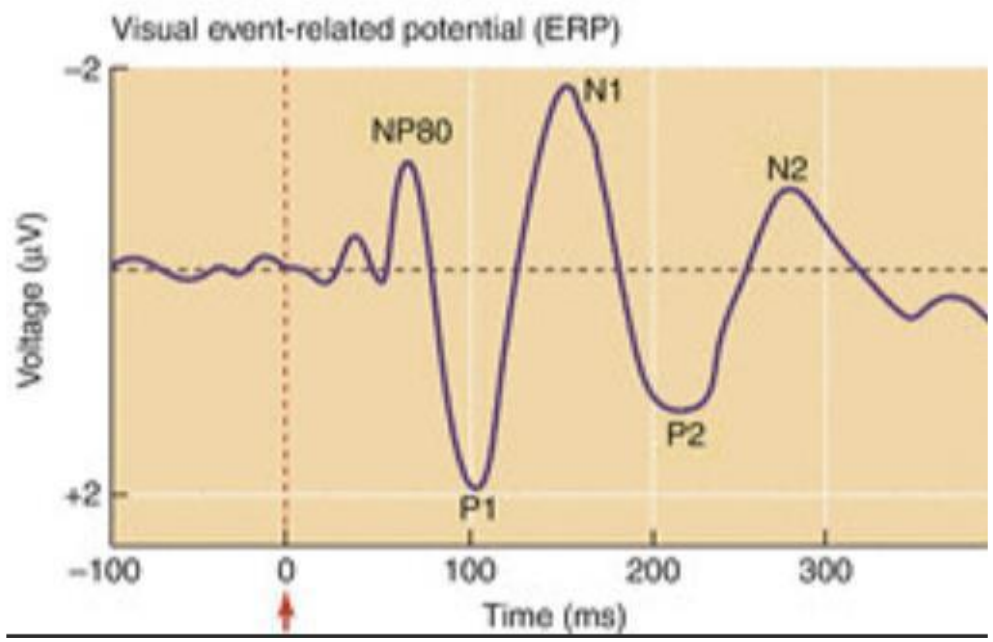
For EEG:

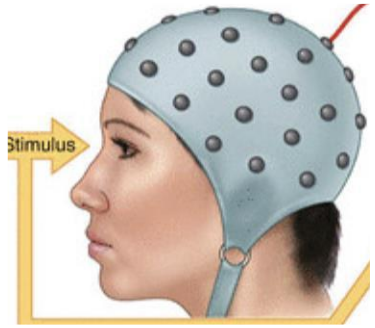
trials and participants

ERPs, Fourier spectra, or TFRs

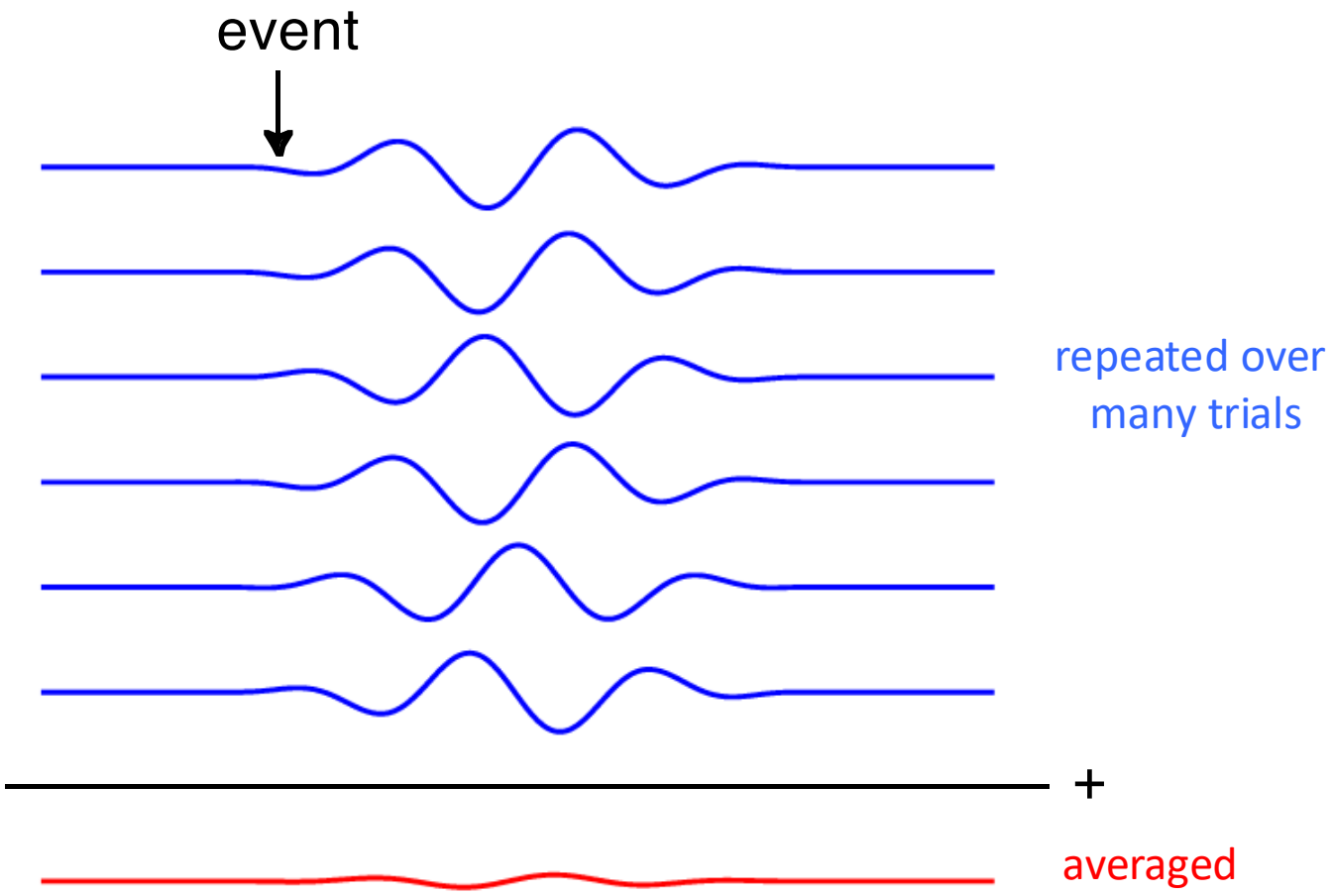
Visual Evoked Potential (EP) or Event-Related Potential (ERP)

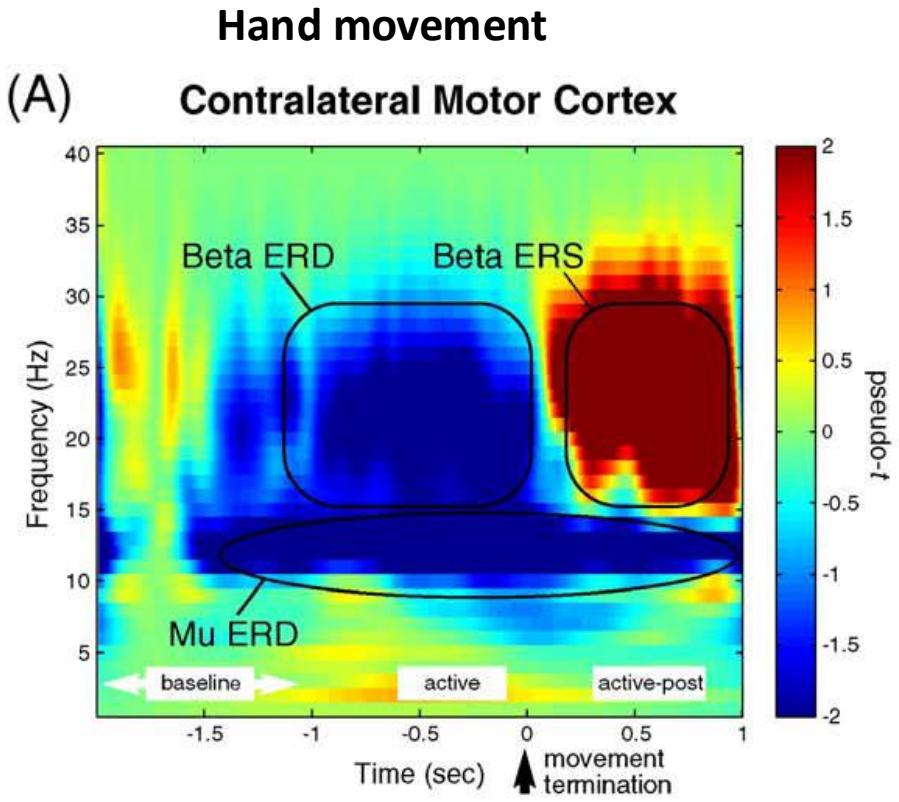






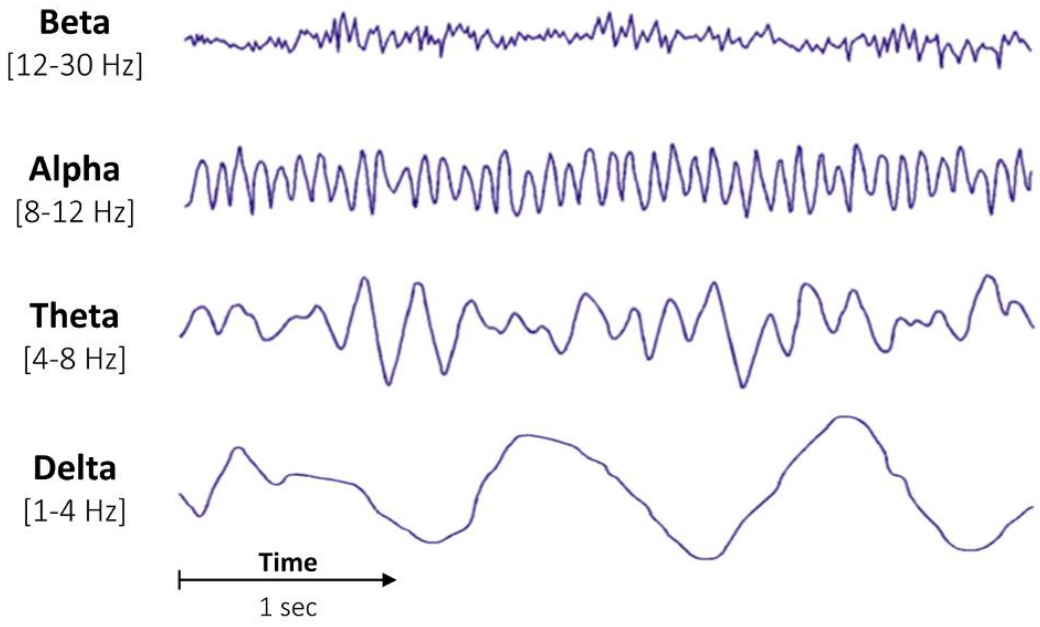
Time-Frequency Response (TFR)
Event Related (de)synchronization (ERD or ERS)

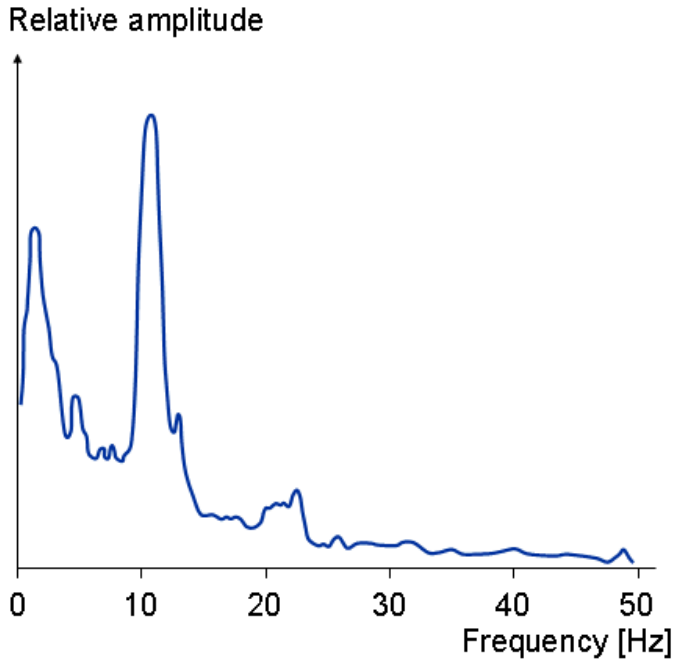




Frequency or spectral or Fourier analysis

Fourier analysis is a math trick that takes a complicated wave (like sound, or EEG) and breaks it down into its basic ingredients—pure sine waves of different pitches/frequencies and volumes/amplitudes.





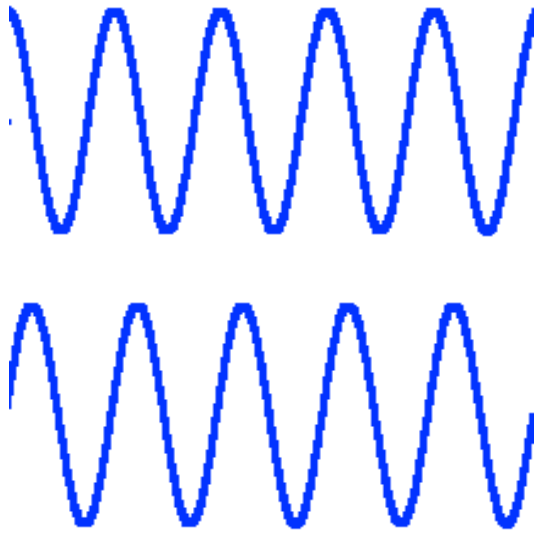
Frequency analysis

Deconstructing a time-domain signal into its components, using simple oscillatory functions: cosines and sines.

When it goes up and down *once* per second, it is a 1 Hz signal

When it goes up and down *twice* per second, it is a 2 Hz signal

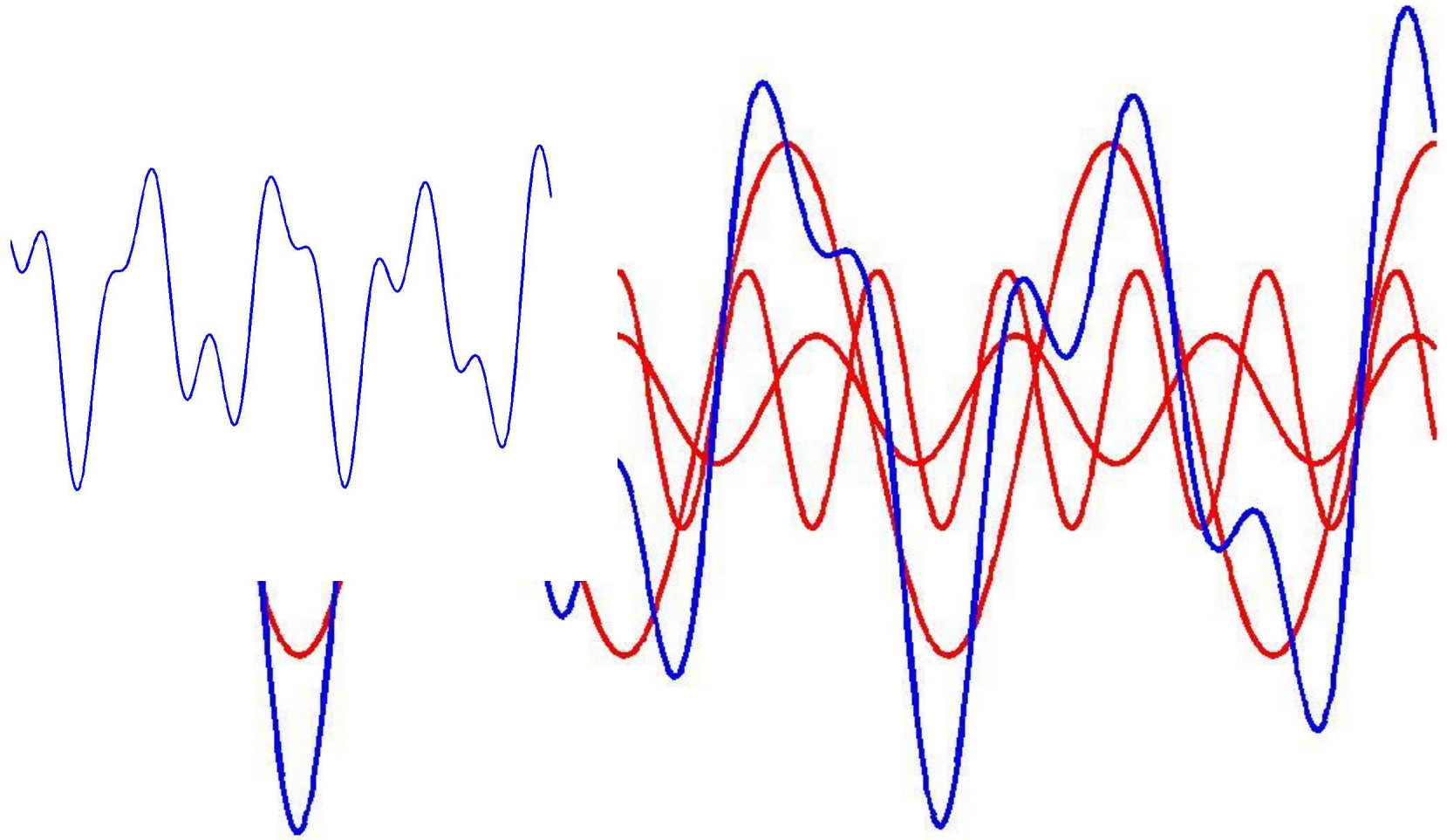
When it goes up and down *once per ½ second*, it is a 2 Hz signal.



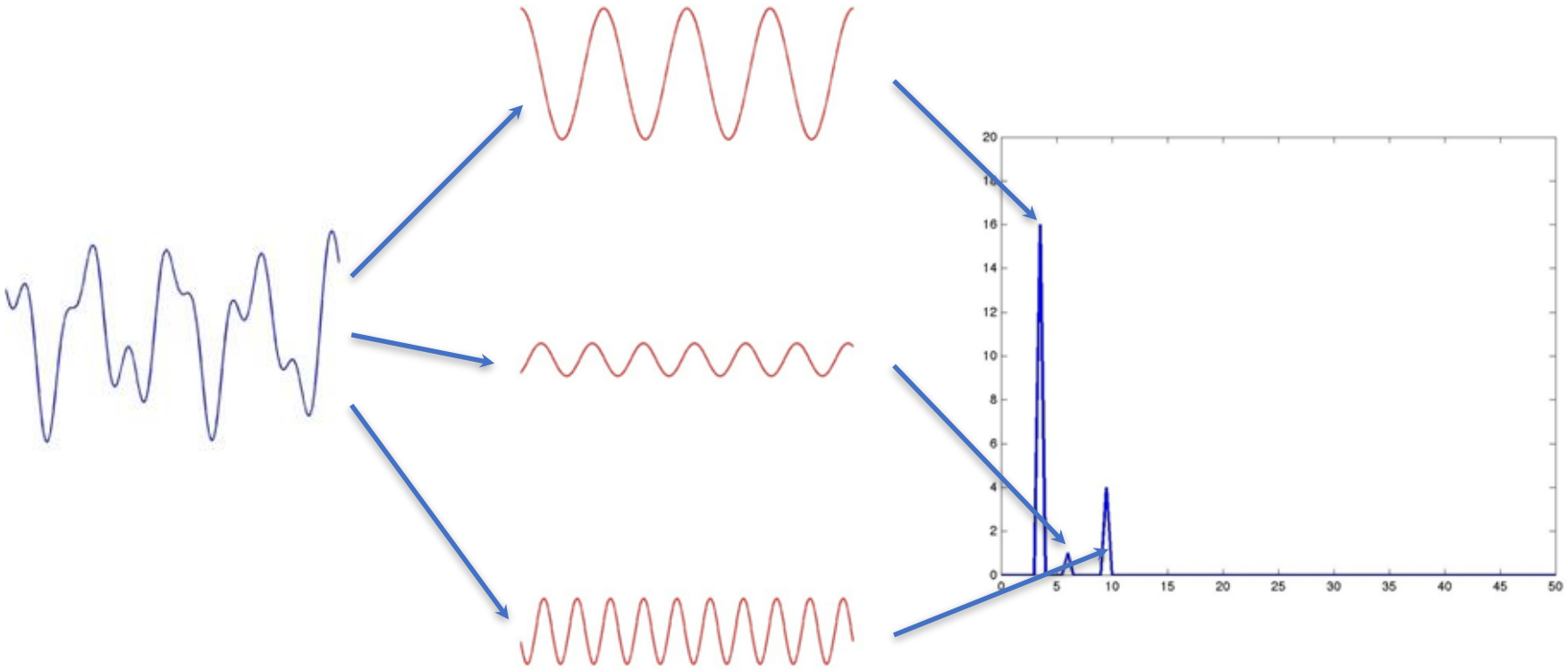
The frequency is one-divided-by the time that it takes to go up and down.

F = 1/T

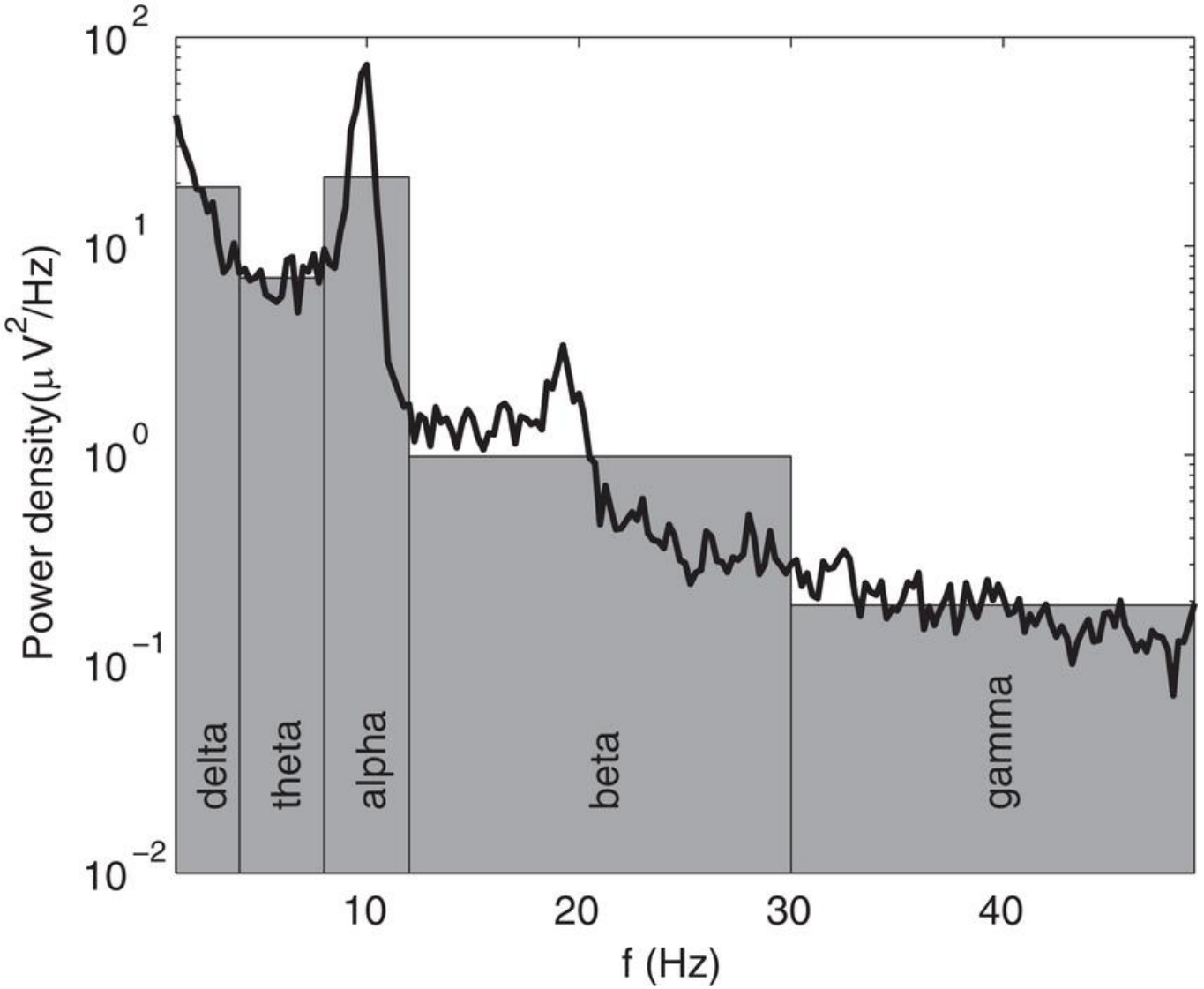
Spectral decomposition: the principle



Spectral decomposition: the power spectrum



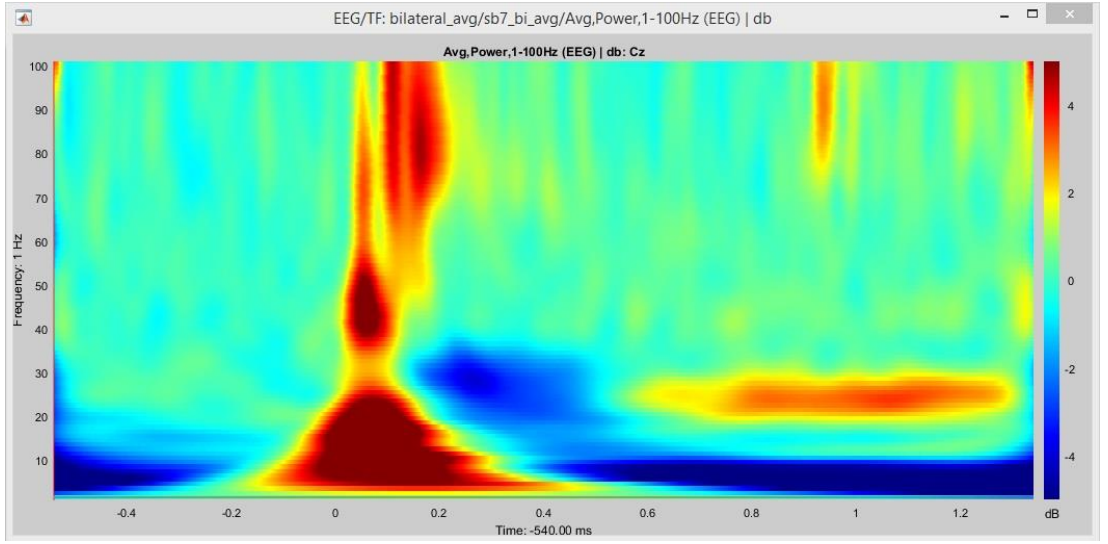
The spectrum of EEG



Time frequency analysis

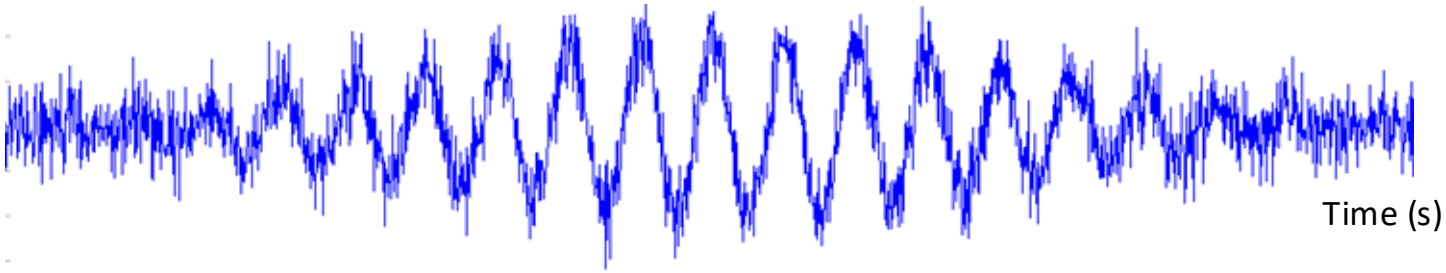
Fourier analysis on a sliding window

Wavelet analysis

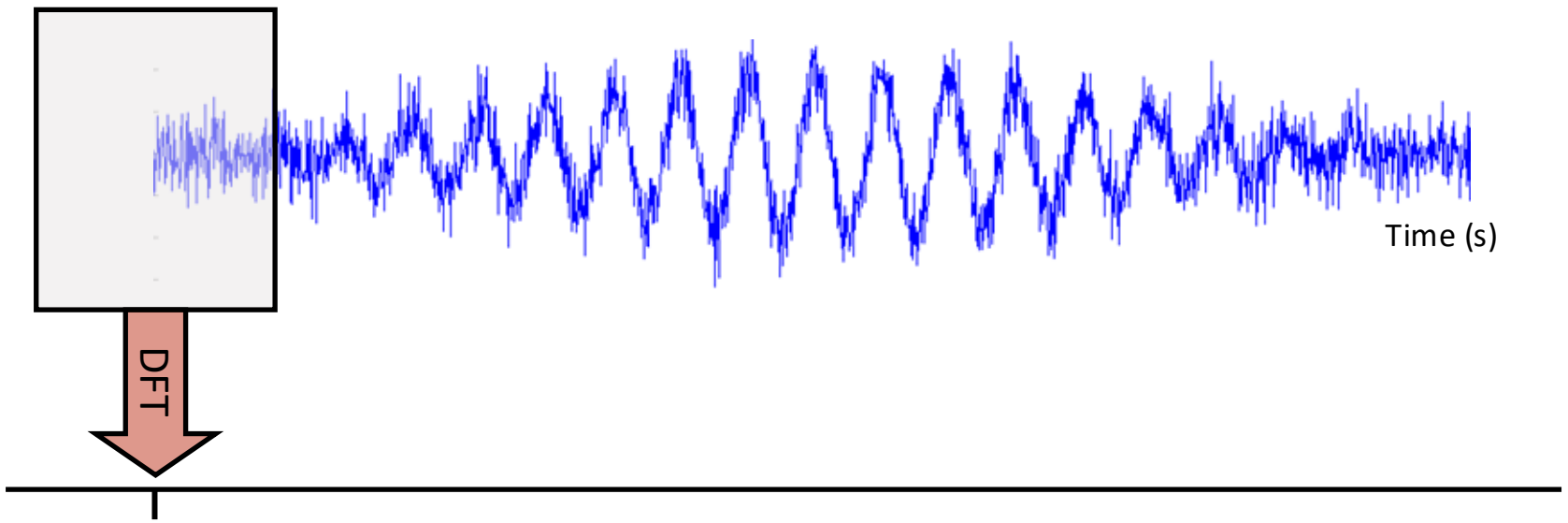


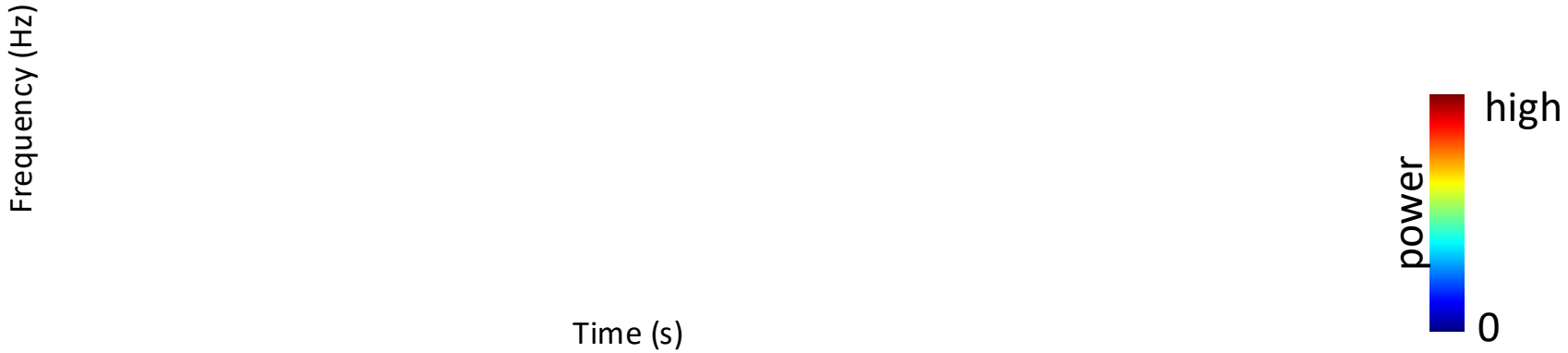
For each timepoint (z-axis) you get a power spectrum for all frequencies (y-axis), which is usually color coded (red=high power, blue is little power).

Time frequency analysis

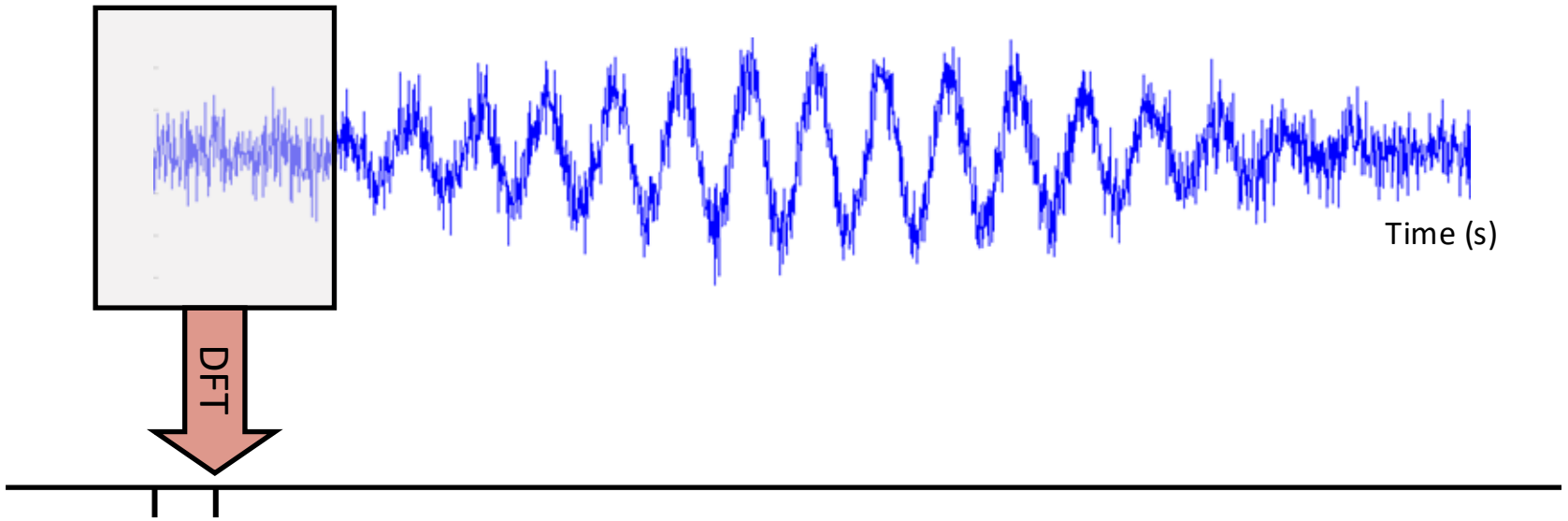


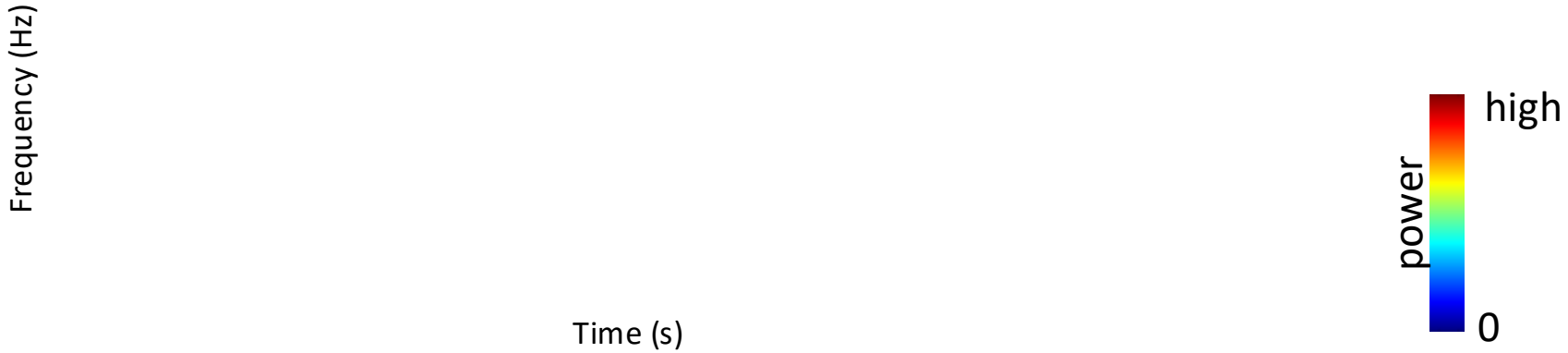
Time frequency analysis



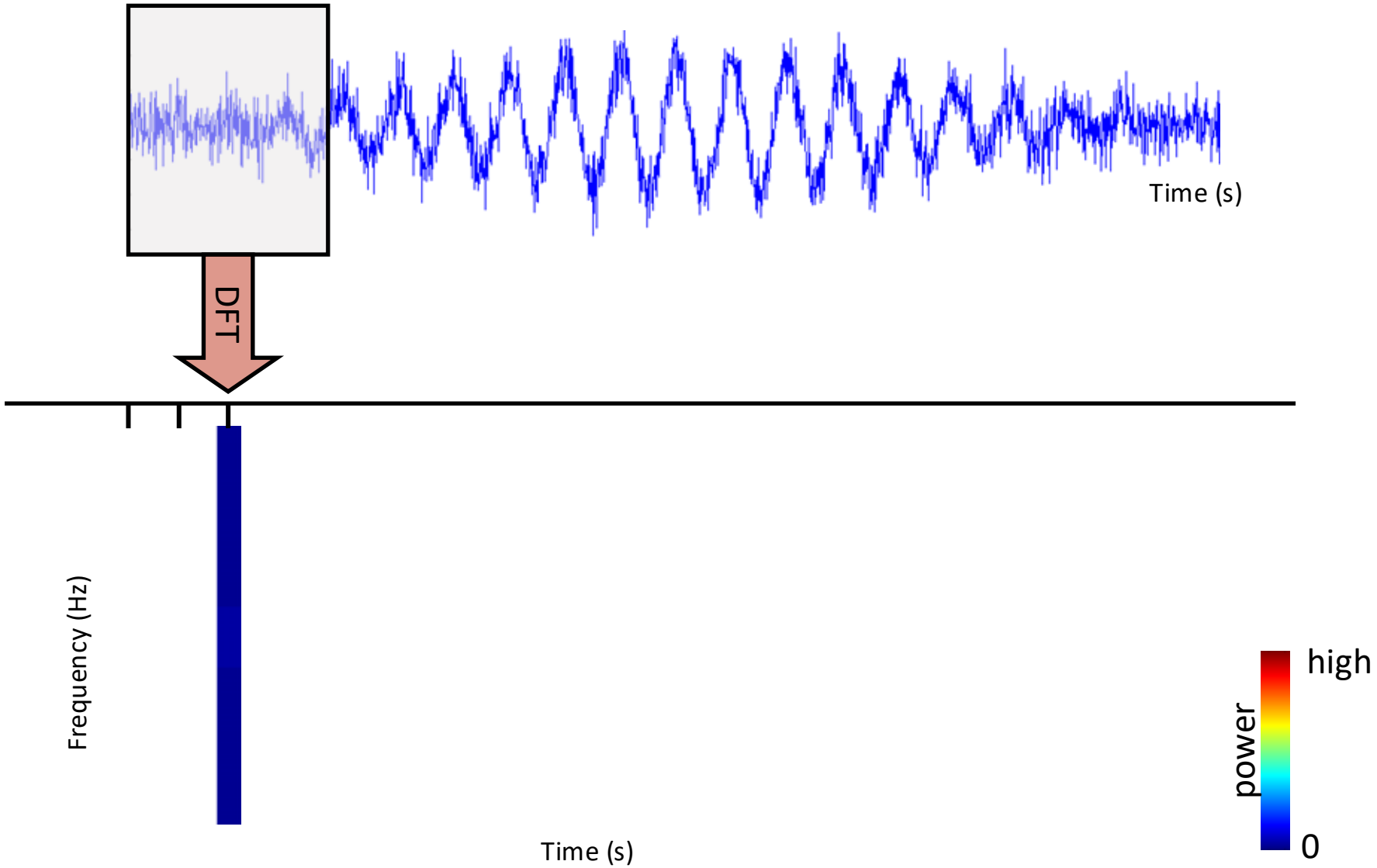


Time frequency analysis

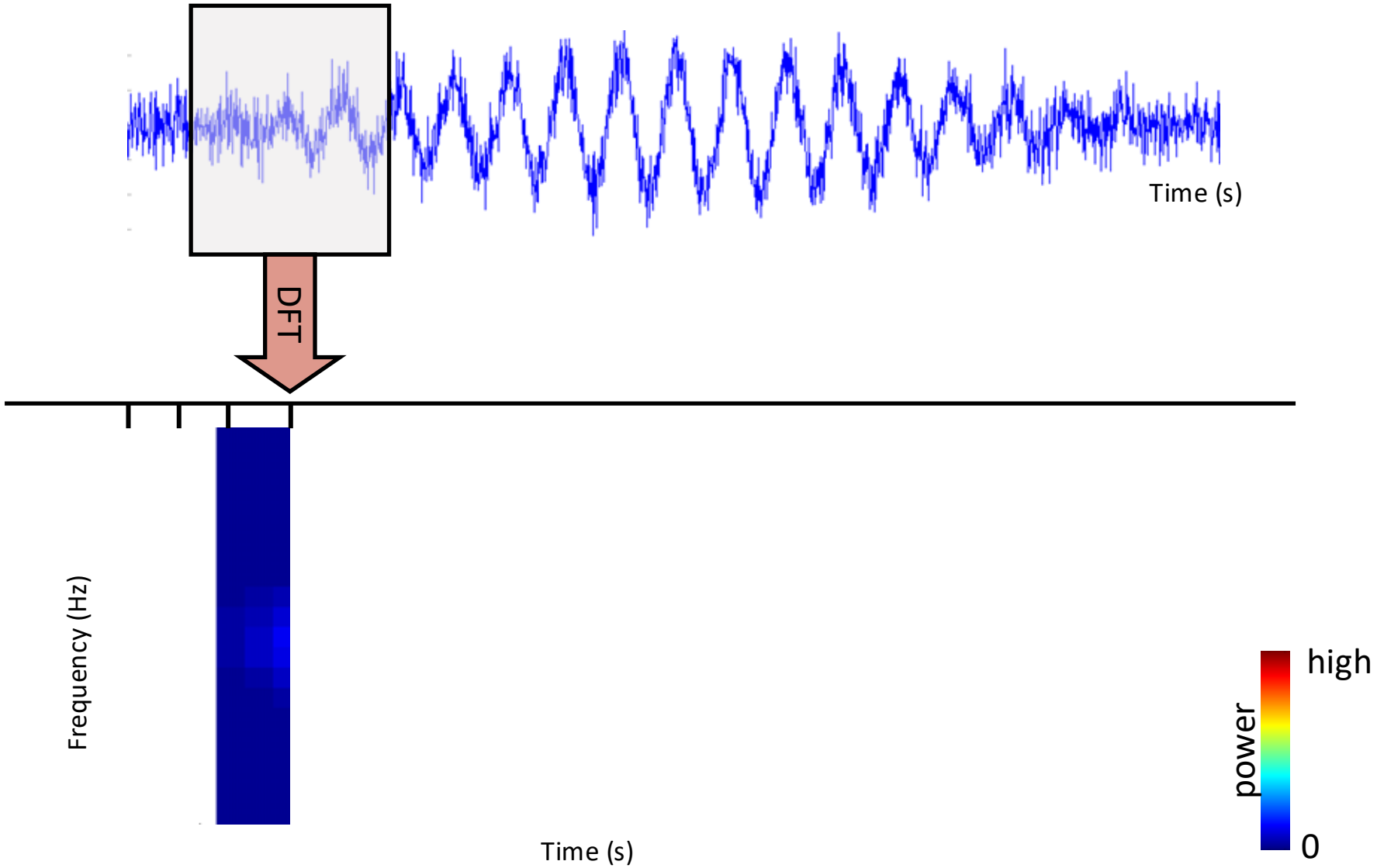




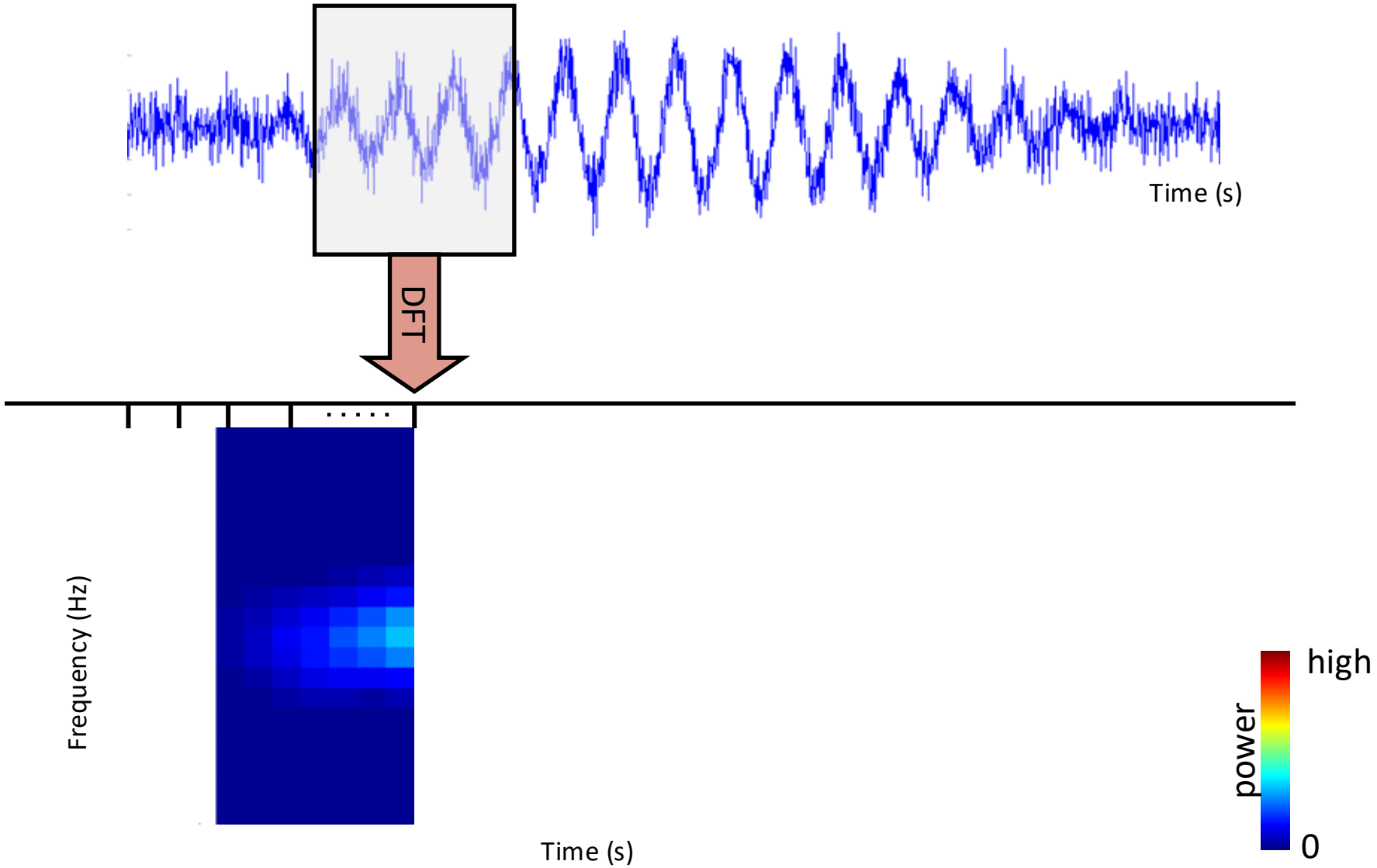
Time frequency analysis



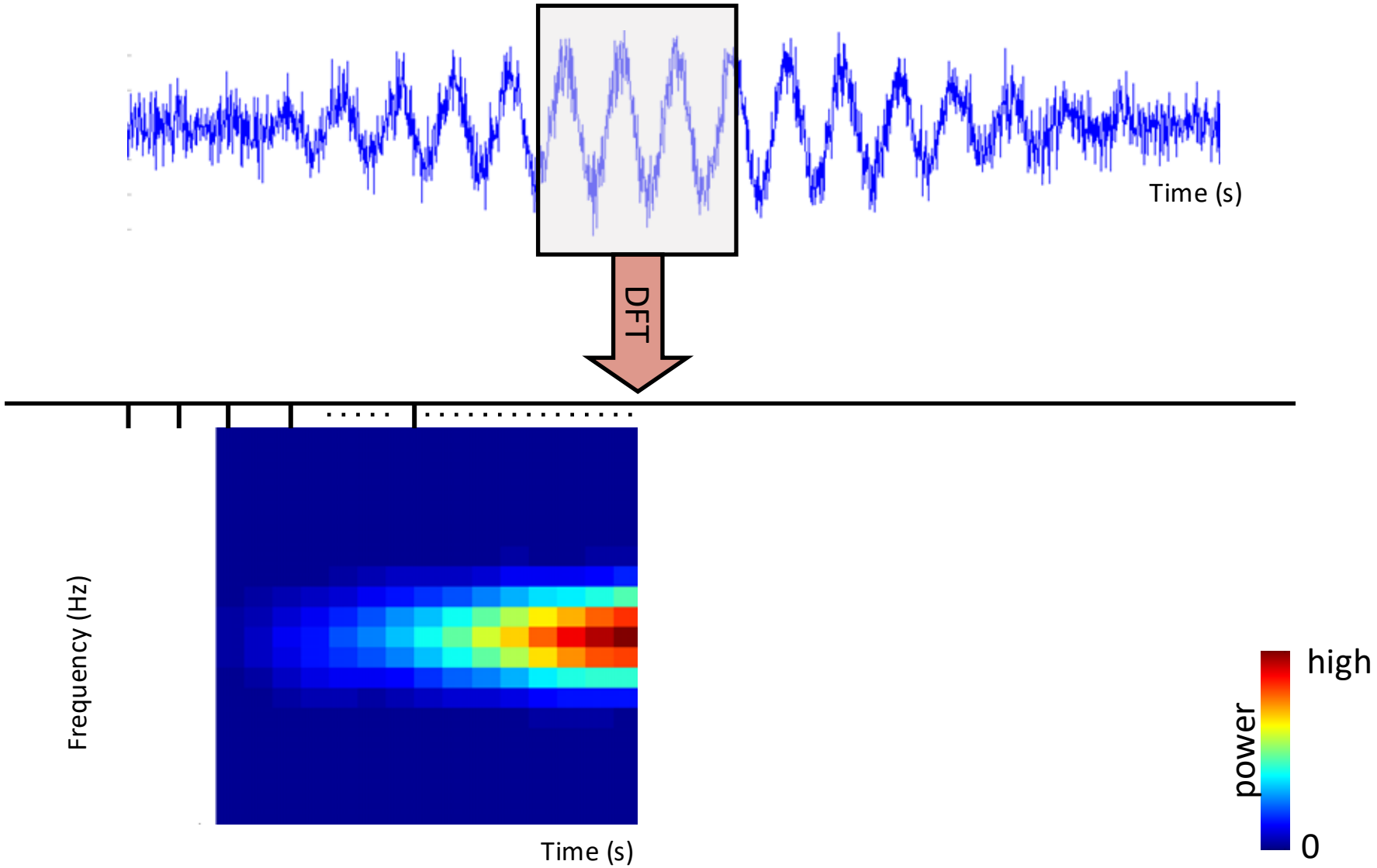
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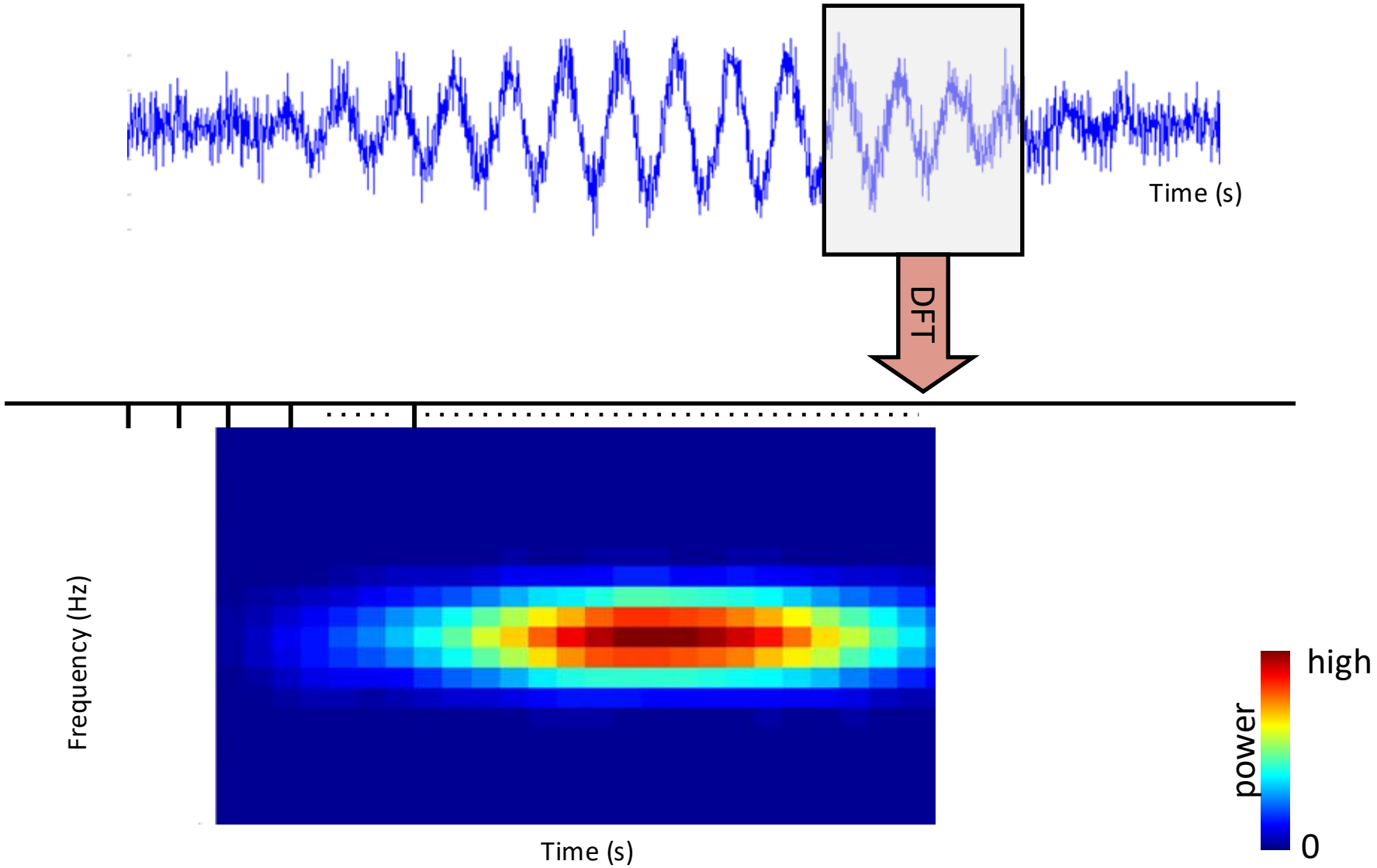
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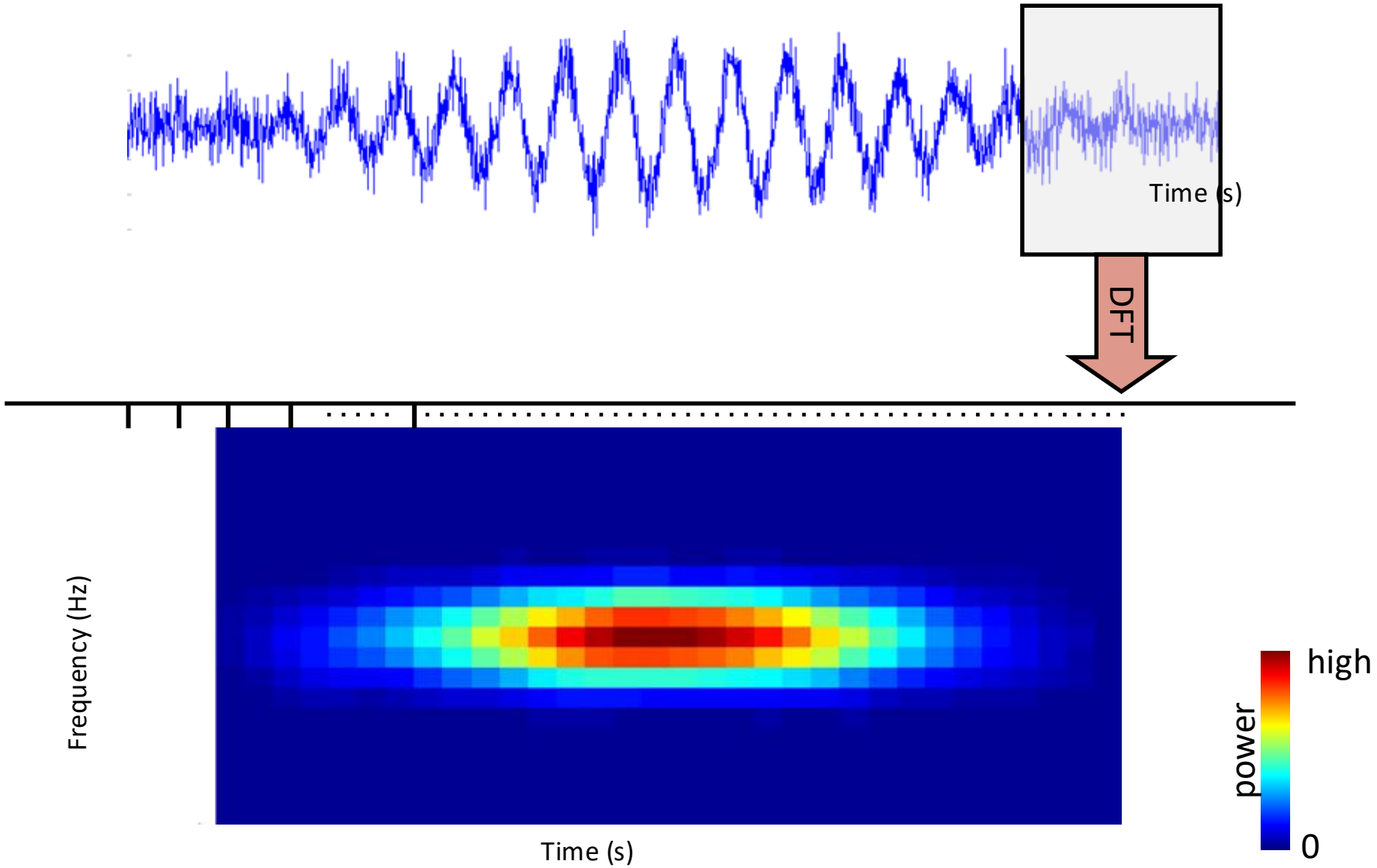
Time frequency analysis



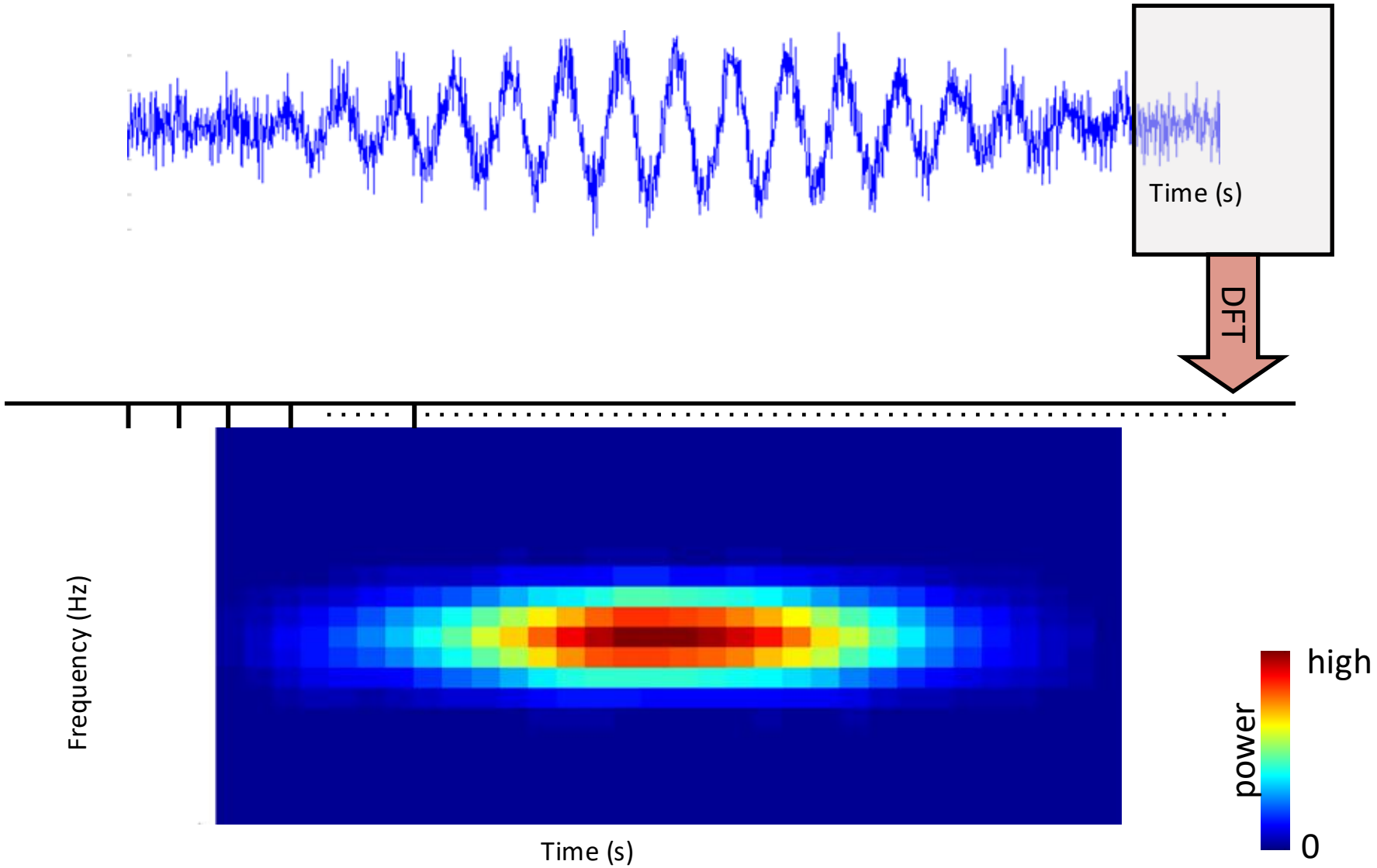
Time frequency analysis



Time frequency analysis

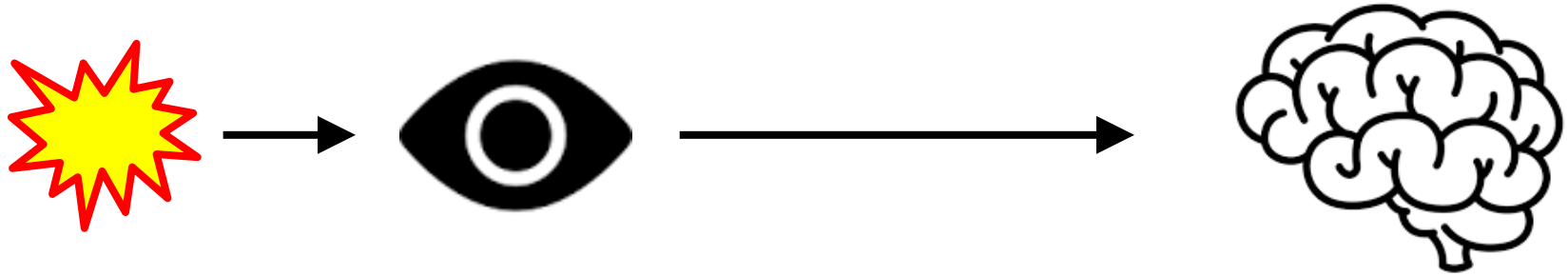


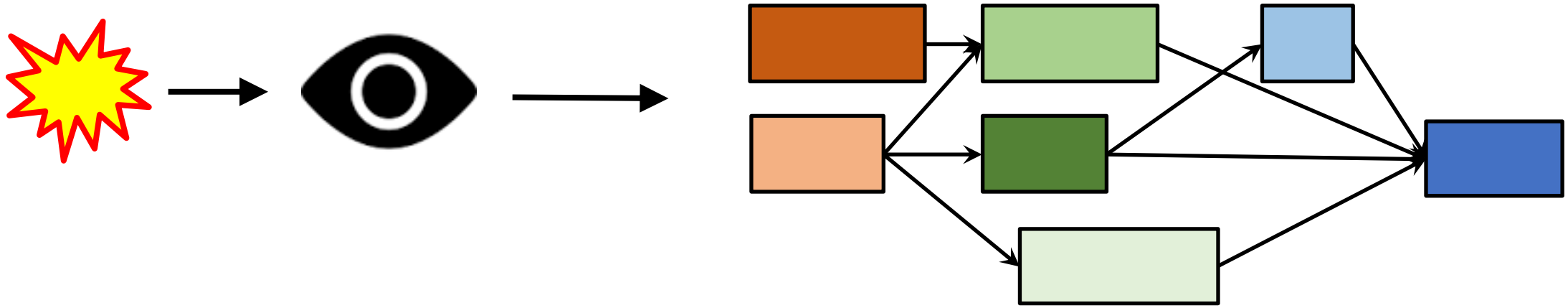
Time frequency analysis



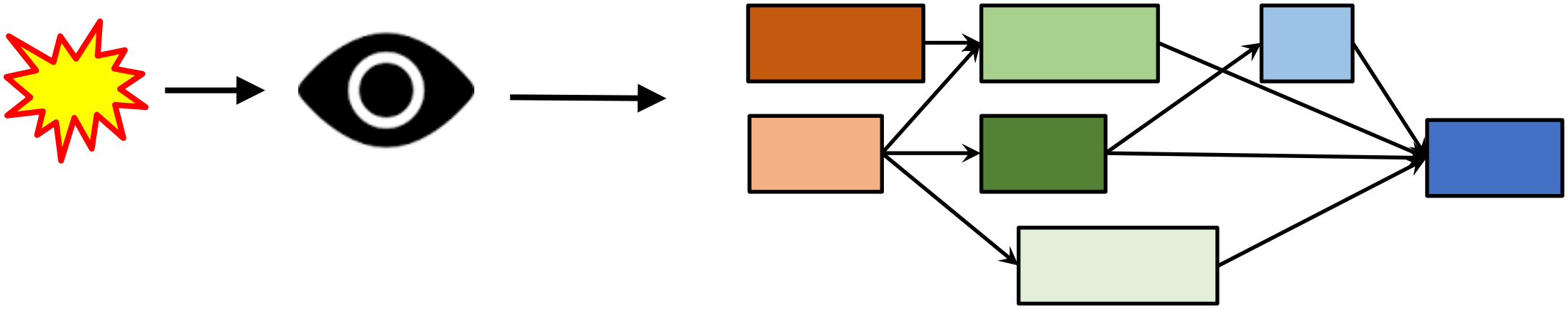
How to use EEG technology for a scientific study

Why study the EEG in response to events?





ERP and TFR components reveal the *when* and *where*



Different processes at different time-points relative to the event

Different processes in different brain areas

Identifying the *latency* and *topography* of ERP components helps to disentangle these functional networks.

A typical EEG study …

100-500 trials and 20-50 participants

You present one trial every second or every few seconds

- 100 trials = 3 minutes
- 500 trials = 15 minutes

Add the instructions, time for breaks, 15-30 mins

Add the preparation time, 15-30 mins

A whole experiment (one session) with a single participant takes 1-1.5 hours.

So executing the EEG data acquisition easily takes up to 2 weeks to 2 months.

The data analysis also takes a few months.

Real-time closed-loop feedback for BCI

EEG signal is analyzed in (more-or-less) real time

EEG signal features are translated into a control signal

Control signal is used as feedback, or to control something

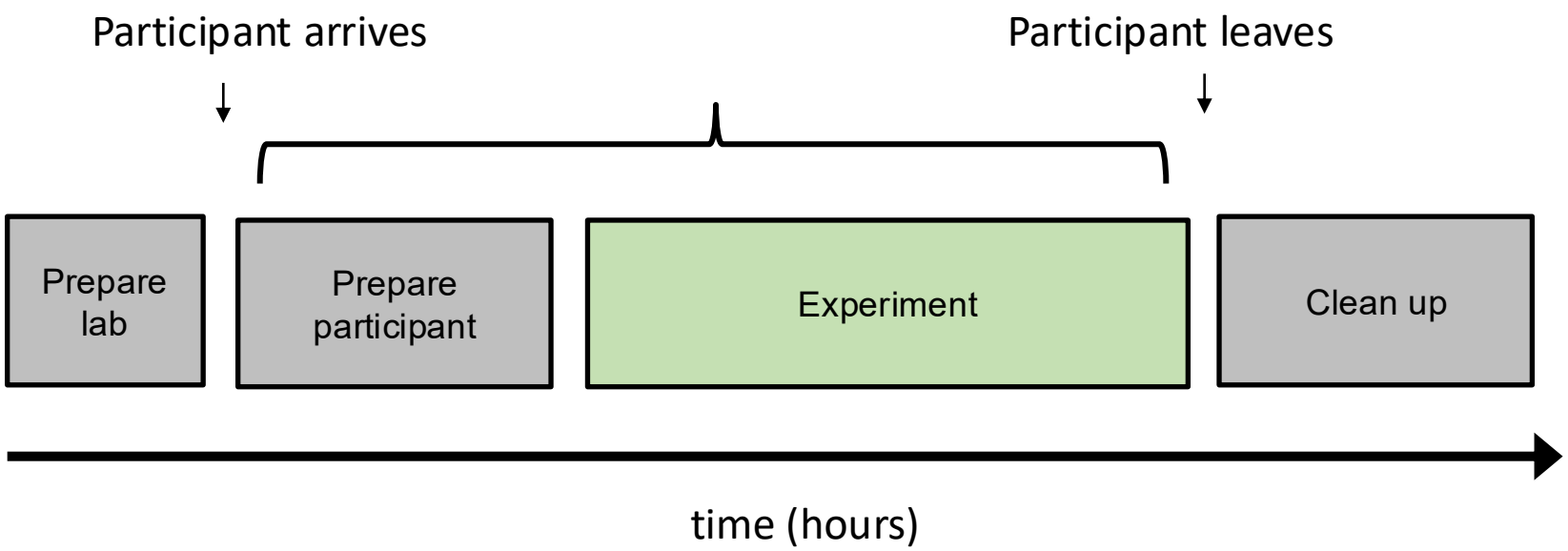
"Real time" means that within a few seconds the EEG should have a consequence

We only have a few seconds to capture the EEG, hence brain signals for BCI must be large and robust: occipital alpha, motor beta, P300

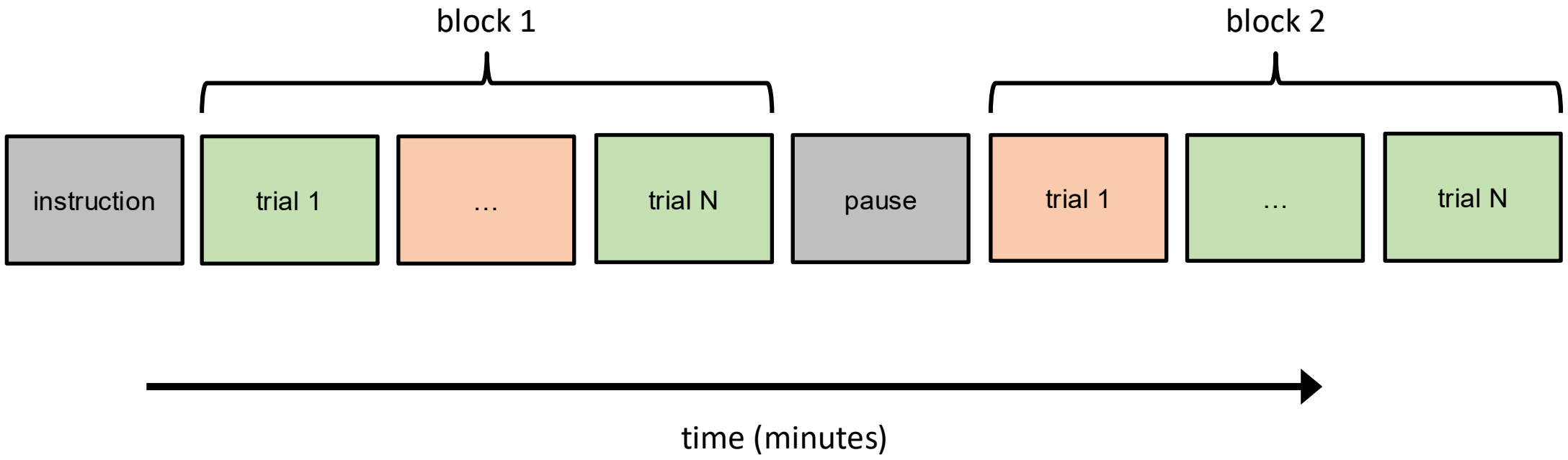
Artifacts are much bigger and can easily cause confounds

Muscular control (frowning or eye movements) provides easy *bio*feedback, but no *neuro*feedback

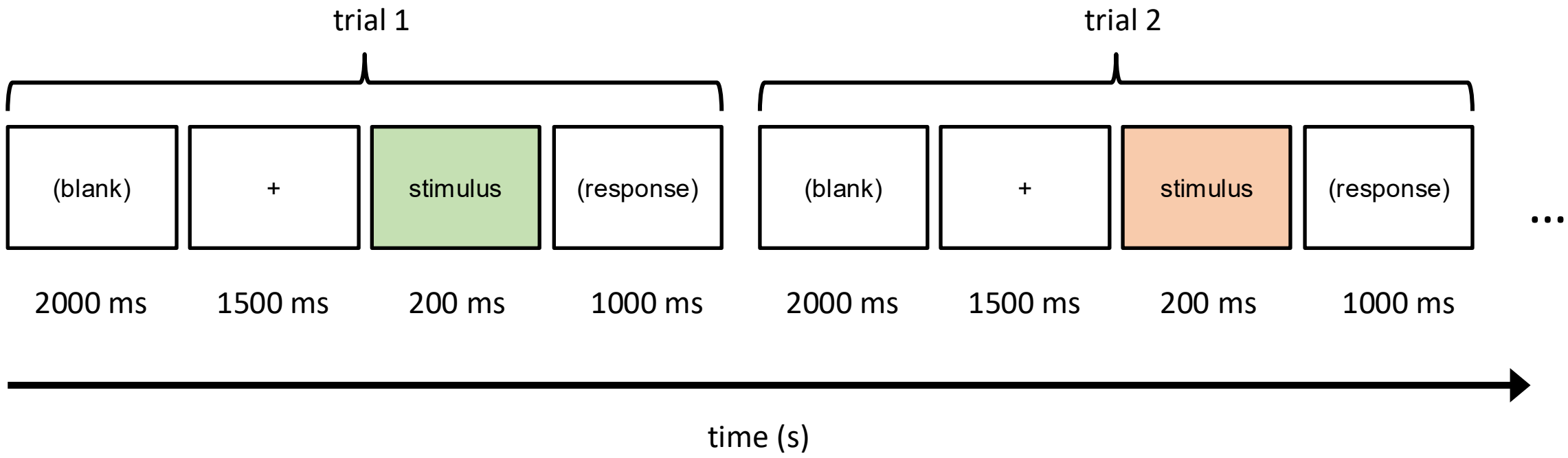
Record a single subject's EEG in the lab



Designing the experiment, global structure



Designing the experiment, more in detail



EEG data analysis pipeline

EEG preprocessing and analysis

Visual inspection and artifact rejection

Bad channel detection

Filtering

Re-referencing

ICA and artifact removal

Segmenting

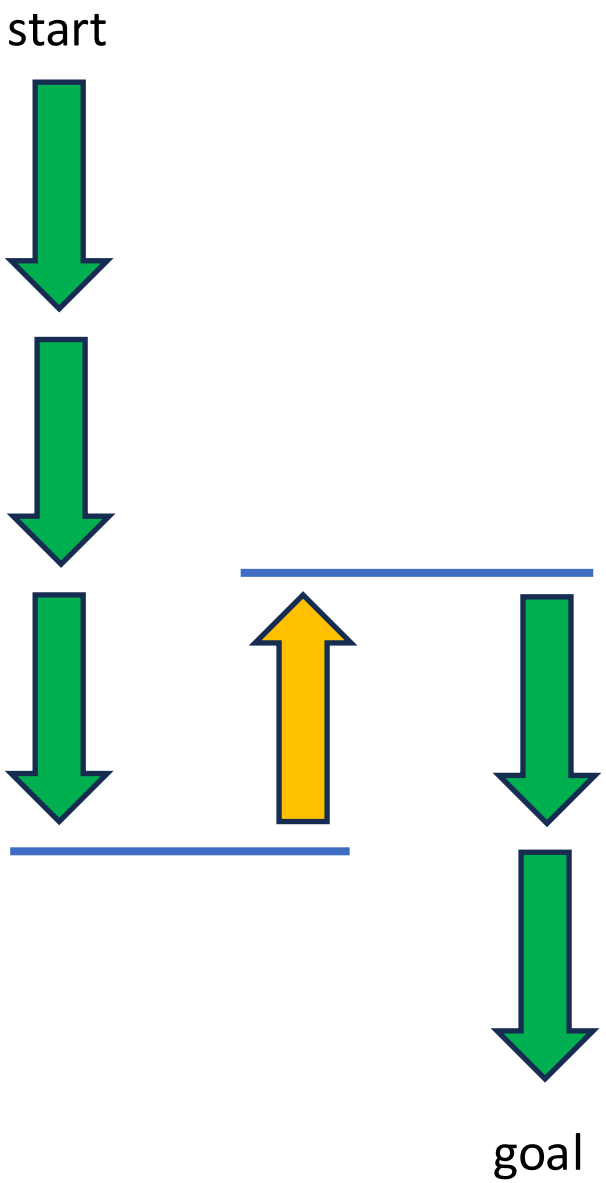
Averaging over trials to get the ERP

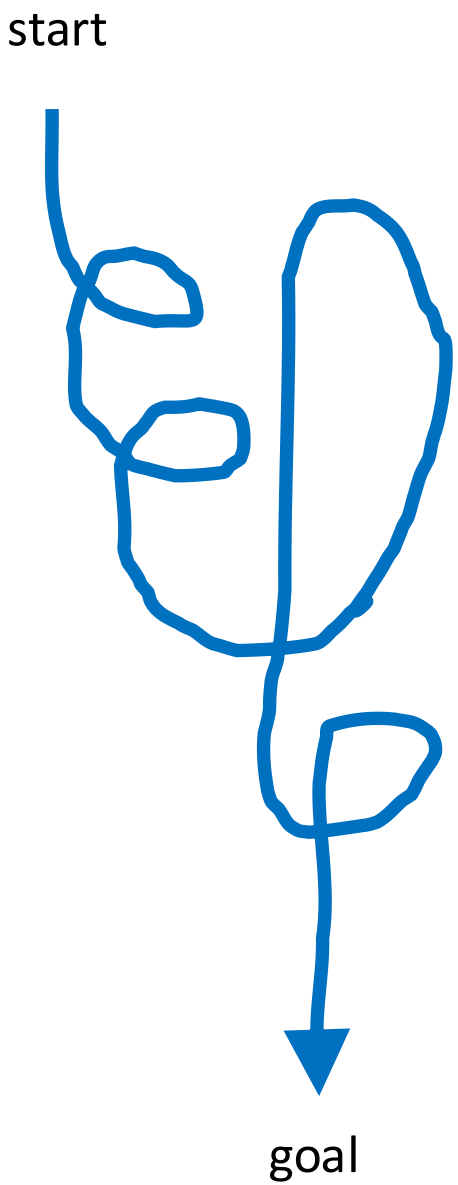
Computing TFRs and averaging over trials

Frequency analysis

Statistical evaluation over participants

EEG preprocessing often requires multiple iterations





EEG preprocessing and analysis

Visual inspection and artifact rejection

Bad channel detection

Filtering

Re-referencing

ICA and artifact removal

Segmenting

Averaging over trials to get the ERP

Computing TFRs and averaging over trials

Frequency analysis

Statistical evaluation of condition differences or treatment effects over participants

EEG Data Processing Demonstration