Time Frequency Analysis

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Outline

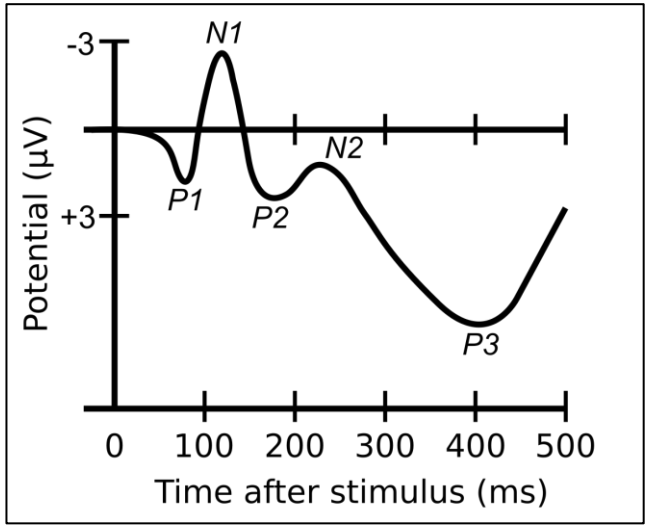
1. There‘s more in the data than ERPs
2. What are brain oscillations?
3. How to compute them
    1. Properties of a wave
    2. Fourier transform
    3. Practical tips
    4. Visualization in EEG
4. Outlook: more advanced / other methods

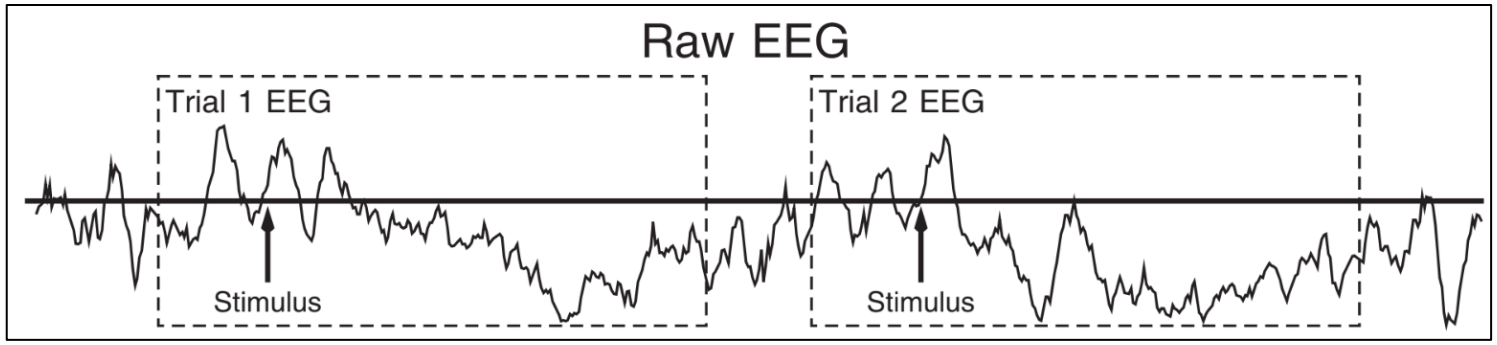
Not covered: python implementation

There‘s more in the data than ERPs

Basic idea of ERPs:

- Brain response to a discrete, isolated event
  → **time-locked and averaged**





A lot of information gets lost by averaging!

There‘s more in the data than ERPs

A lot of information gets lost by averaging!

(Cohen, 1972)

Other aspects that ERPs can‘t capture:

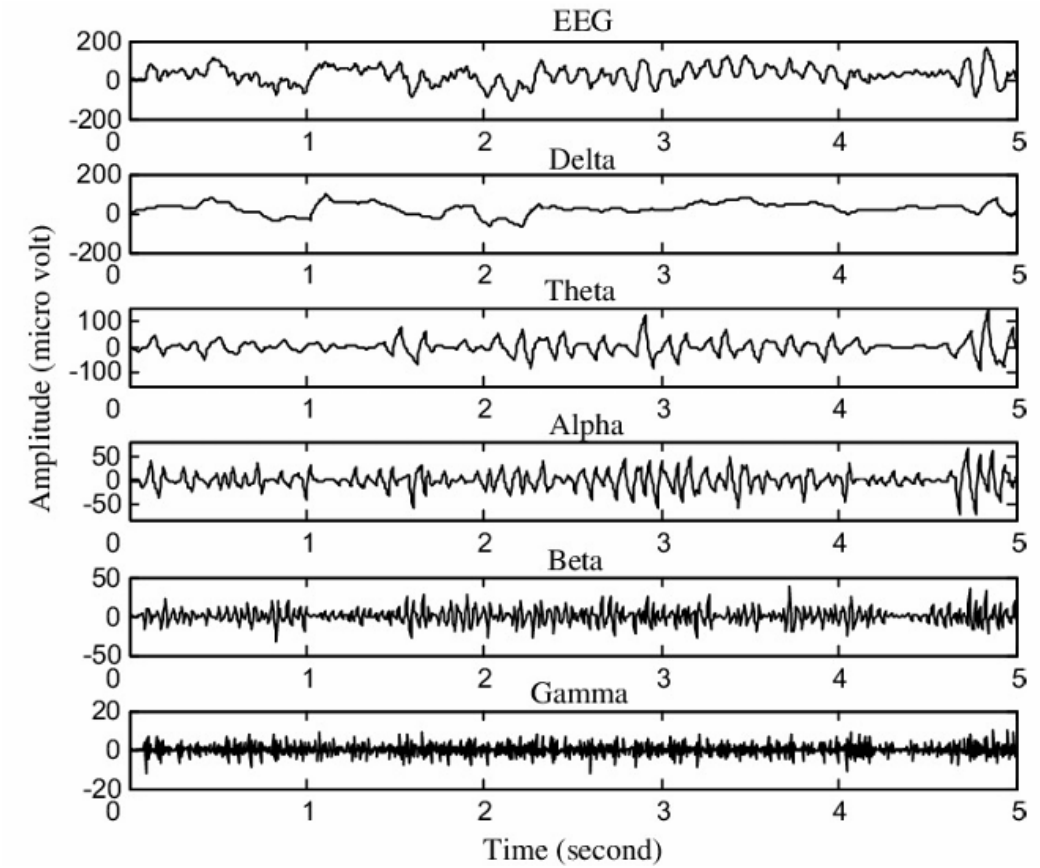
- Natural stimuli like speech
- Intrinsic brain functions (not triggered by event)

Brain Oscillations

- rhythmic / repetitive patterns of brain activity
- oscillations of different frequencies overlaying in our signal

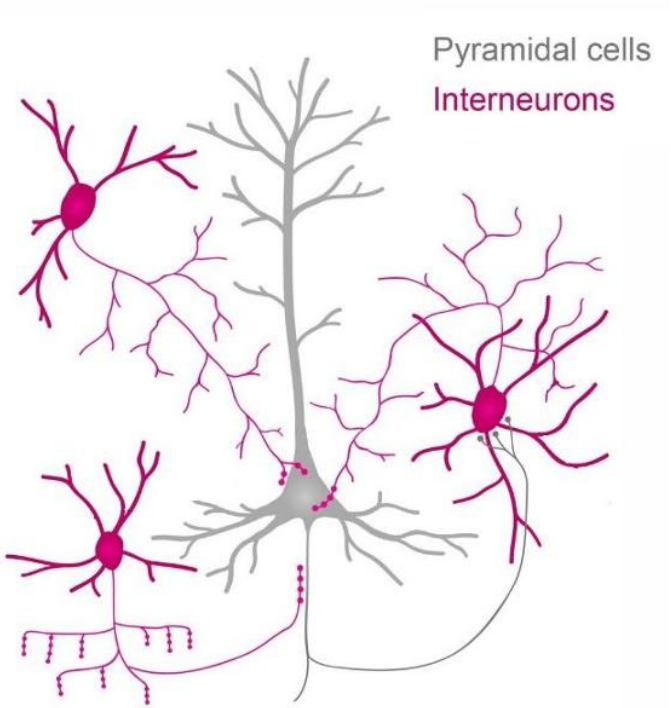
Why is there oscillating activity in the brain?

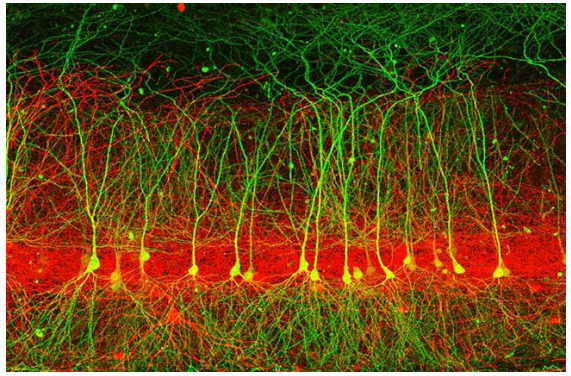
- Coordination of activity in neural ensembles → synchronous firing
- Communication between brain regions
- Feature binding



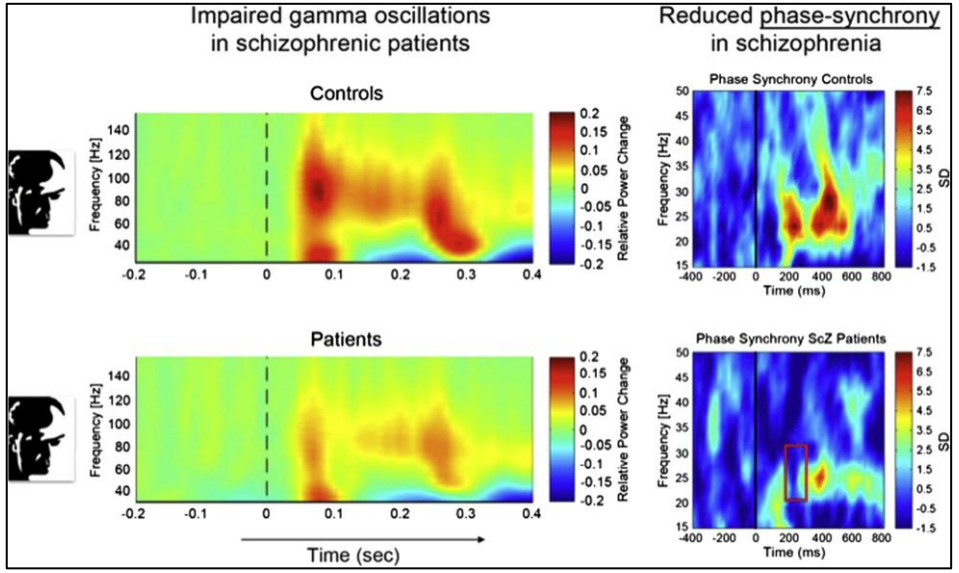
Brain Oscillations

- Coordination of activity in neural ensembles → synchronous firing





→ recurrent, synchronized activity in gamma range

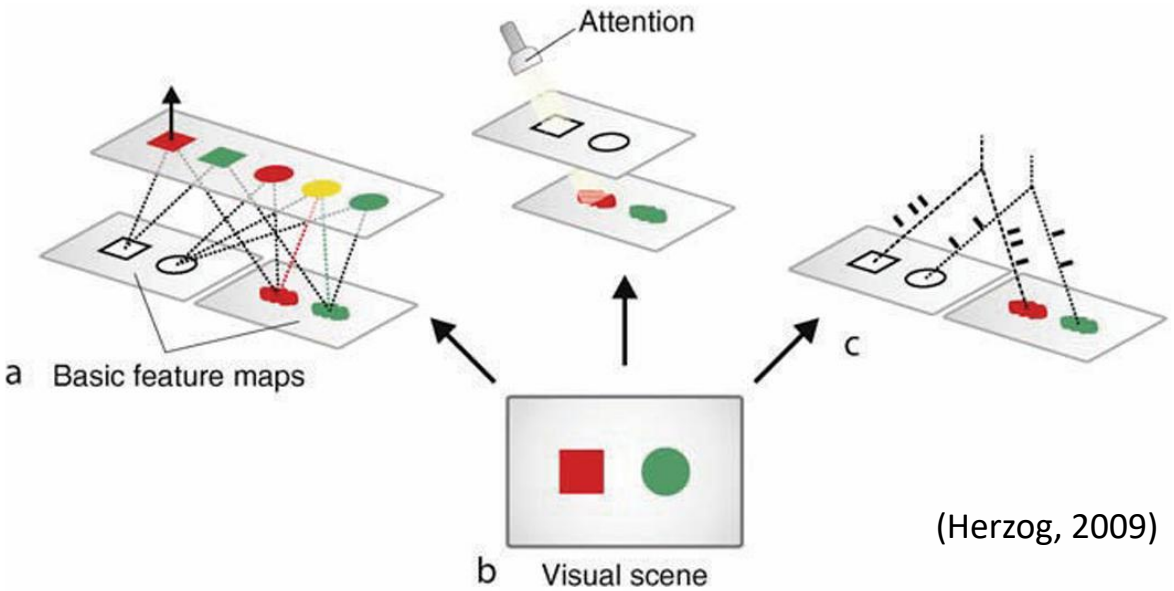


(Buszaki et al., 2013)

Brain Oscillations

Why is there oscillating activity in the brain?

- Feature Binding

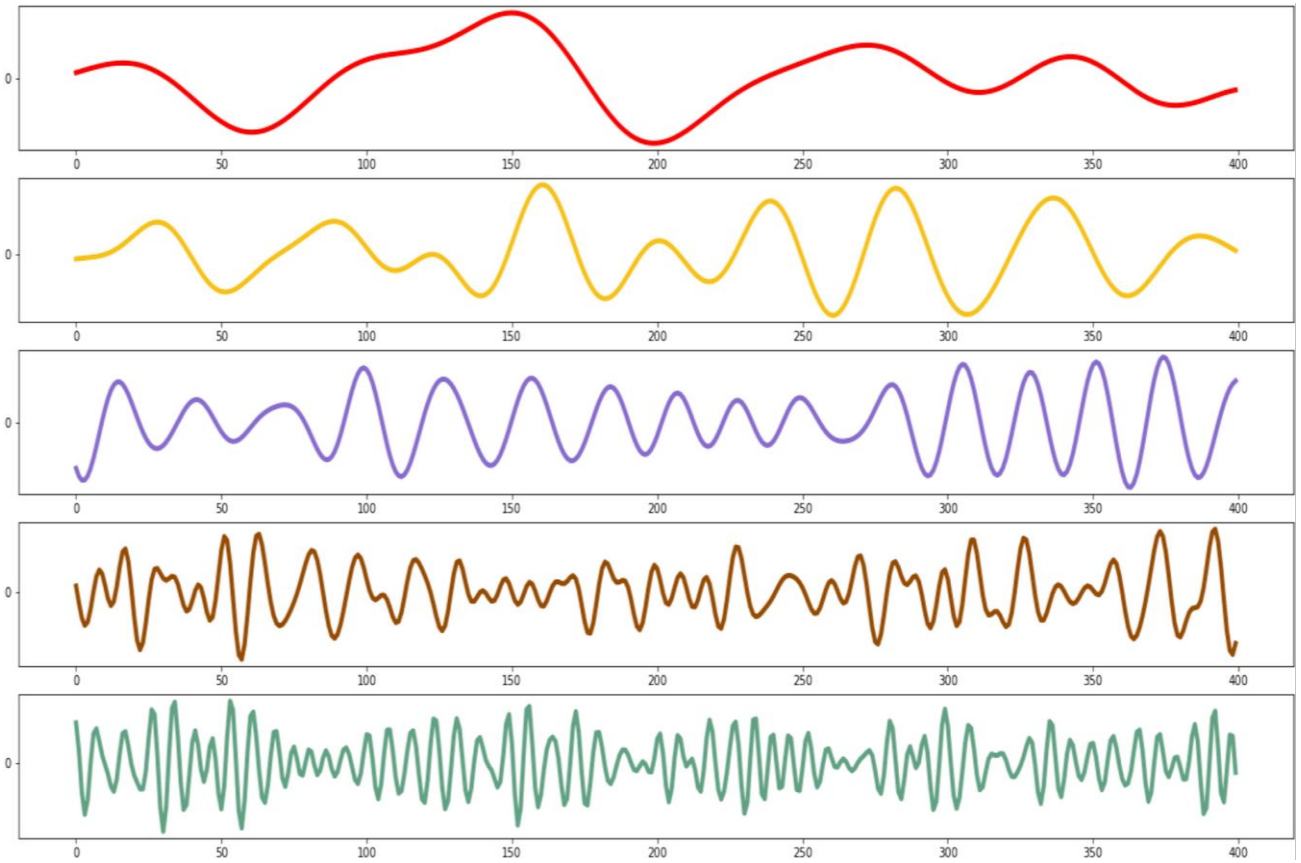


(Herzog, 2009)

Oscillations could be **possible solution to binding problem**:

- Neurons coding for features belonging to the same object fire in synchrony

Brain Oscillations



Delta (< 4 Hz): deep sleep

Theta (4-8 Hz): dreaming, working memory

Alpha (8-12 Hz): relaxed wakefulness

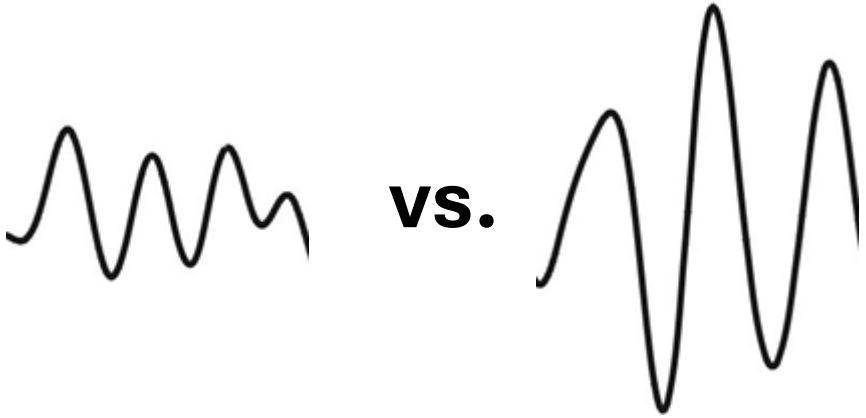
Beta (13-30 Hz): active concentration

Gamma (30-90 Hz): sensory input

(Pandey et al., 2022)

Time-frequency analysis

How can one describe a wave?



vs.

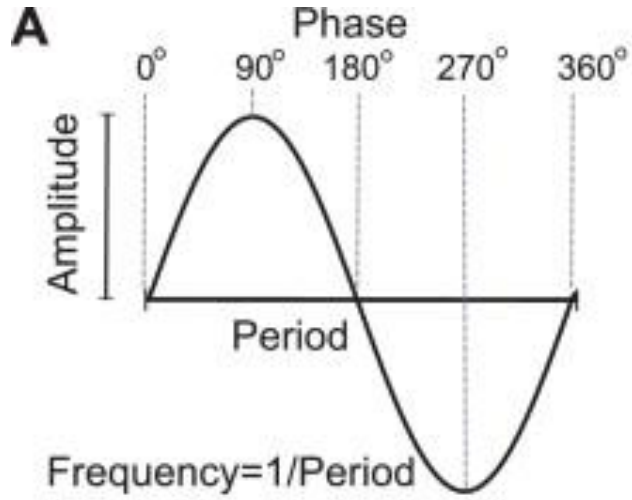
→ Amplitude / Power

vs.

→ Frequency

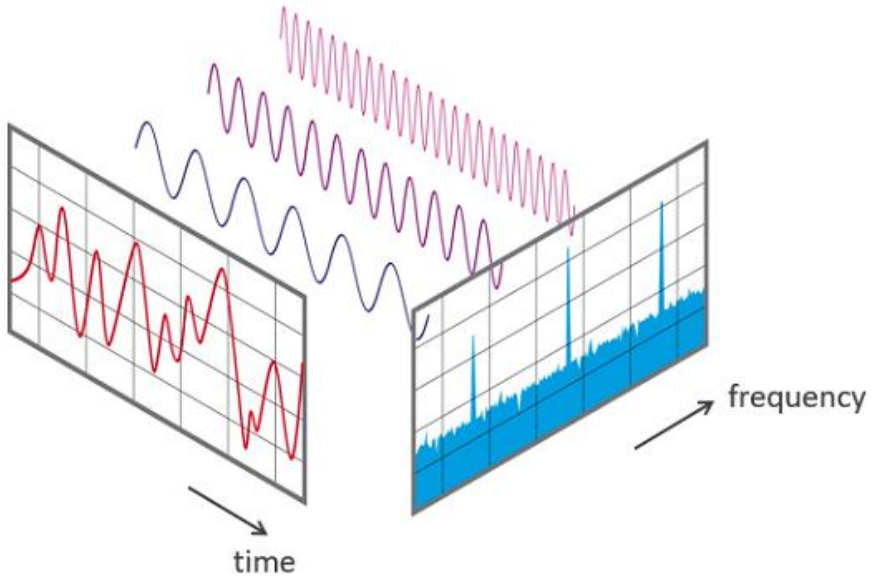
vs.

→ Phase



Fourier Transform

Idea: You can decompose **every continuous signal** into sine waves of varying frequencies, amplitudes and phases



Calculate power for each frequency

→ Frequency domain

→Loose time information

→You can slide a window through your data to get some time information

https://www.nti-audio.com/en/support/know-how/fast-fourier-transform-fft

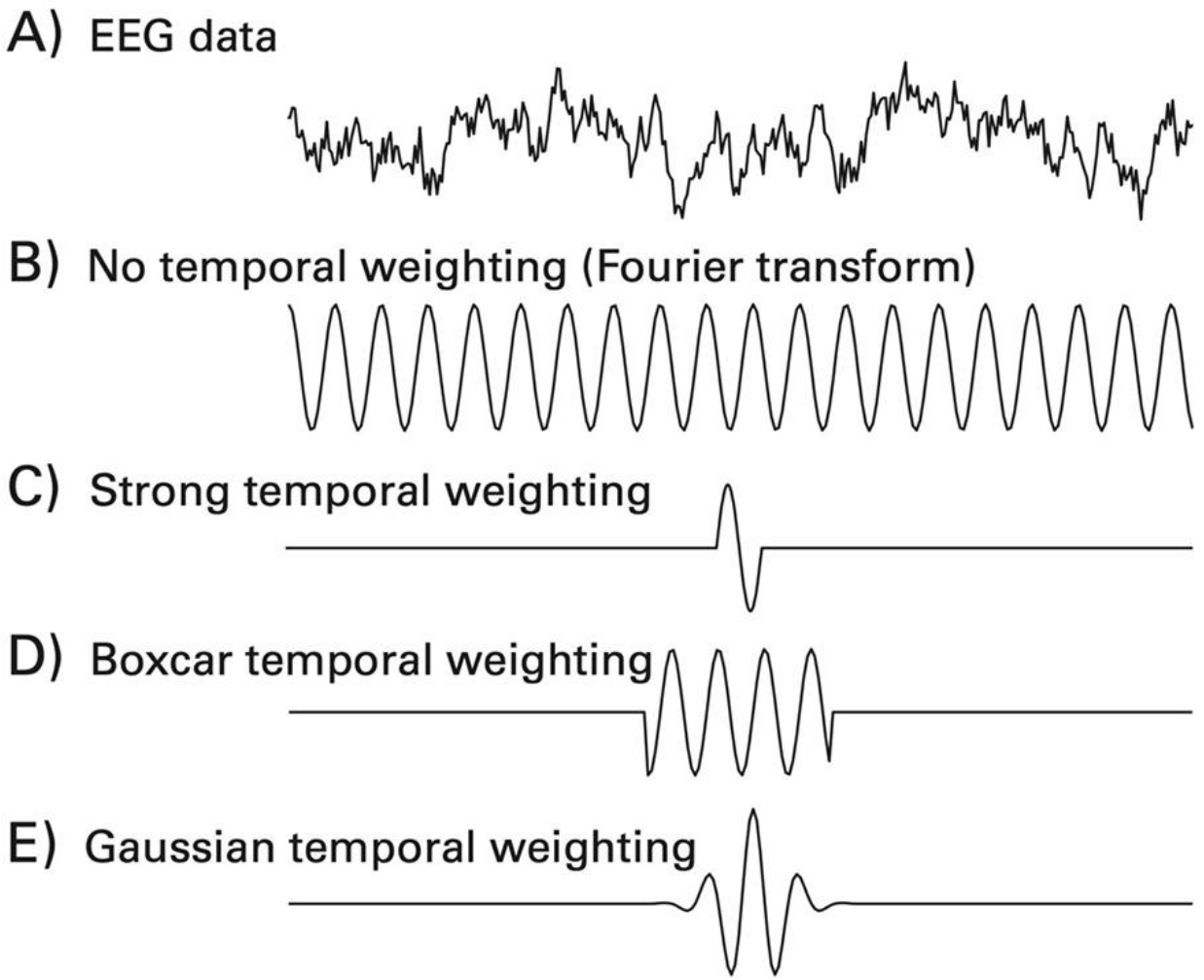
Wavelet convolution

To extract frequency-specific information from EEG data the data must be **convolved with a sine wave**

C) **one cycle** maximizes temporal precision but less frequency precision

D) **boxcar tapering**: decreased temporal specificity and potential artifacts from sharp edges

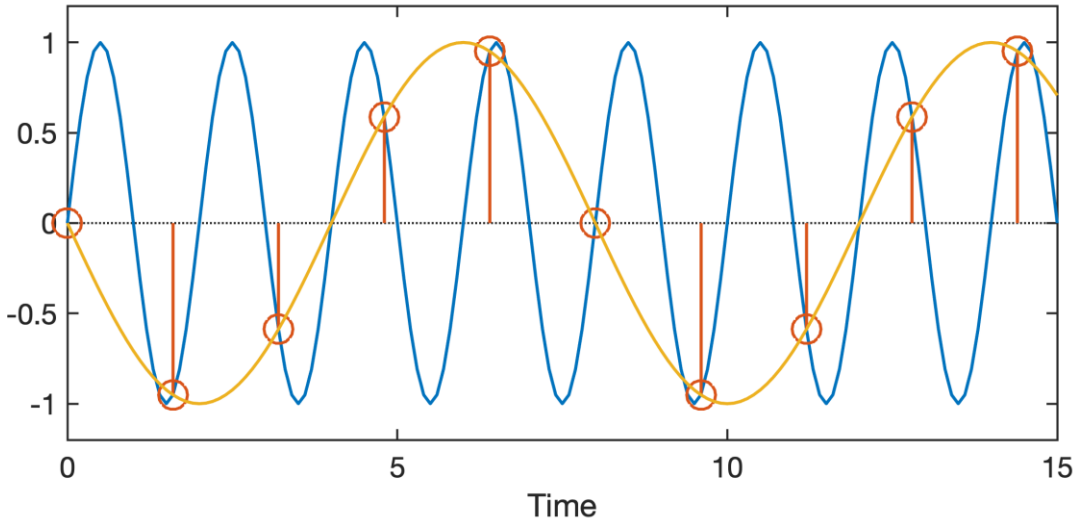
E) Gaussian tapering (= **Morlet wavelet**): balance between temporal and frequency precision



Basic Rules

1. You can only analyze frequencies for which you have several cycles in your epoch (e.g. 1s epoch → not less than 4 Hz).

2. Don‘t look at frequencies above the Nyquist frequency (= half your sample rate): sampling rate of 500 Hz → up to 250 Hz



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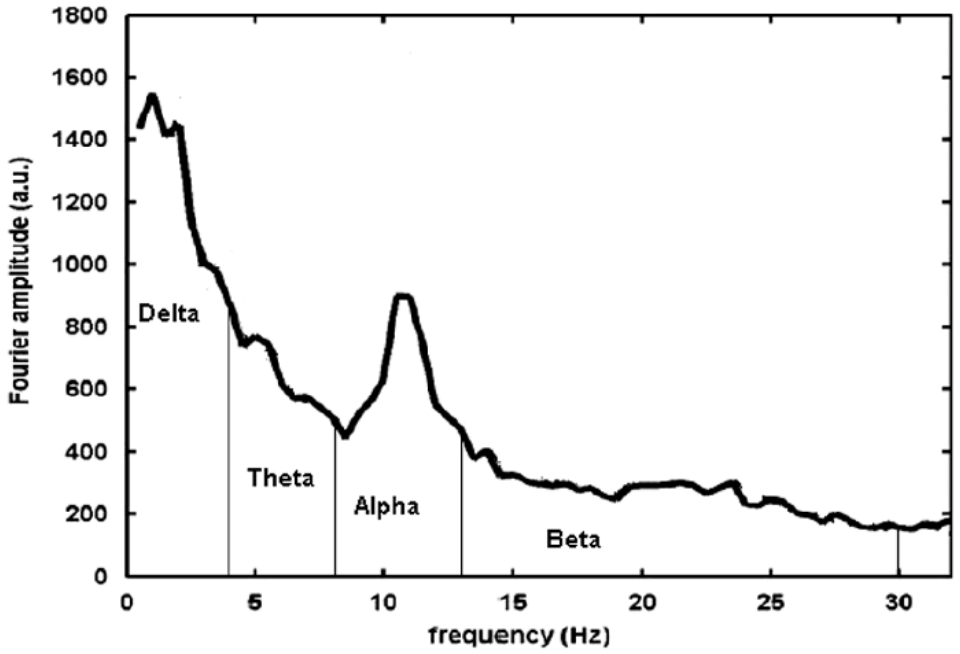
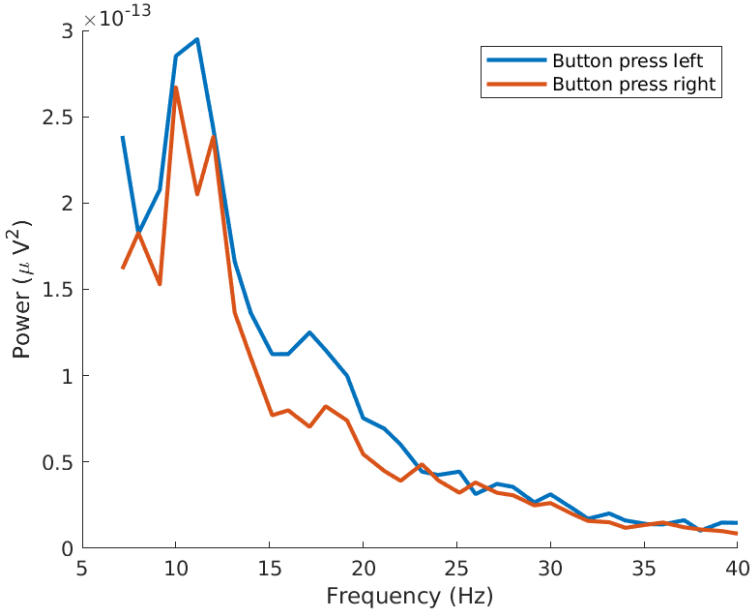
3. Frequencies that are very close to each other will provide similar results (because of time-frequency precision trade-offs)

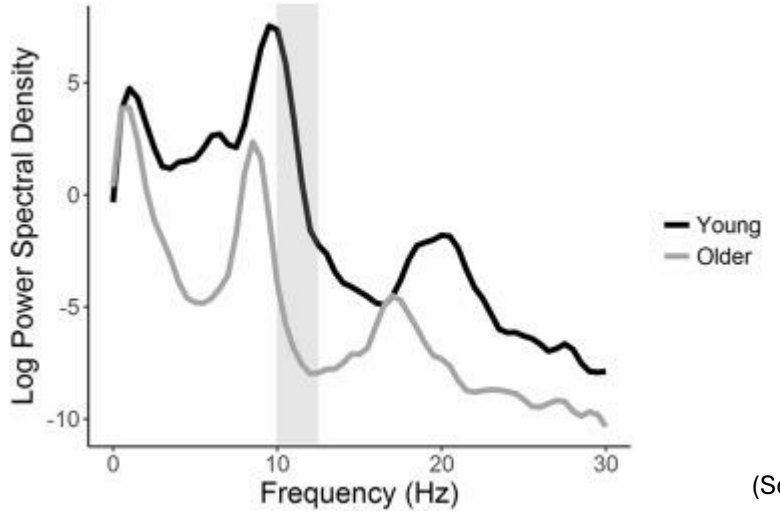
Visualization in EEG

Frequency Domain (PSD plot)
(no temporal resolution)



(Namazi & Kulish, 2012)





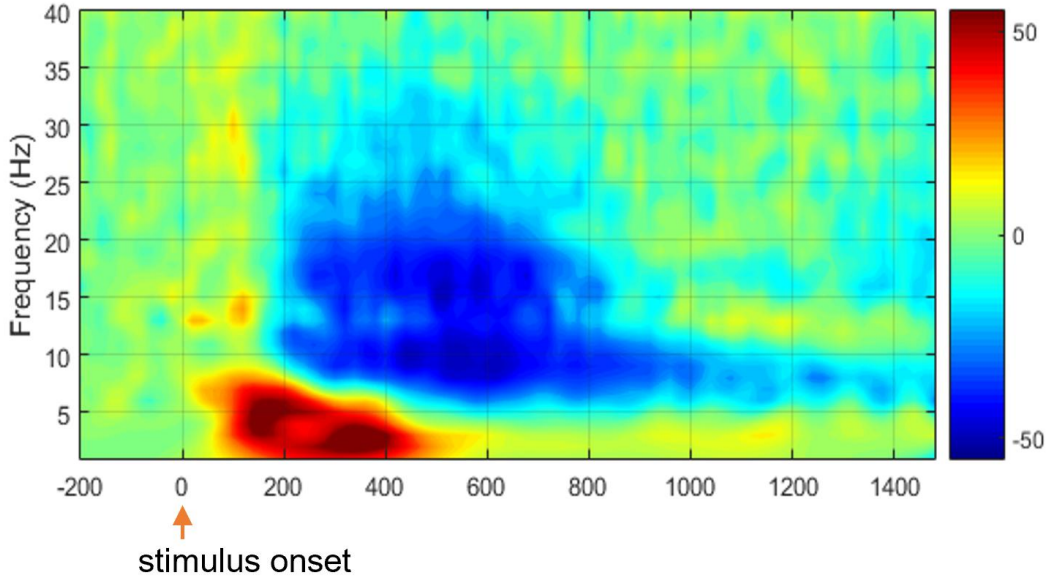
(Scally et al., 2018)

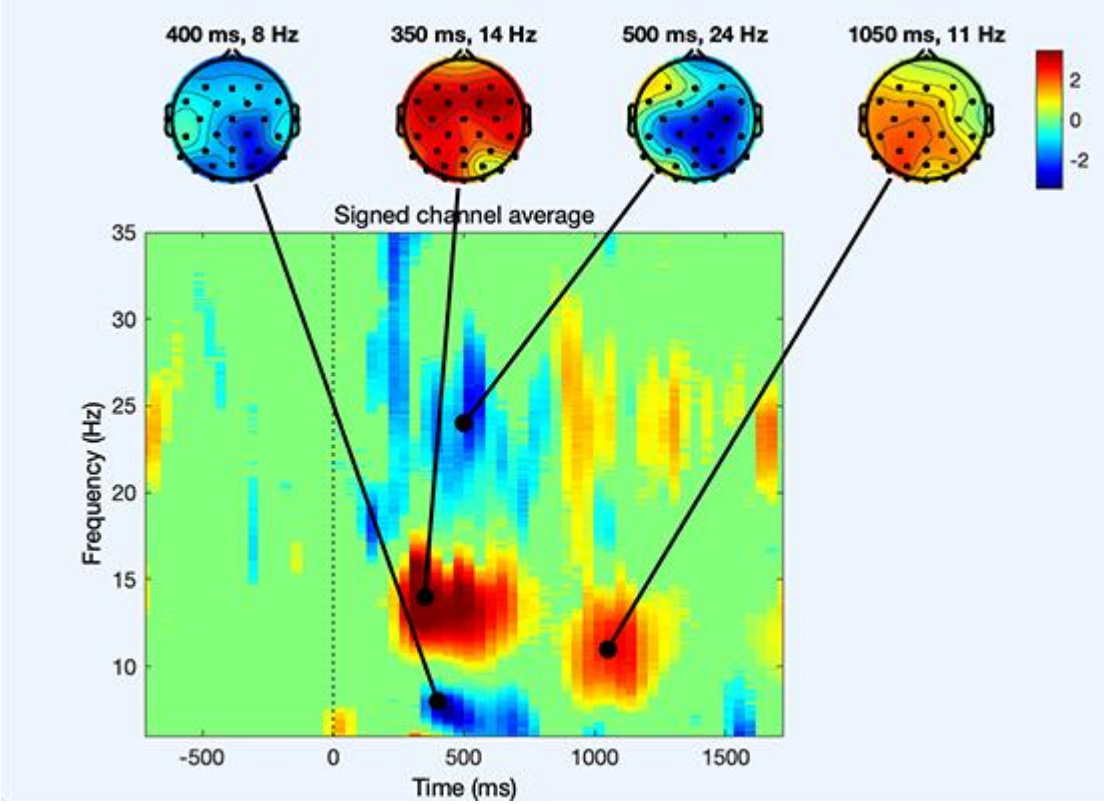
Power is often Log-scaled!

https://www.fieldtriptoolbox.org/workshop/oslo2019/timefrequency/

Visualization in EEG

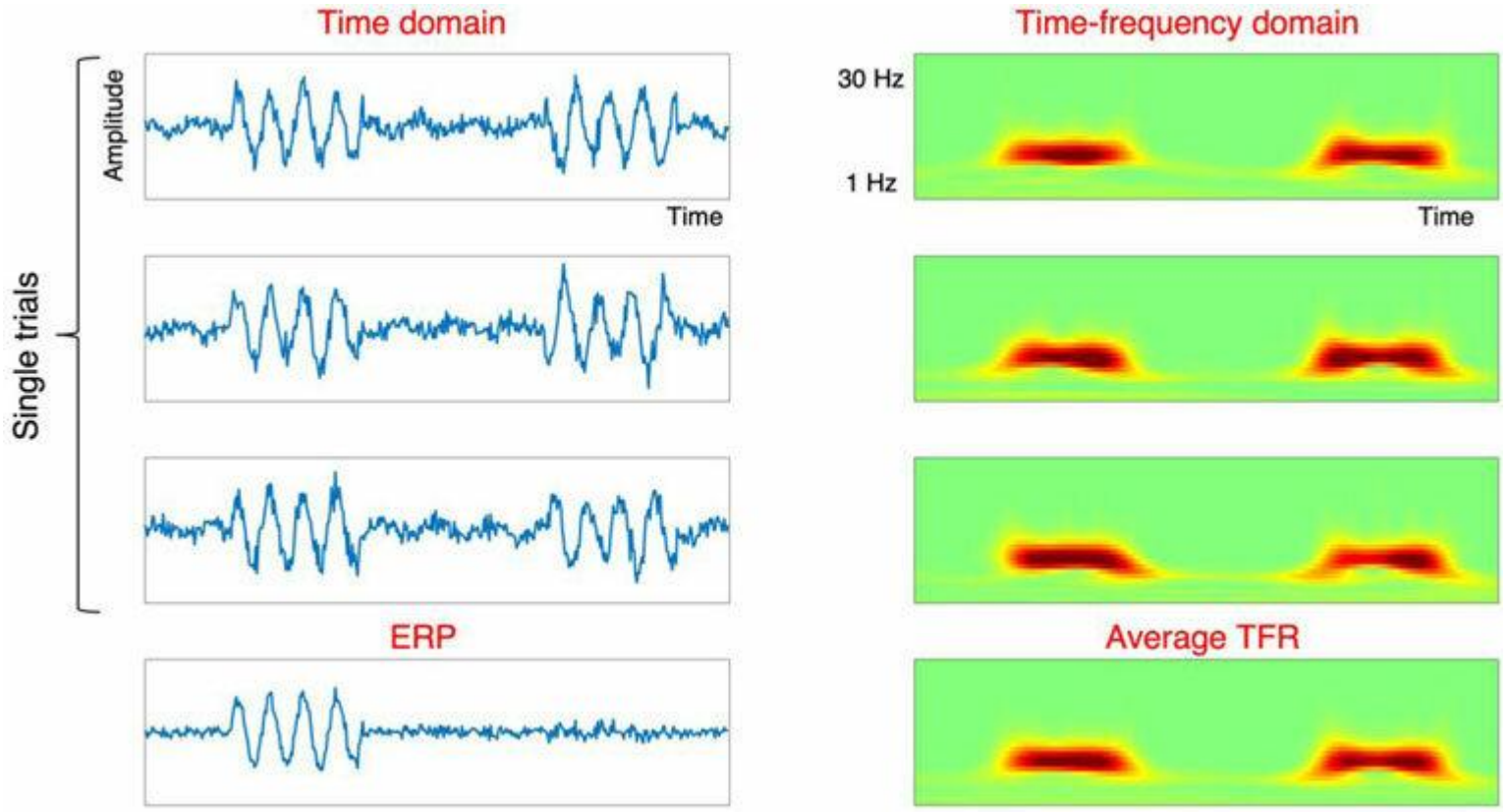
Frequency and Time





https://cerebral-computing.com/Method_EEG_overview.html
https://eeglab.org/tutorials/11_Scripting/EEG_scalp_measures.html

Evoked vs. Induced Oscillations



(Rossi et al., 2022)

Caveat

Power at a given frequency does not necessarily mean that the brain was oscillating at that frequency…

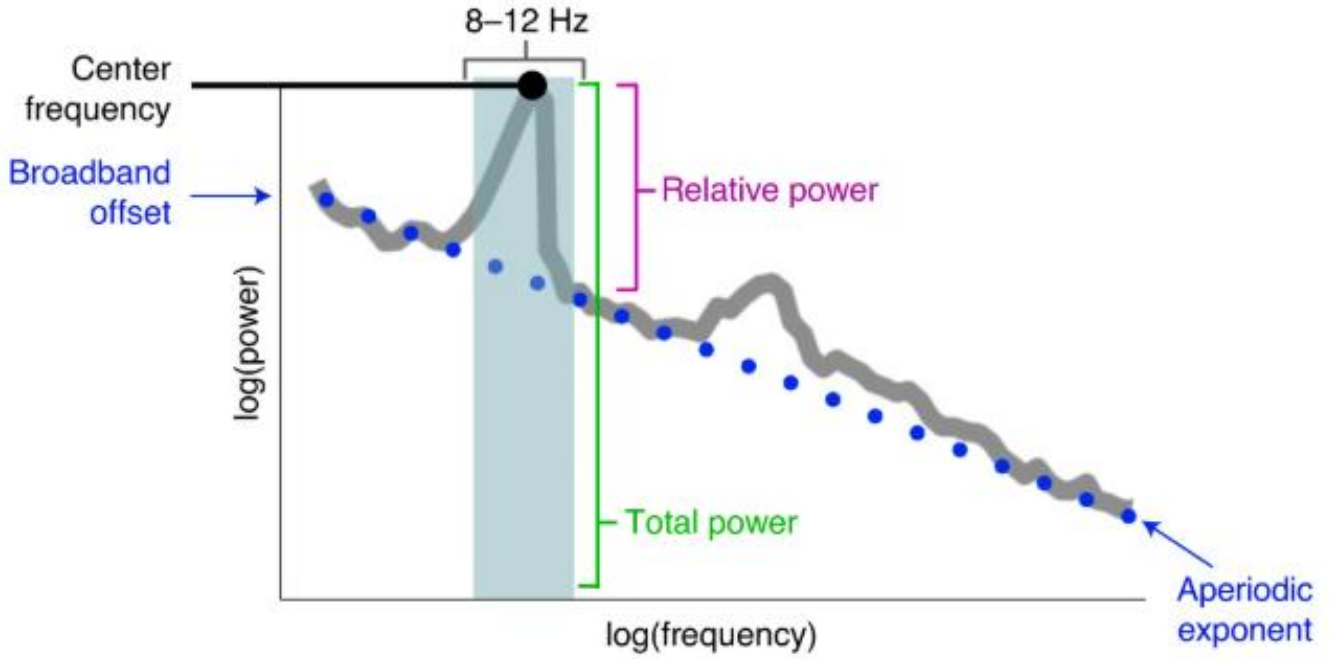
Think of the definition of the Fourier principle!

- Lower frequencies: ERP-like brain processes
- Higher frequencies: random neural noise /background activity
- Artefacts like blinks, heart beat, movement, line noise lead to power in specific bands

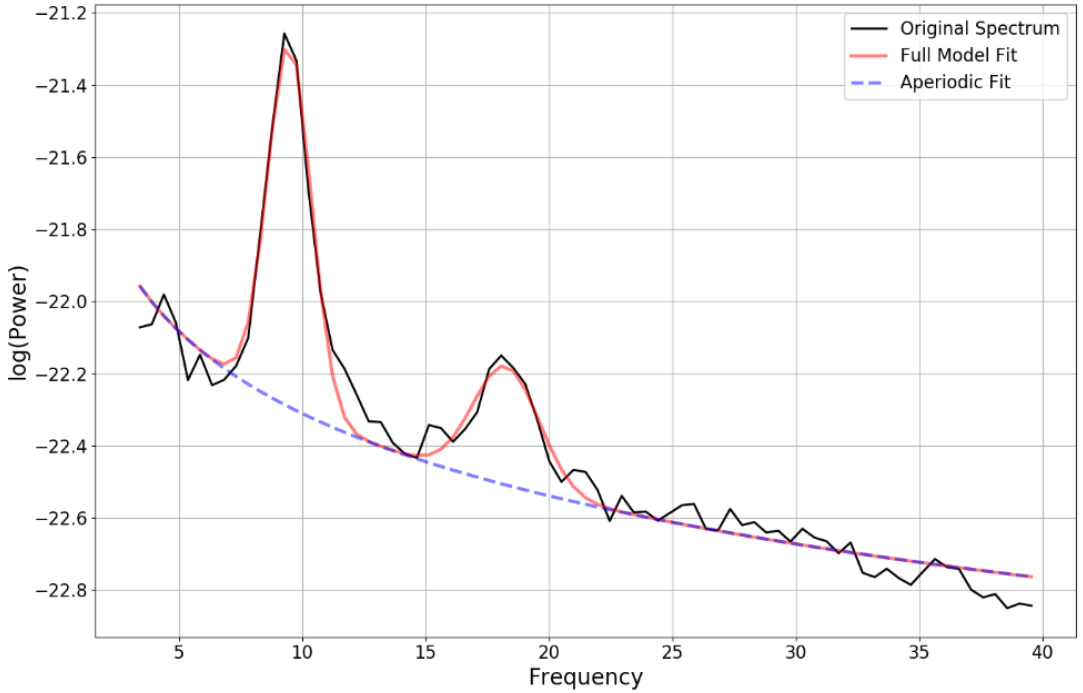
→ Clean data, no systematic differences between conditions!

Additional analysis methods

- Seperating oscillatory (periodic) from non-oscillatory (aperiodic) power



(Donoghue et al., 2020)



https://fooof-tools.github.io/fooof/auto_tutorials/plot_02-FOOOF.html

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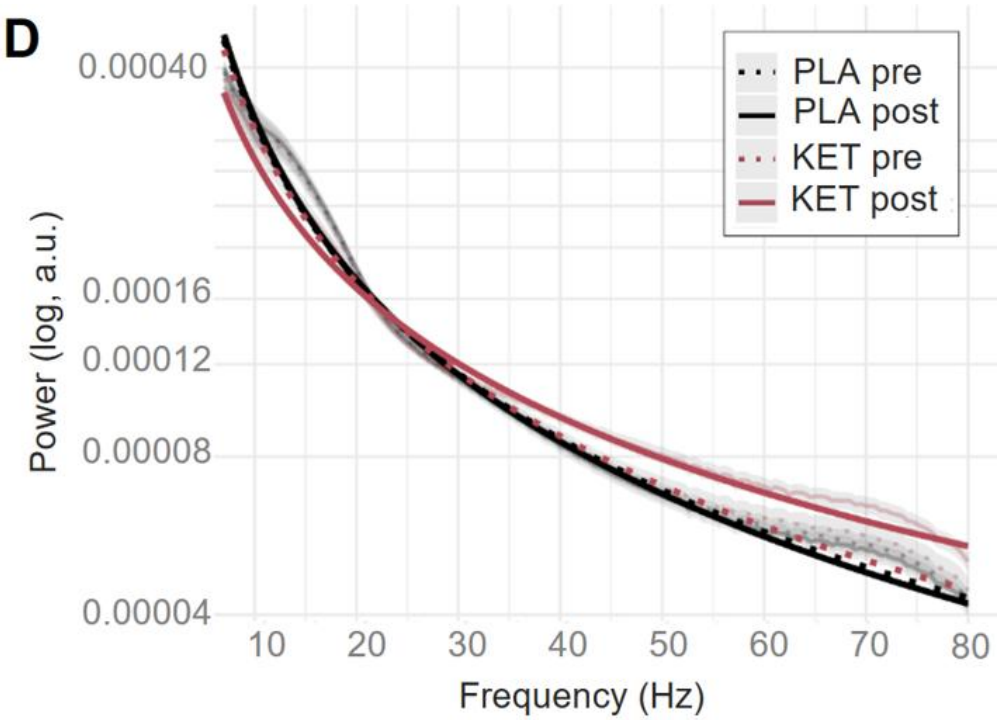
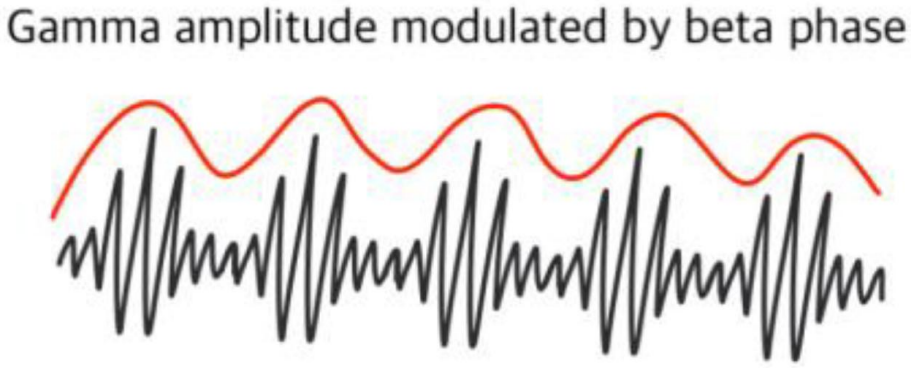


Additional analysis methods

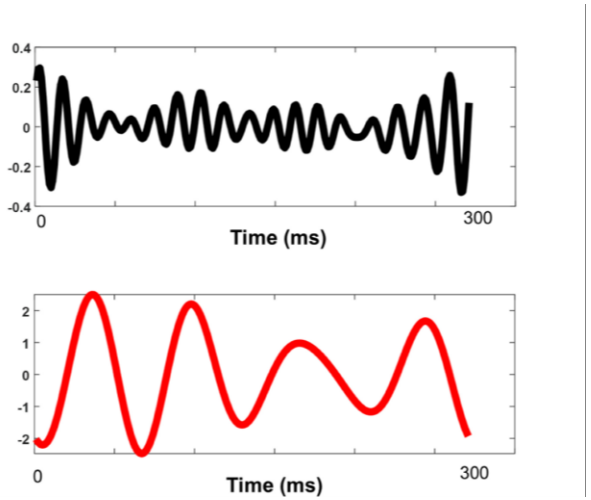
- Cross-Frequency-Coupling

- activity of neuronal assemblies, each supporting a specific frequency band, influences or modulates the activity of others

- Phase-amplitude coupling: amplitude of faster oscillations is coupled to phase of slower oscillations



(Hodnik et al. 2024)



What we‘ve covered

Why time-frequency analysis complements ERP analysis

Potential physiological mechanisms of oscillations

How to compute time-frequency analysis

Outlook on more advanced / other methods

Any Questions?

Partly based on

“Analyzing Neural Time Series Data: Theory and Practice“

Mike X Cohen
The MIT Press, 2014