Introduction to EEG/ERP

EEG signals, brain rhythms, and ERP components

Robert Oostenveld

8 June 2026
Nairobi, Kenya

robert.oostenved@donders.ru.nl

Outline

Short into of myself

What is the EEG

Volume conduction and spatial topographies

Time-series, spectra and ERPs

Designing an EEG study

Preprocessing and analyzing EEG and ERPs

Research questions to address with EEG

Introductions

African Brain Data Network

Robert Oostenveld

Mikkel Vinding

https://www.fieldtriptoolbox.org/workshop/nigeria2025/

Donders Institute for Brain, Cognition and Behaviour
Radboud University Nijmegen, The Netherlands

Short background on EEG

Electro · Encephalo · Graphy (EEG)

A brief history of EEG

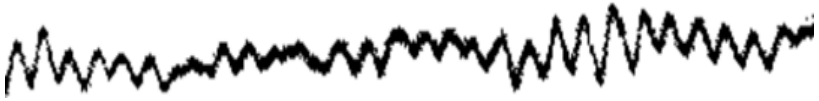
Hans Berger reported the first non-invasive human EEG in 1924

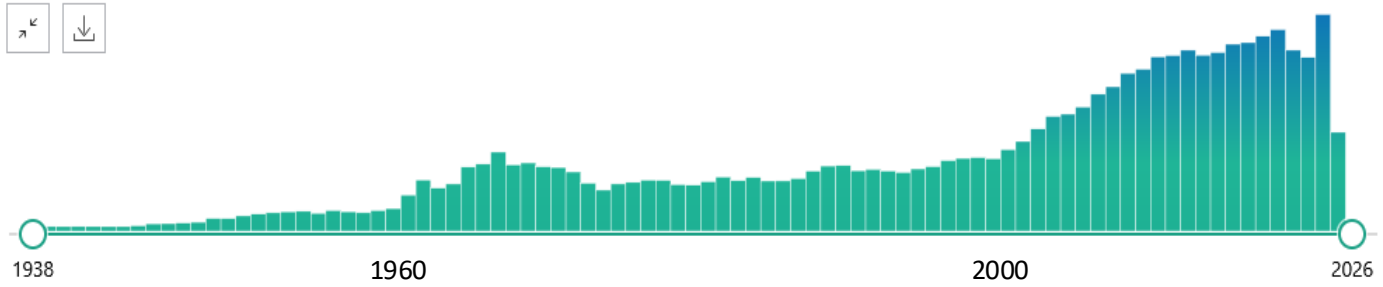
Established measurement

- Known canonical signals
- Standardised measurement schemes

Emerging technology

- Advanced analyses and (open-access) software
- Massive investment in R&D





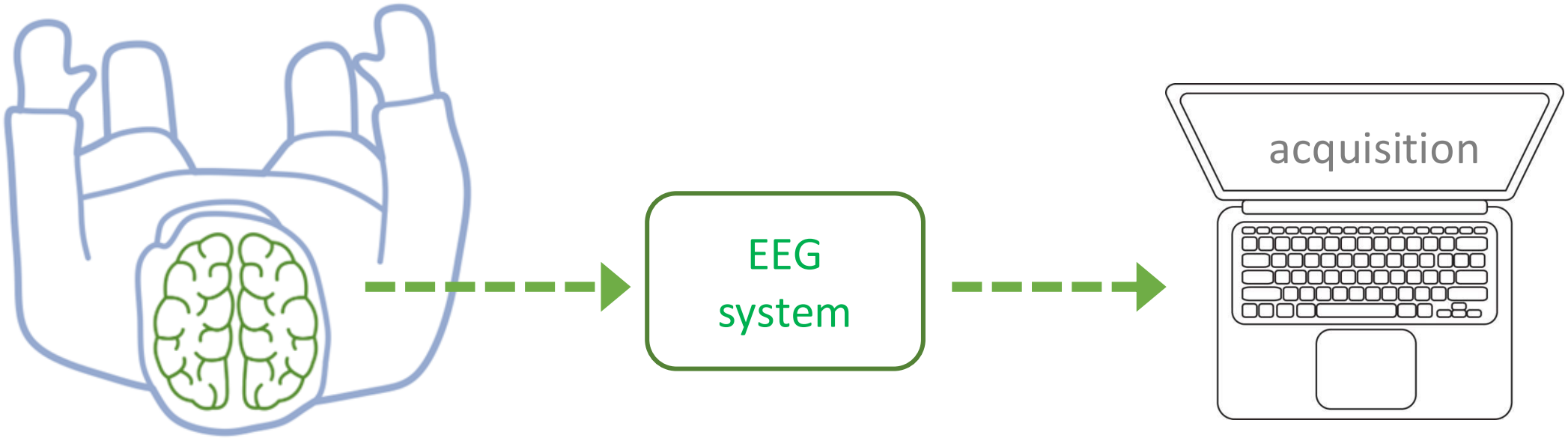
Comment

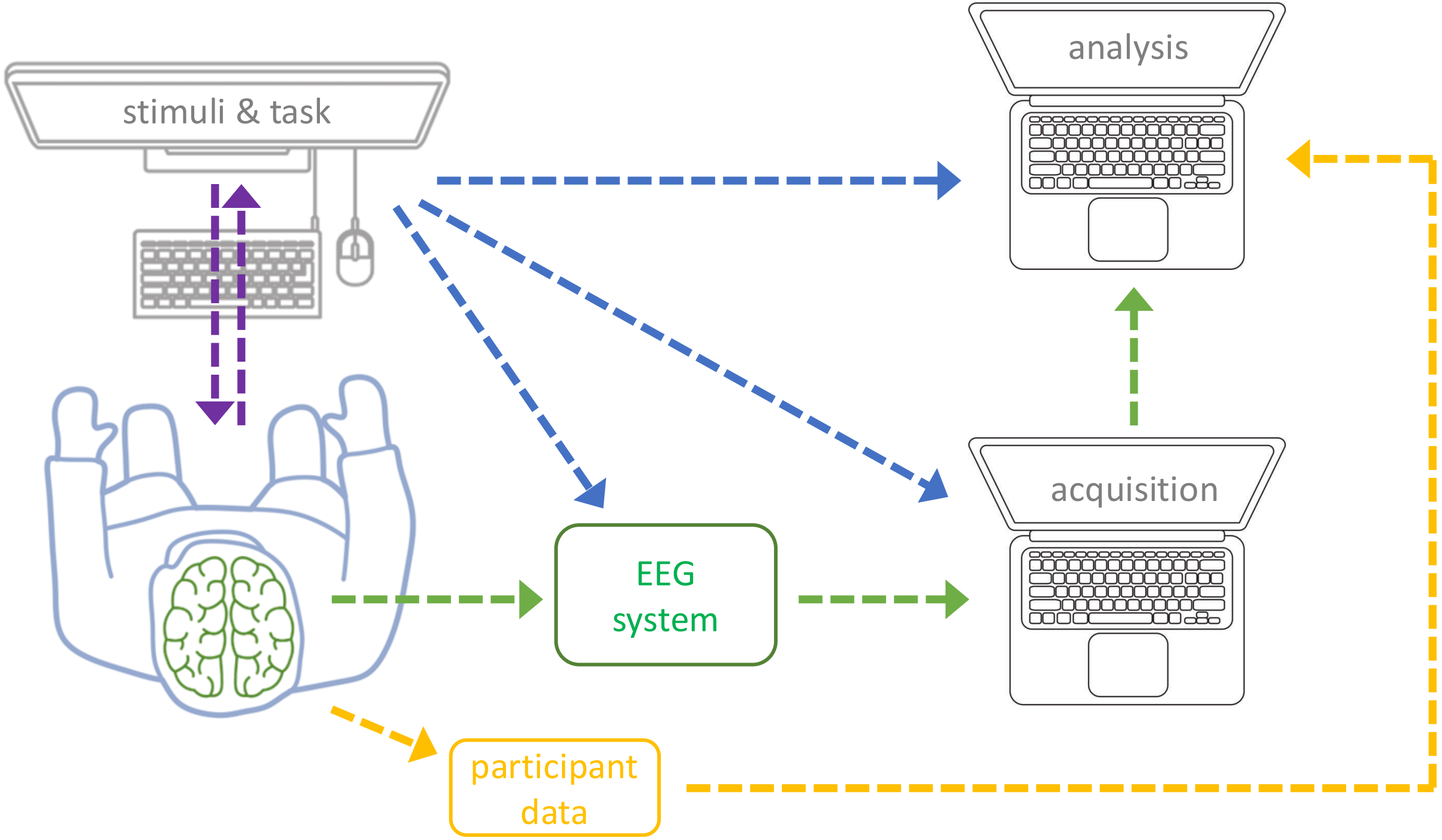
https://doi.org/10.1038/s41562-024-01941-5

One hundred years of EEG for brain and behaviour research

Faisal Mushtaq, Dominik Welke, Anne Gallagher, Yuri G. Pavlov, Layla Kouara, Jorge Bosch-Bayard, Jasper J. F. van den Bosch, Mahnaz Arvaneh, Amy R. Bland, Maximilien Chaumon, Cornelius Borck, Xun He, Steven J. Luck, Maro G. Machizawa, Cyril Pernet, Aina Puce, Sidney J. Segalowitz, Christine Rogers, Muhammad Awais, Claudio Babiloni, Neil W. Bailey, Sylvain Baillet, Robert C. A. Bendall, Daniel Brady, Maria L. Bringas-Vega, Niko A. Busch, Ana Calzada-Reyes, Armand Chatard, Peter E. Clayson, Michael X. Cohen, Jonathan Cole, Martin Constant, Alexandra Corneyllie, Damien Coyle, Damian Cruse, Ioannis Delis, Arnaud Delorme, Damien Fair, Tiago H. Falk, Matthias Gamer, Giorgio Ganis, Kilian Gloy, Samantha Gregory, Cameron D. Hassall, Katherine E. Hiley, Richard B. Ivry, Karim Jerbi, Michael Jenkins, Jakob Kaiser, Andreas Keil, Robert T. Knight, Silvia Kochen, Boris Kotchoubey, Olave E. Krigolson, Nicolas Langer, Heinrich R. Liesefeld, Sarah Lippé, Raquel E. London, Annmarie MacNamara, Scott Makeig, Welber Marinovic, Eduardo Martínez-Montes, Aleya A. Marzuki, Ryan K. Mathew, Christoph Michel, José d. R. Millán, Mark Mon-Williams, Lilia Morales-Chacón, Richard Naar, Gustav Nilsonne, Guiomar Niso, Erika Nyhus, Robert Oostenveld, Katharina Paul, Walter Paulus, Daniela M. Pfabigan, Gilles Pourtois, Stefan Rampp, Manuel Rausch, Kay Robbins, Paolo M. Rossini, Manuela Ruzzoli, Barbara Schmidt, Magdalena Senderecka, Narayanan Srinivasan, Yannik Stegmann, Paul M. Thompson, Mitchell Valdes-Sosa, Melle J. W. van der Molen, Domenica Veniero, Edelyn Verona,

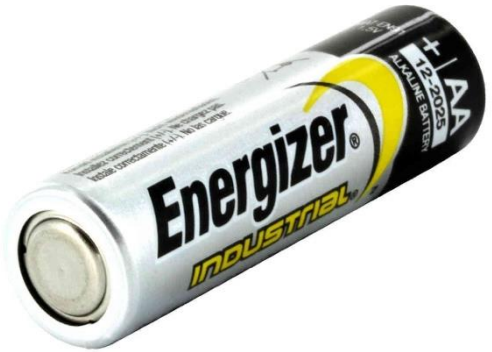
Examples of EEG


EEG
system
acquisition


stimuli & task
analysis
acquisition
EEG
system
participant
data

How do we record the EEG?

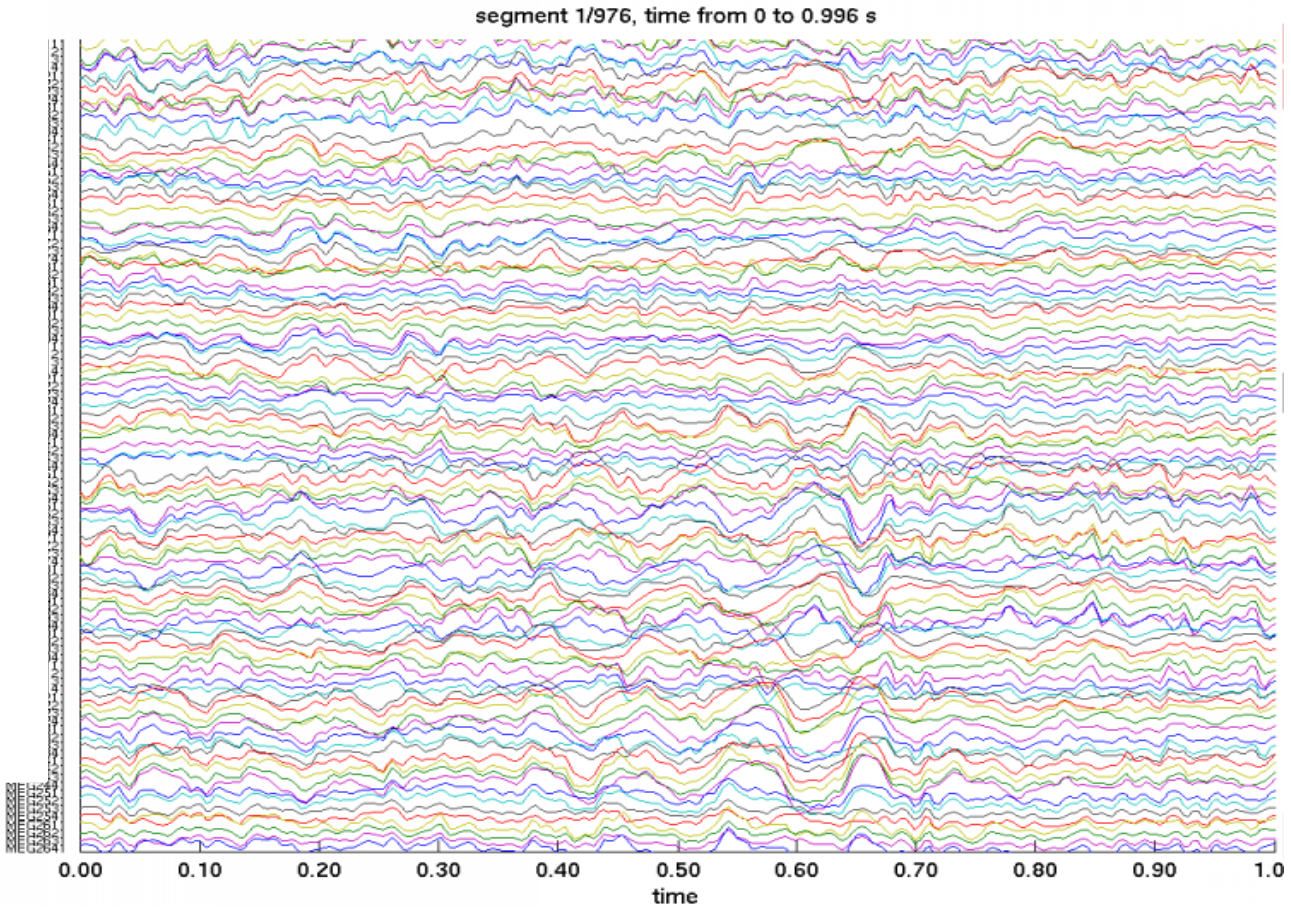
A common AA battery is 1.5 Volt



EEG signal also consists of voltages

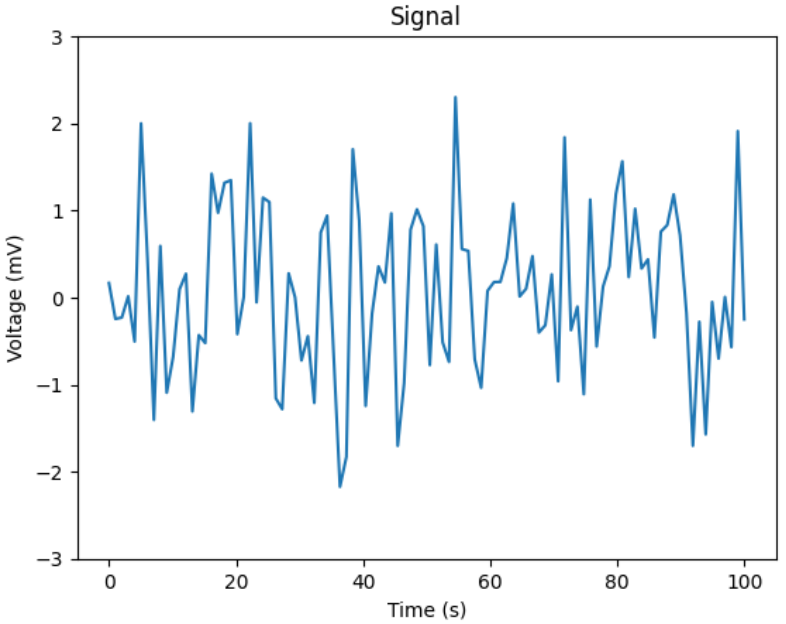
Voltage between electrodes measured in microvolts (µV)

EEG channels



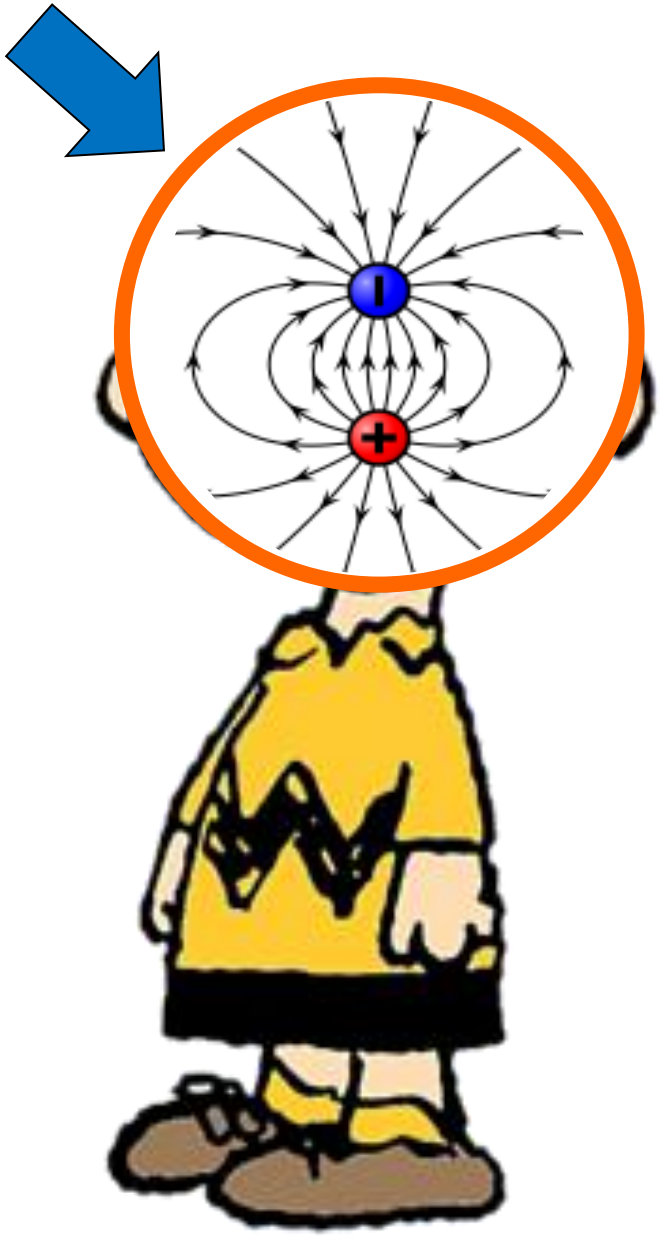
Time

Multiple microphones recording the sound in a ropom

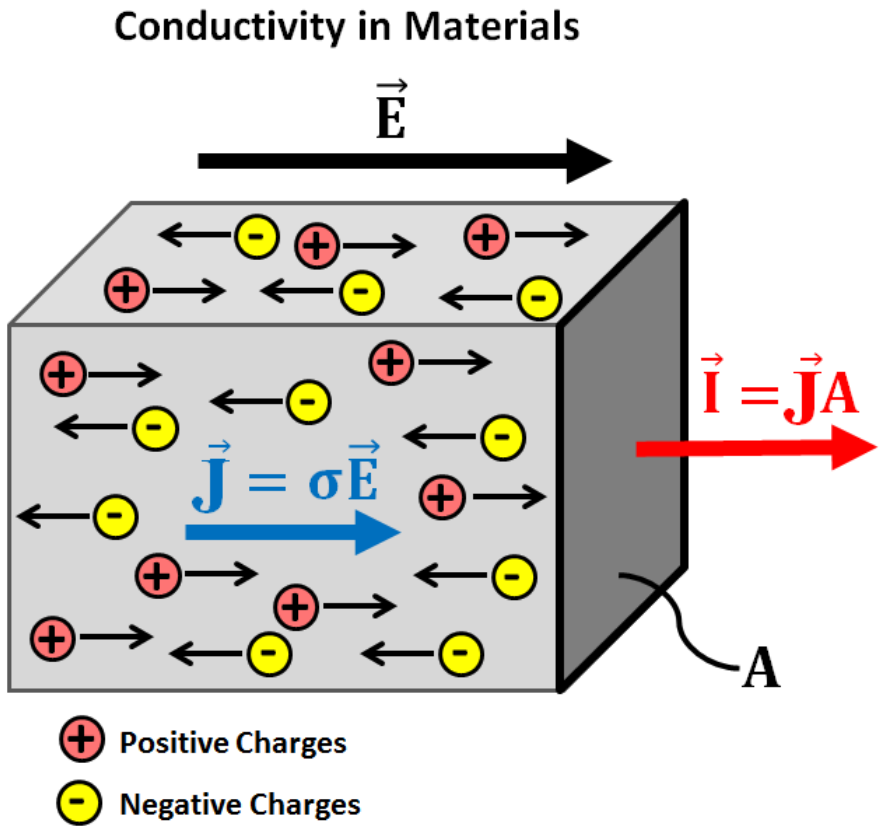


Electric currents in a volume

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

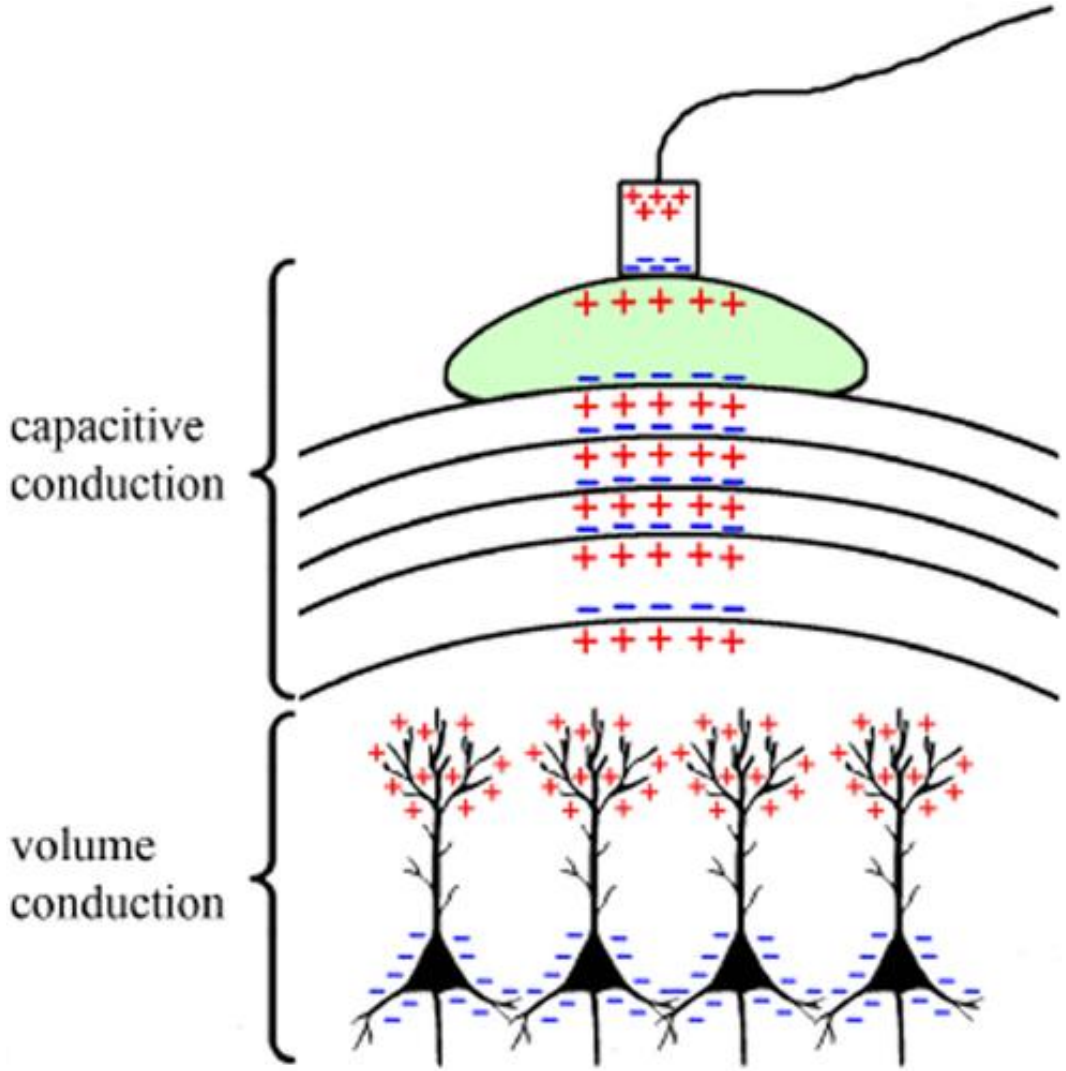


Electric currents in a volume



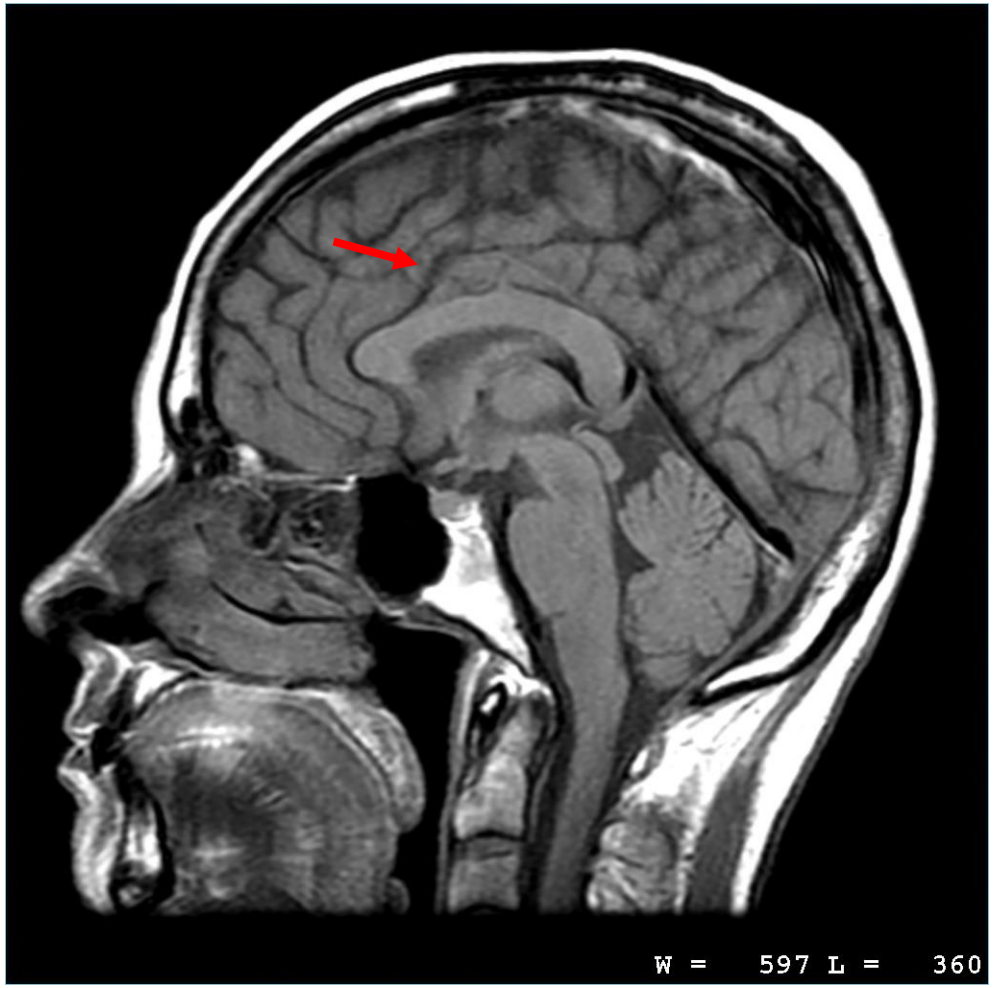
Resistivity

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

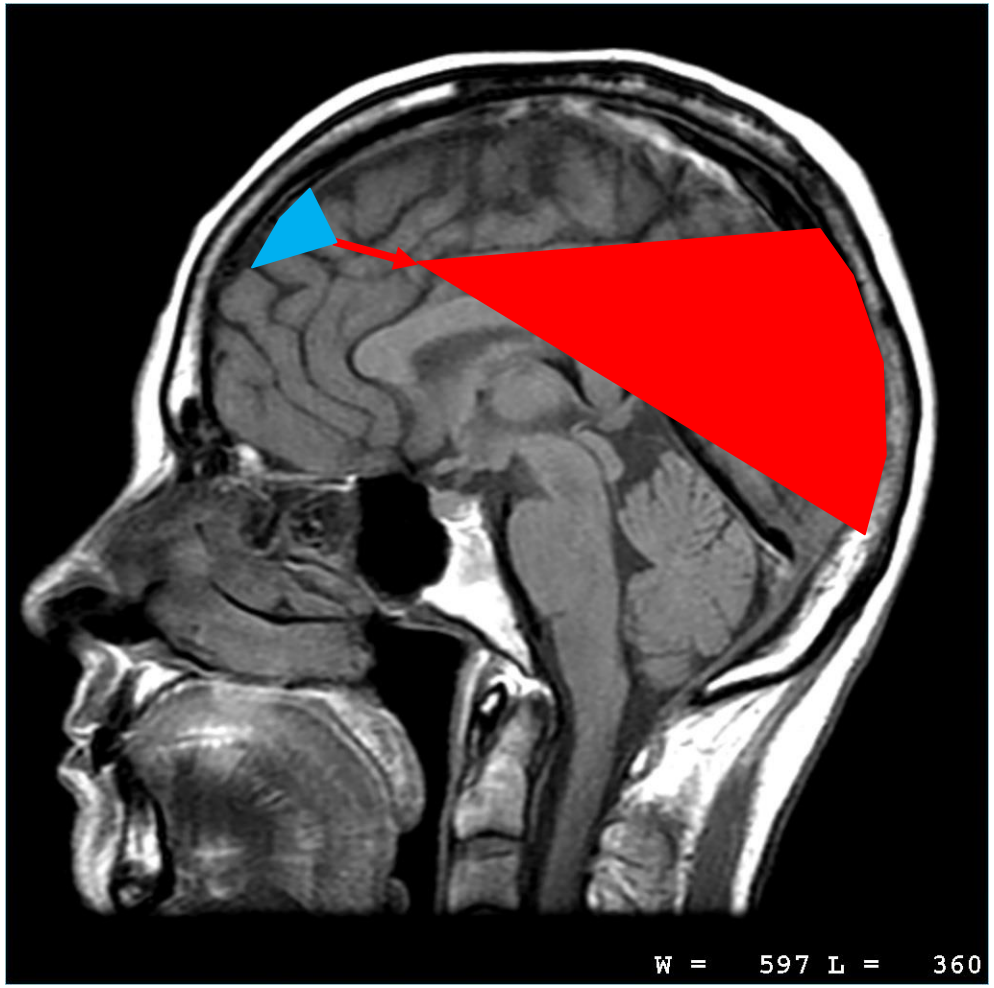


Jackson and Bolger (2014)

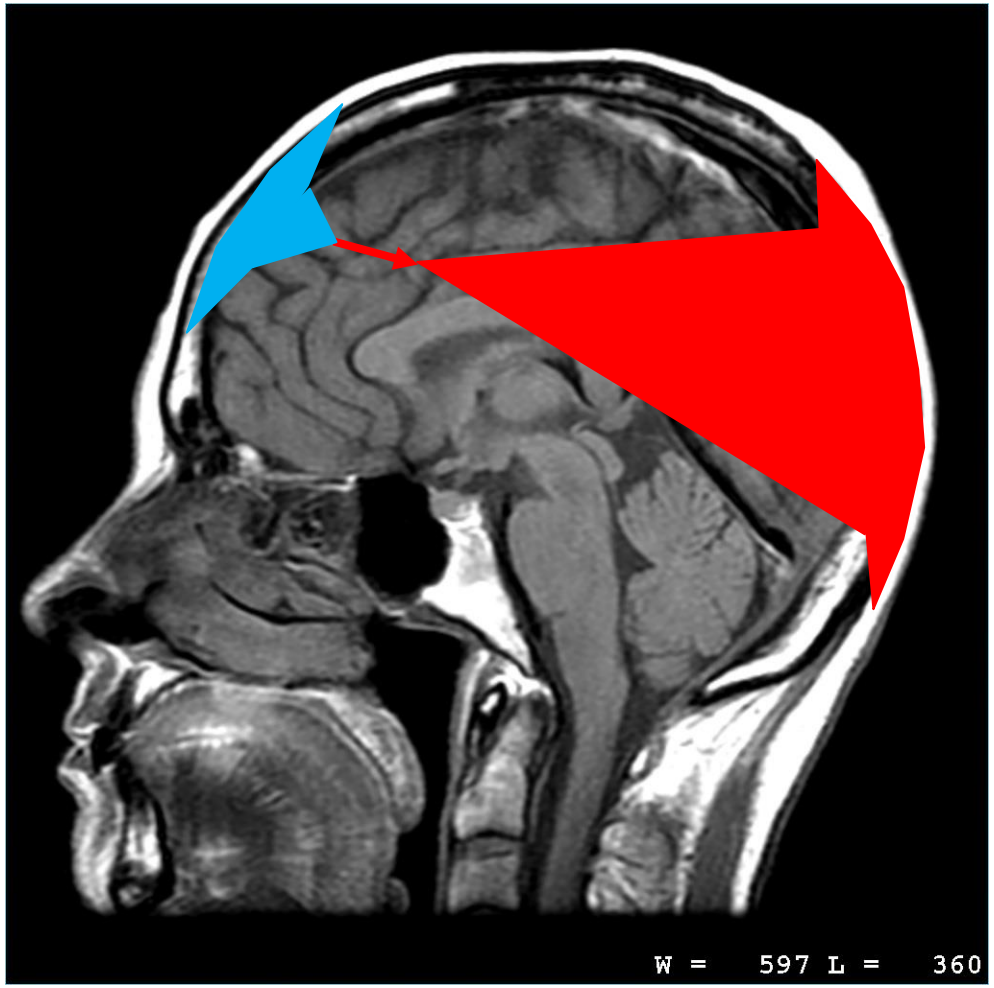
Volume conduction



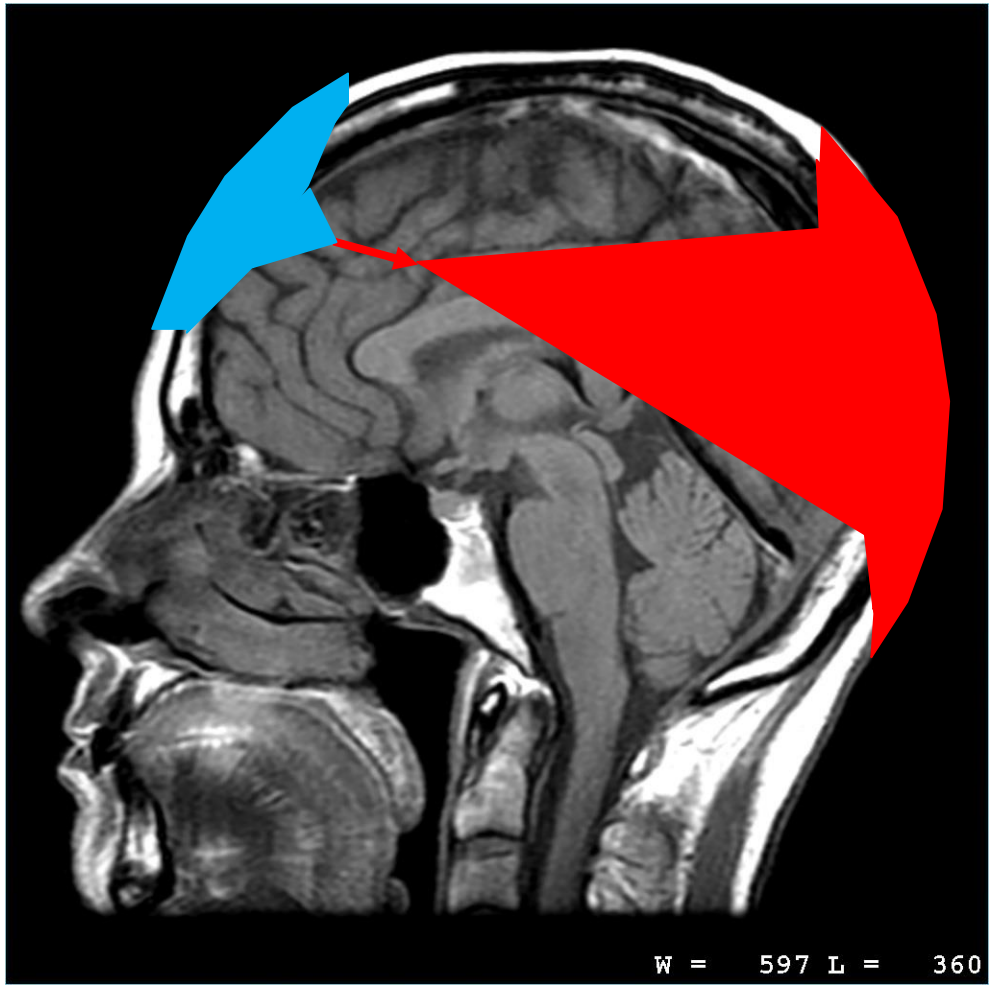
Volume conduction



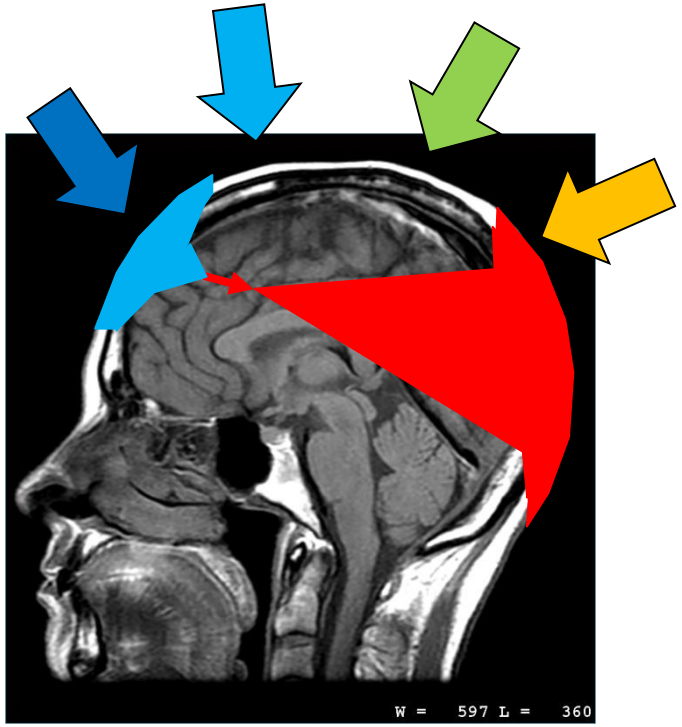
Volume conduction

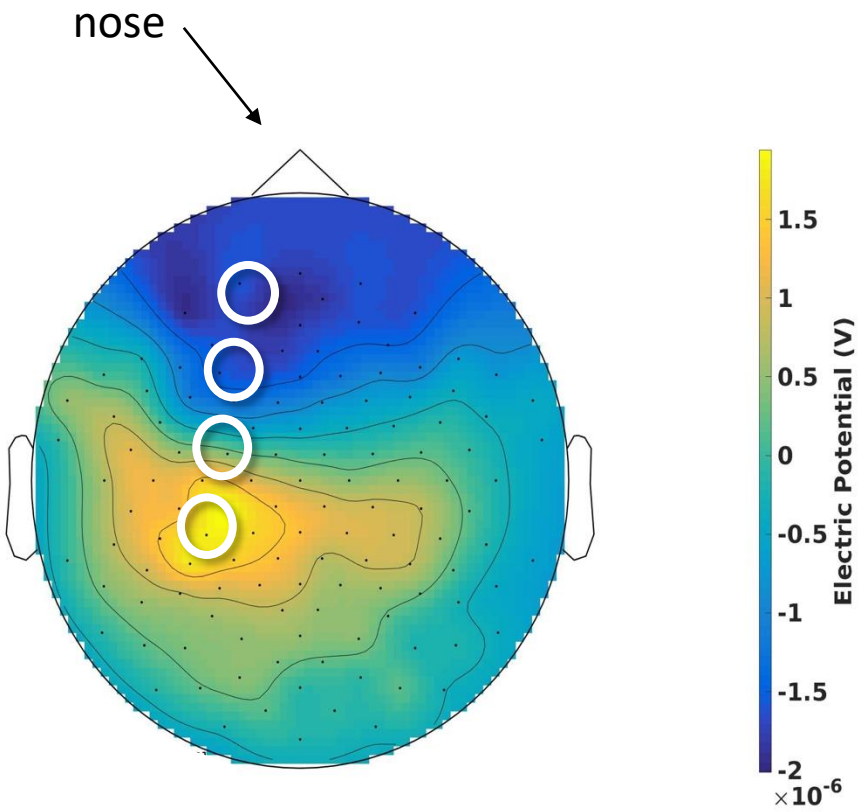


Volume conduction



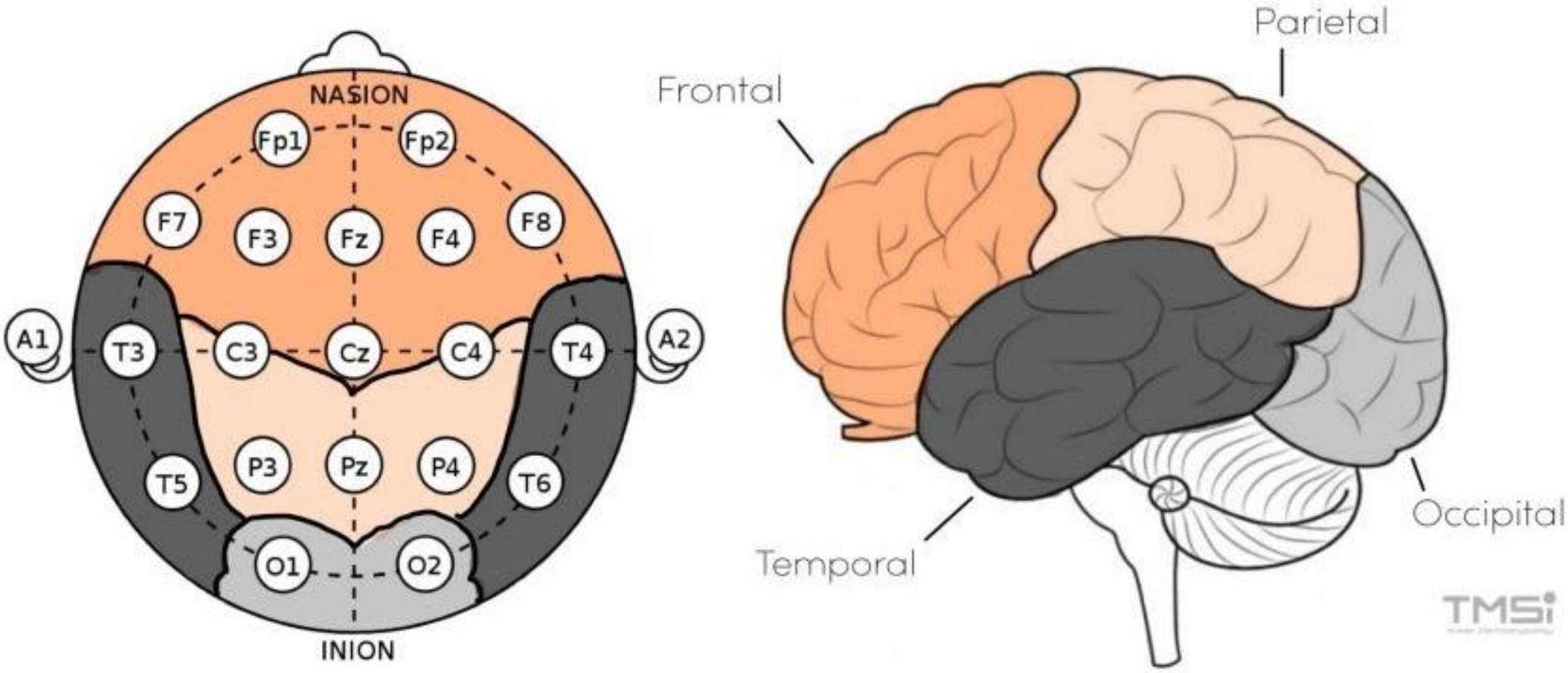
Spatial distribution of the voltage over the scalp





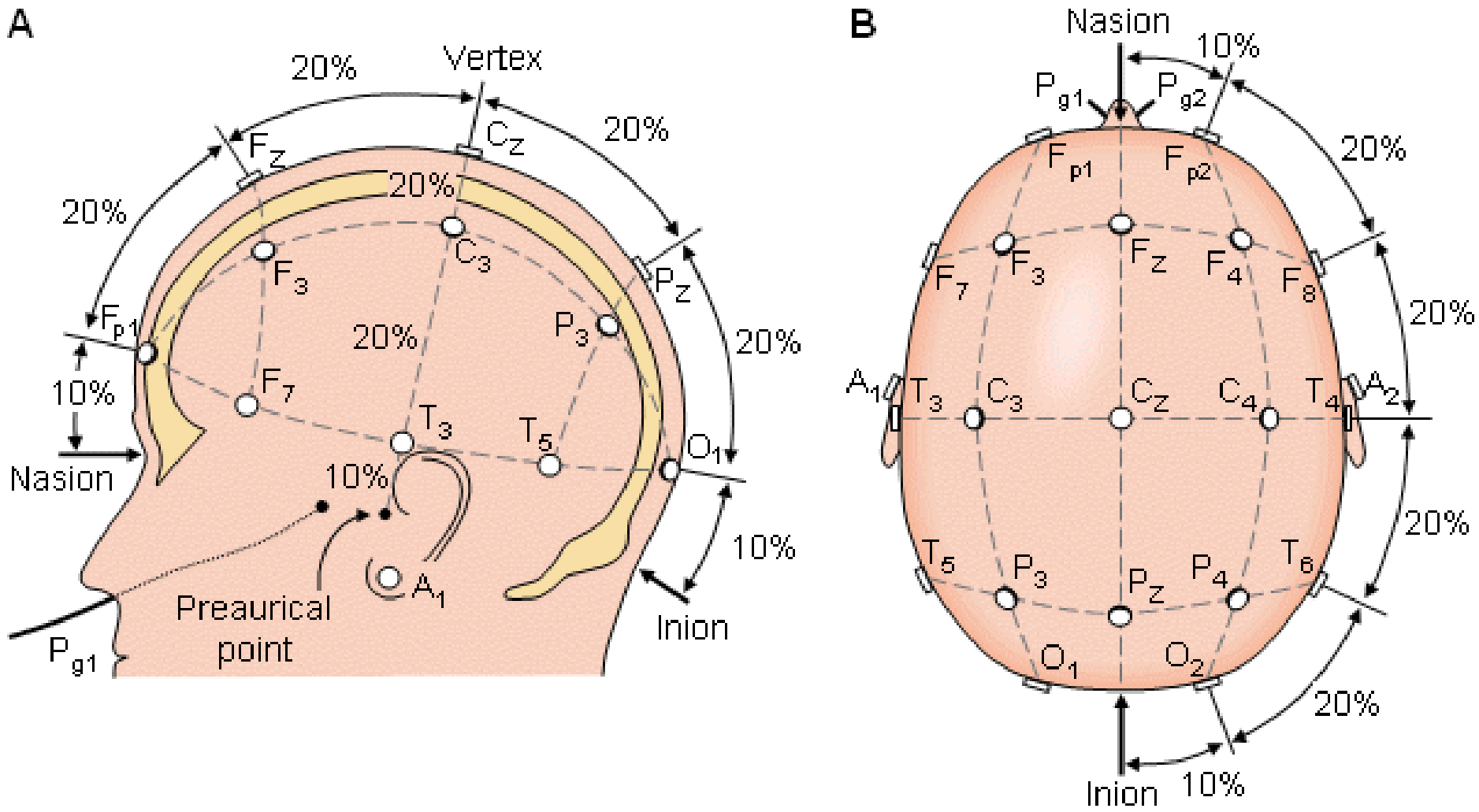
the head seen from the top

The 10-20 electrode placement system - naming

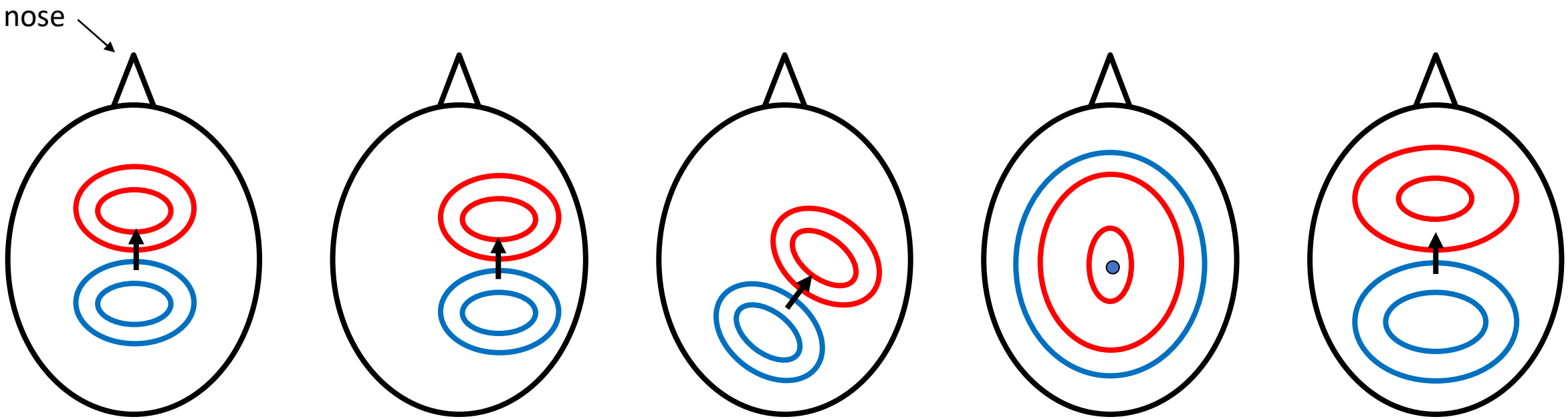


Electrodes T3/4 are nowadays mostly called C7/8, and T5/6 are called P7/8.
The ear lobes are called A1/2, the mastoids are called M1/2.

The 10-20 electrode placement system - placement



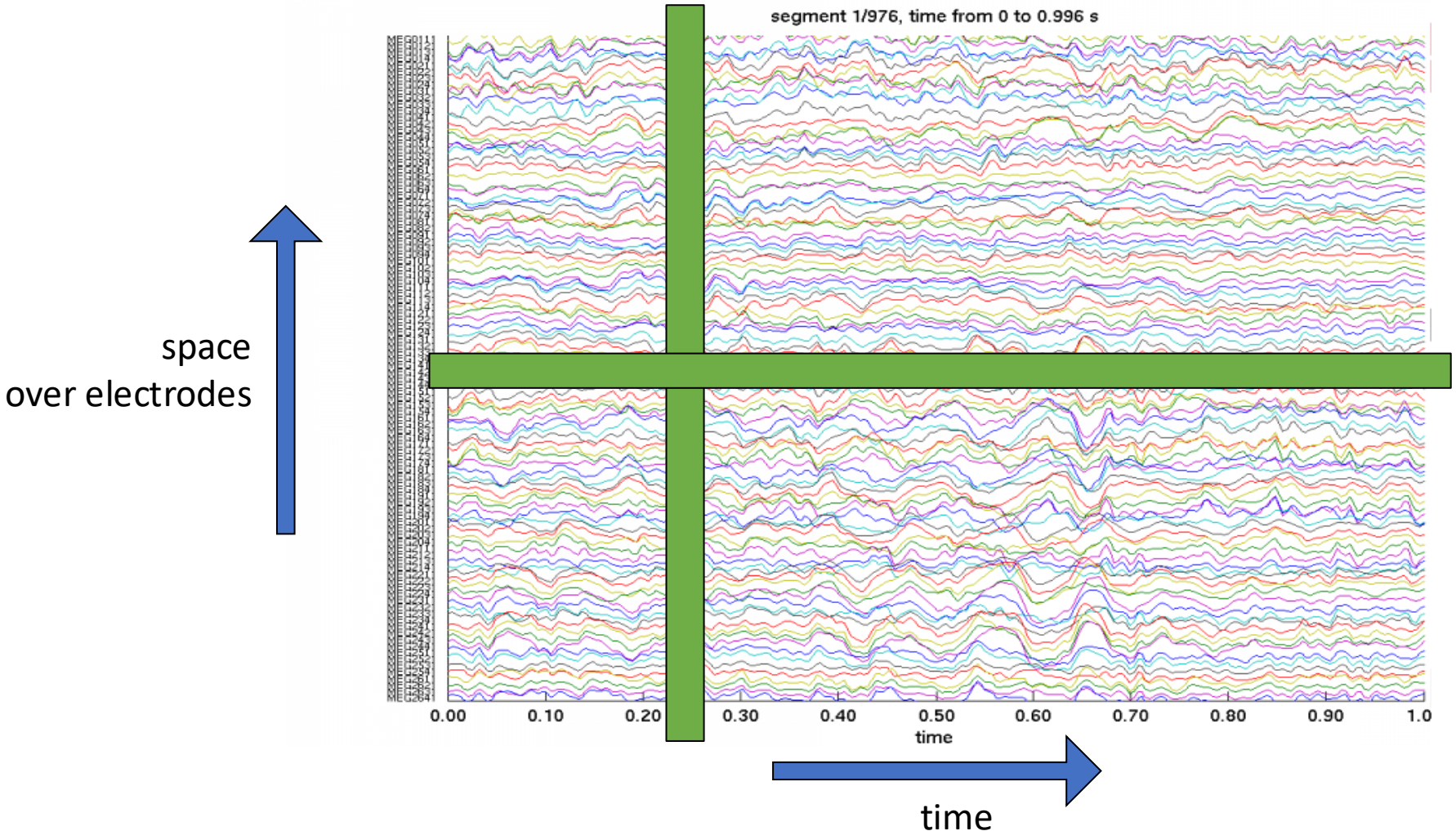
Spatial distribution for different generators



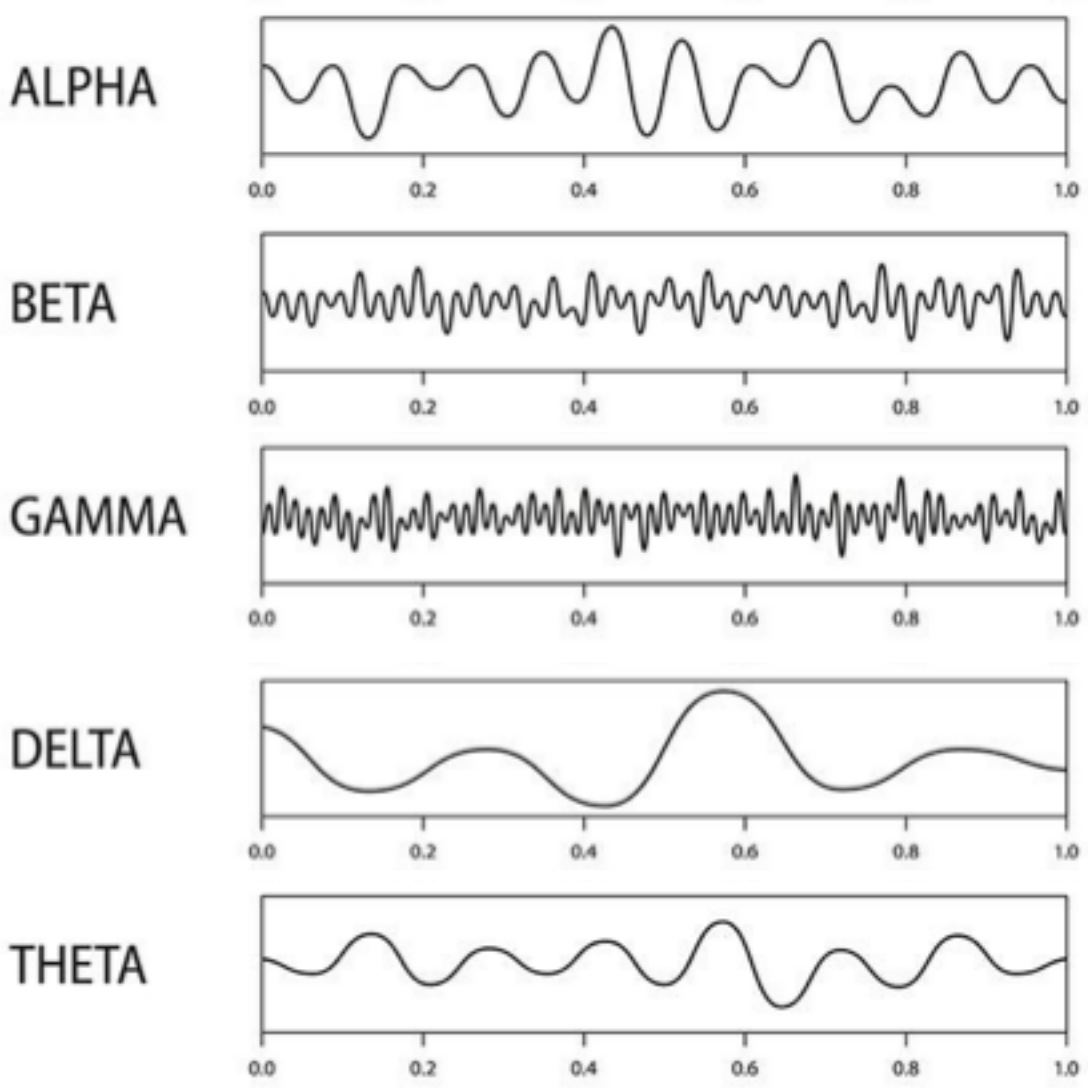
Spontaneous EEG is a mixture of many sources

Many parts of the brain are active simulteneously.

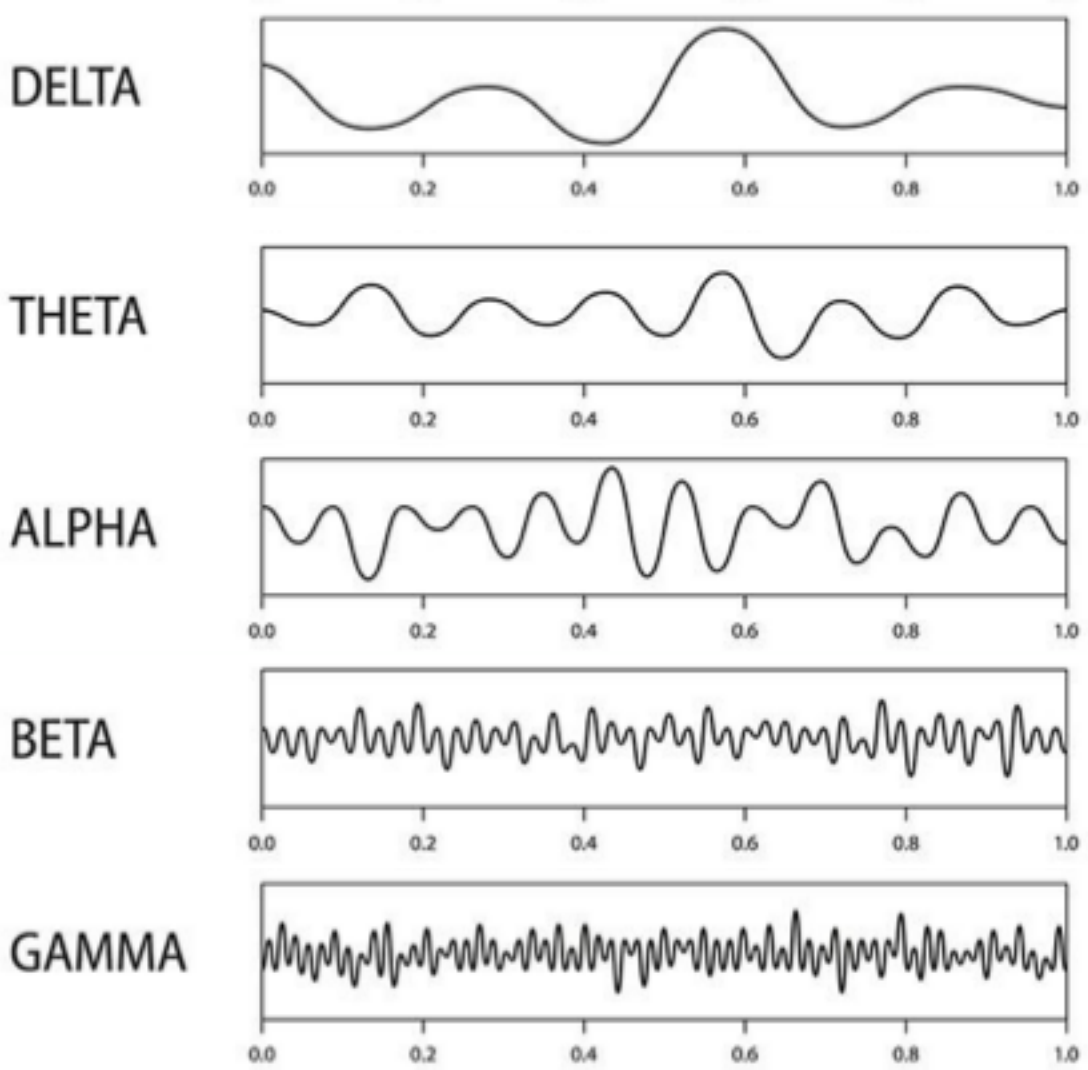
The activity of each brain region fluctuates over time.



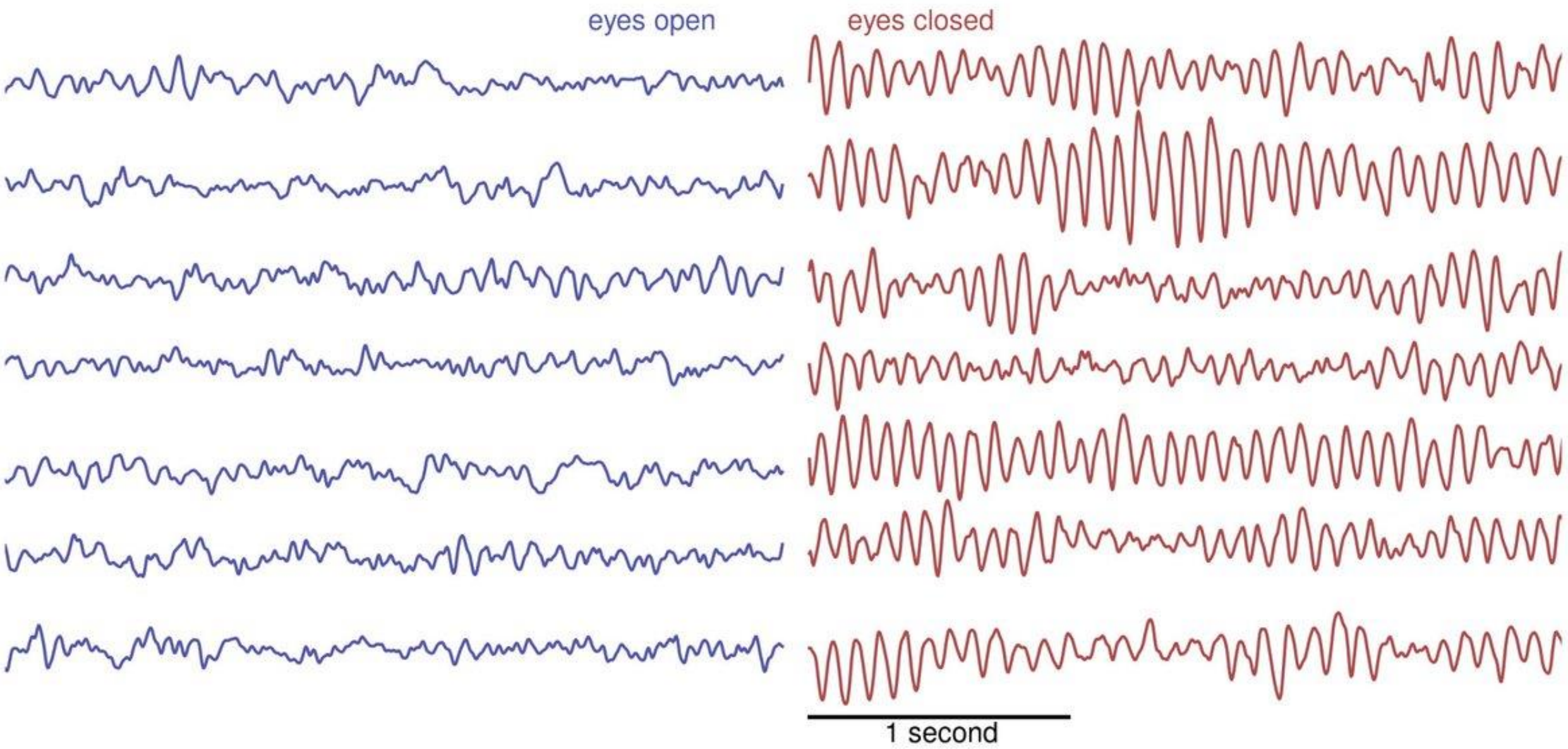
Spontaneous rhythms in the EEG



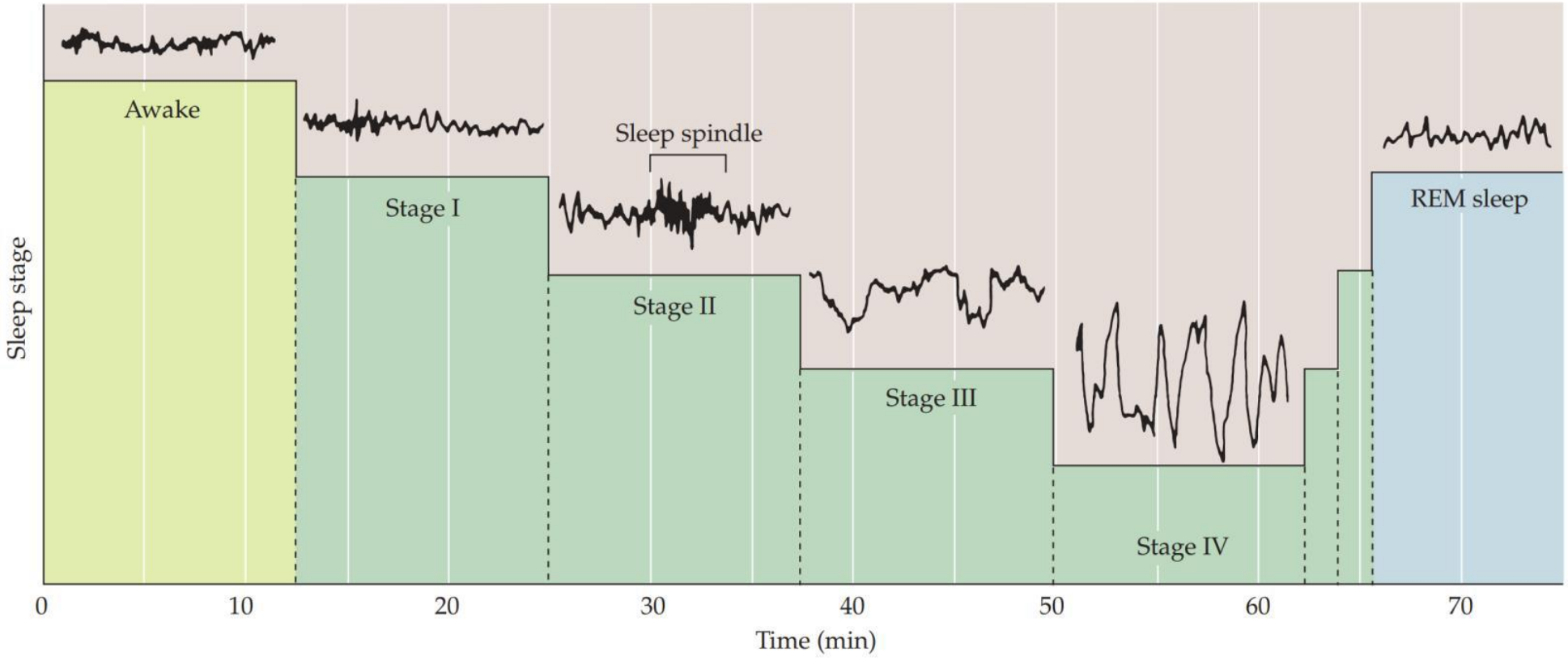
Spontaneous rhythms in the EEG, sorted by frequency



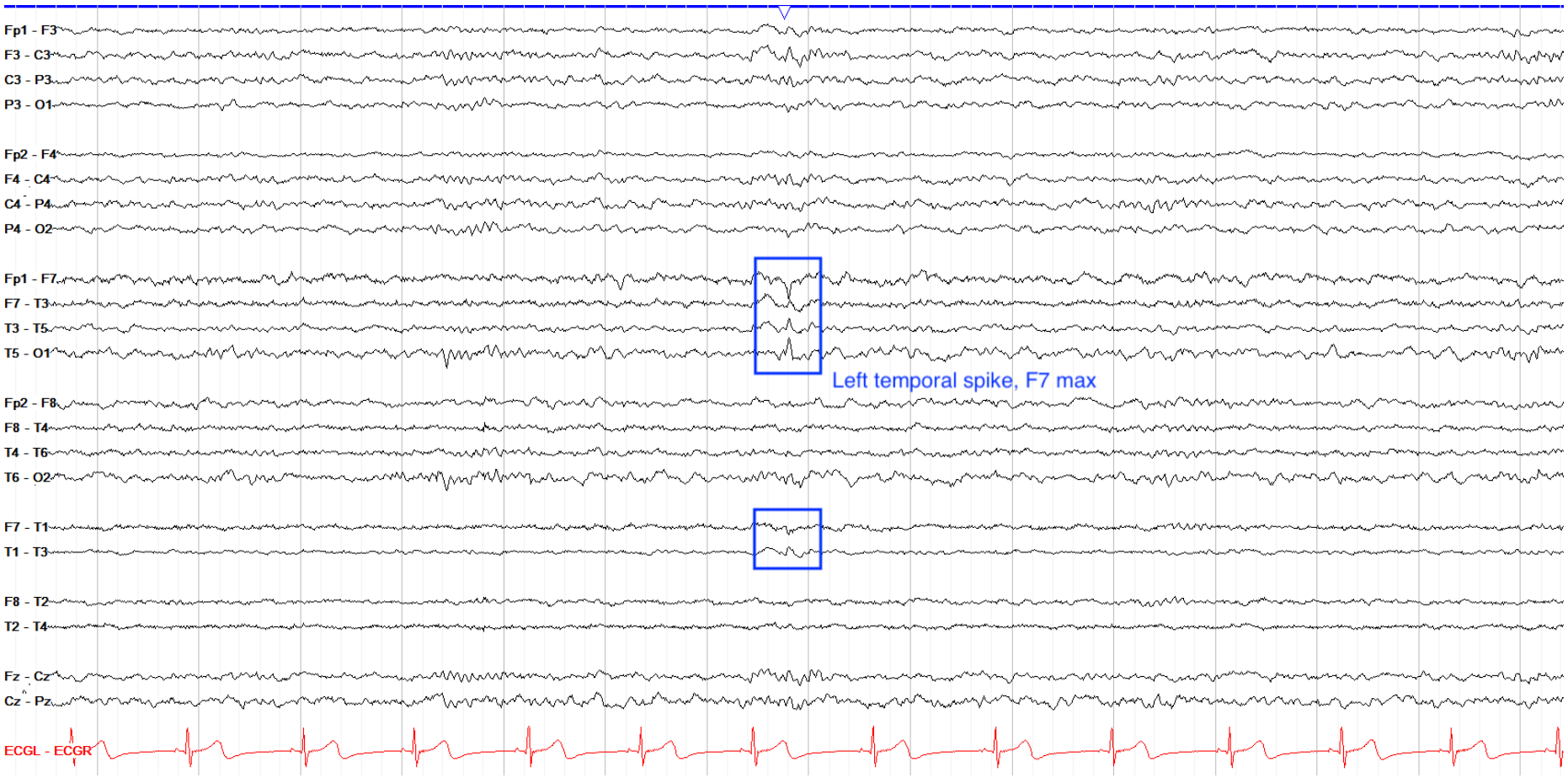
EEG when you close your eyes: occipital alpha



EEG during sleep: change in rhythms

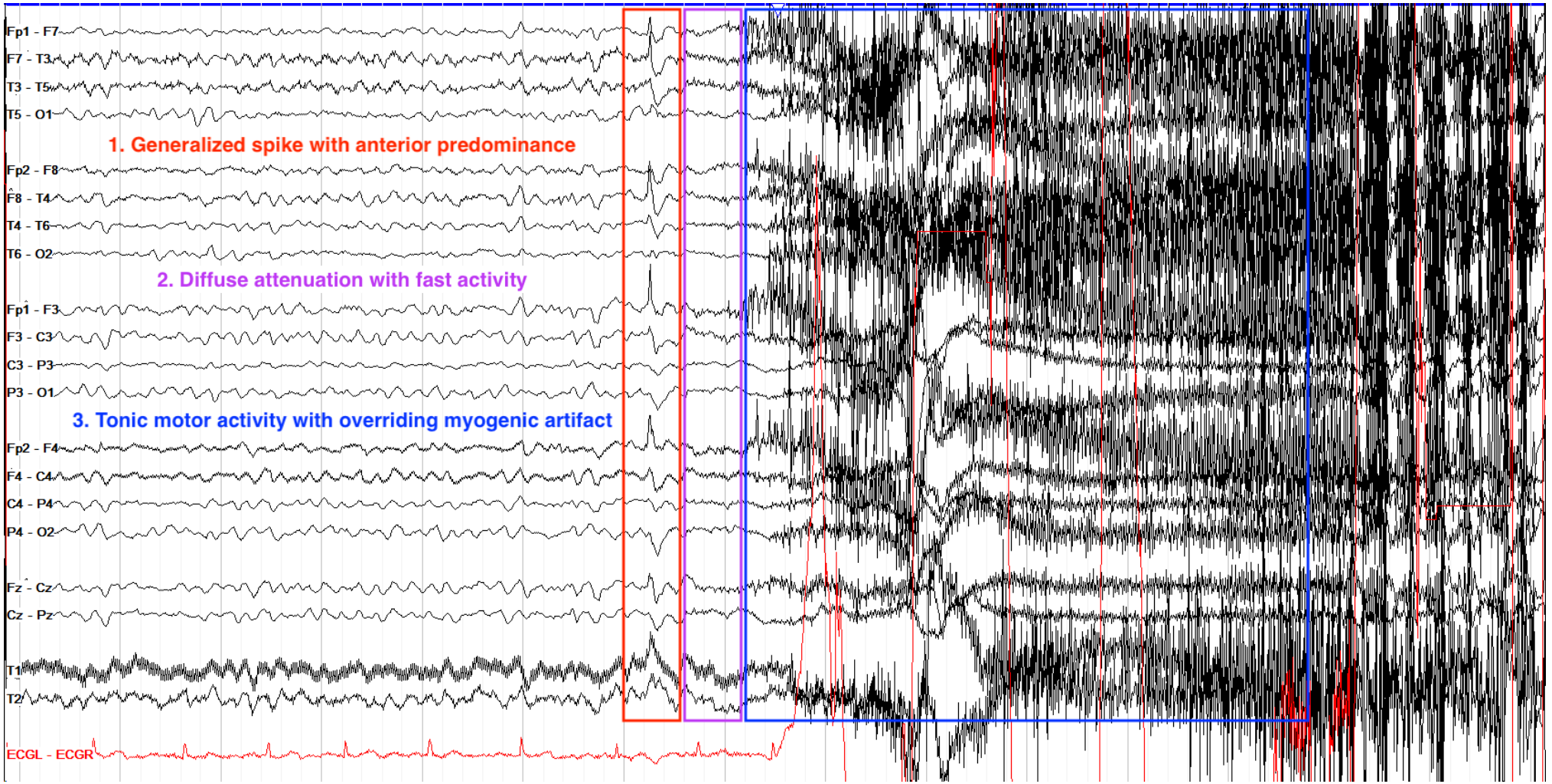


EEG in neurological disorders: epileptic spike



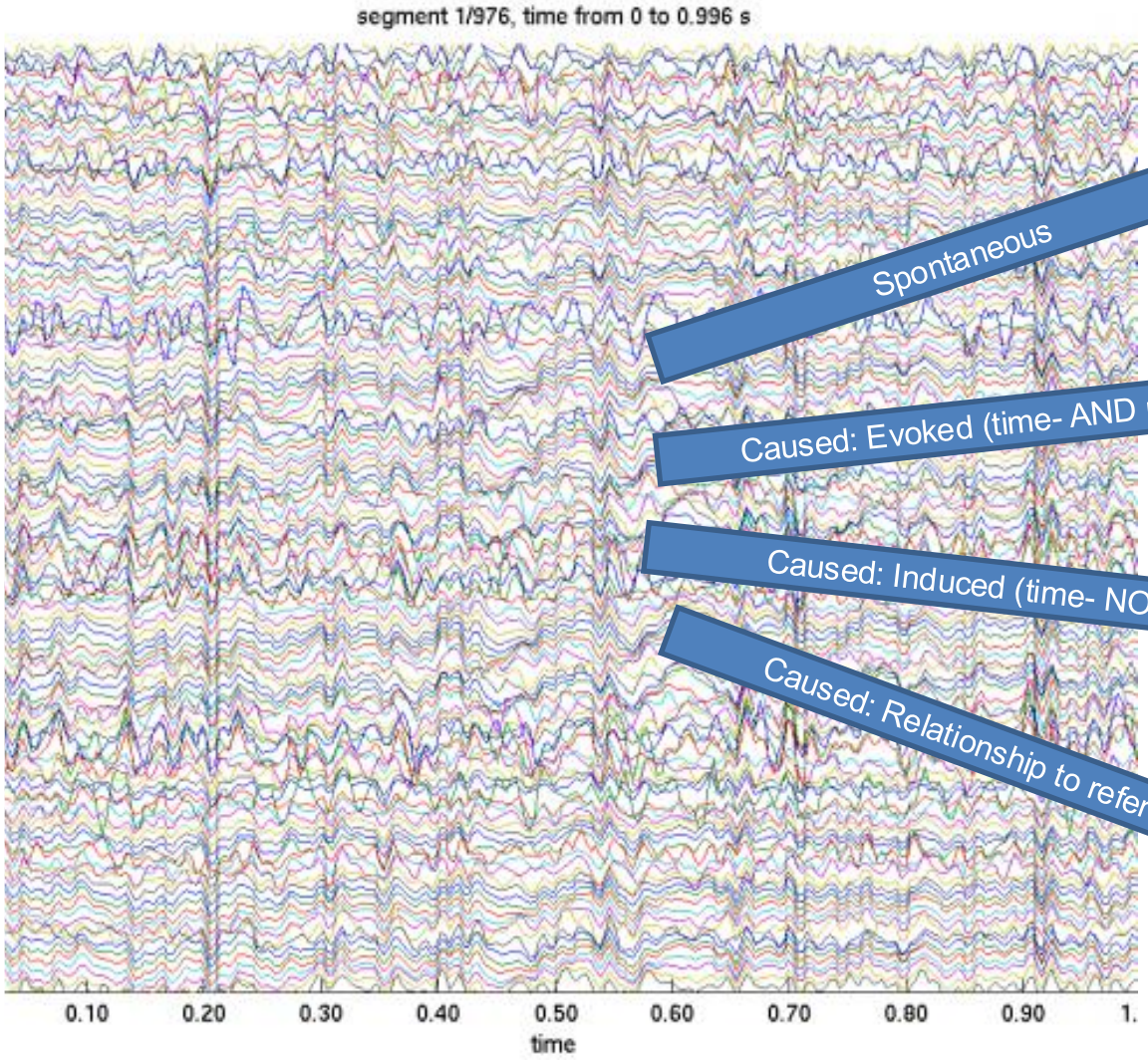
https://www.learningeeg.com/

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

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 measure 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(N)

10 trials -> 3x lower noise

100 trials -> 10x lower noise

Averaging the EEG over trials and subjects

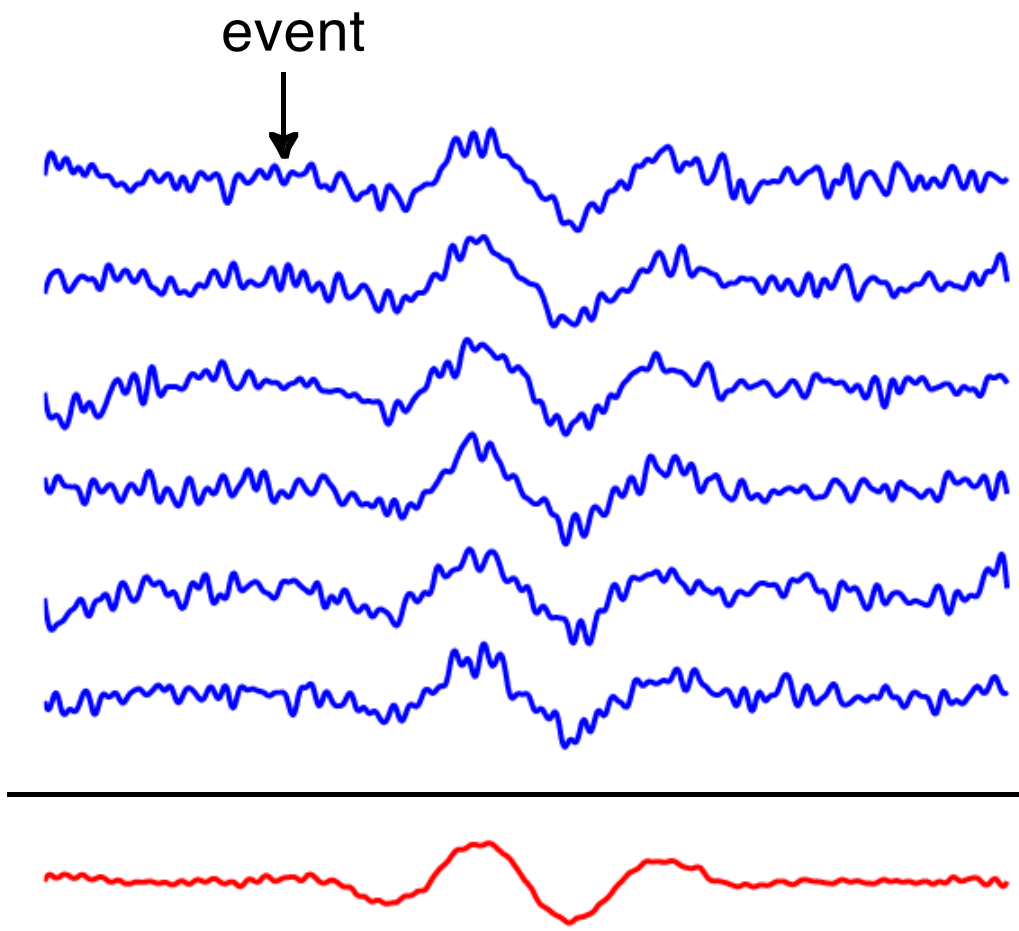
A typical experiment with a single participant has 100-500 trials, over the different conditions.

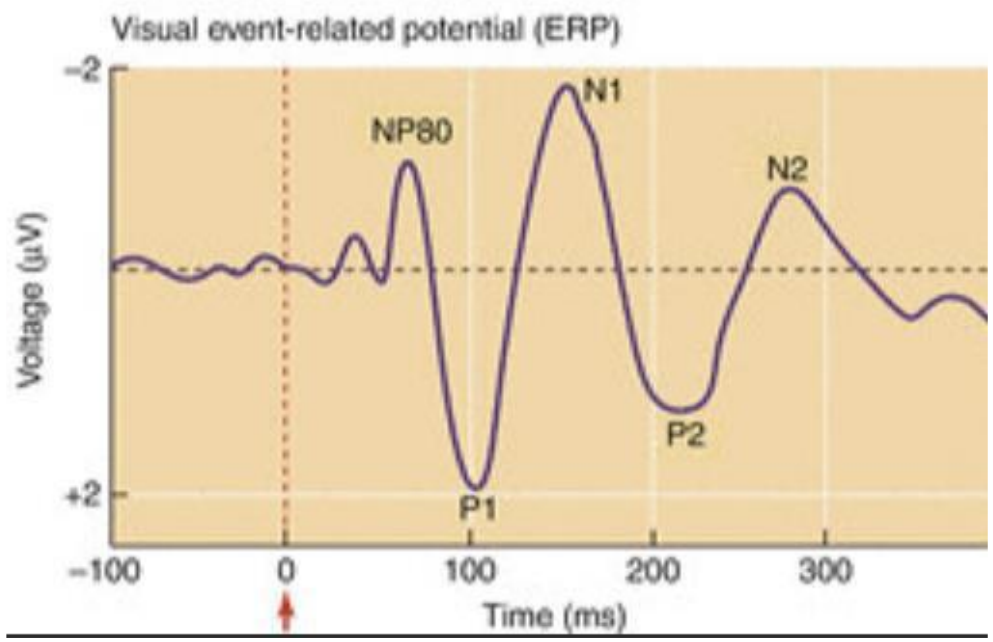
This allows to recognize the ERP (after averaging over trials) over the background spontaneous brain activity (noise).

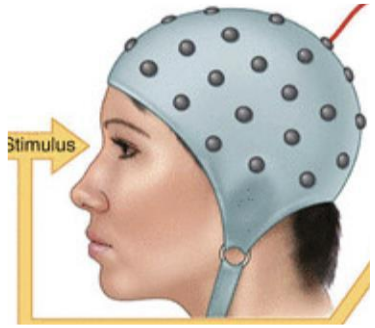
A typical study has 20-50 participants.

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

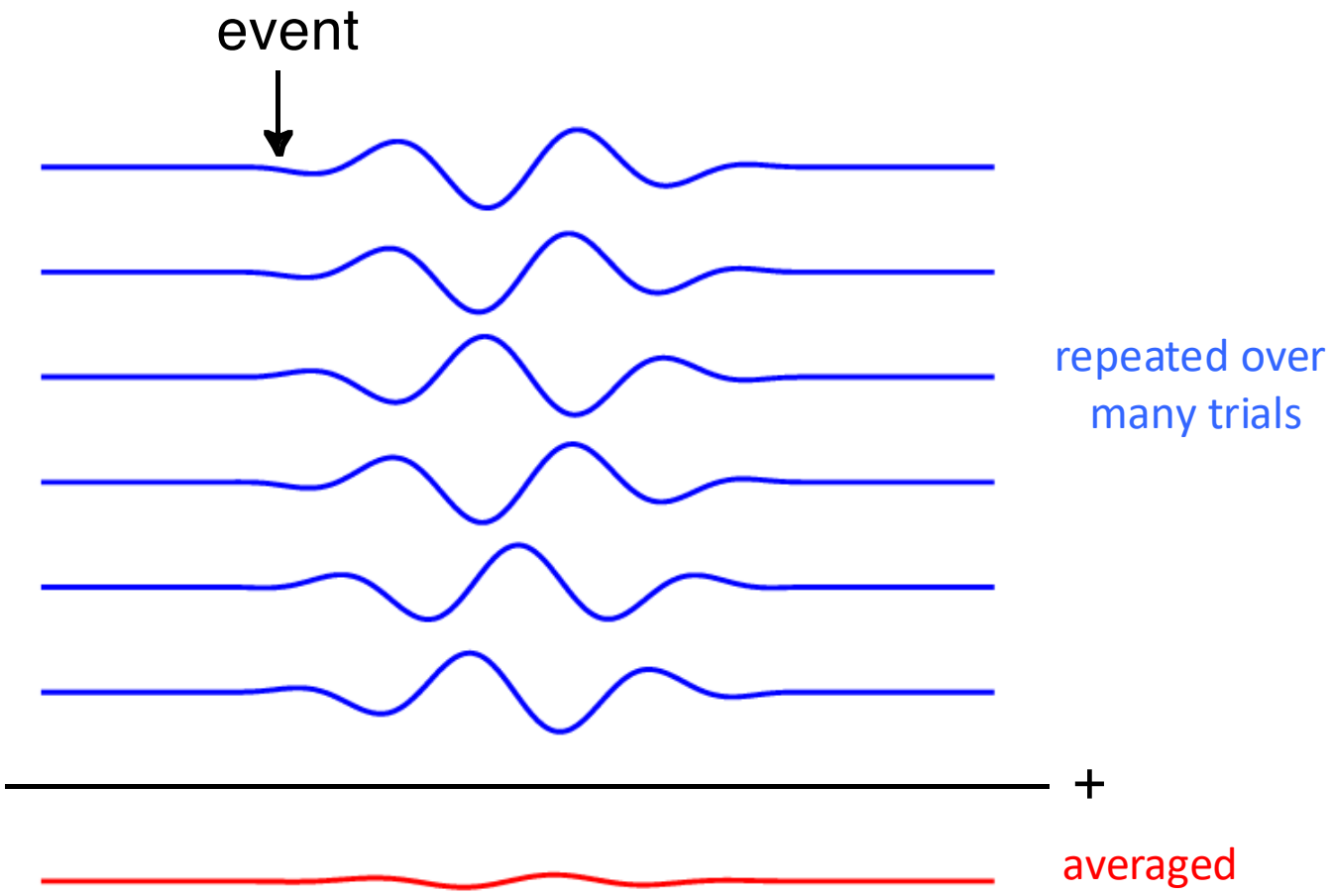
Visual Evoked Potential (EP) or Event-Related Potential (ERP)

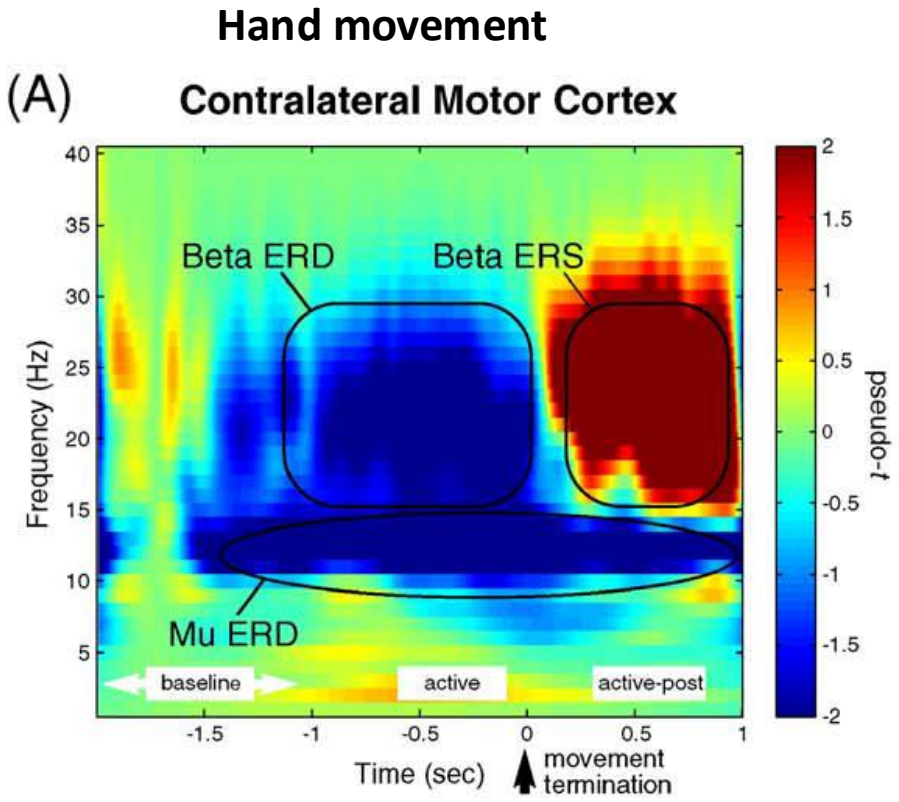






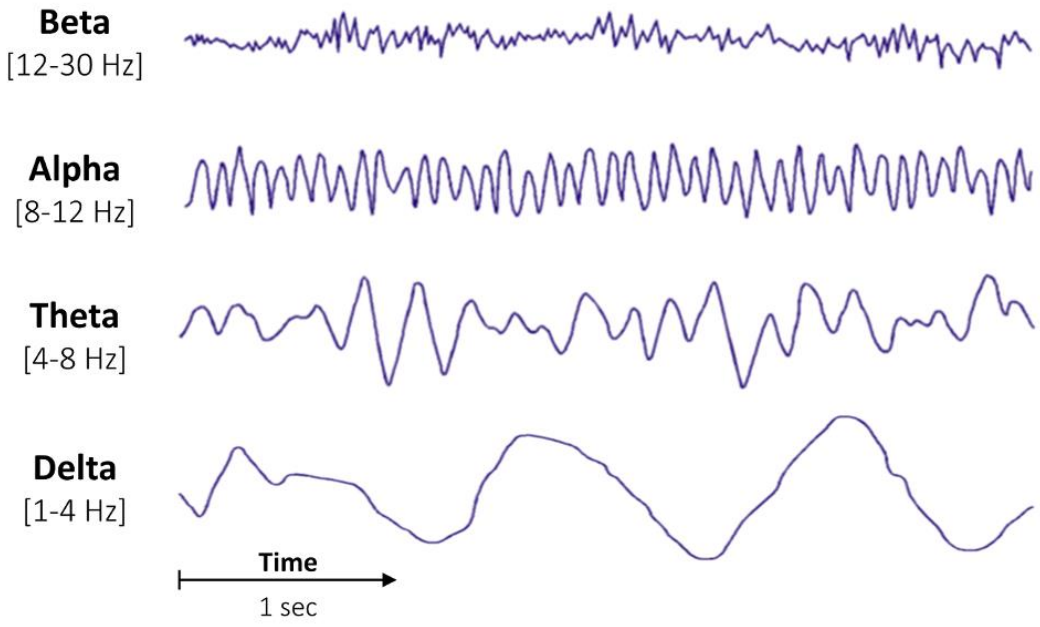
Time-Frequency Response (TFR)
Event Related (de)synchronization (ERD or ERS)

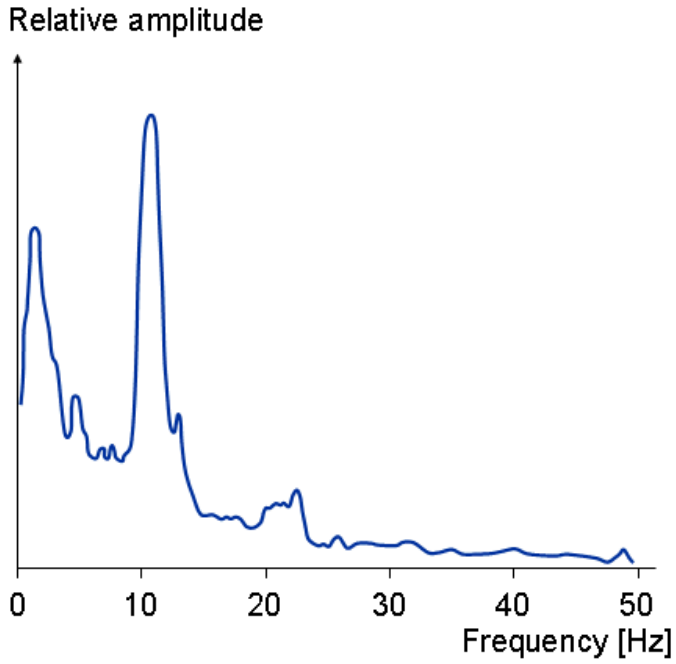




Frequency or spectral or Fourier analysis

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.





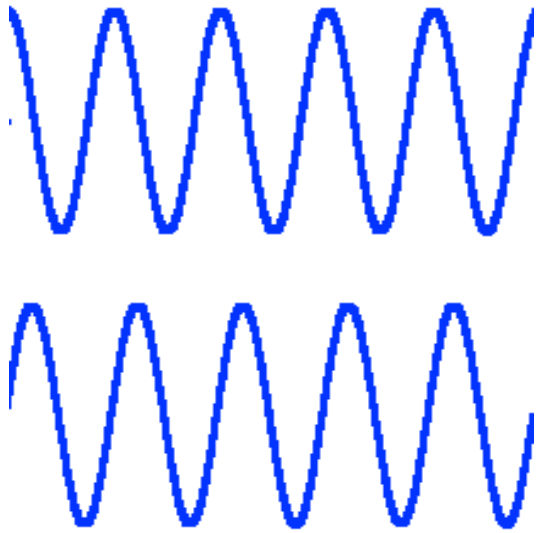
Frequency analysis

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

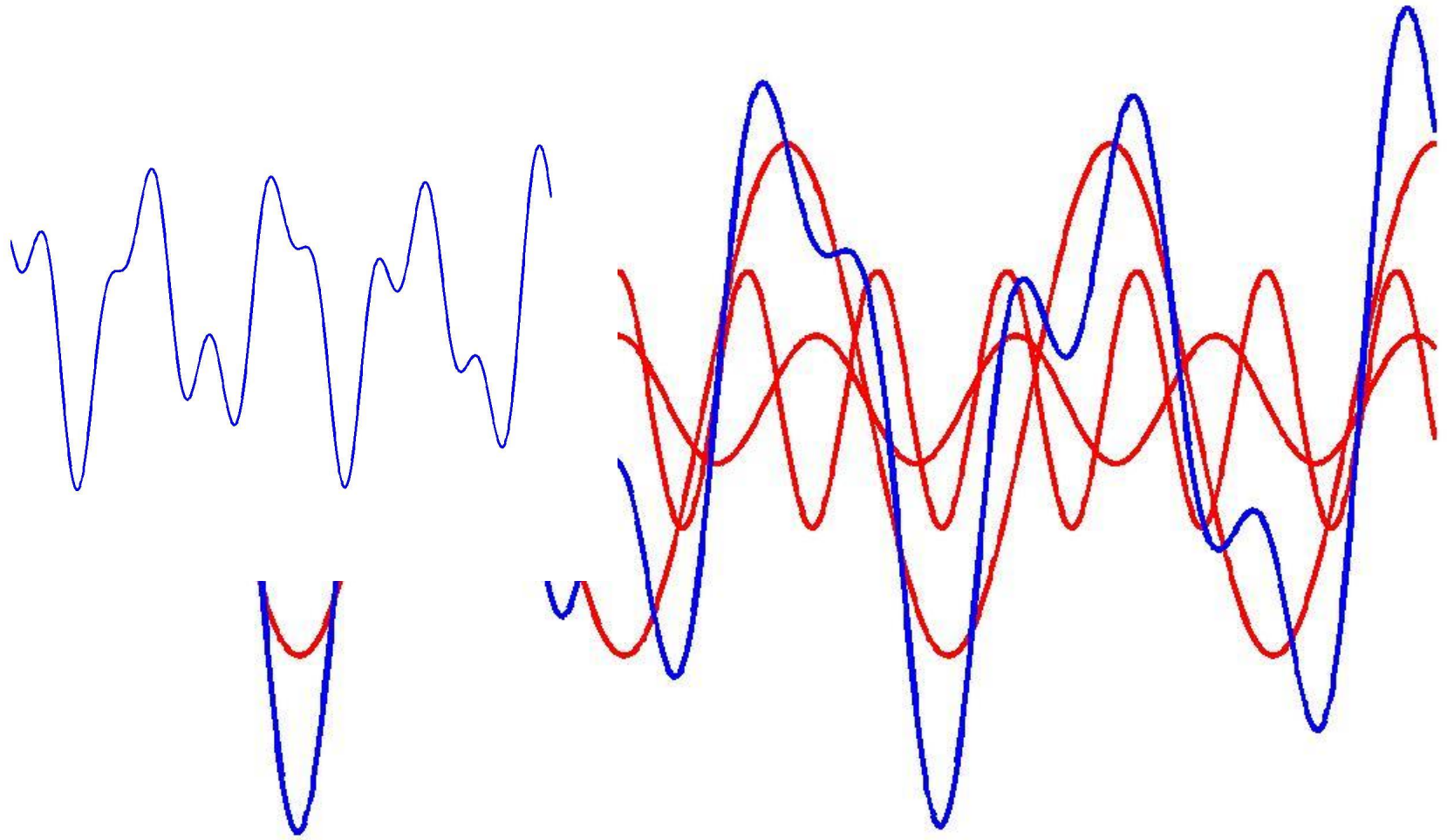
When it goes up and down *once per ½ second*, it is a 2 Hz signal.



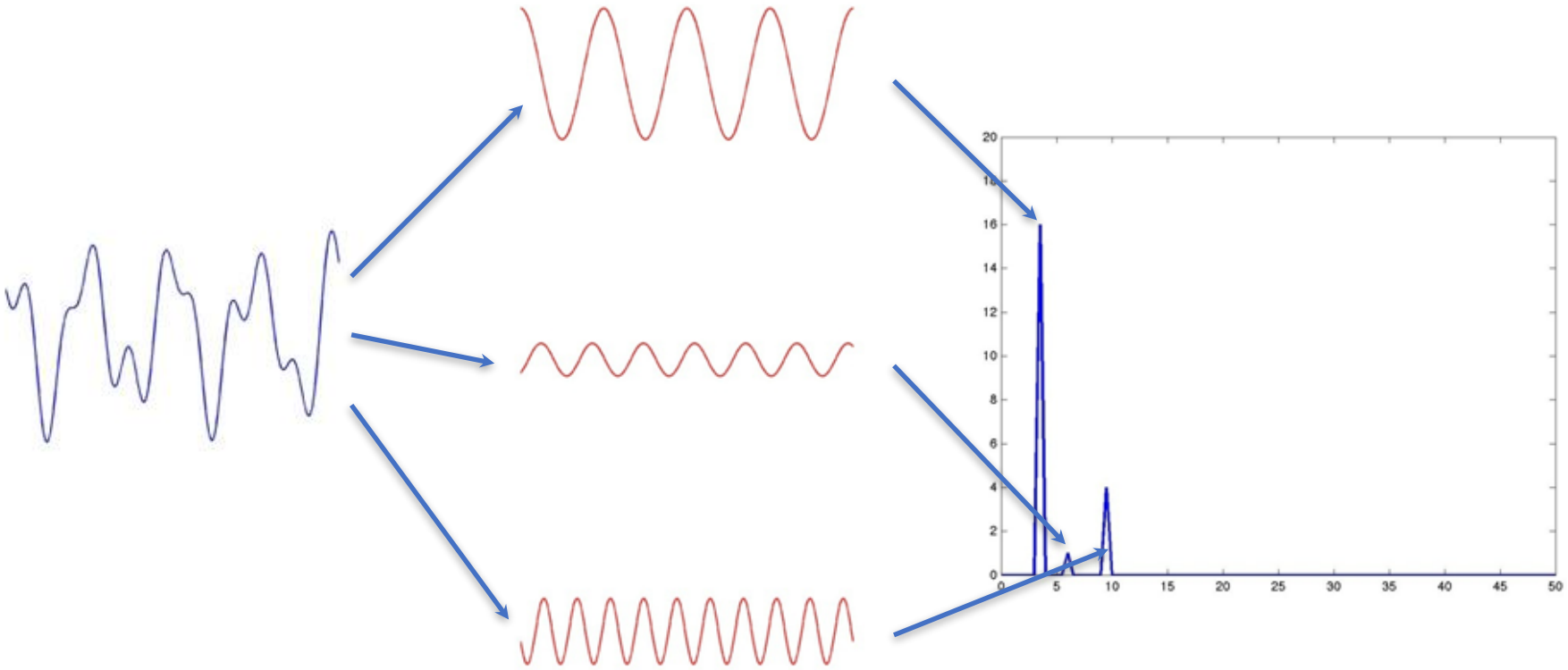
The frequency is one-divided-by the time that it takes to go up and down.

F = 1/T

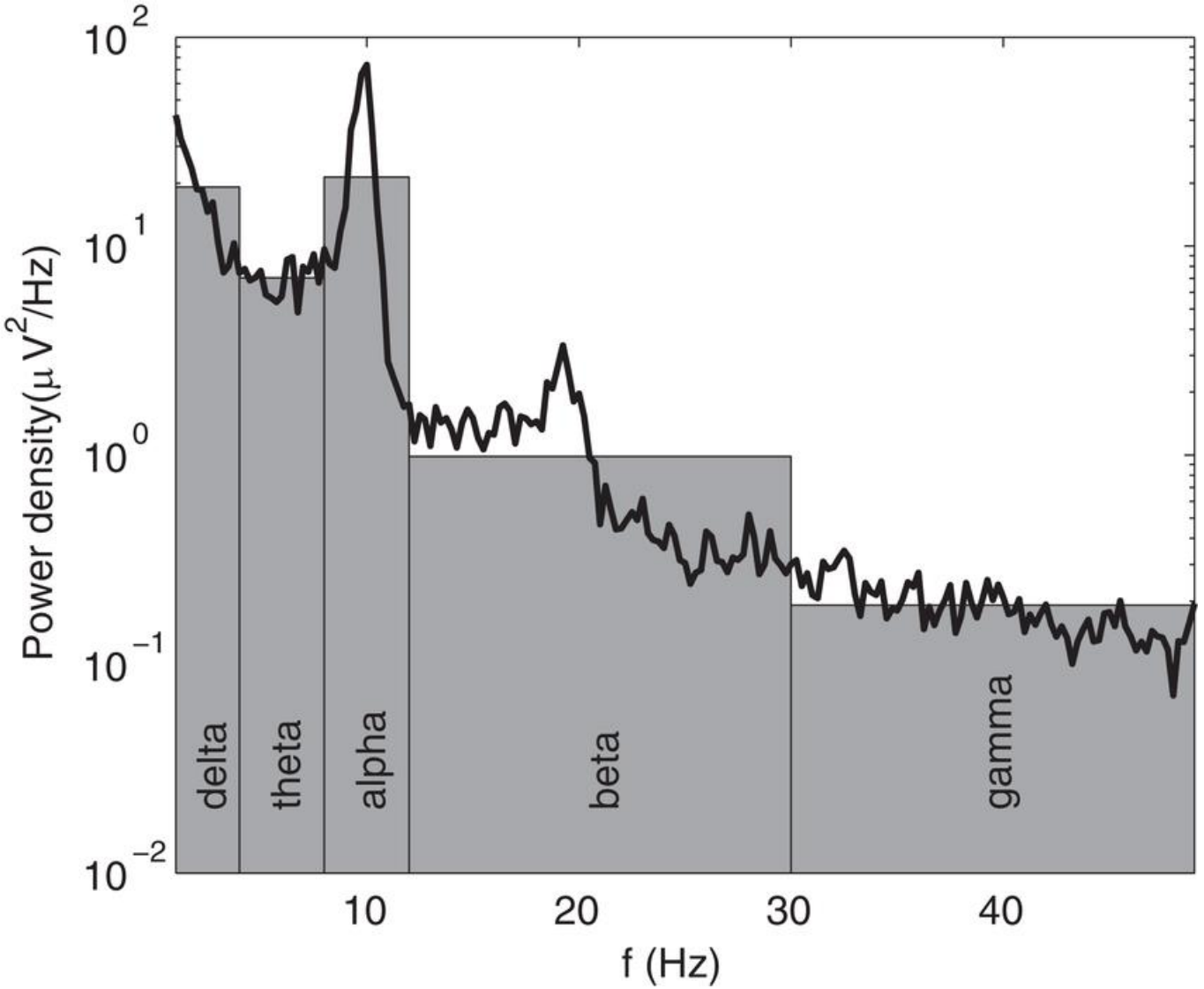
Spectral decomposition: the principle



Spectral decomposition: the power spectrum

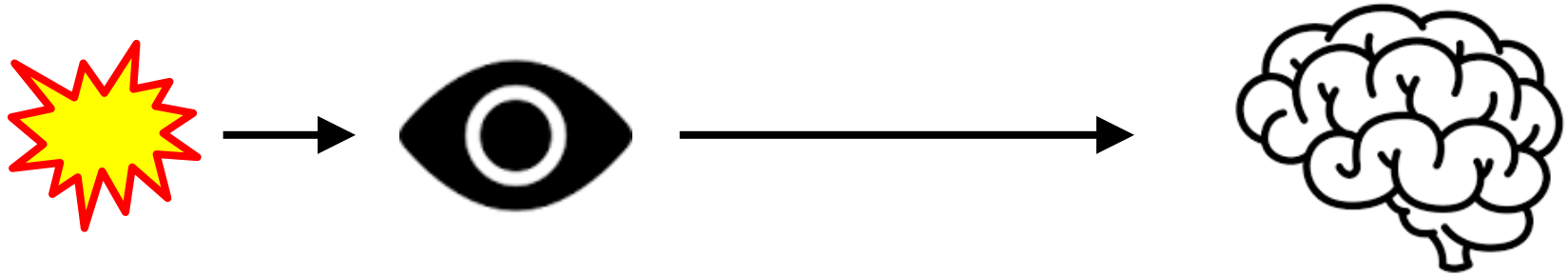


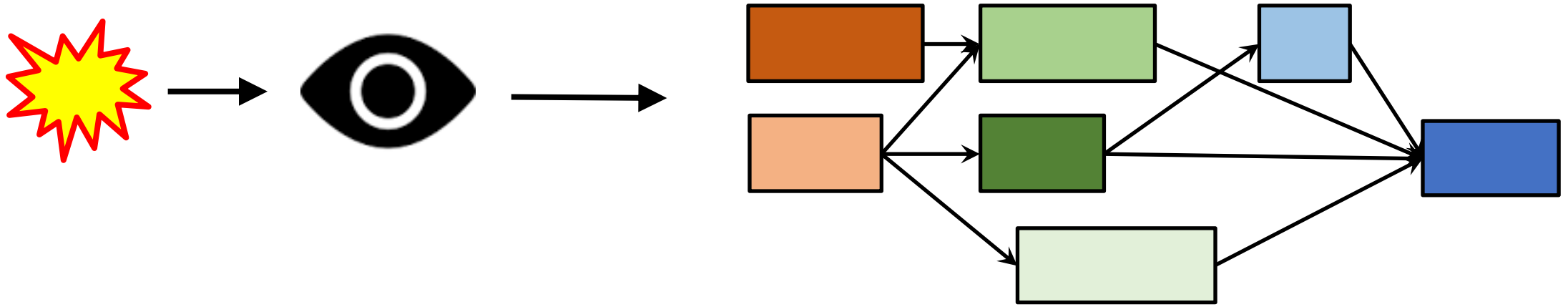
The spectrum of EEG



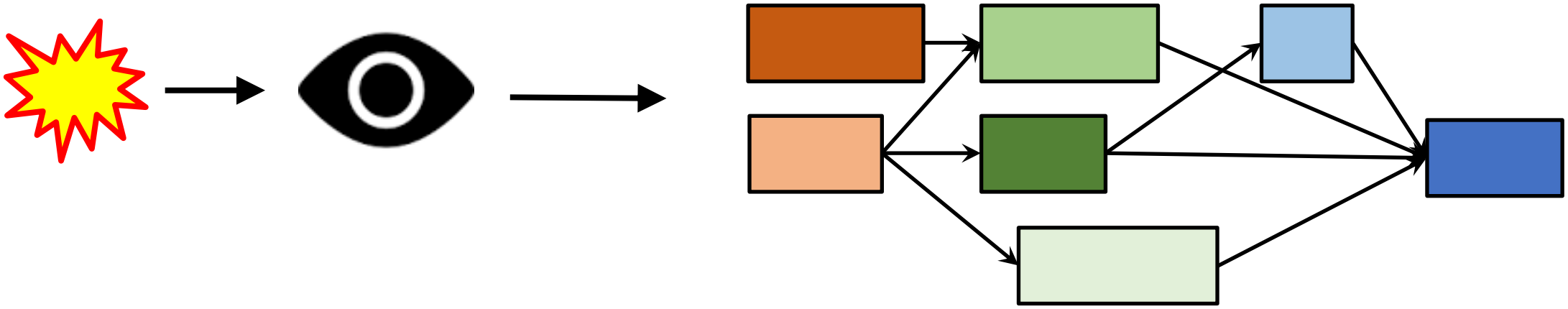
How to make a scientific study out of this EEG technology

Why study ERPs or TFRs?





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

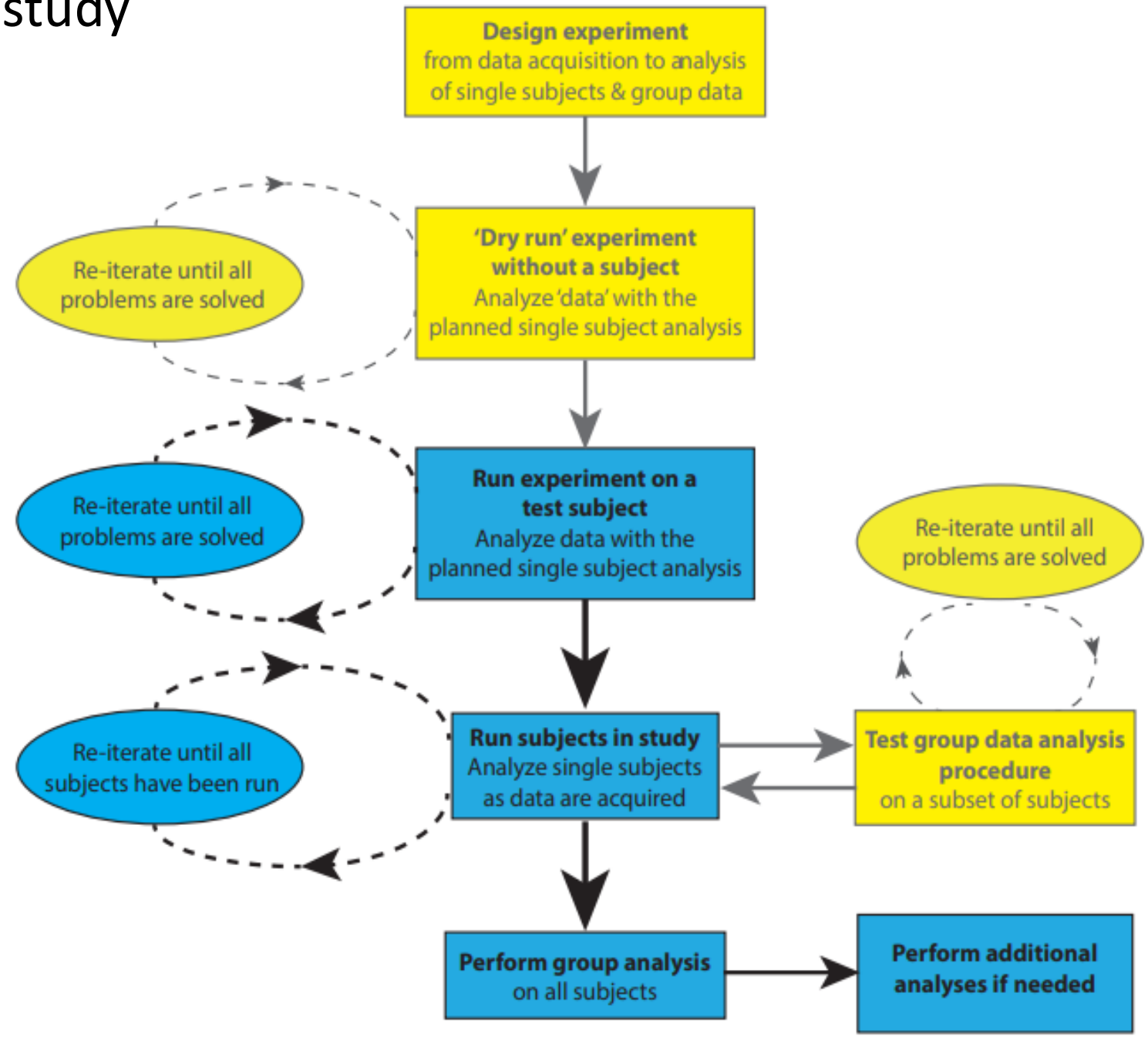
A whole experiment (one session) with a single participant takes 1-1.5 hours.

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

The data analysis also takes a few months.

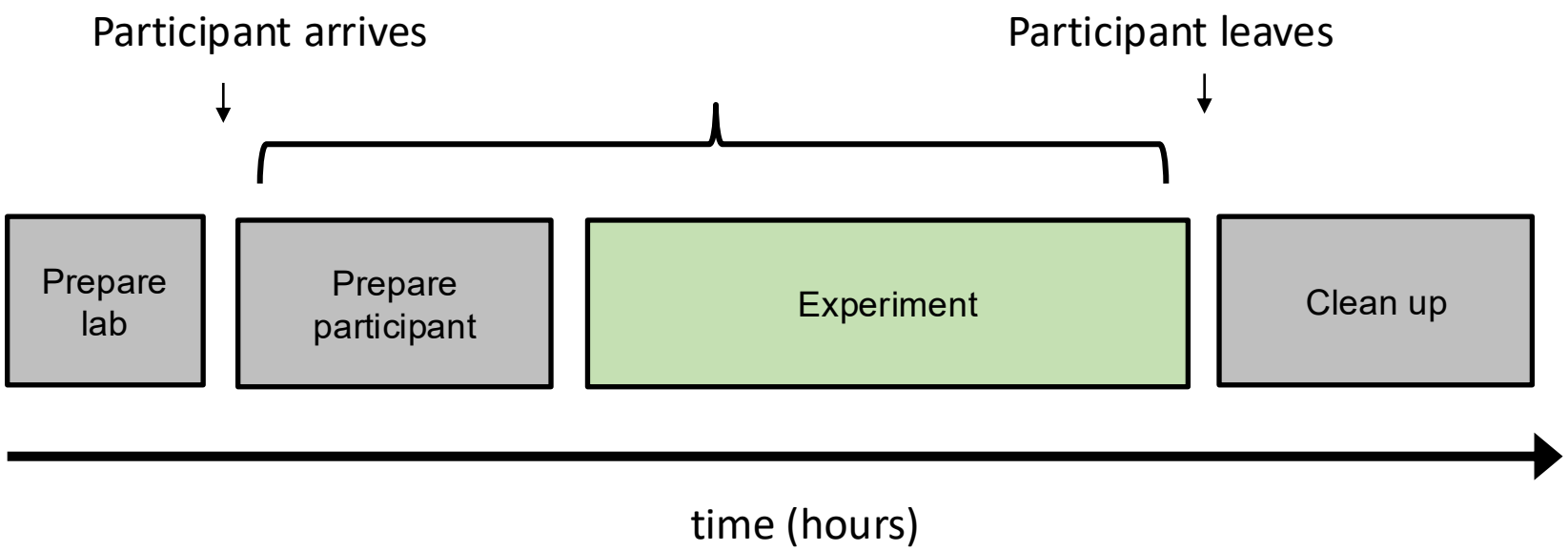
Large (time) investment but also large reward!

Planning an EEG study

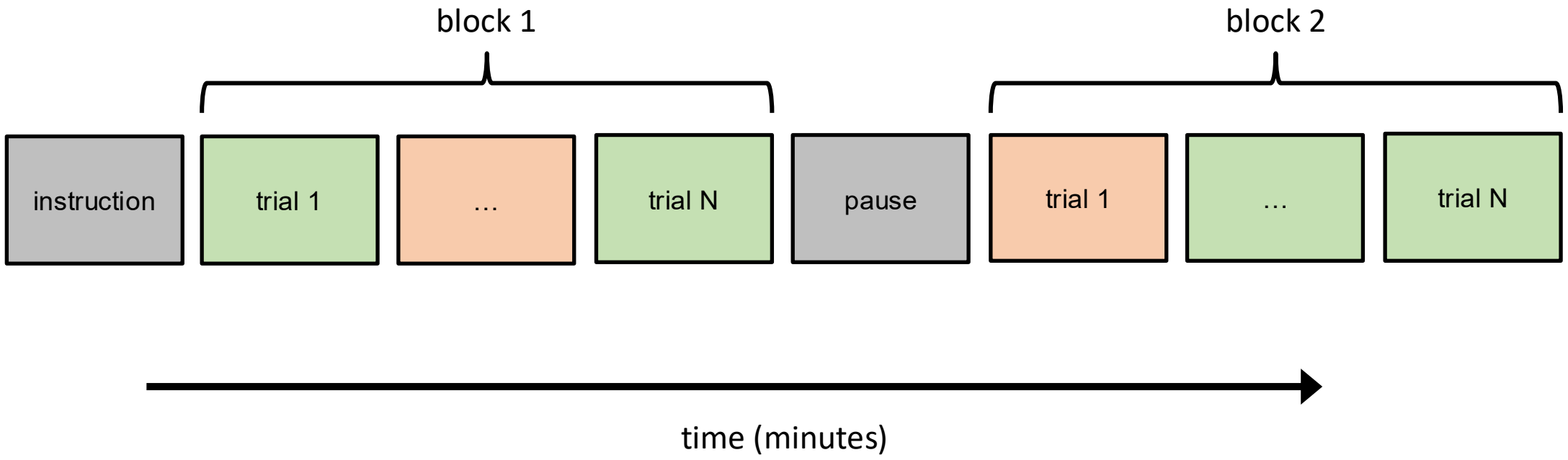


Puce & Hämäläinen (2017)

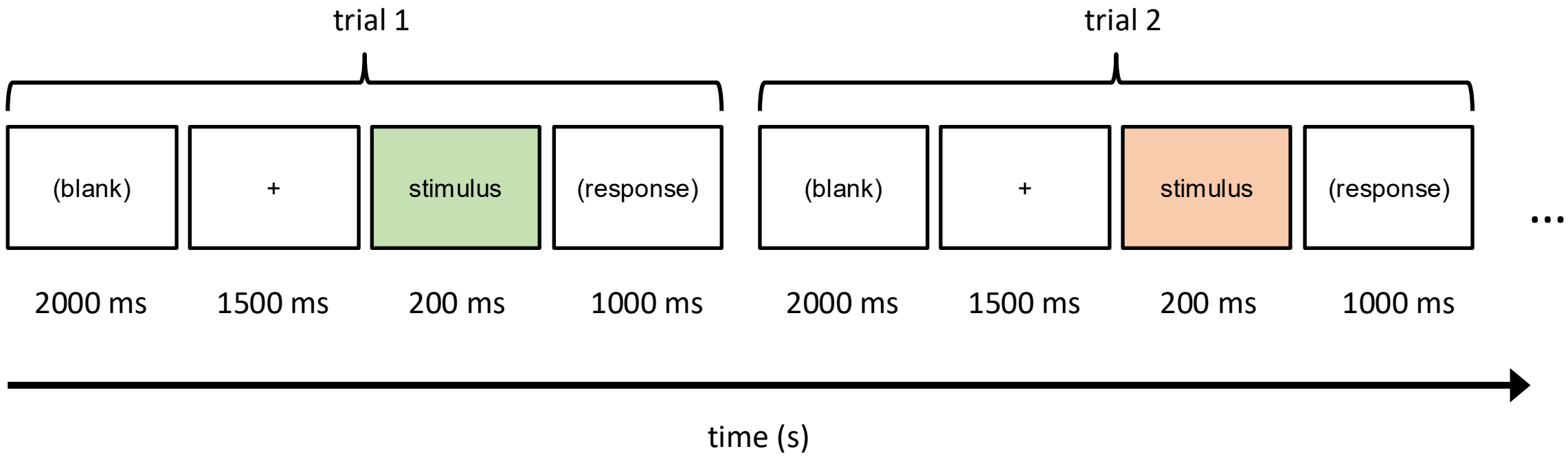
Record a single subject's EEG in the lab



Designing the experiment, global structure



Designing the experiment, more in detail



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.

Usually the stimulus presentation software allows you to “program” an experiment in the form of a script.

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, since the brain is so flexible in auditory-visual integration.

Demonstration of an EEG and ERP recording

How to preprocess, analyse, and interpret EEG & ERP data

Robert Oostenveld

8 June 2026
Nairobi, Kenya

robert.oostenved@donders.ru.nl

EEG preprocessing and analysis

Visual inspection and artifact rejection

Bad channel detection

Filtering

Re-referencing

ICA and artifact removal

Segmenting

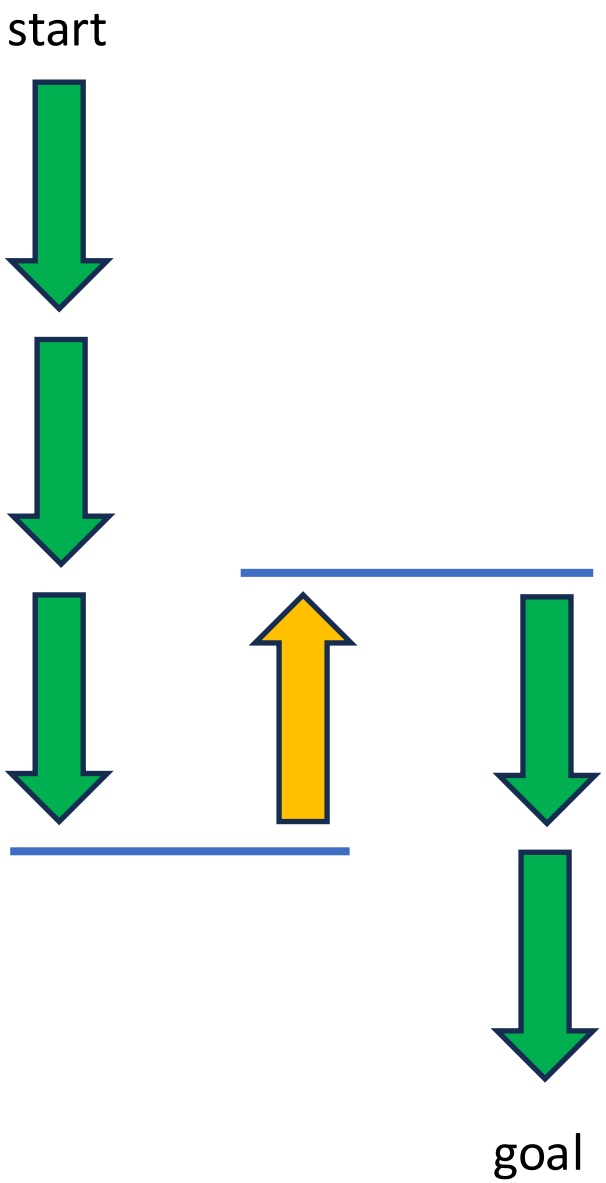
Averaging over trials to get the ERP

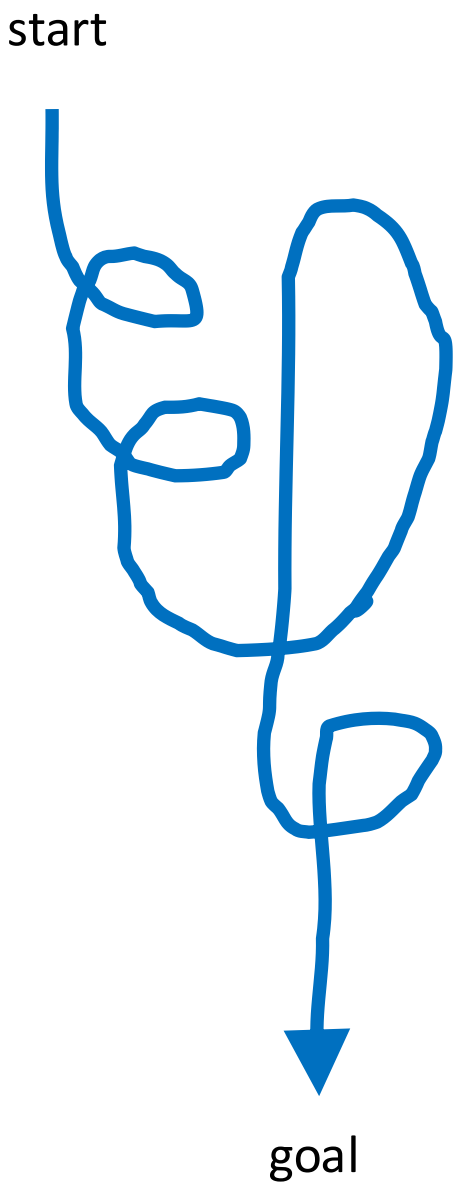
Computing TFRs and averaging over trials

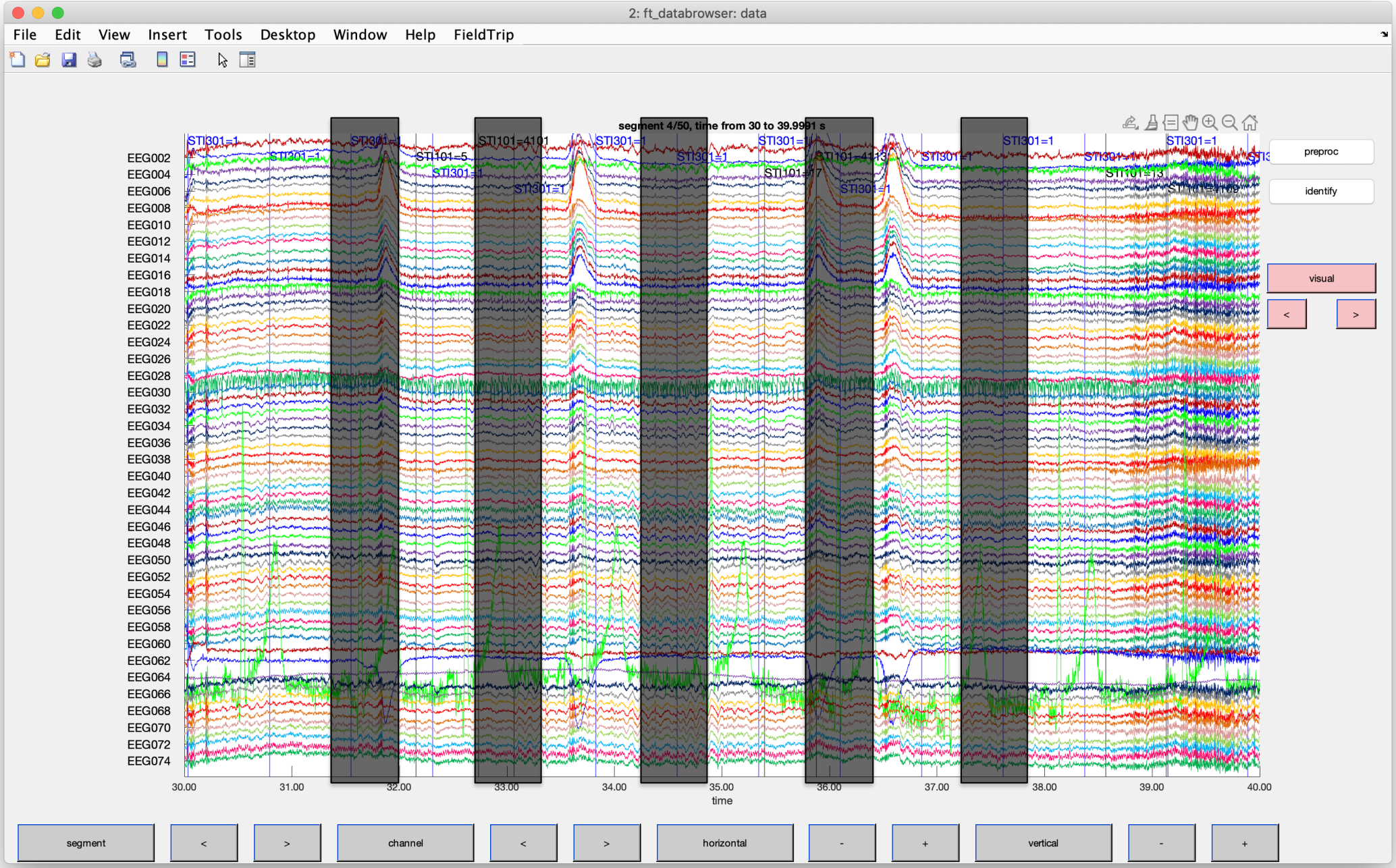
Frequency analysis

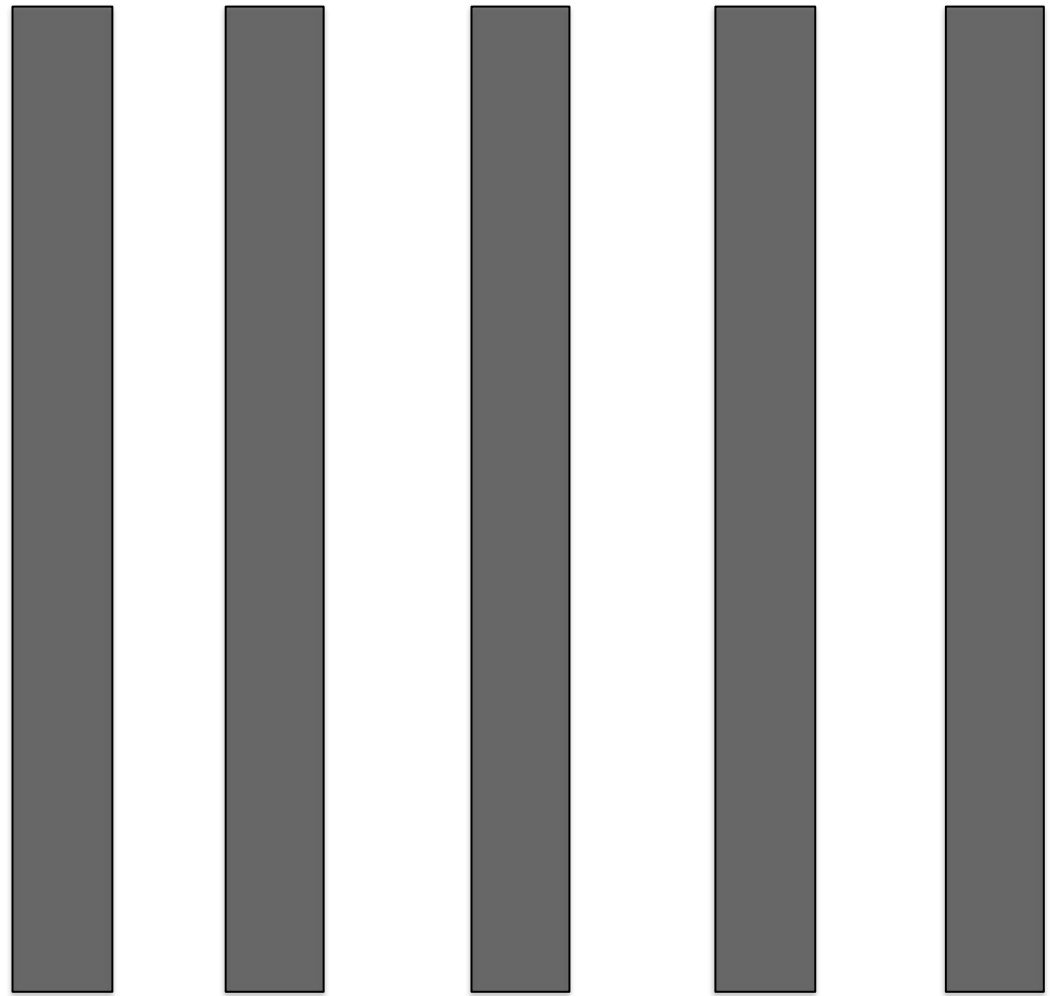
Statistical evaluation over participants

EEG preprocessing often requires multiple iterations

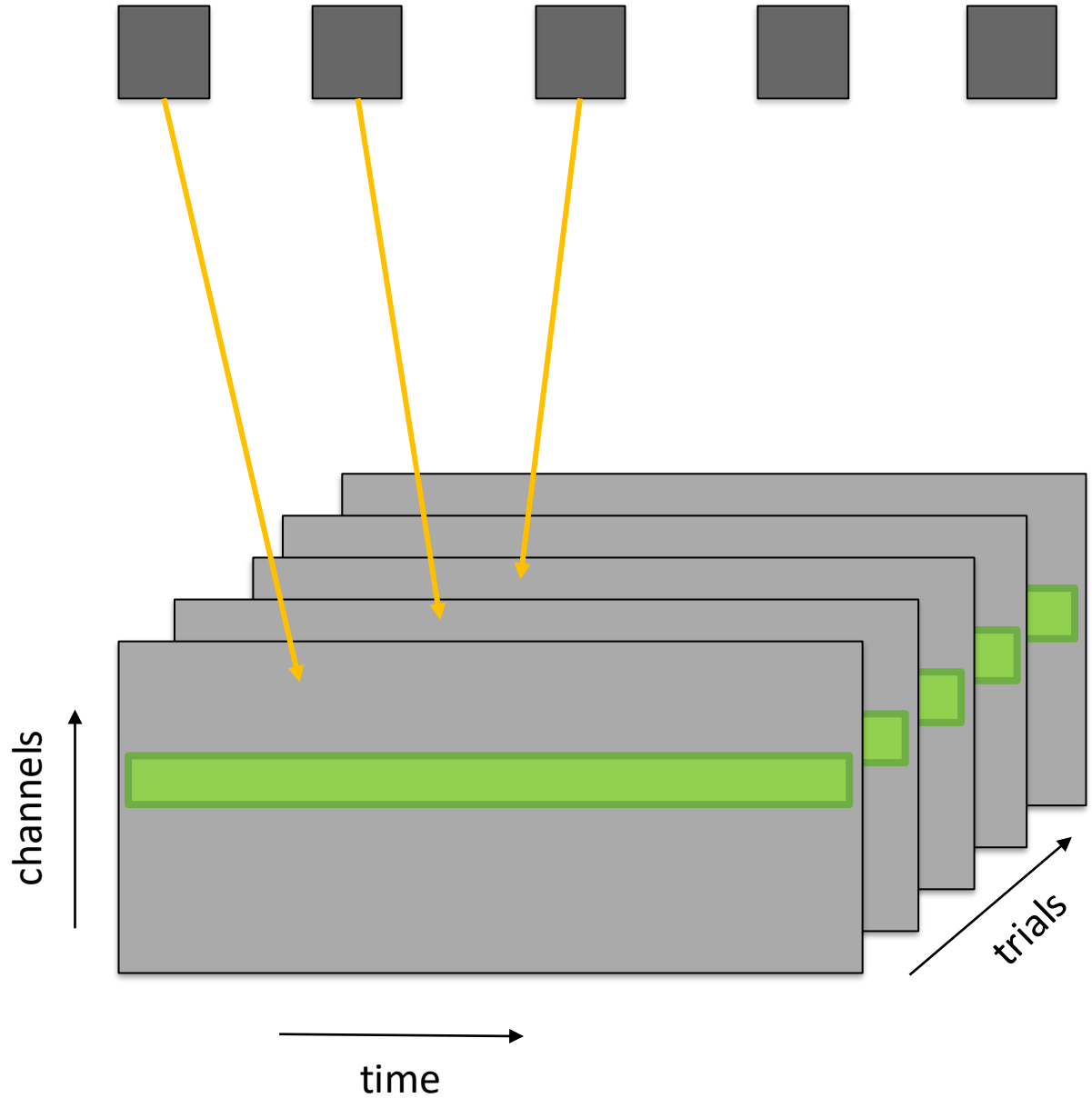





2: ft_databrowser: data
File Edit View Insert Tools Desktop Window Help FieldTrip
segment 4/50, time from 30 to 39.9991 s
EEG002 EEG004 EEG006 EEG008 EEG010 EEG012 EEG014 EEG016 EEG018 EEG020 EEG022 EEG024 EEG026 EEG028 EEG030 EEG032 EEG034 EEG036 EEG038 EEG040 EEG042 EEG044 EEG046 EEG048 EEG050 EEG052 EEG054 EEG056 EEG058 EEG060 EEG062 EEG064 EEG066 EEG068 EEG070 EEG072 EEG074
STI301=1
STI101=4101
STI101=5
STI101=4113
STI101=7
STI101=13
30.00 31.00 32.00 33.00 34.00 35.00 36.00 37.00 38.00 39.00 40.00
time
preproc
identify
visual
<
>
segment
<
>
channel
<
>
horizontal
-
+
vertical
-
+



~ 100 channels
~ 1 second = 500 samples
So 100x500=50.000 numbers


channels
time
trials

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

Demonstration of EEG analysis

Applications of EEG: what types of research questions?

Robert Oostenveld

8 June 2026
Nairobi, Kenya

robert.oostenved@donders.ru.nl

Types of research questions to answer with EEG

Questions about the brain and how its fundamental principles works

Questions about cognitive brain processes

- Disentagle the process into steps
- When and where does something happen

Questions where the participant or patient cannot give the answer

- Patients might not be aware of a disorder
- Pre-verbal infants cannot be instructed in their behavior

Discussion on experimental research questions for EEG