MAX PLANCK INSTITUTE FOR PSYCHOLINGUISTICS

# Introduction to Electrophysiology

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Some slides were adapted with the kind permission of Robert Oostenveld and Jan-Matthijs Schoffelen from the Donders Institute

# First of all, hello!


Cold Spring Harbor Lab

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# Learning objectives

Have a **general understanding** of, and be able to explain to someone else:

- What electrophysiology is, in particular EEG
- How we use it to study language processing

Have a clear and **complete overview** of:

- The underlying biology of the brain signals we measure
- The format of these measurements once they reach a computer

Get ready for the **future**: Leave the class with knowledge you can revisit and build upon in future coursework or internships.

# Lecture outline

1. A bird's eye view of neuroimaging
2. How are the signals generated in the brain?
3. Example of an EEG lab and workflow
4. Event-related potentials (ERPs): Evoked activity
5. Fundamentals of neuronal oscillations and synchrony
6. Time-frequency representations: Induced activity

**Bonus (if time allows): Choose your own adventure!**

Intracranial recordings / Functional connectivity and phase coherence

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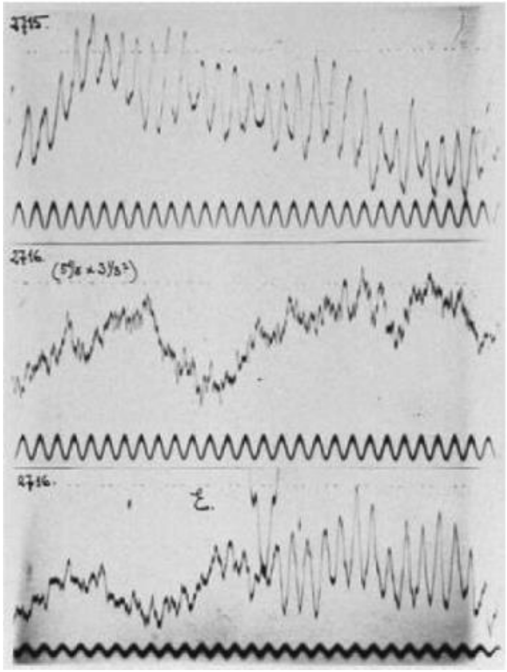
# A bird’s eye view of neuroimaging

We can infer many things by observing and measuring the behavior of people. But, there are things we just can’t study by looking at behavior alone. This is where neuroimaging can help.

Neuroimaging methods measure indexes of the activity of neurons:

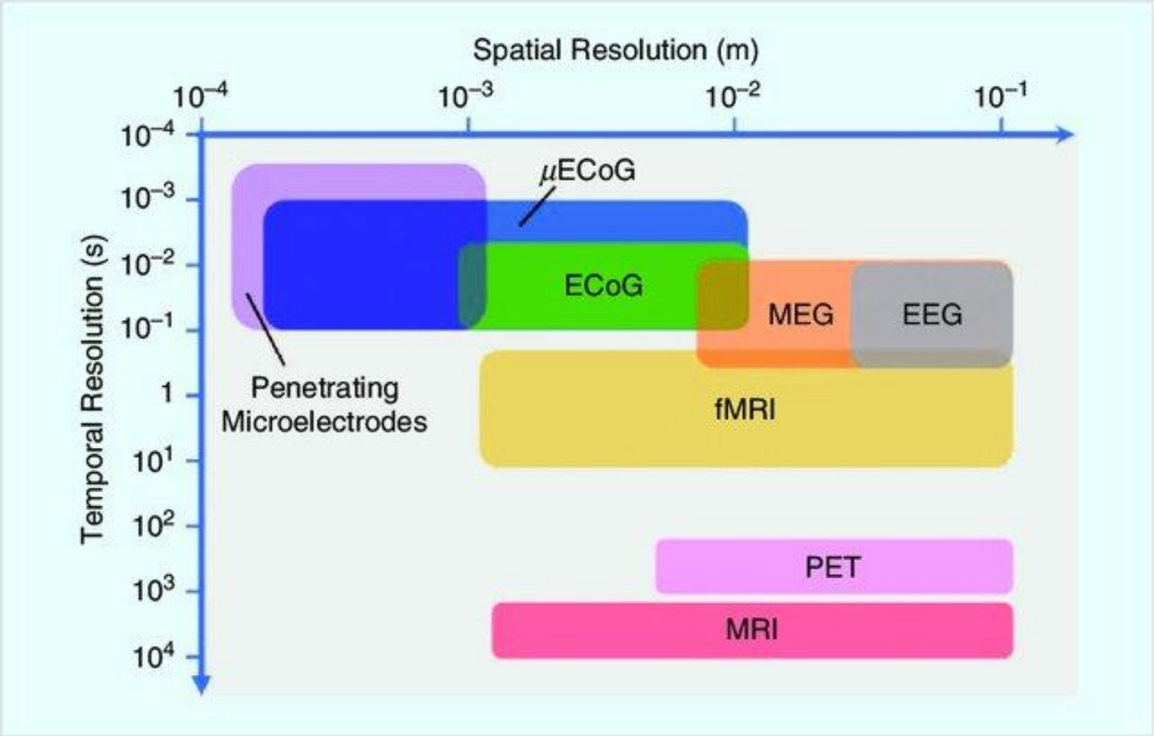
- Electrophysiology: Measures electrical or magnetic activity generated when neurons fire.

- fMRI: Measures the Blood Oxygen Level-Dependent (BOLD) signal, which reflects oxygen delivery to active neurons.



Hans Berger (1873 – 1941) was the first person to measure electrical brain activity in 1924, 100 years ago.

# A bird’s eye view of neuroimaging




**Each technique has its own spatial and temporal resolution, its own advantages and inconvenients.**

For example, intracranial recordings have the best temporal resolution and we know quite precisely where the electrodes are placed (great spatial resolution), but we only record from a few sites in the brain.

*Figure from Thukral et al., 2018*

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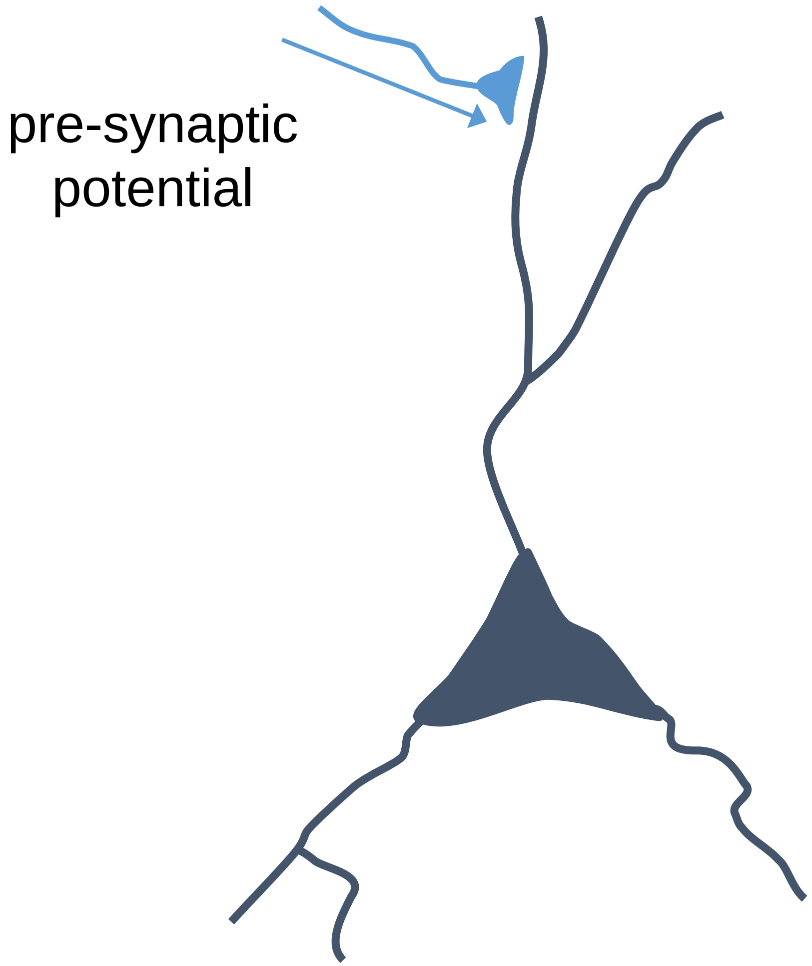
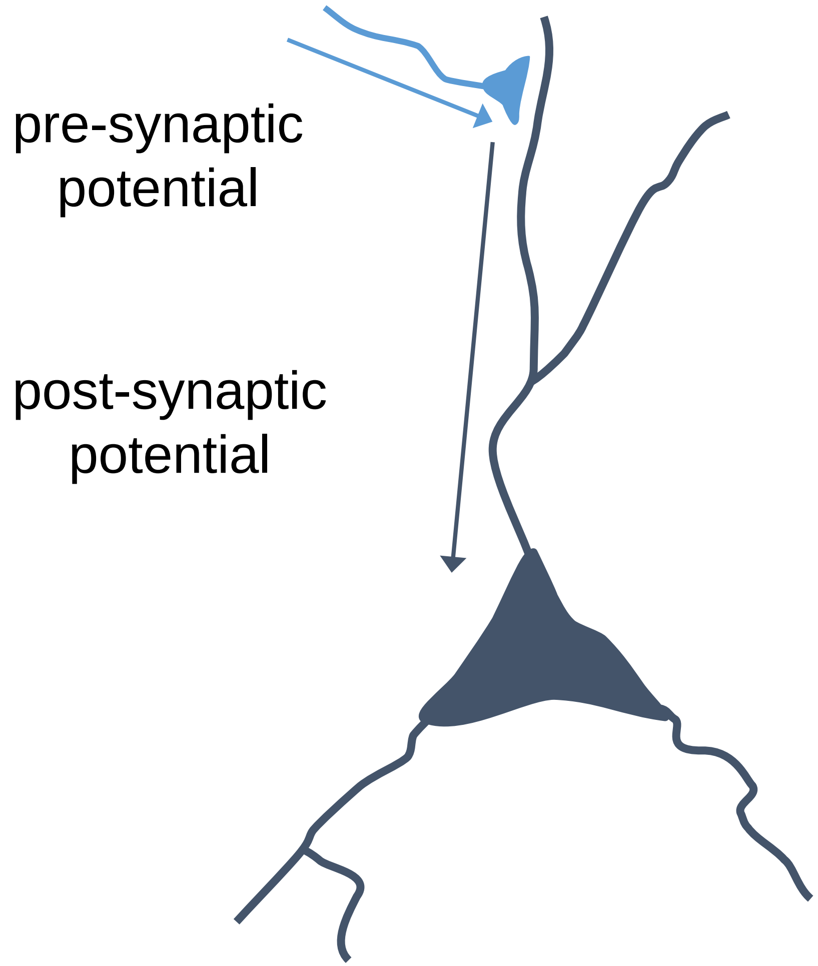
# Neurons have a resting state and an active state




**Resting state**: The **neuron** is inactive.

- The inside of the neuron is negatively charged compared to the outside, this is a stable state.
- The **resting membrane potential** (the difference between inside and outside) is around -70 mV.

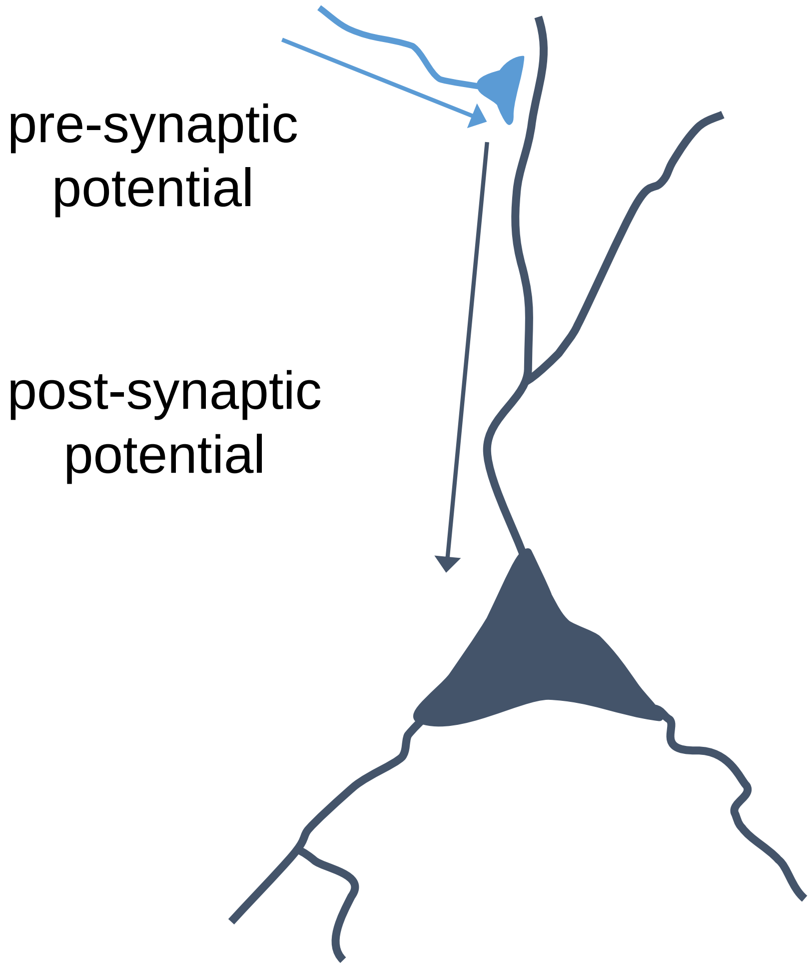
# Neurons have a resting state and an active state




**Active state**: When the neuron fires.

- The **neuron** has received a strong enough signal form another **neuron**, so it becomes **depolarized** (=more positive inside).
- If the membrane potential is -55 mV or less, this triggers an **action potential**, which propagates the electrical signal down the cell.

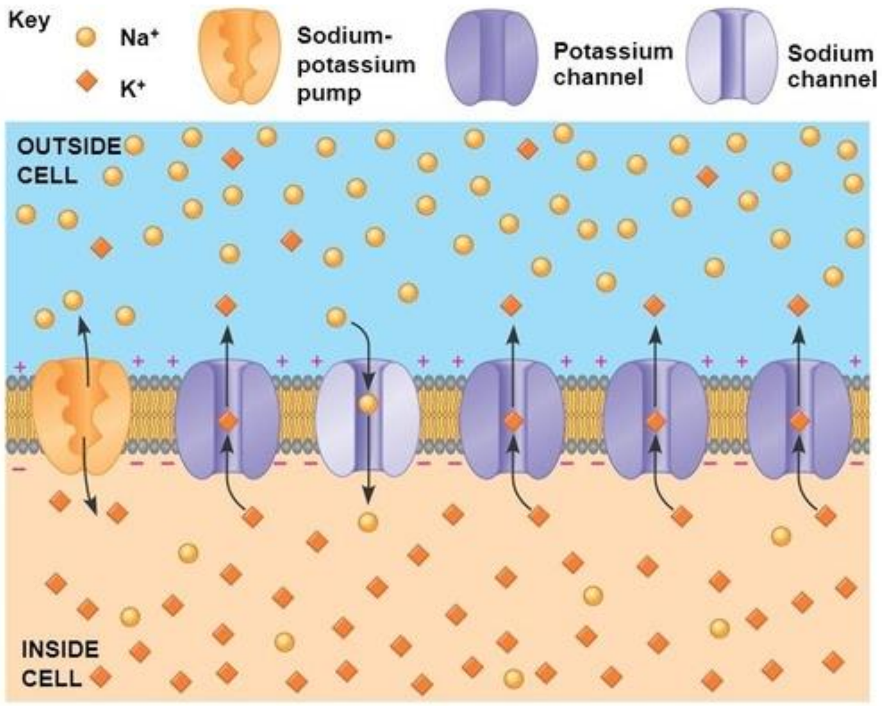
# Neurons have a resting state and an active state




**(1) How does a neuron become more depolarized?**

**(2) How does a neuron « receive signal » from another neuron?**

# (1) Ion channels mediate changes in membrane potential



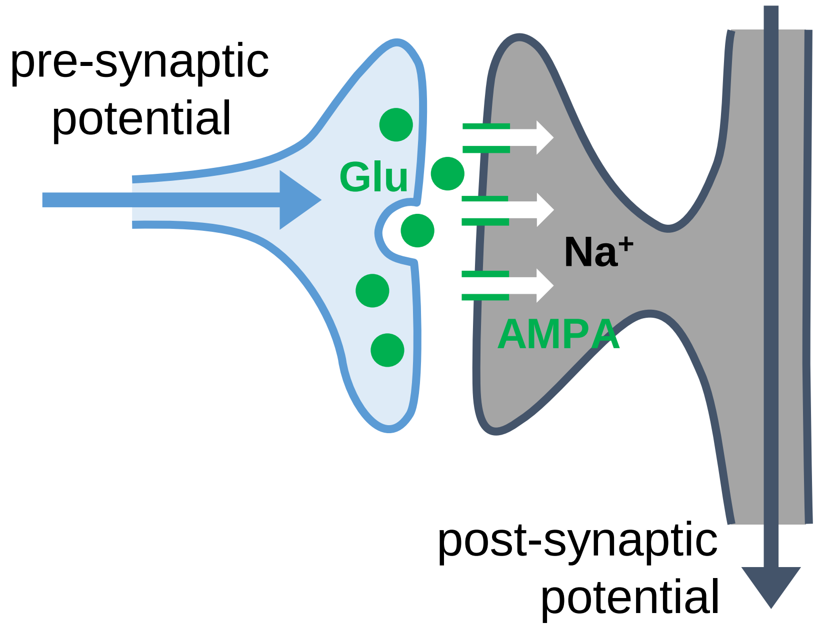

Some ion channels are **voltage-gated**: they open only when the membrane potential reaches a certain threshold (e.g., -55 mV).

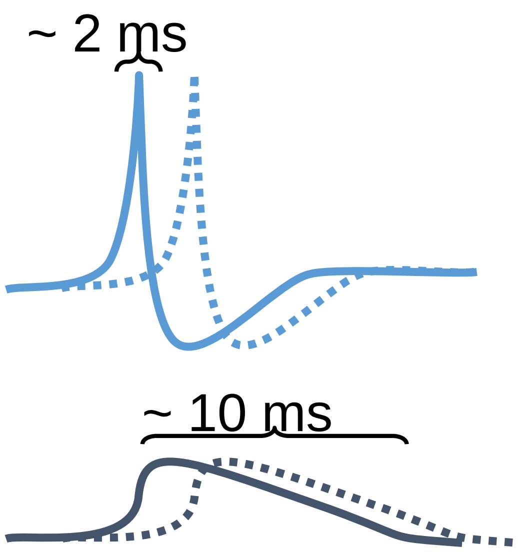
These channels allow certain ions to enter or exit the cell:

- Sodium ($Na^+$): typically flows into the cell, causing depolarization (makes the inside less negative).
- Potassium ($K^+$): typically flows out of the cell, leading to repolarization (returns the inside to a more negative state).
- Calcium ($Ca^{2+}$): enters the presynaptic terminal during an action potential, triggering neurotransmitter release.

Because these ions carry small charges, their movement across the membrane directly changes the voltage across the cell membrane.

# (2) Neurons communicate via the synapse (here, chemical)




Action potential → release of **neurotransmitters** from the **presynapse** into the synaptic cleft → **Neurotransmitters** bind to the (ligand-gated) ion channels on the **postsynapse** (e.g. AMPA receptors → Na+ ions enter → and thereby changes in membrane potential of the **neuron**.

If strong enough, it will in turn fire an action potential.

1. **A bird's eye view of neuroimaging**
2. **How are the signals generated in the brain?**
3. **Example of an EEG lab and workflow (not for the exam)**
4. Event-related potentials (ERPs): Evoked activity
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6. Time-frequency representations: Induced activity

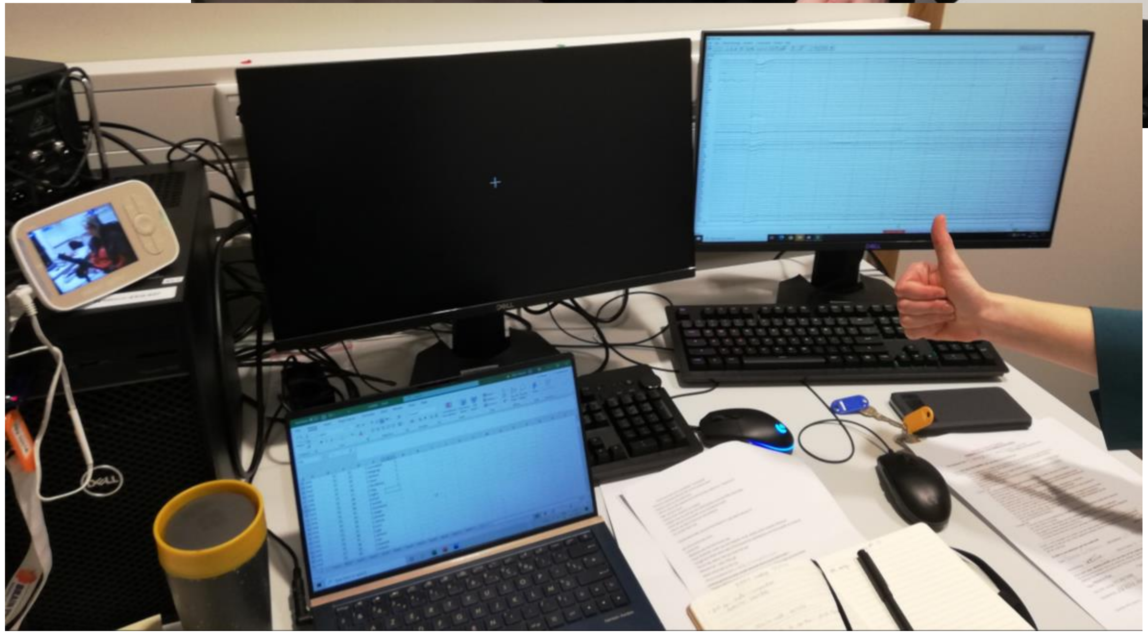
# Example of an EEG lab

Experiment room

- EEG cap and electrodes
- Gel, seringue, alcohol wipes, NuPrep gel
- Amplifiers
- Experiment presentation monitor
- Participant

Control room

- Data acquisition computer
- Experiment presentation computer
- Monitor to see/speak to participant
- Own computer to annotate accuracy



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# Example workflow

- Design experiment carefully, to answer a carefully defined research question
- Program the experiment for presentation to the participant
- Pilot the experiment
- Ideally, pre-register the study
- Recruit participants
- Data collection
- Annotate behavioural data, if applicable
- Preprocess the data: Clean your data (e.g., remove inaccurate trials, remove artifacts)
- Analyse the data and statistically test the effects
- Make good-looking figures
- Write up the study and disseminate the findings

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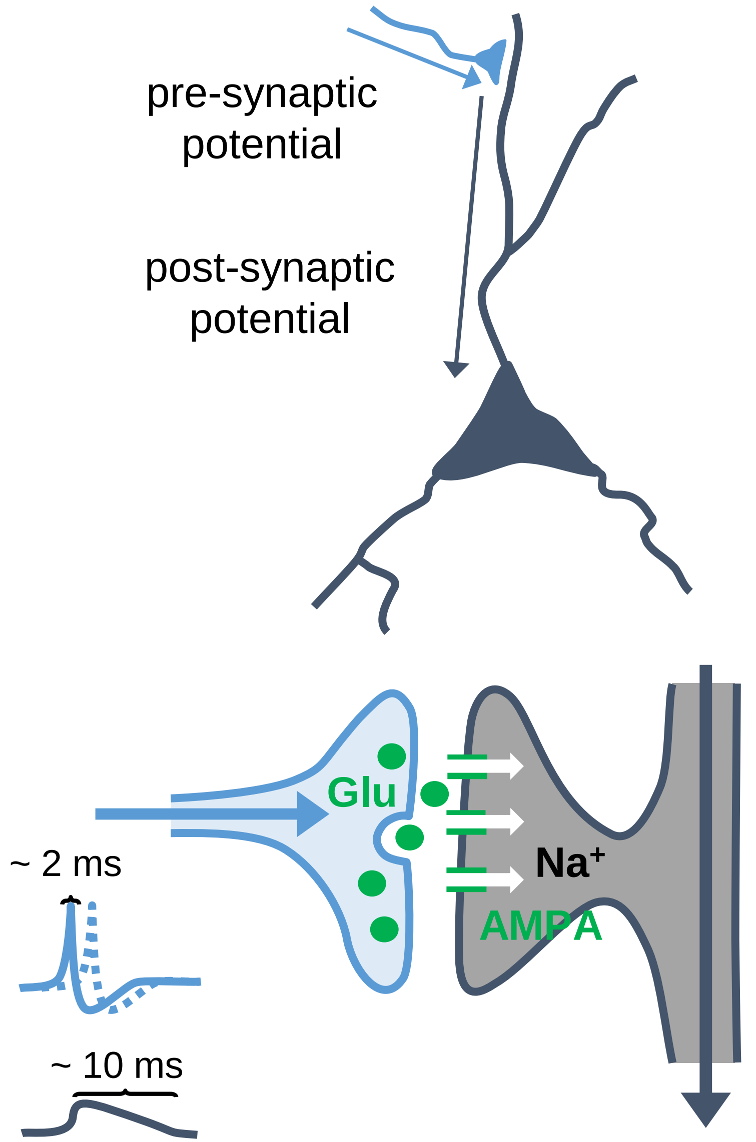
# Electrical activity measured at the scalp is generated by PSPs




As we saw, when a **neuron** receives input from another **neuron**, this causes a **post-synaptic potential (PSP)**.

With **EEG**, we measure electrical activity at the scalp, which arises from the electric current of **PSPs** in **pyramidal neurons**.

In order to pick up a signal at the scalp, a large population of neurons needs to be active at the same time (10.000 – 50.000).

Usually, we study neuronal activity following the presentation of a stimulus.

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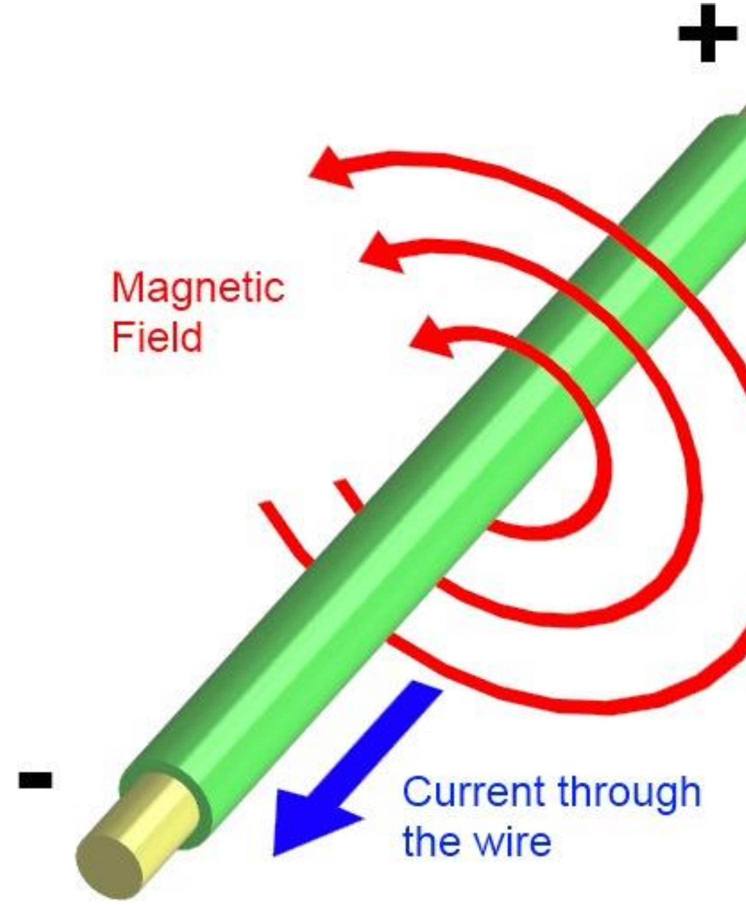
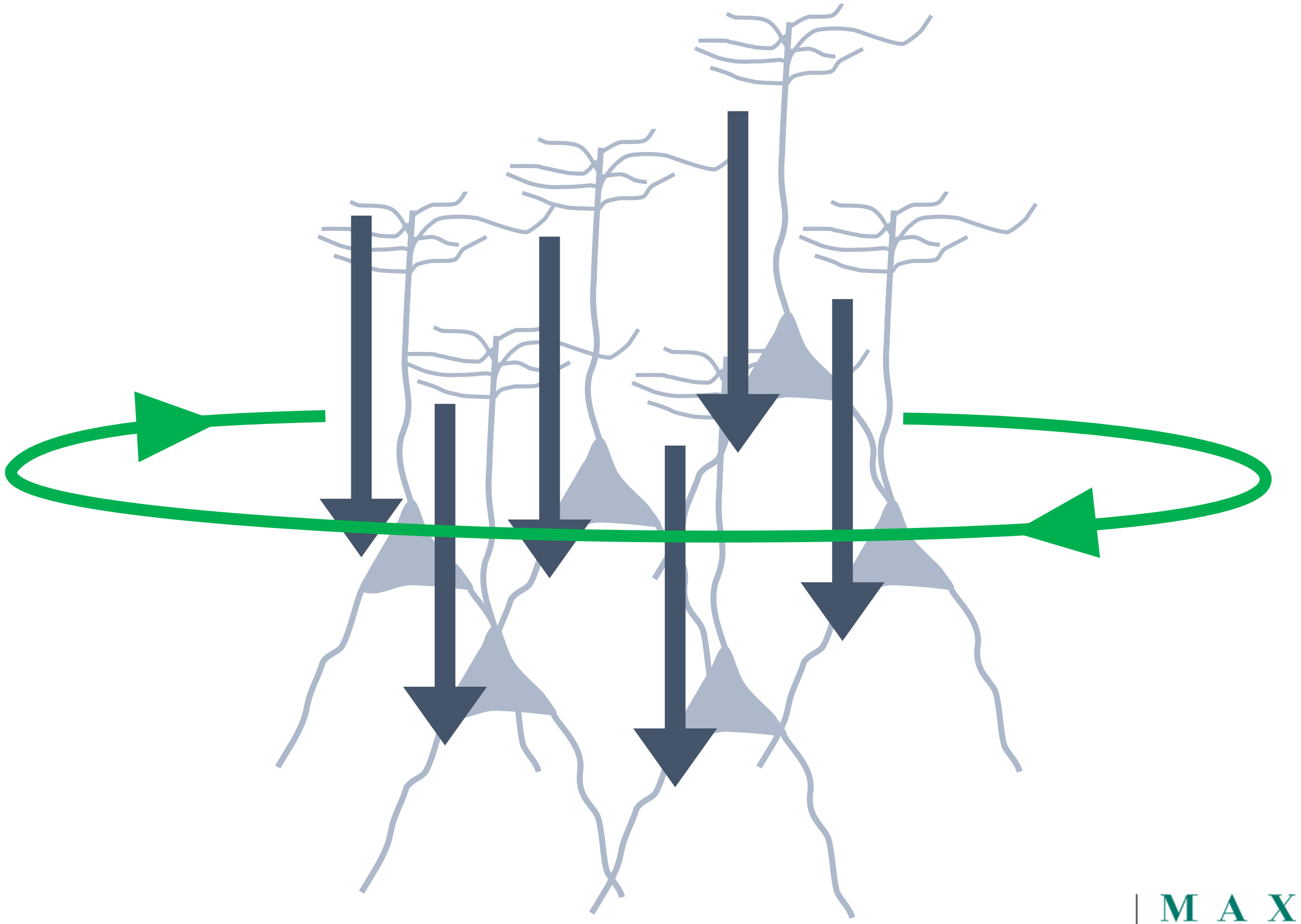
# Electric currents generate a magnetic field



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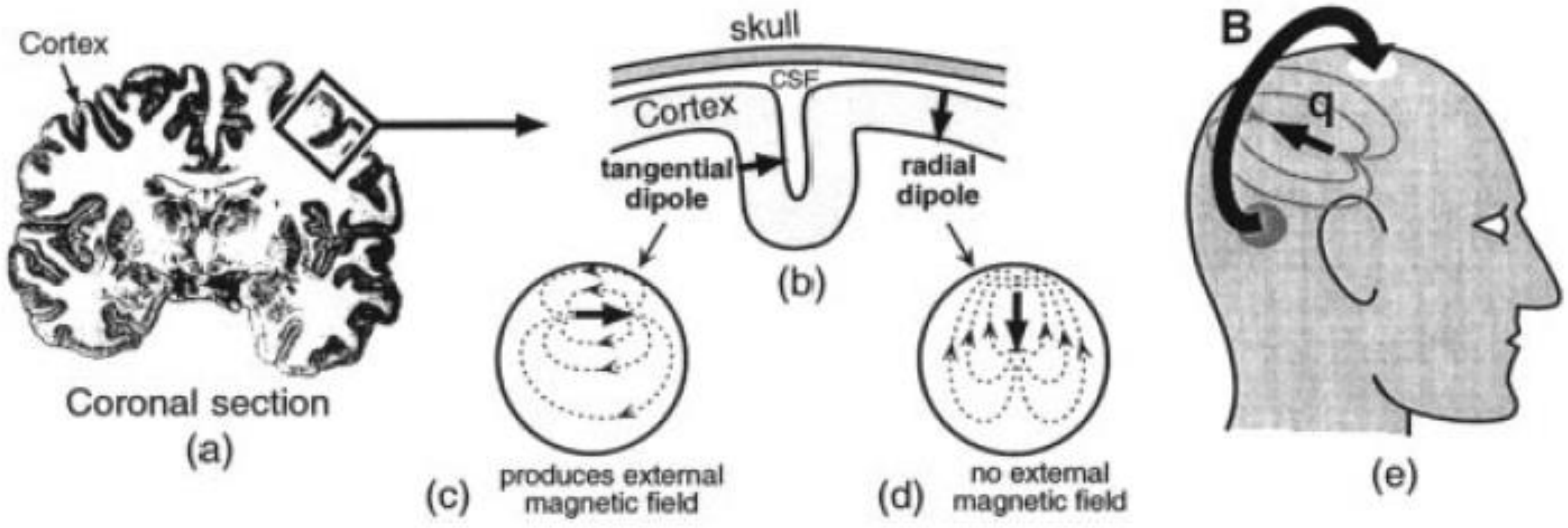
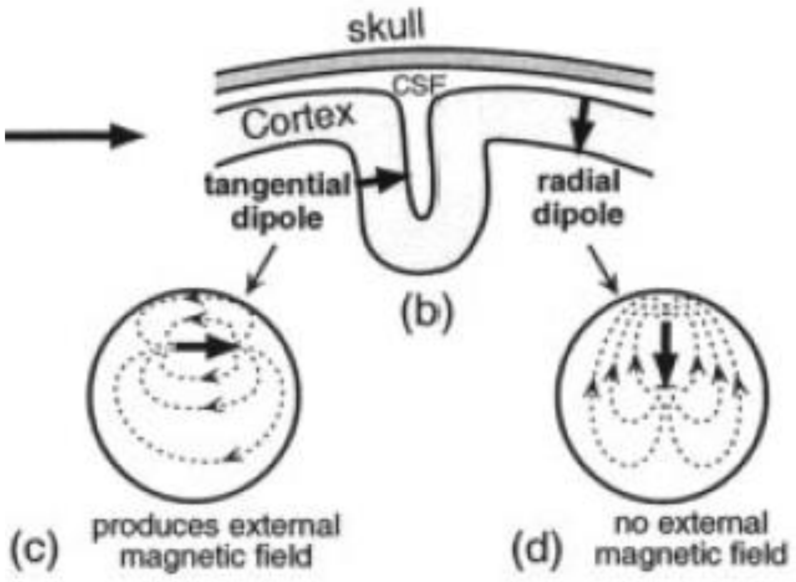
# With MEG, we record magnetic fields




MEG sensors capture magnetic fields generated by electric currents that flow parallel to the scalp.

# With MEG, we record magnetic fields





Magnetic fields are not distorted by the scalp, this is why MEG has a better spatial resolution.

With EEG, it is not possible to *accurately* reconstruct where the electric currents originally came from.

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# Event-related potentials (ERPs)

**Evoked activity**: Activity that is aligned to the stimulus onset.

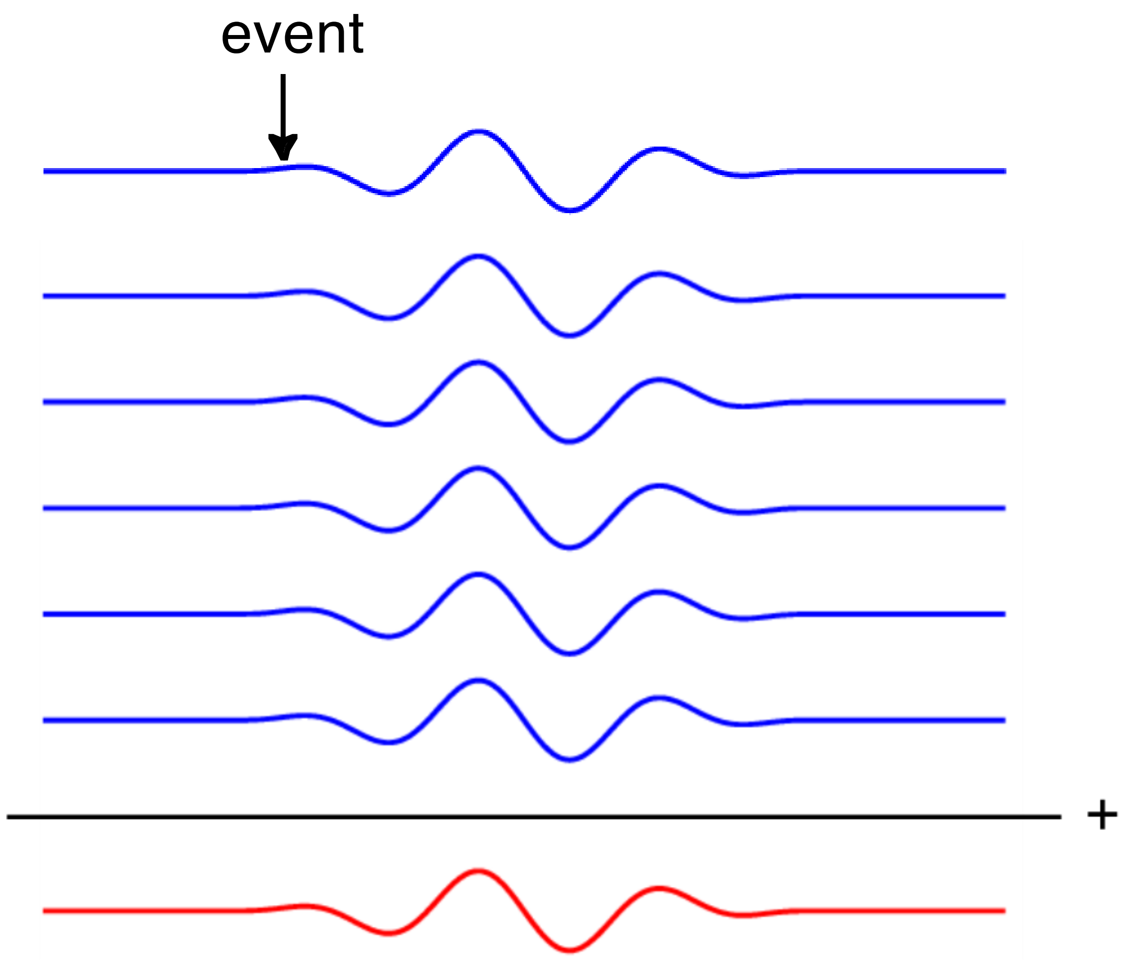
The brain signal of interest is assumed to be **constant over all trials**. For example:

- *Semantic integration: ~400 ms*
- *Visual or auditory response: ~100 ms*

Different terminology:

- EEG: Event-Related Potential (**ERP**)
- MEG: Event-Related Field (**ERF**)

# Evoked activity over trials (cf. figure 2.27, page 60)

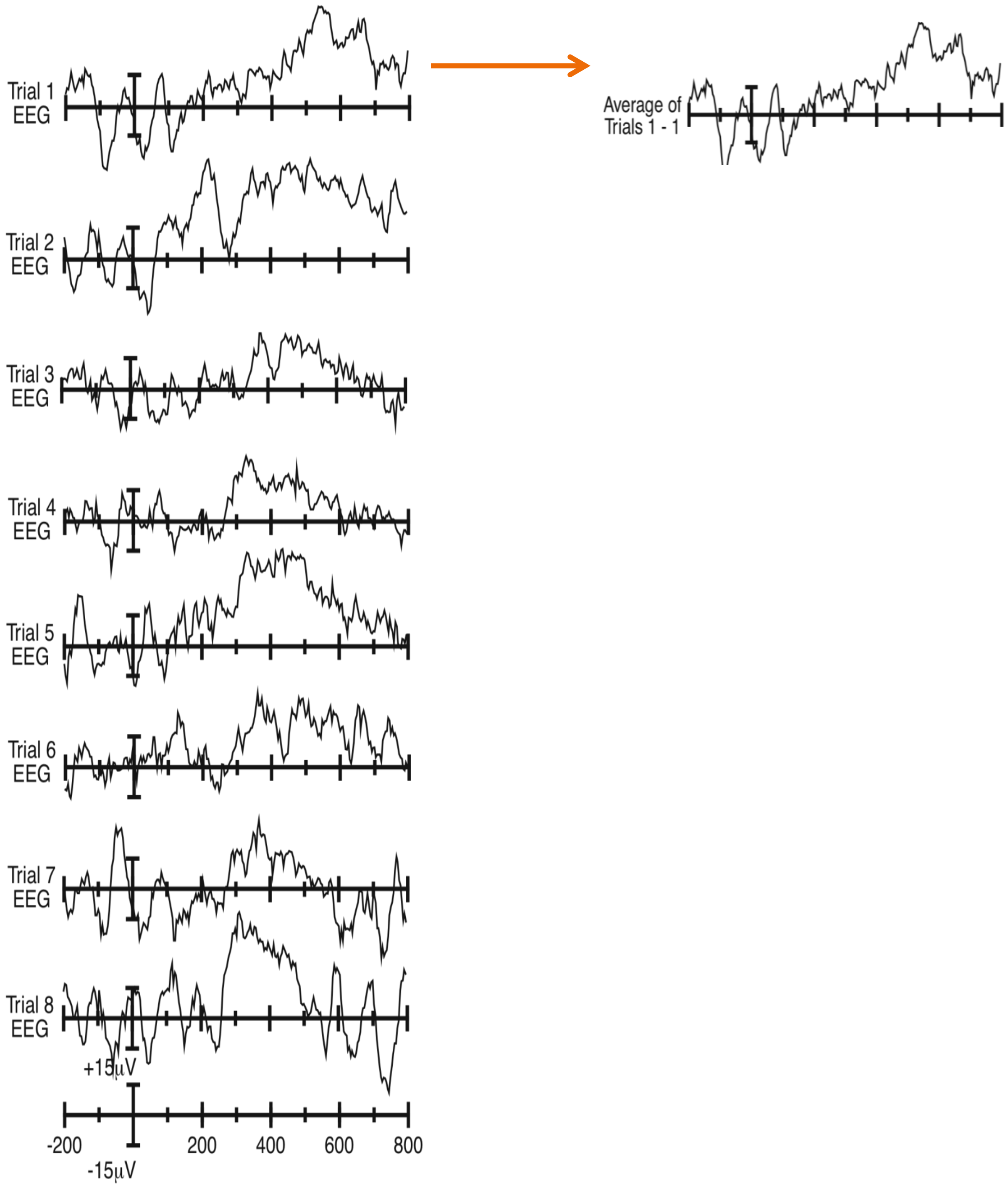



repeated over
many trials

averaged

# ERPs in real life

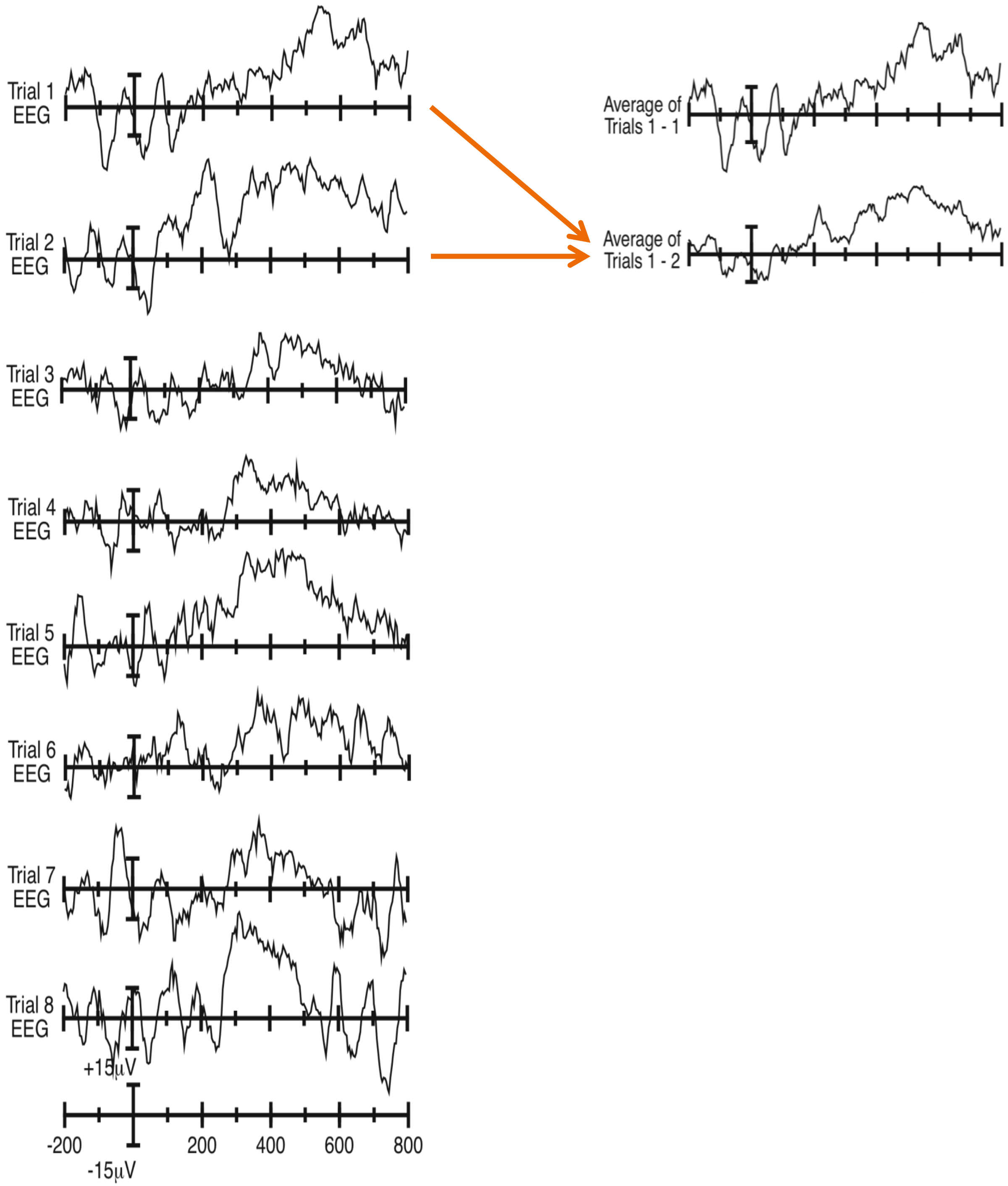
Each trial contains some random noise.



# ERPs in real life

Each trial contains some random noise.

But if we average...



# ERPs in real life

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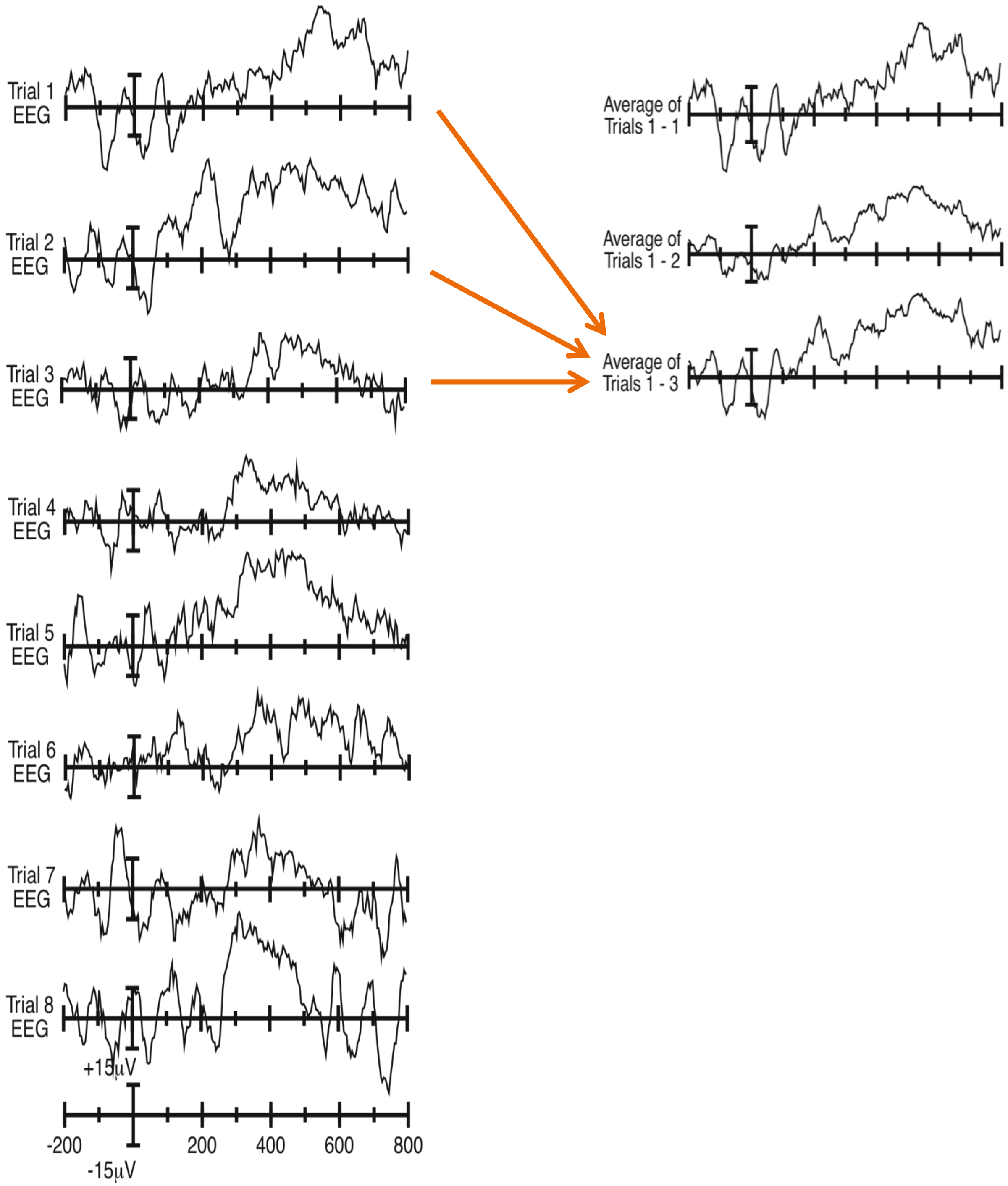


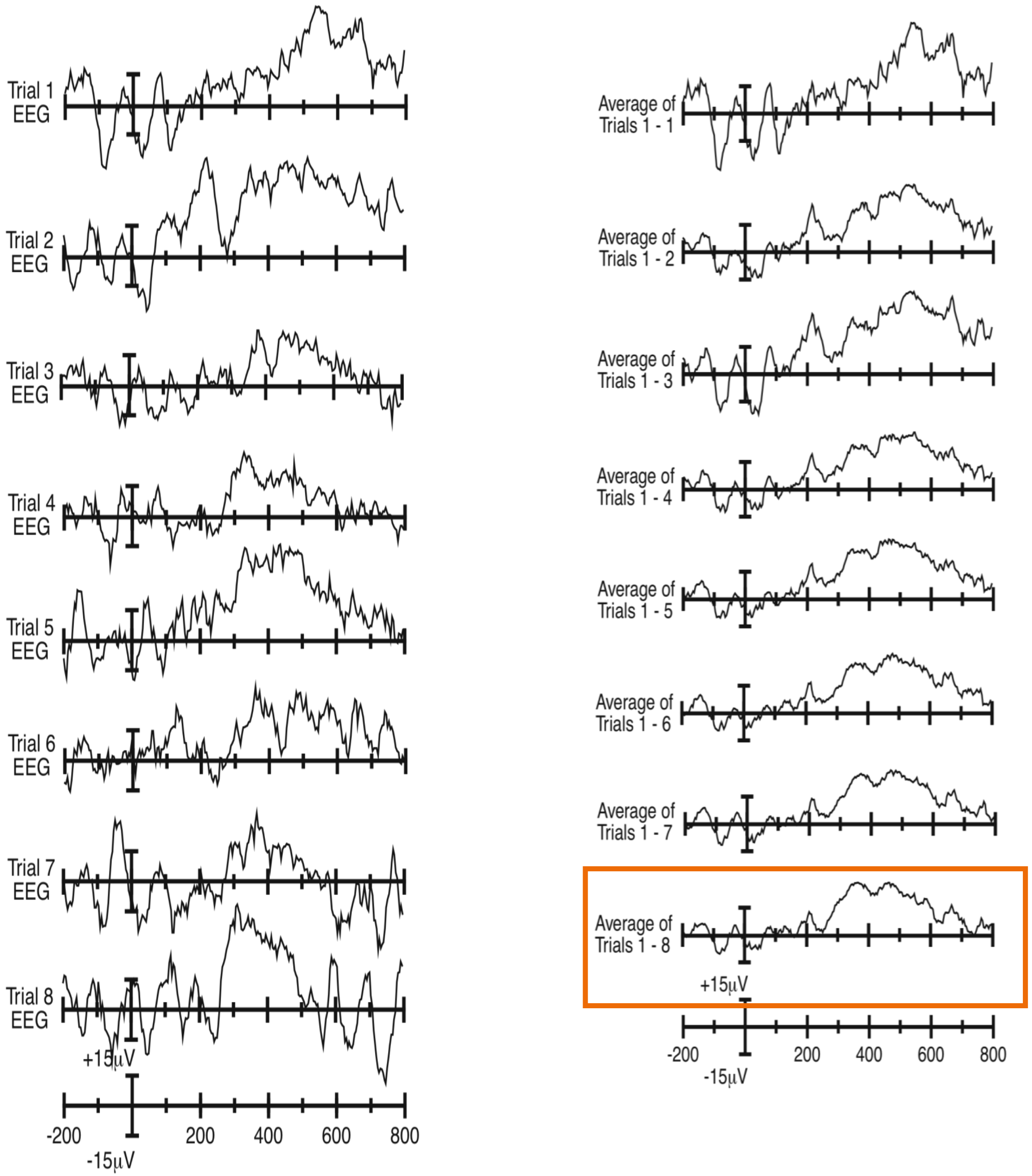
# ERPs in real life

Each trial contains some random noise.

But if we average, we effectively cancel out this noise.

And because the signal of evoked activity is constant over trials we can even see this signal better!

**= Averaging over trials improves the signal-to-noise ratio!**

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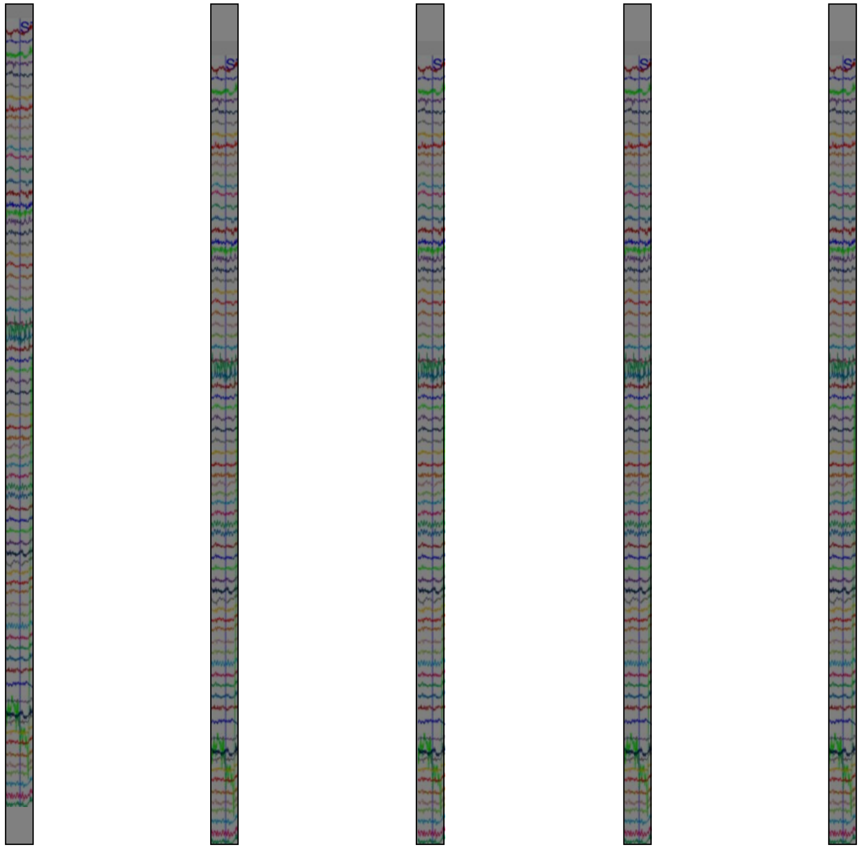
# ERPs in real real life: the databrowser

# ERPs in real real life



75 sensors

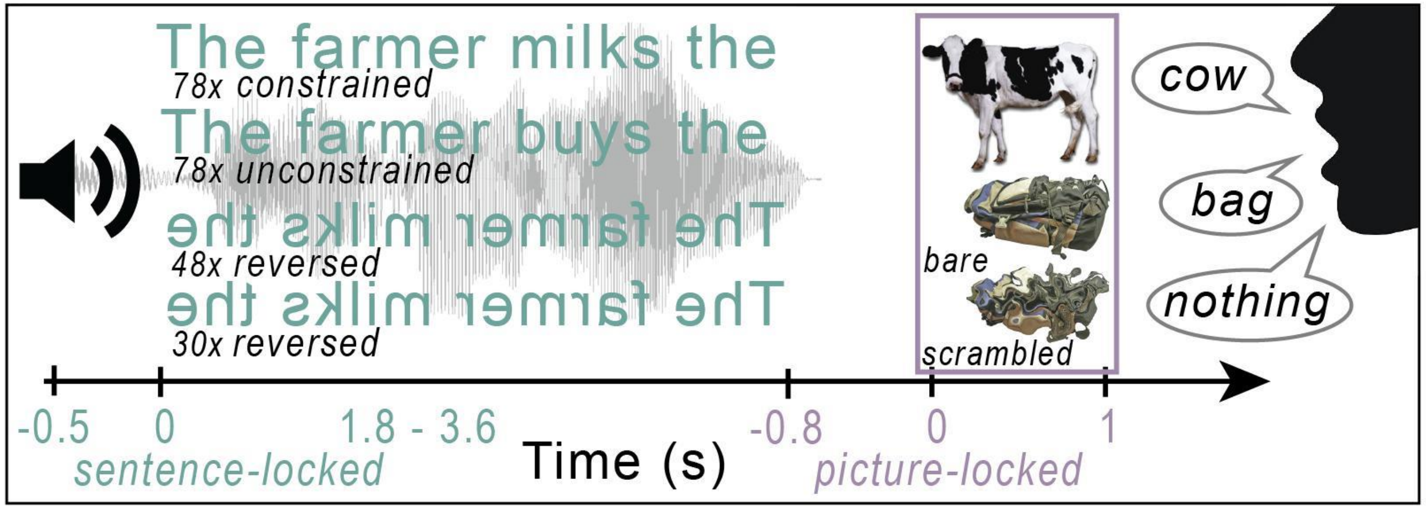
3 seconds per trial

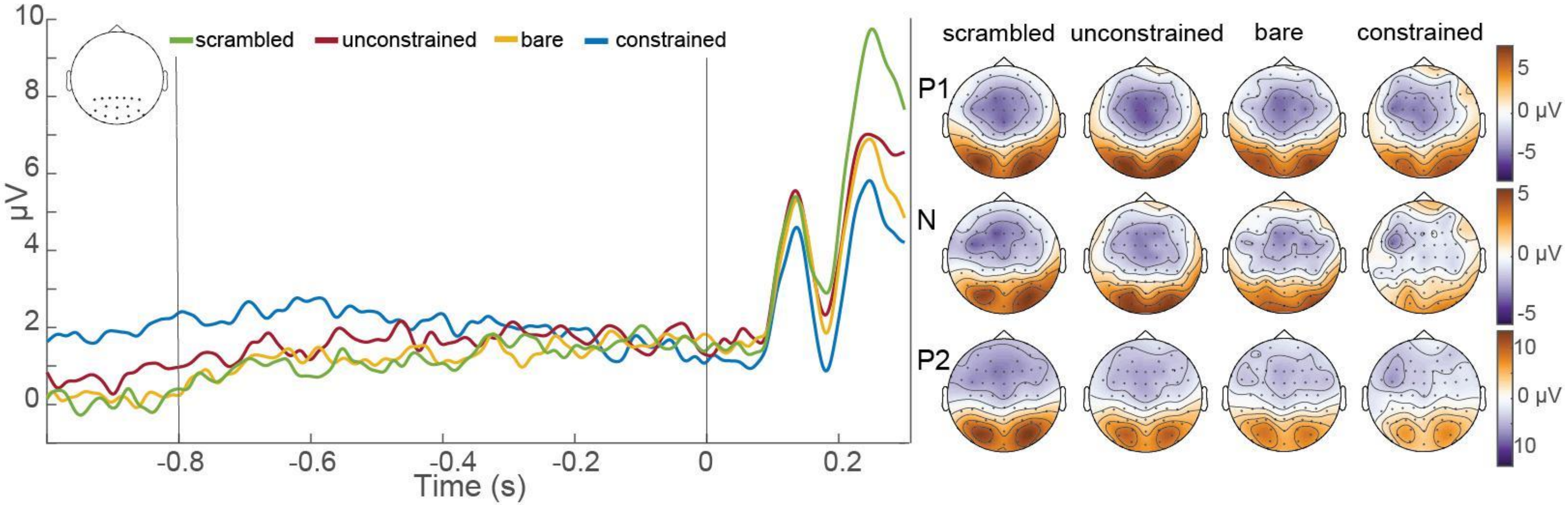
500 samples per second

75 x 1500 = 112.500 numbers

(data points) for one trial

# Example of evoked activity in a picture naming task




*Figures from Roos, Chauvet & Piai, 2024*

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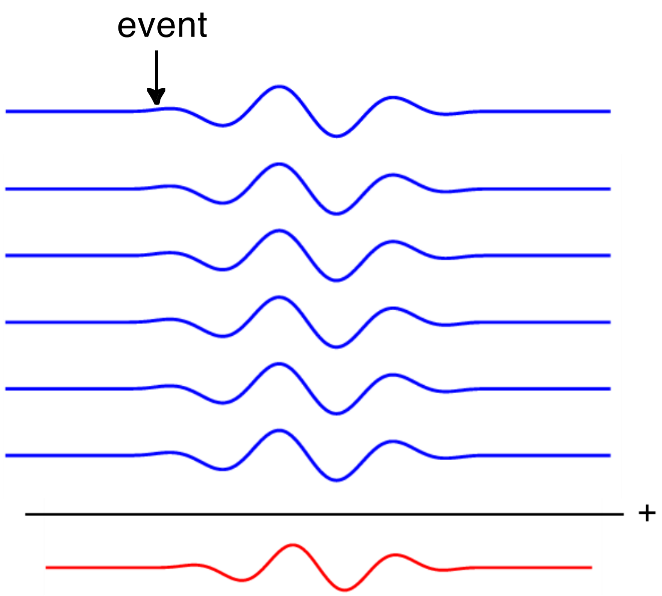
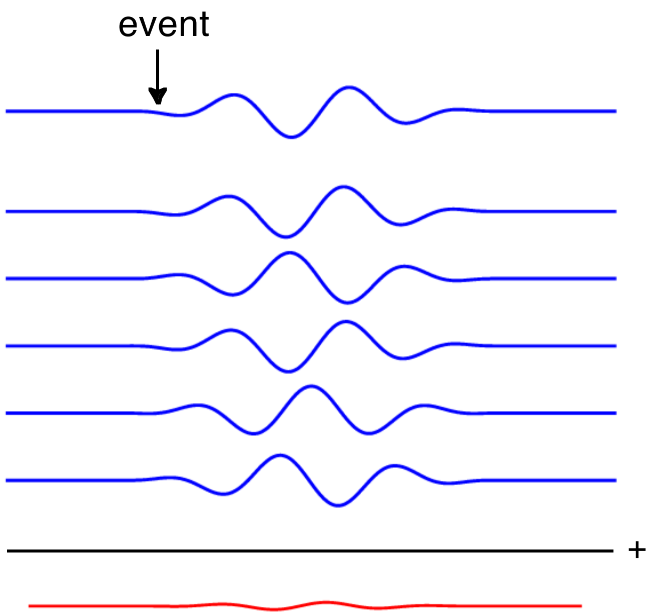
# Fundamentals of neural oscillations

First, why do we care about neural oscillations?

Because not all activity is evoked. Sometimes, the brain process of interest does not have a constant activity over trials, so we cannot average over trials to get an informative waveform.




**Evoked activity**




**Induced activity**

# Fundamentals of neural oscillations (a.k.a. brain rhythms)

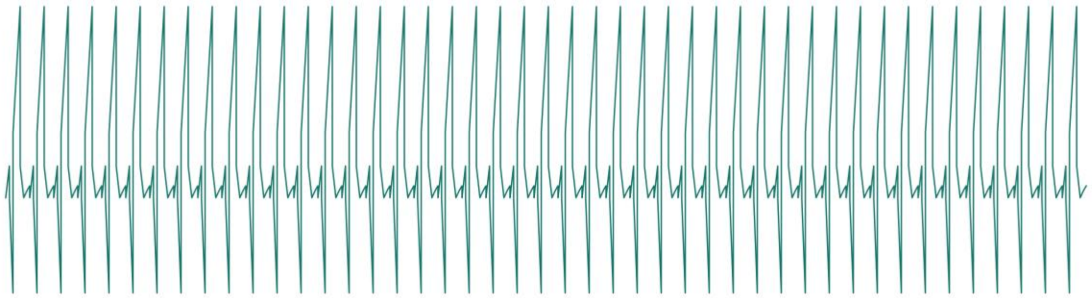
**Neural**: Refers to the activity of neurons.

**Oscillation**: A repetitive variation or fluctuation in a system, typically moving back and forth between two points or states at regular intervals.

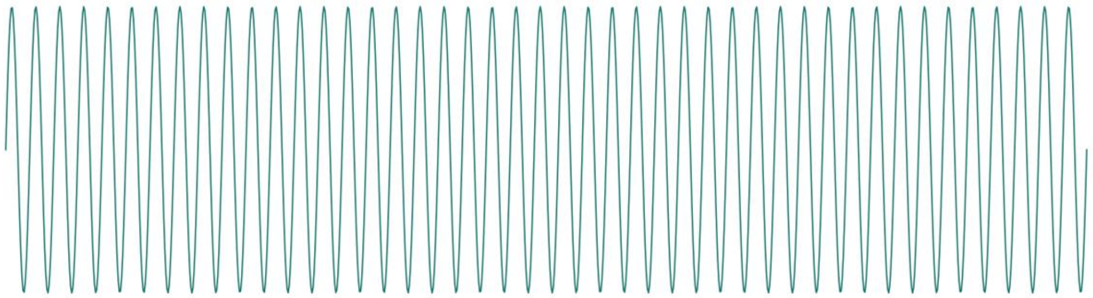
The speed or rate at which it moves between the two states is called the **frequency**.

Examples of things that oscillate:
- Heartbeat: measured in **BPM**, based on the frequency of contractions of the heart
- A sound wave: measured in **hertz**, based on the frequency of the sound vibrations

30 Seconds ECG at 90 BPM



45 Cycles of a 90 Hz Sound Wave



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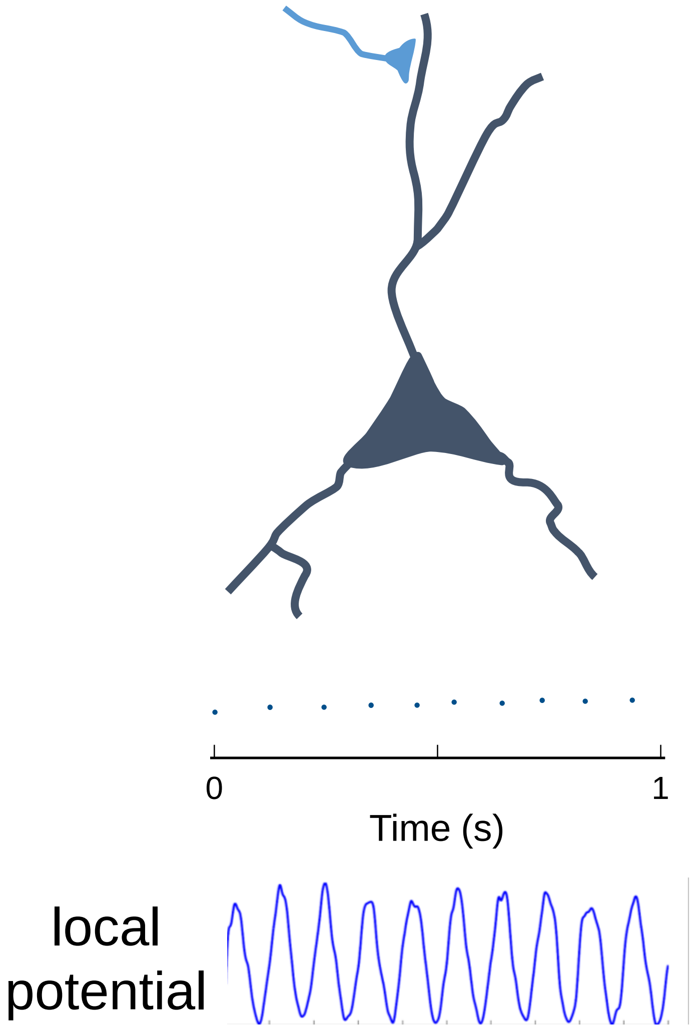
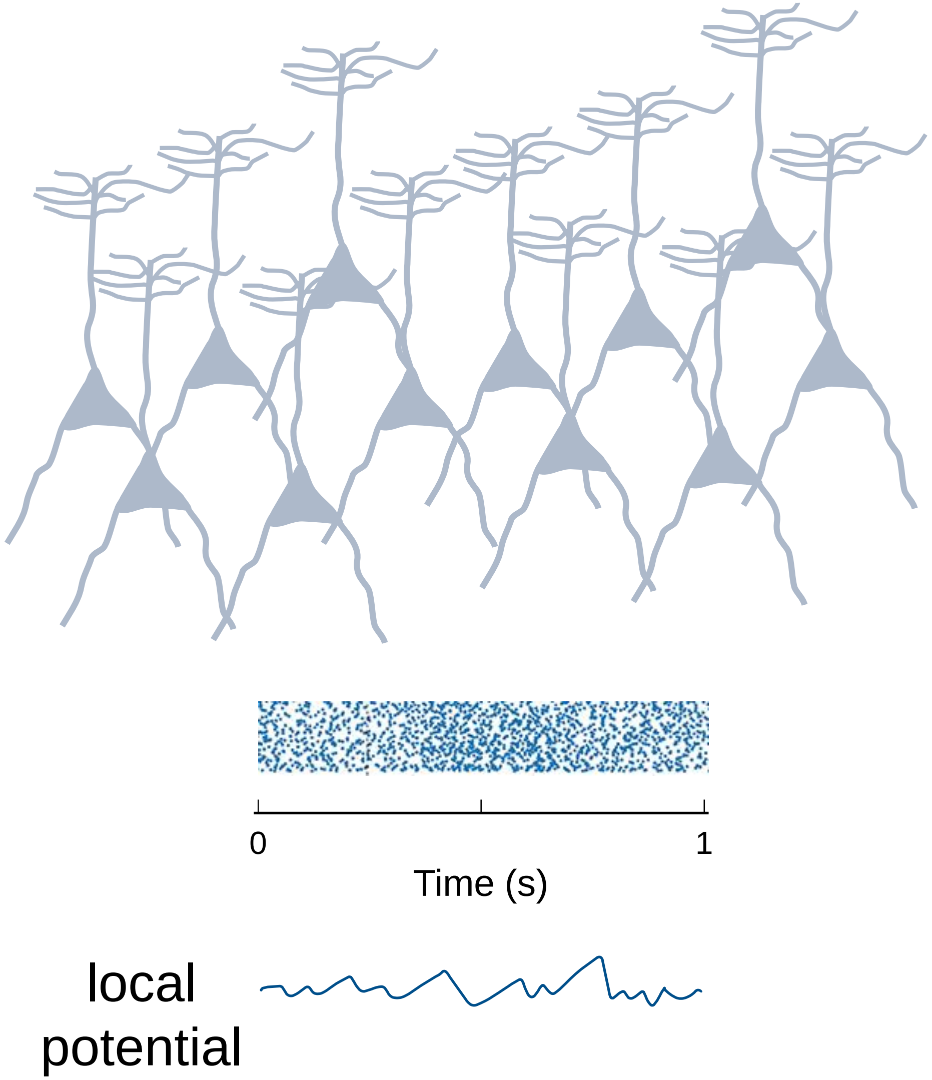
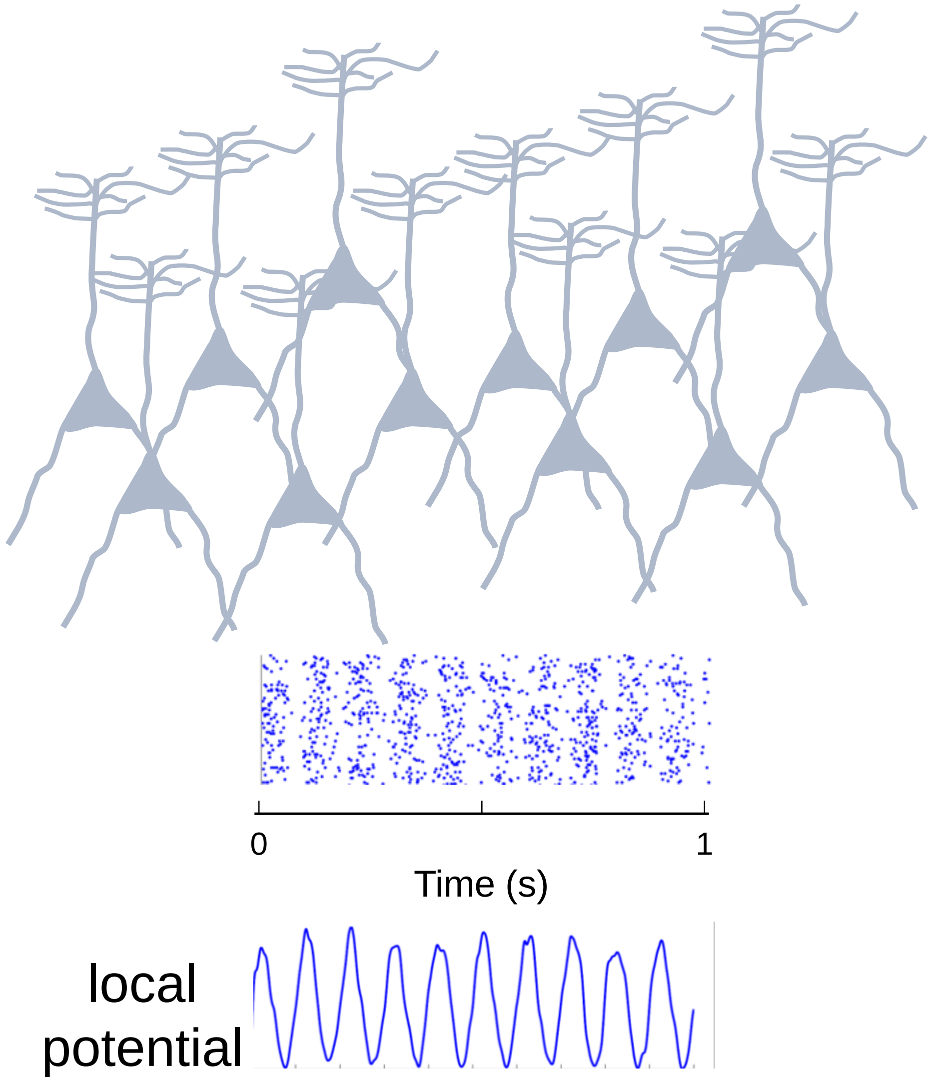
Examples of things that oscillate:
- Heartbeat: measured in **BPM**, based on the frequency of contractions of the heart
- A sound wave: measured in **hertz**, based on the frequency of the sound vibrations
- Neurons: measured in **hertz**, based on the frequency of going between active and inactive states

# Develop an intuition about neural oscillations

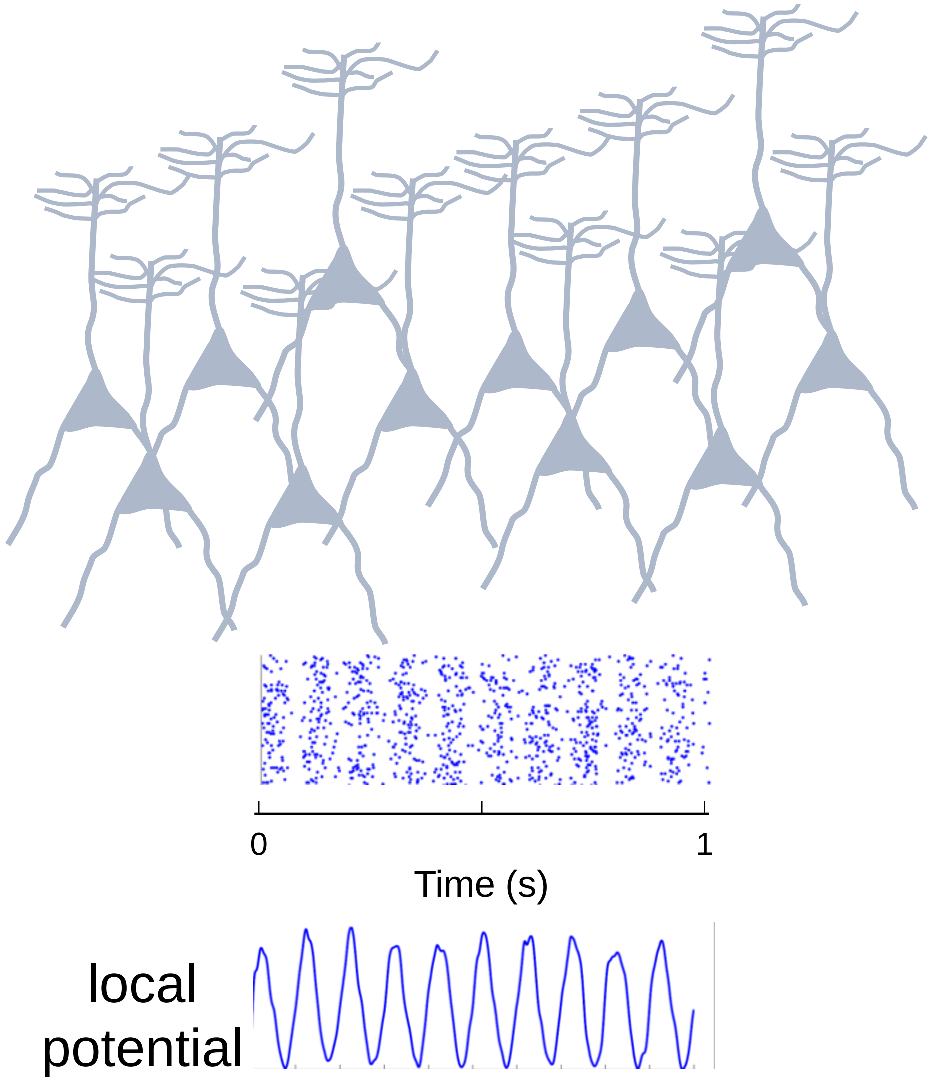


# Develop an intuition about neural oscillations

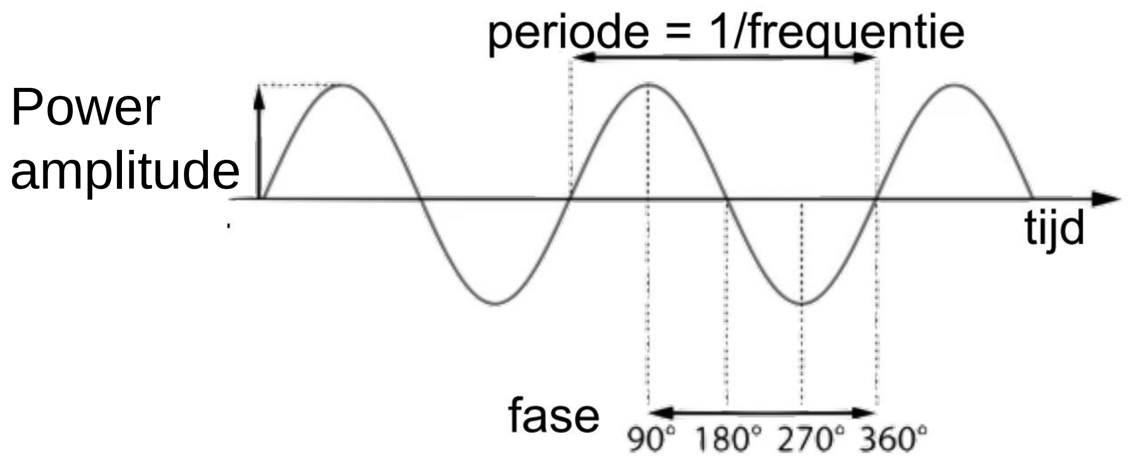


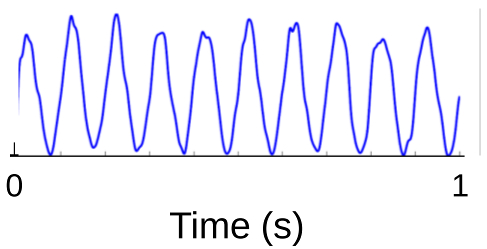
# Neural oscillations = **synchronized PSPs** of neurons



# An oscillation has a frequency and amplitude

## (also a phase and period)



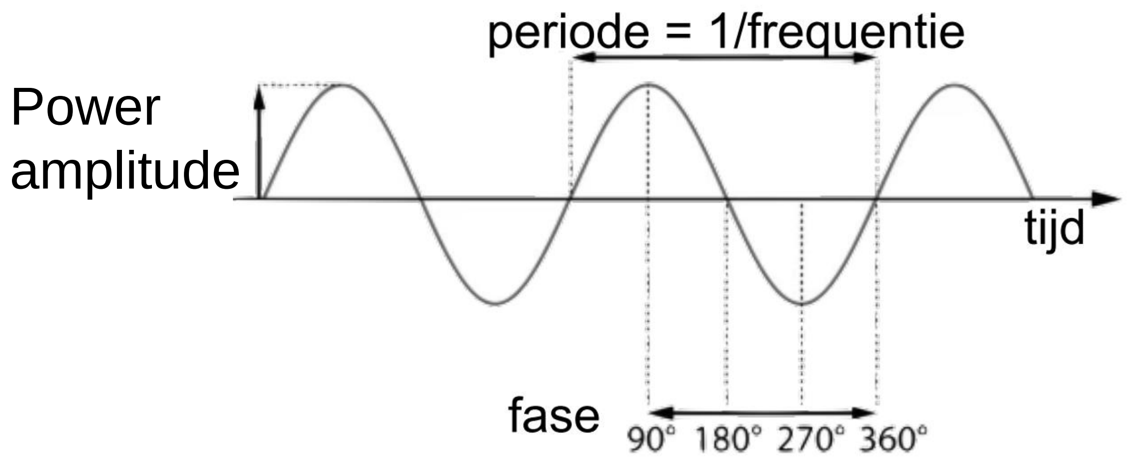



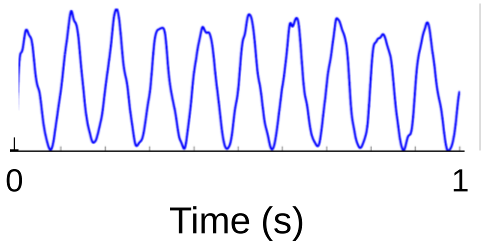

What is the frequency of this signal?

*Hint: number of peaks / 1 (second)*

M A X
P L A
N C K

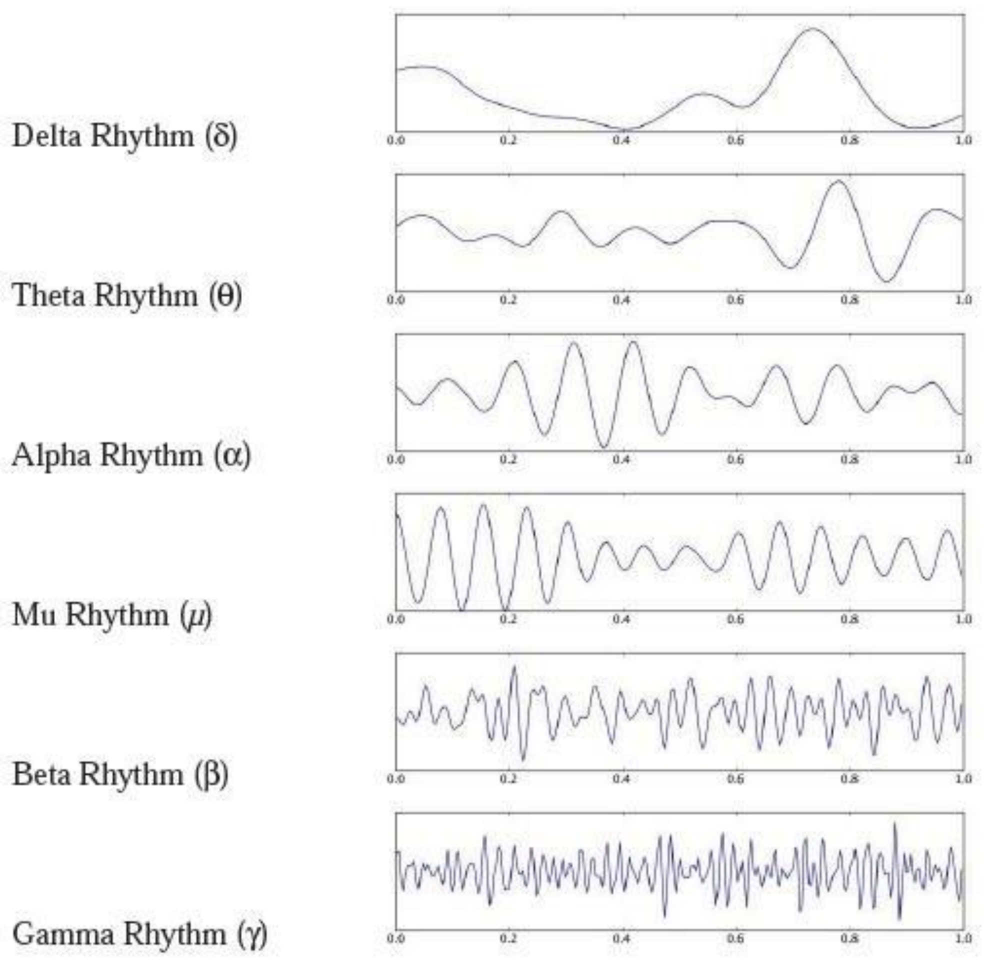
# An oscillation has a frequency and amplitude
## (also a phase and period)




The frequency is **10 Hz**.

# There are six main canonical frequency bands




Scientists have given different labels to frequency bands, based on the brain process they are associated with

=

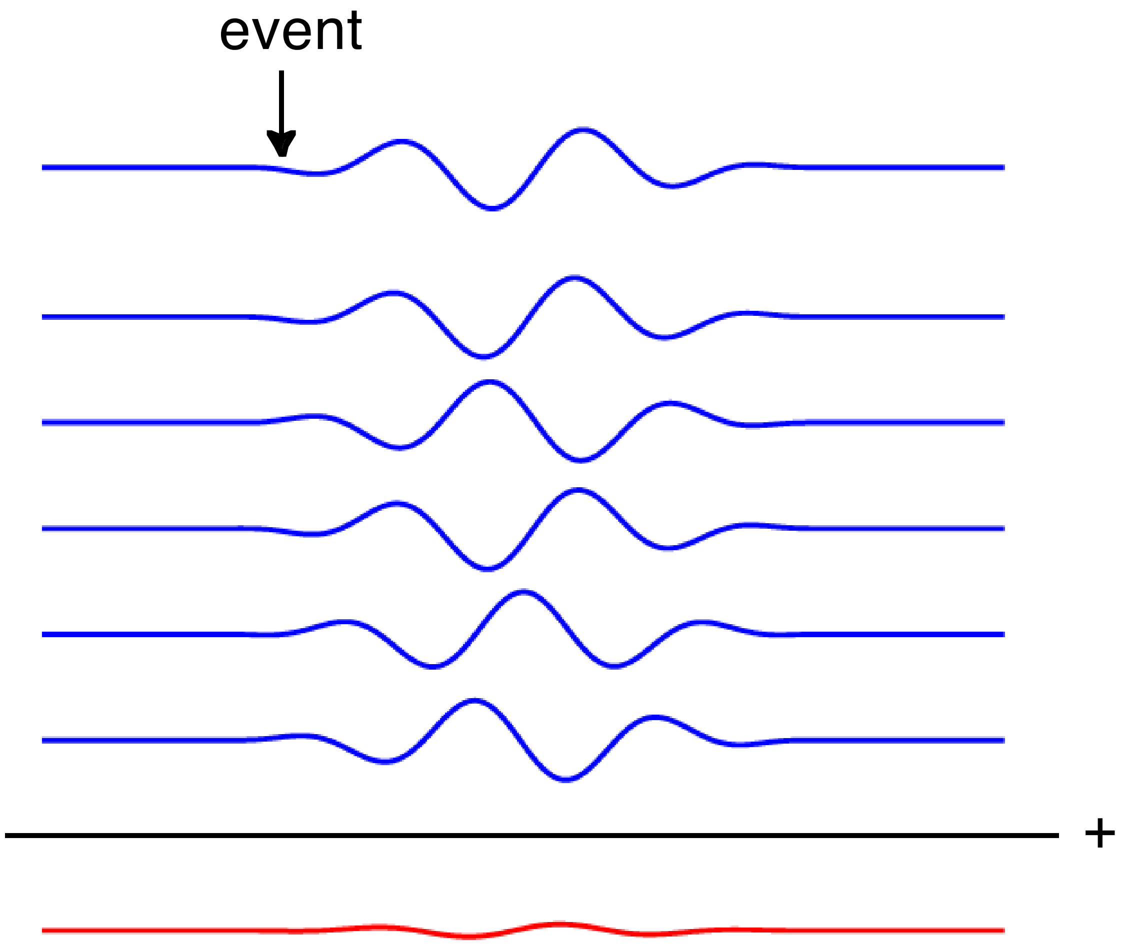
Different rhythms are **associated with** different functions or states
(it is not known which causes the other)

*Alpha → more power amplitude when drowsy, less when calculating maths*

*Beta → less when preparing to move, and lexical retrieval*

*Gamma → more when processing visual information*

# Induced activity does not have a constant signal over trials

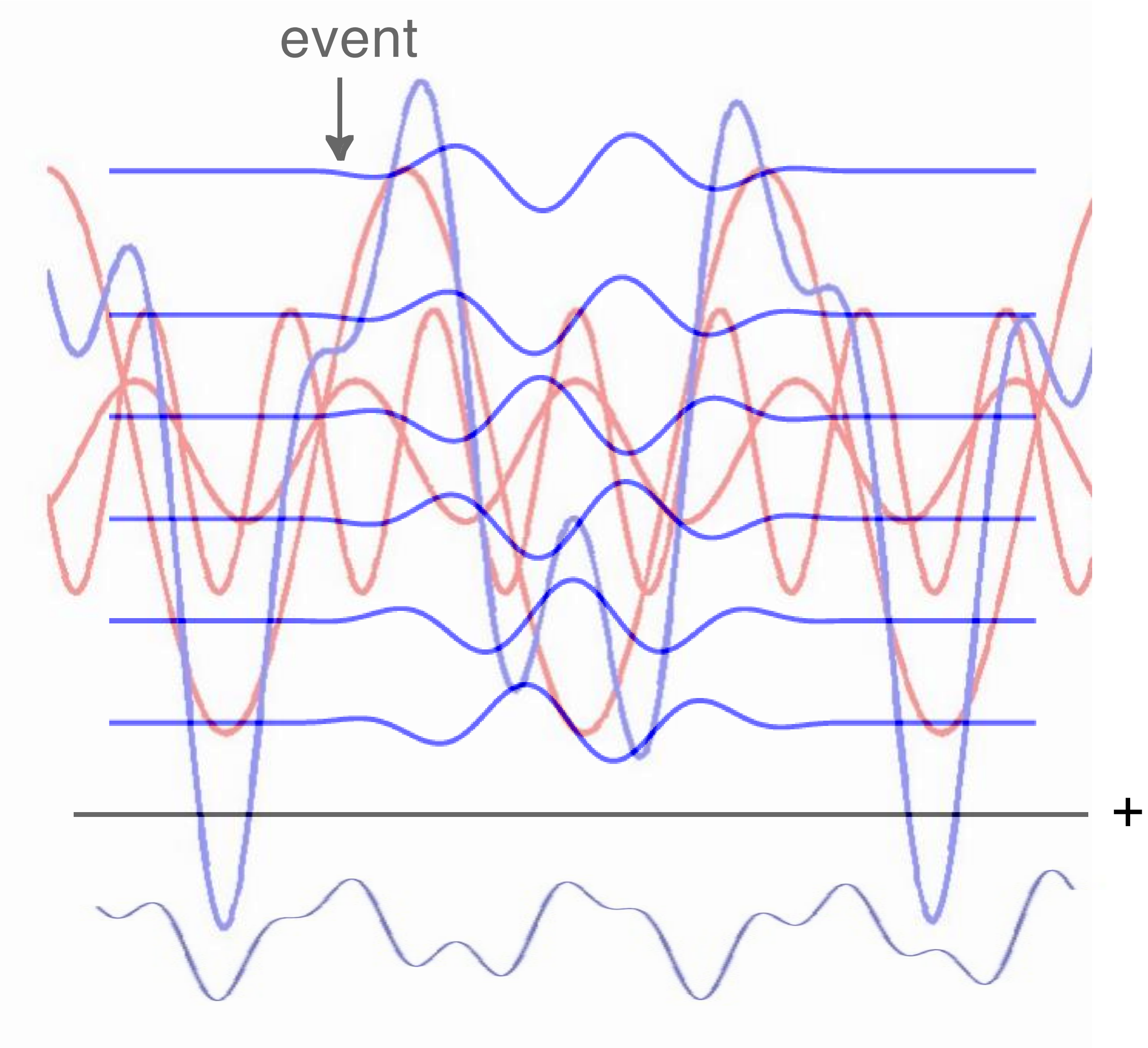



As we saw, we care about oscillations when we have a different processing speed at each trial so the amplitude and phase of the signal differ.

**Induced activity** refers to when the brain process triggered by the stimulus is more variable.

For example, if you see a visual cue to produce a word (such as a **+**), you will first have an evoked response for seeing the **+**, and an induced response for the process of retrieving and planning the word.

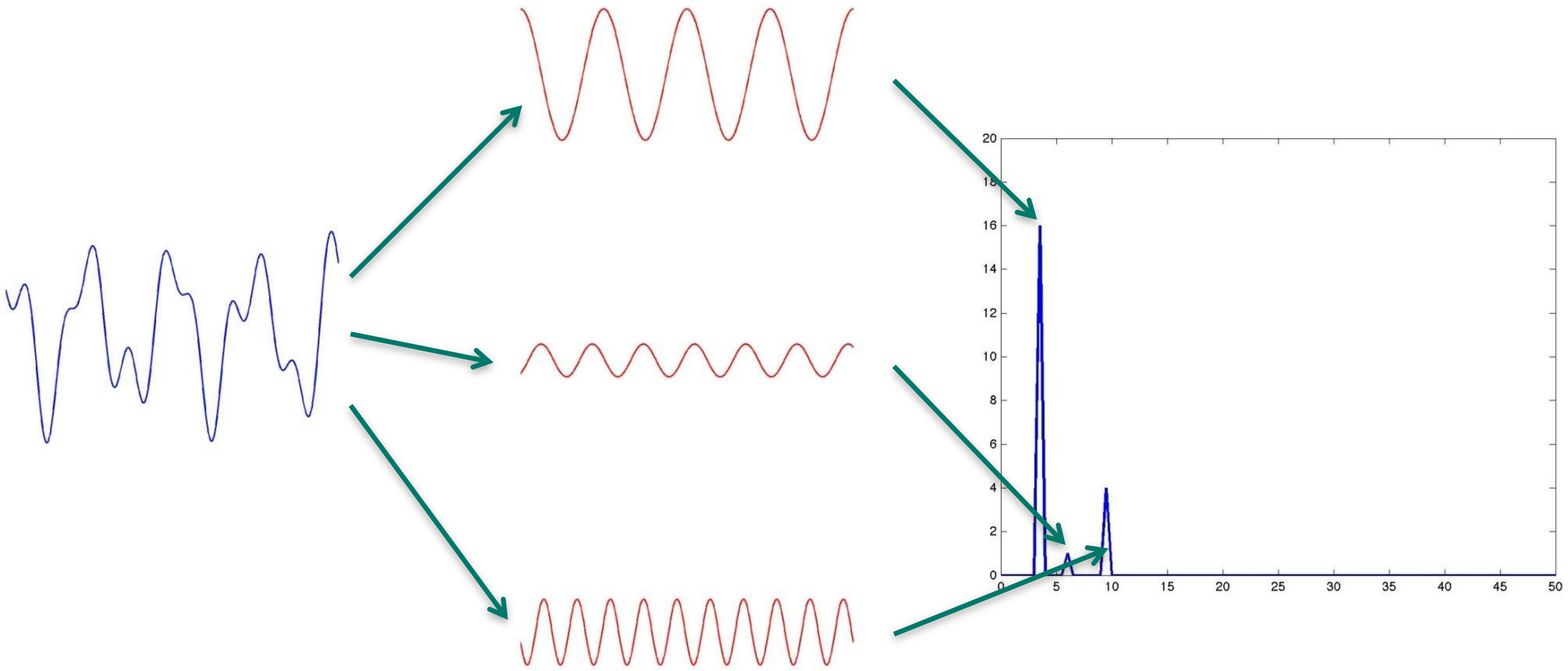
# Induced activity does not have a constant signal over trials




In addition to different processing speeds, there is also ongoing activity in the different frequency bands.

*... What now?*

# One option: decomposing signals (spectral decomposition)




We can use a **Fourier analysis** to decompose a time domain signal into its constituent oscillatory components, and know **which frequency** is present in the signal and **how much** for a given time segment.

→ **Express signal as function of frequency, rather than time.**

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# Another option: Time-frequency analysis

Typically, brain signals are not ‘stationary’ and we wish to measure a dynamic effect over time.

We divide the measured signal in shorter time segments and **apply Fourier analysis to each segment of the signal**.

→ Express signal as function of both **time and frequency**.

*... Hence the name “time-frequency analysis”* ☺

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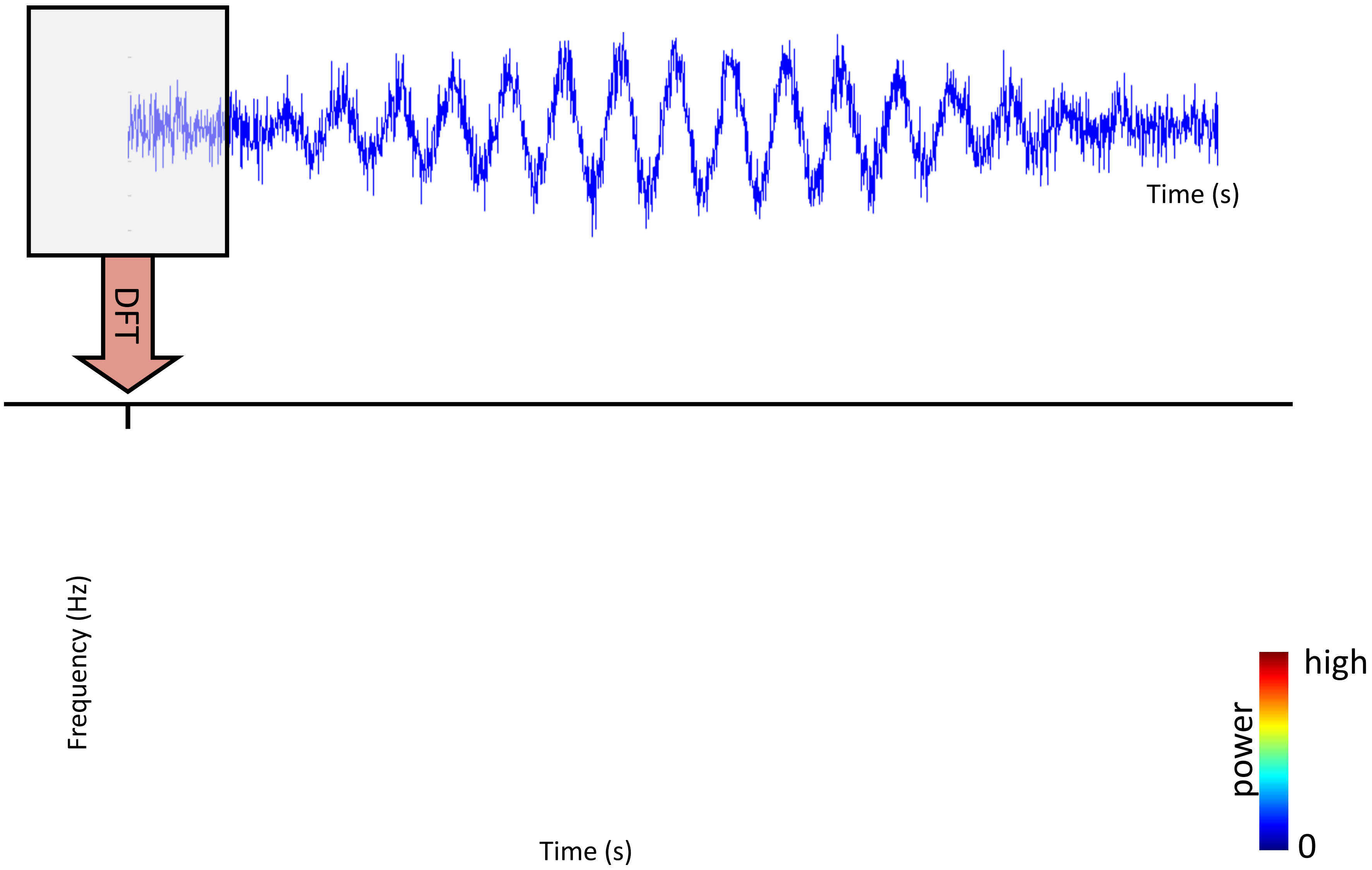
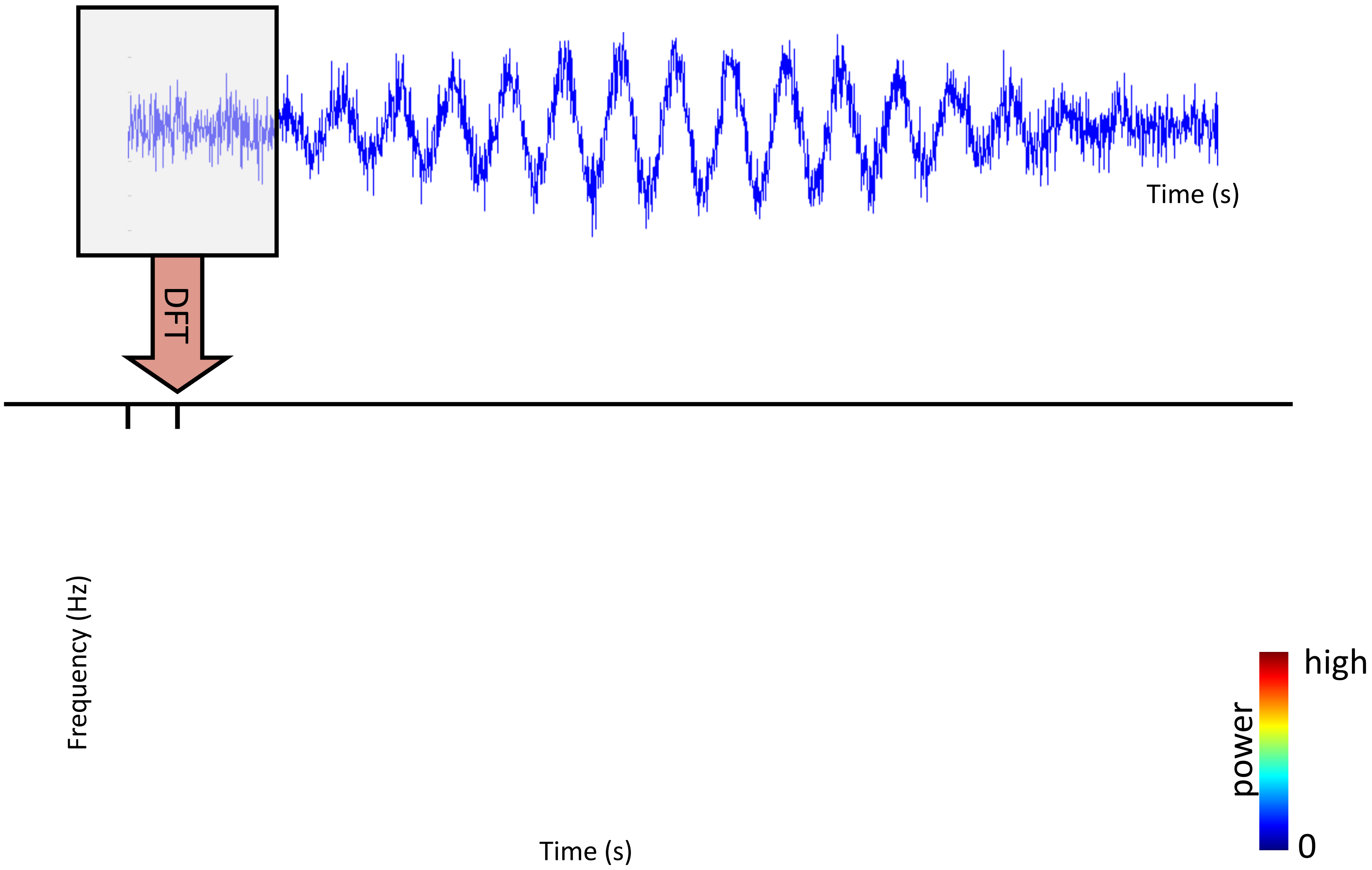
# Time-frequency analysis



# Time-frequency analysis



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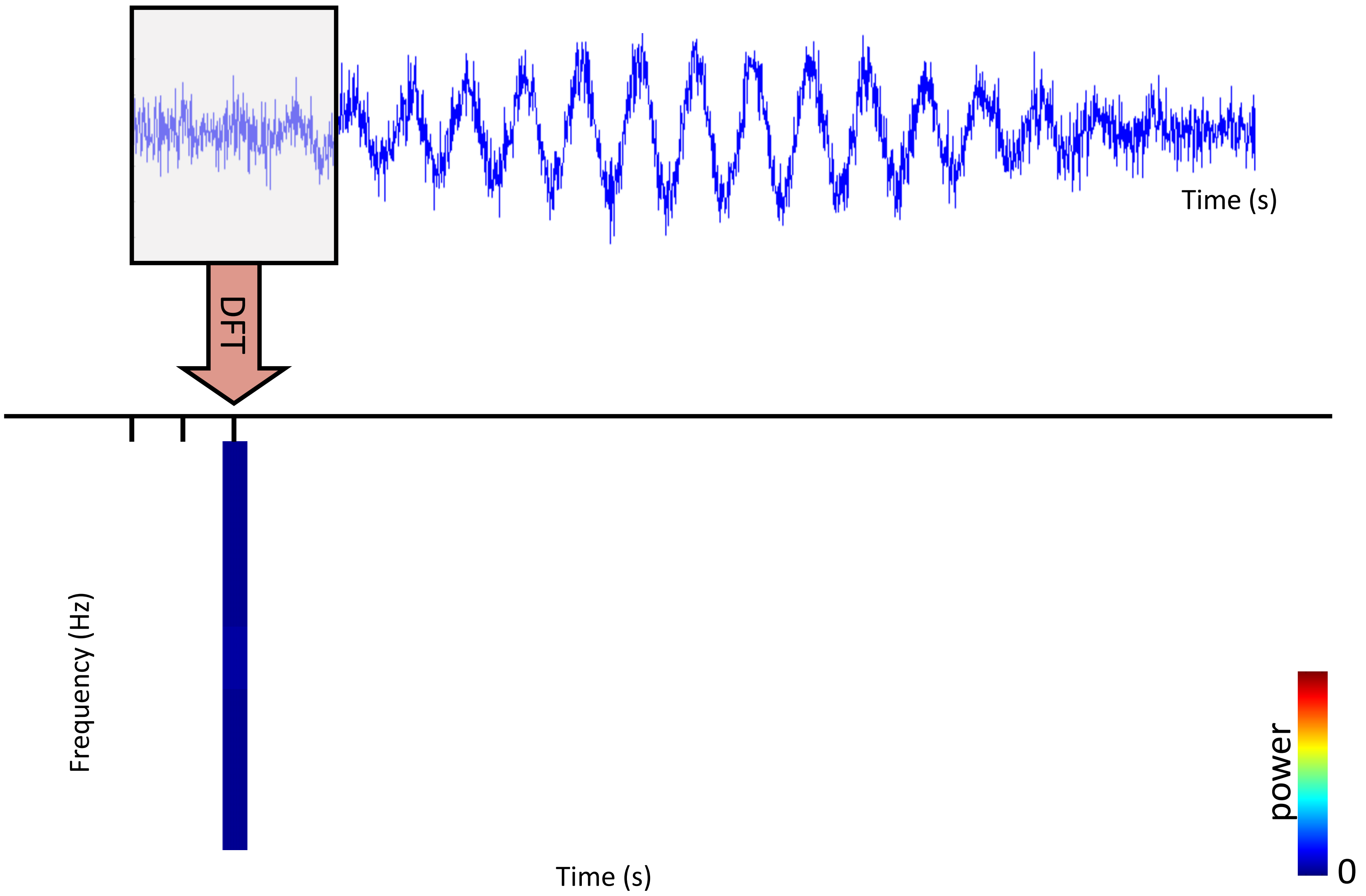

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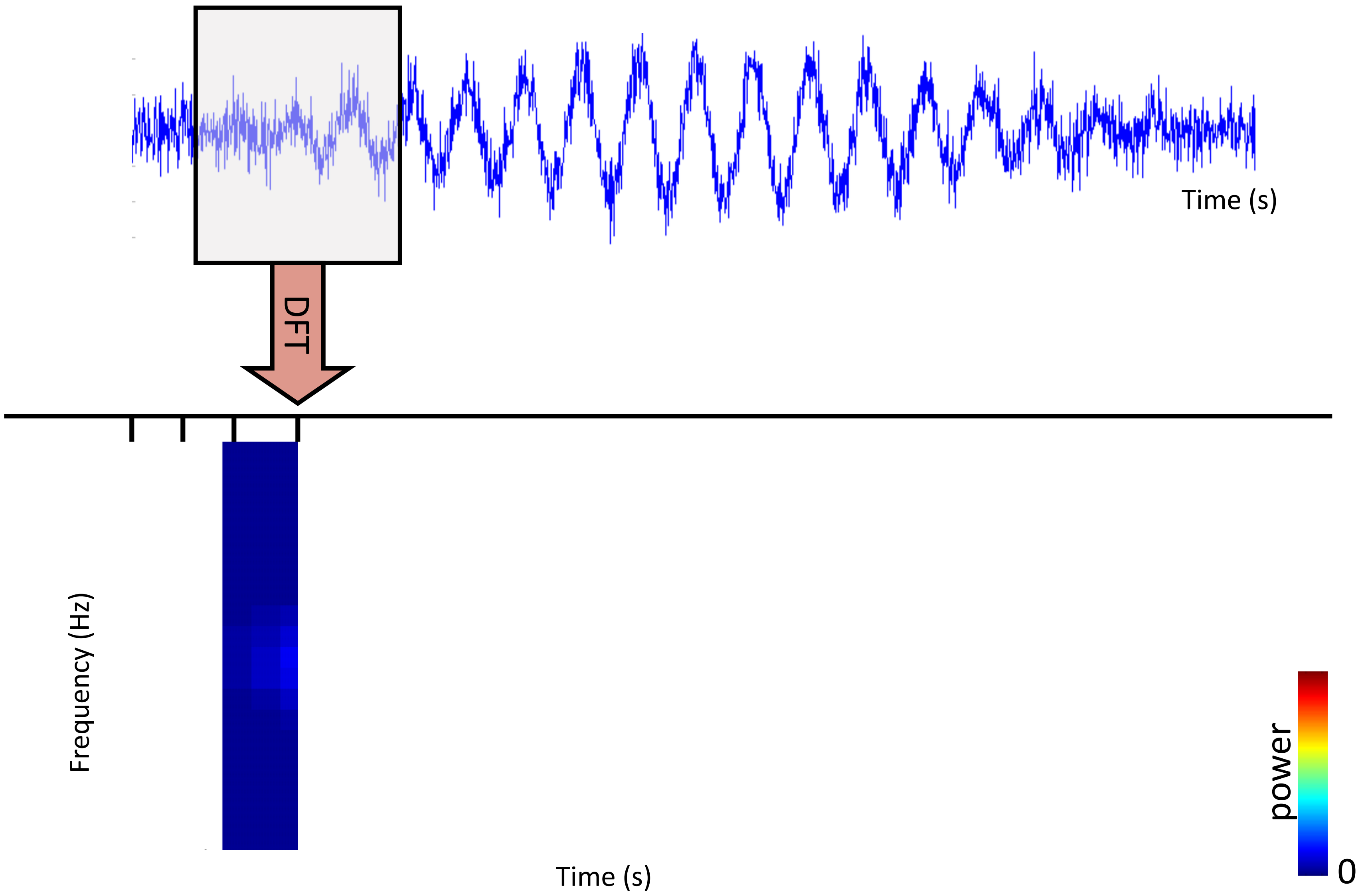

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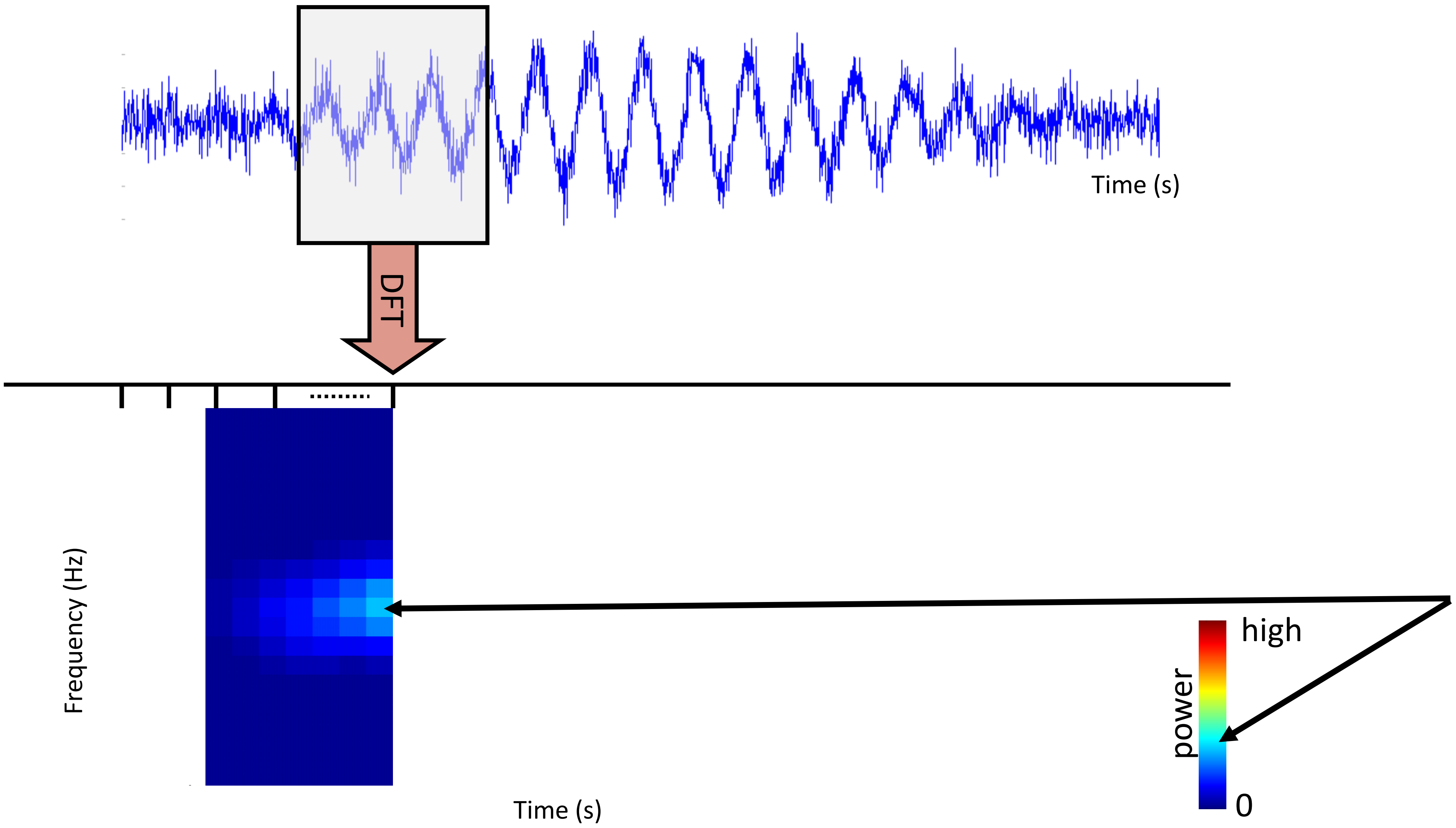
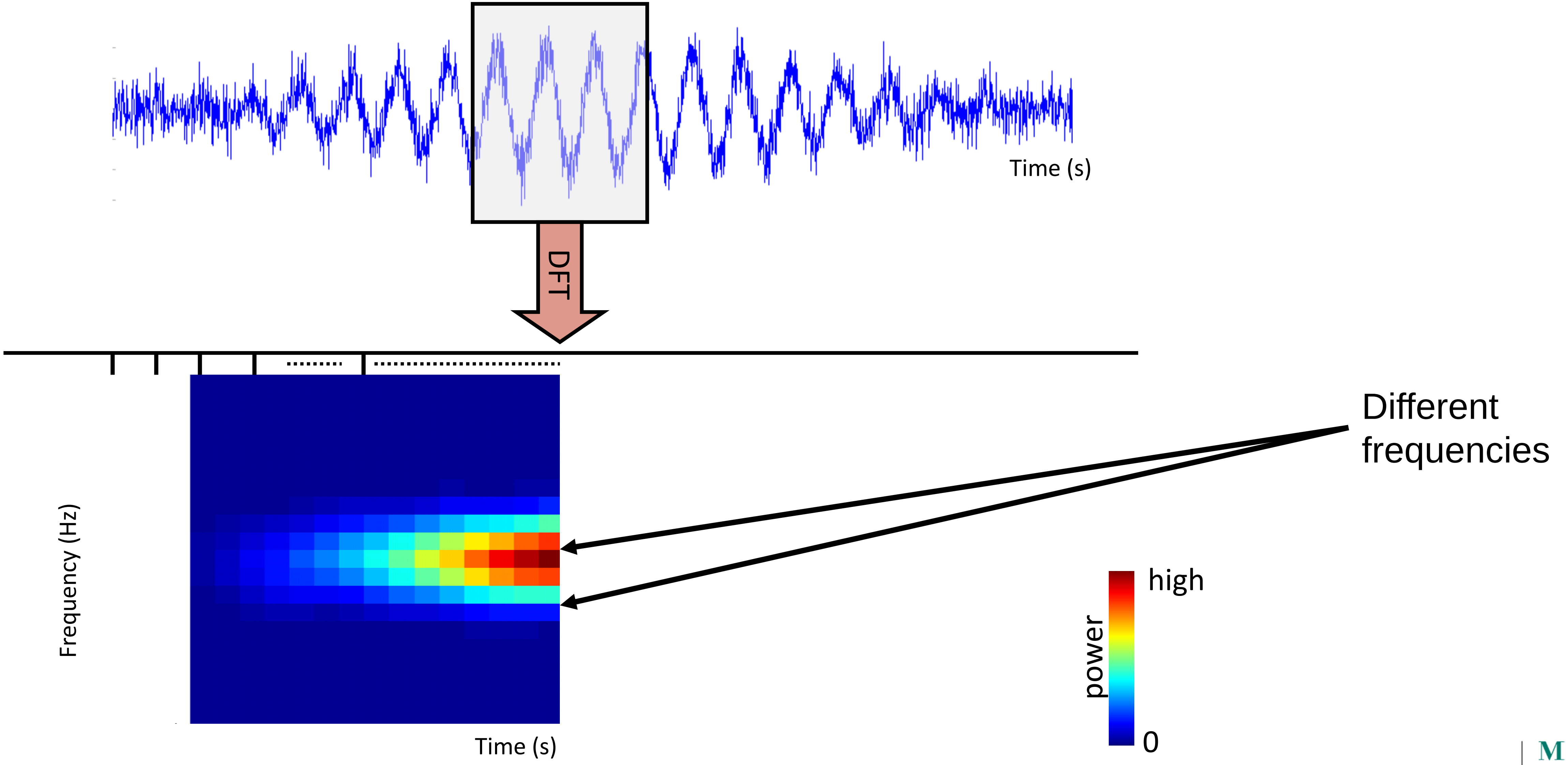



How much power amplitude

# Time-frequency analysis



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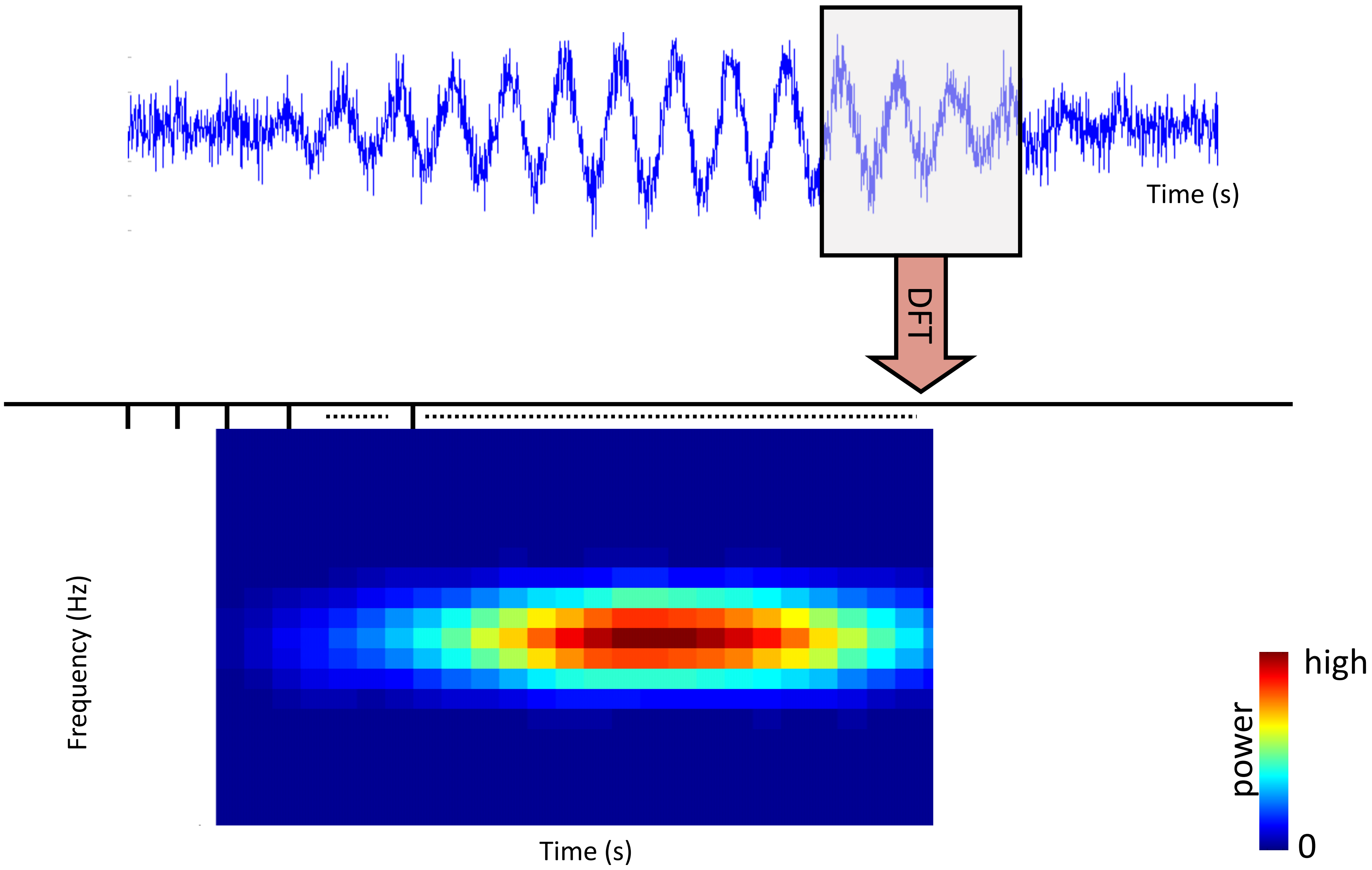

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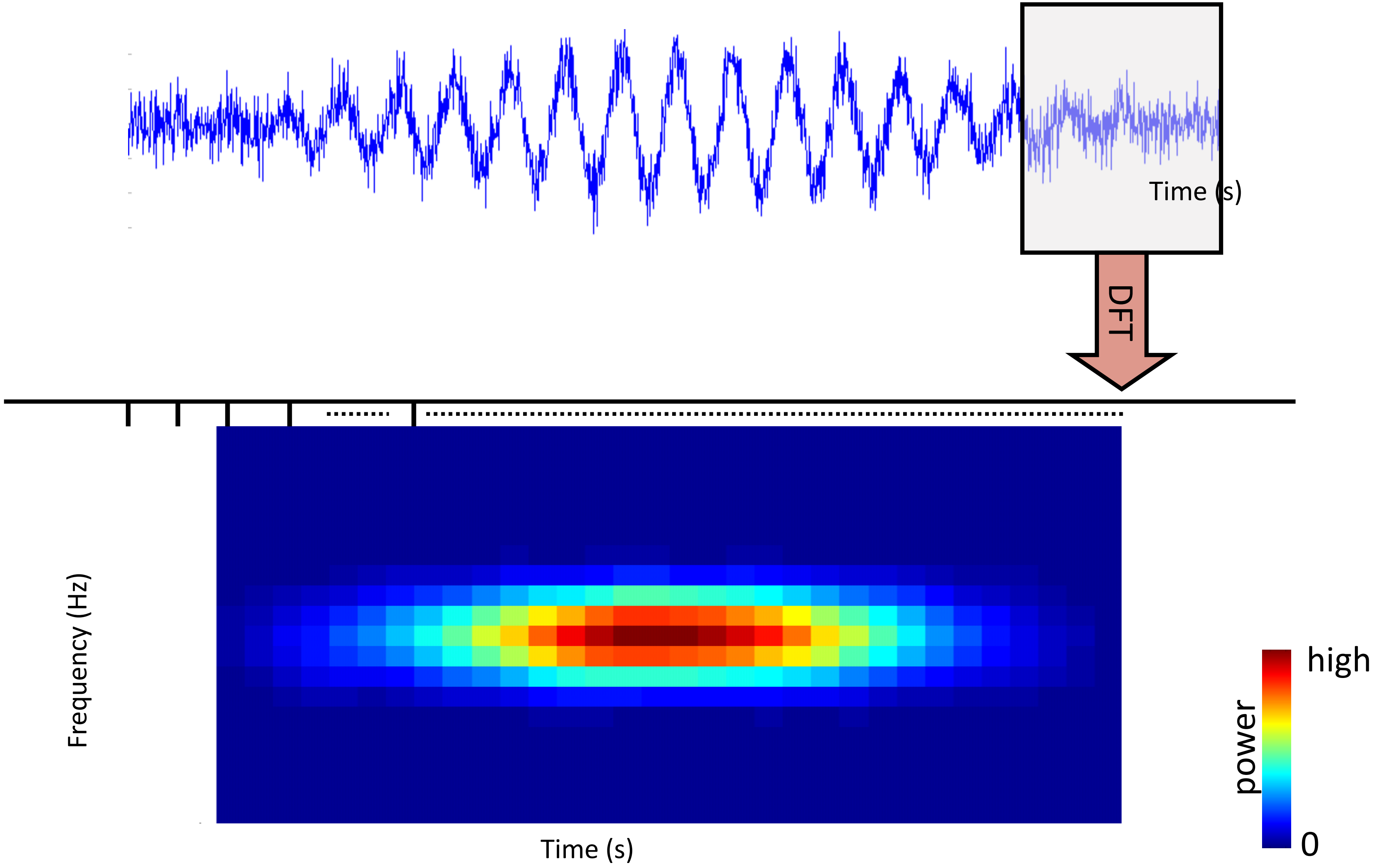
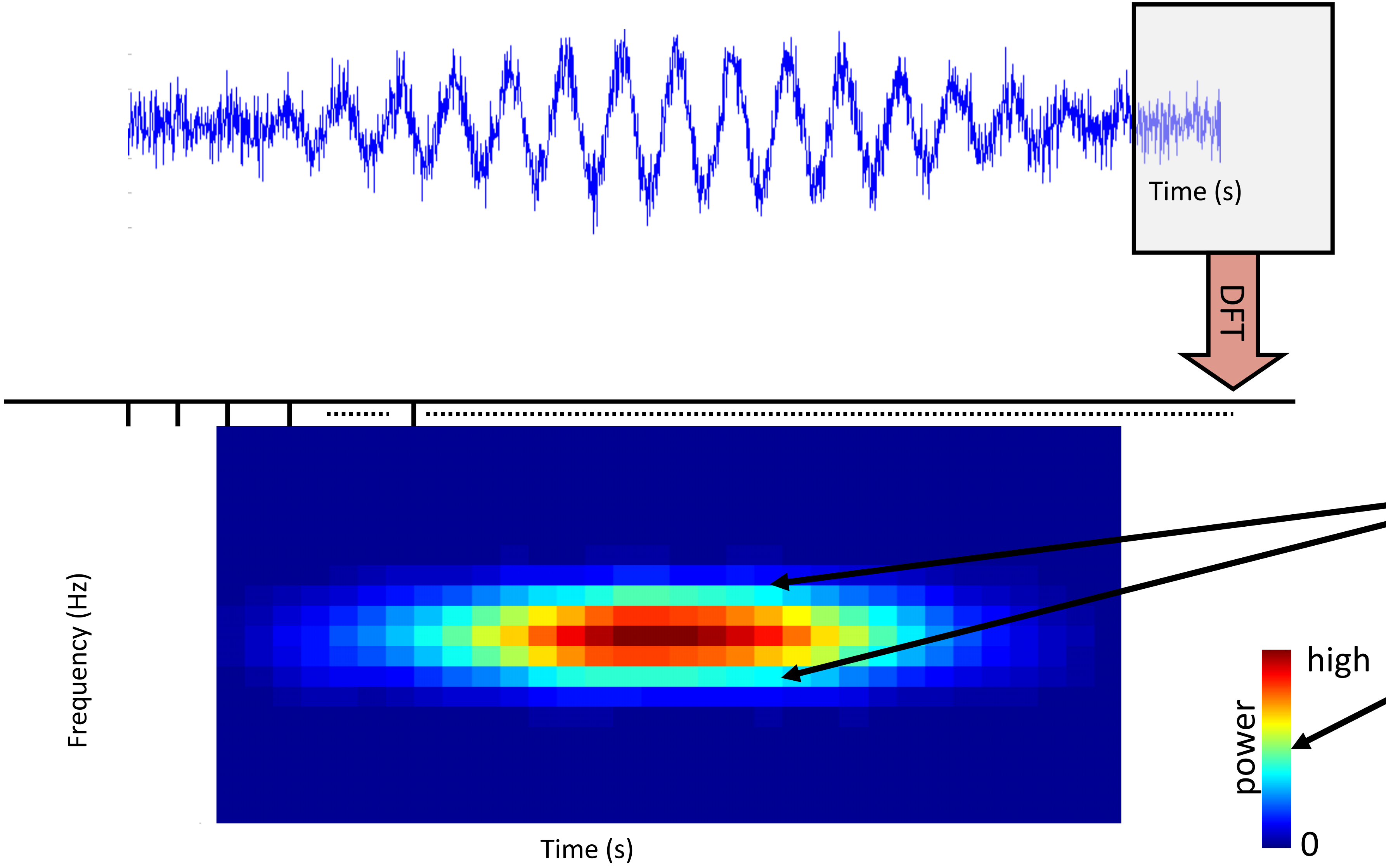


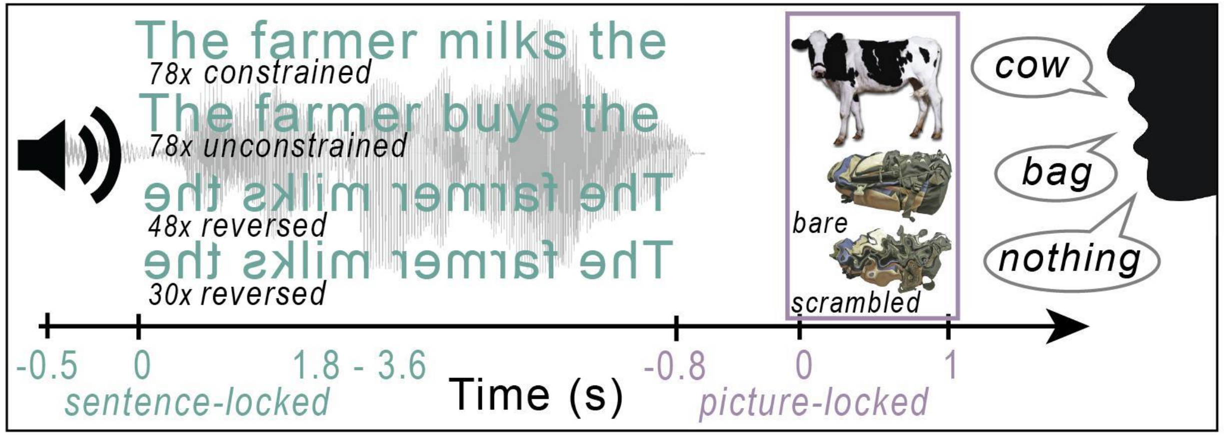
# Time-frequency analysis

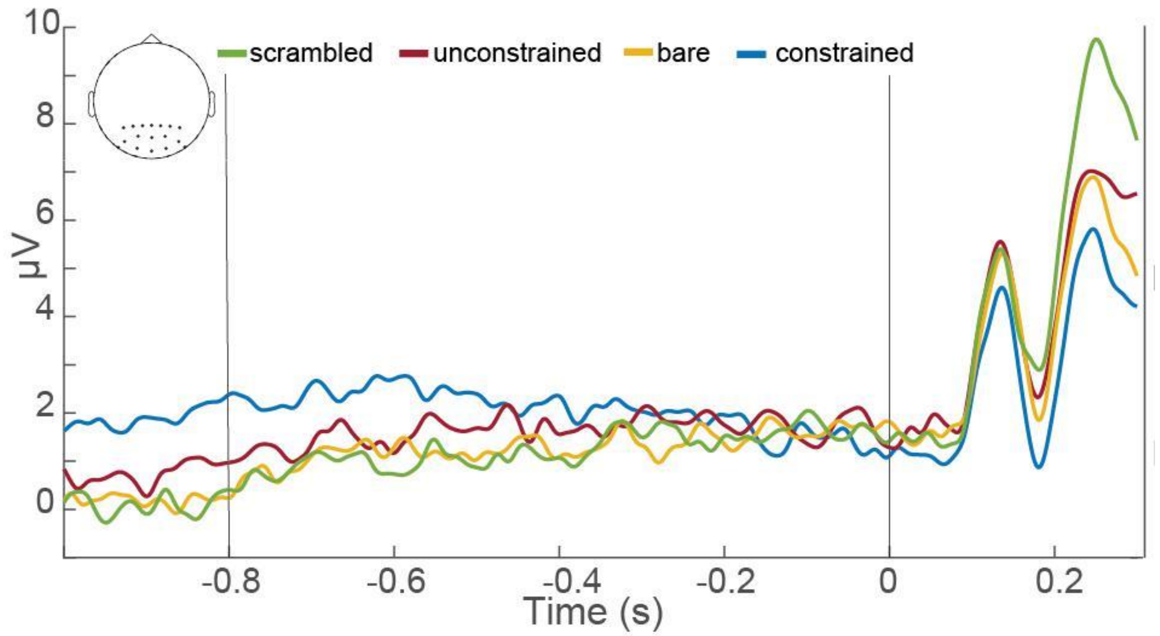


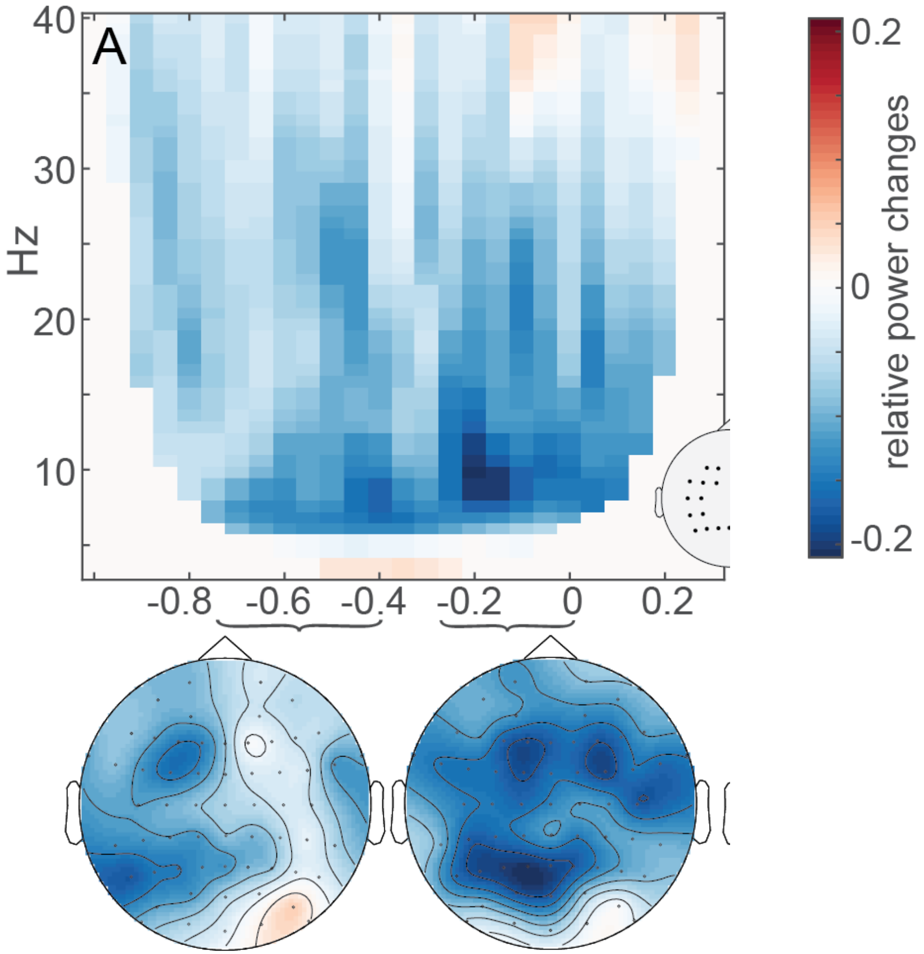

Different frequencies

How much power amplitude

# Example of induced activity in a picture naming task




*Figures from Roos, Chauvet & Piai, 2024*

# Summary: Evoked vs induced activity

**Evoked activity**: Average over trials to get feature of interest.

Activity is aligned to the stimulus each time – you can obtain the feature of interest by averaging (e.g. **ERP** analysis).

**Induced activity**: Averaging does not extract feature because activity is variable across trials.

For this, we can analyse brain rhythms (neural oscillations). We can perform frequency decomposition using a **Fourier transform**. If we wish to see the neural oscillations over time, we can perform a **time-frequency analysis** (TFR).

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# Summary: Evoked vs induced activity

**Evoked activity**: Average over trials to get feature of interest.

Examples of brain processes that are constant at each trial:

- Early visual response to seeing a picture
- Early auditory response to hearing a tone
- Semantic integration when listening to speech (N400)

**Induced activity**: Averaging does not extract feature because the phases vary across trials.

Examples of brain processes that are not constant at each trial:

- Lexical retrieval (e.g. in picture naming)
- Tracking linguistic structure during comprehension

These are example of considerations to take into account when determining the best method of analysis: Think about your task, think about your process of interest.

# Learning objectives

Have a **general understanding** of, and be able to explain to someone else:

- What electrophysiology is, in particular EEG: Measuring PSPs using EEG or MEG (magnetic fields).
- How we use it to study language processing: We use these methods to look at the signals associated with brain process(es) of interest, whether it is evoked activity or induced activity.

Have a clear and **complete overview** of:

- The underlying biology of the brain signals we measure: When a neuron in a resting state receives input from another neuron, it becomes depolarized. As a result, it releases neurotransmitters into the synaptic cleft, which bind to the postsynapse and depolarize the next neuron. With EEG, we measure PSPs of large populations of pyramidal neurons.
- The format of these measurements once they reach a computer: Each sensor record 500 data points per second. We need to manipulate these data to extract meaningful information.

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