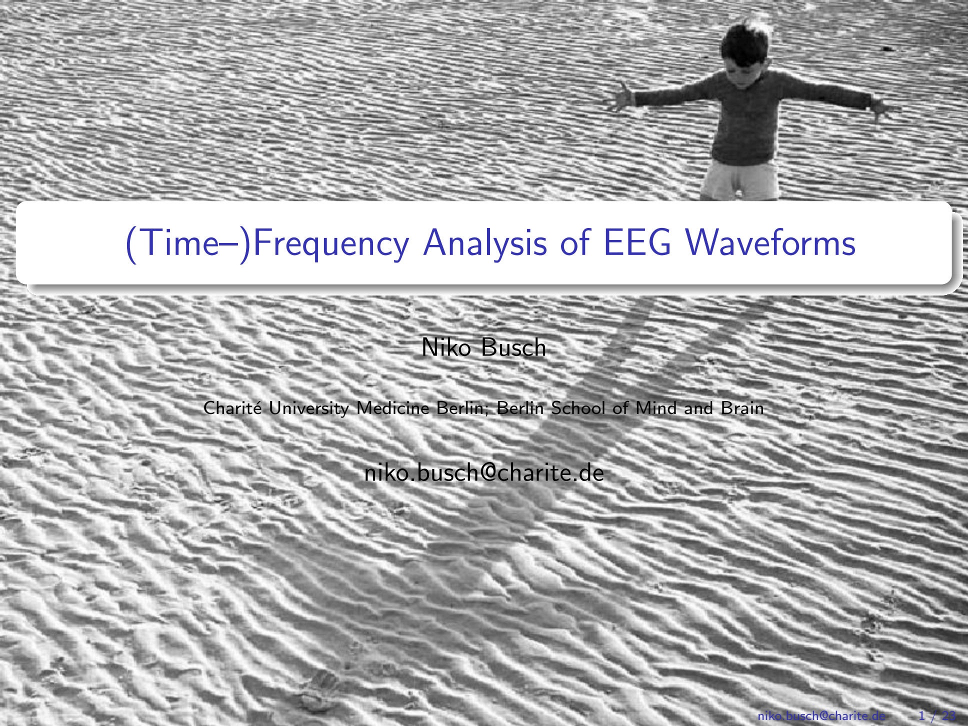


(Time–)Frequency Analysis of EEG Waveforms

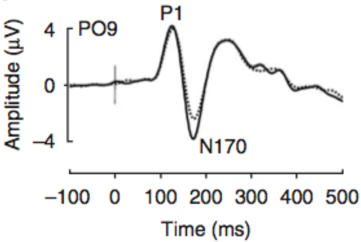
Niko Busch

Charité University Medicine Berlin; Berlin School of Mind and Brain

niko.busch@charite.de

From ERP waveforms to waves

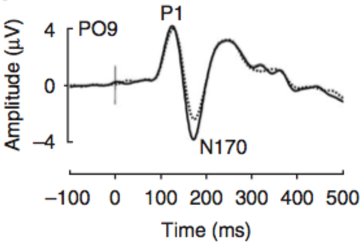
- ERP analysis:
  - time domain analysis: when do things (amplitudes) happen?
  - treats peaks and troughs as single events.



- Frequency domain (spectral) analysis (Fourier analysis):
  - magnitudes and frequencies of waves — no time information.
  - peaks and troughs are not treated as separate entities.
- Time–frequency analysis (wavelet analysis):
  - when do which frequencies occur?

From ERP waveforms to waves

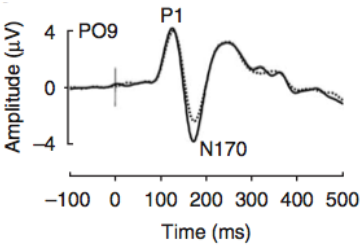
- ERP analysis:
  - time domain analysis: when do things (amplitudes) happen?
  - treats peaks and troughs as single events.



- Frequency domain (spectral) analysis (Fourier analysis):
  - magnitudes and frequencies of waves — no time information.
  - peaks and troughs are not treated as separate entities.
- Time–frequency analysis (wavelet analysis):
  - when do which frequencies occur?

From ERP waveforms to waves

- ERP analysis:
  - time domain analysis: when do things (amplitudes) happen?
  - treats peaks and troughs as single events.



- Frequency domain (spectral) analysis (Fourier analysis):
  - magnitudes and frequencies of waves — no time information.
  - peaks and troughs are not treated as separate entities.
- Time–frequency analysis (wavelet analysis):
  - when do which frequencies occur?

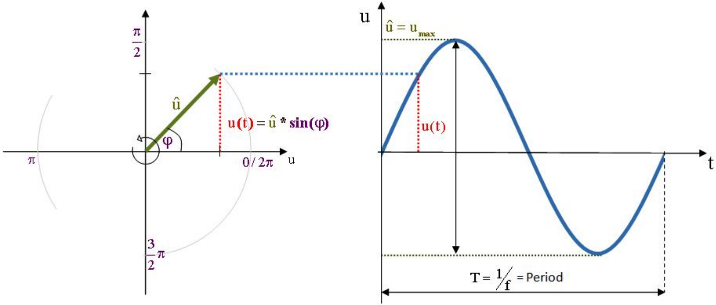
Why bother?

(Time–)Frequency analysis complements signal analysis:

- neurons are oscillating.
- analysis of signals with trial-to-trial jitter.
- analysis of longer time periods.
- analysis of pre-stimulus and spontaneous signals.
- necessary for sophisticated methods (coherence, coupling, causality, etc.).

Parameters of waves

Oscillations	regular repetition of some measure over several cycles.
Wavelength	length of a single cycle (a.k.a. period).
Frequency	$\frac{1}{wavelength}$ — the speed of change.
Phase	current state of the oscillation — angle on the unit circle. Runs from 0° (-π) — 360° (π)
Magnitude	(permanent) strength of the oscillation.

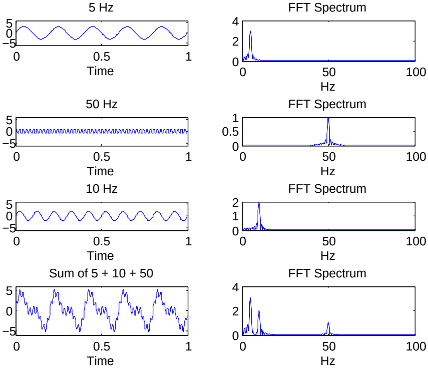


How to disentangle oscillations

Jean Joseph Fourier (1768—1830): *„An arbitrary function, continuous or with discontinuities, defined in a finite interval by an arbitrarily capricious graph can always be expressed as a sum of sinusoids"*.

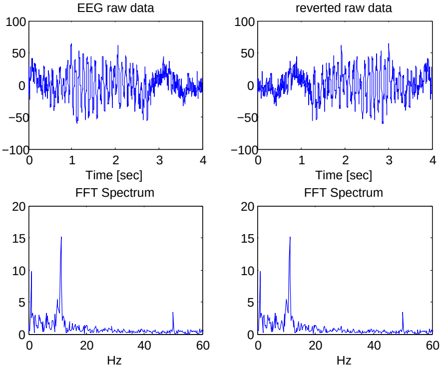
The discrete Fourier transform

- The DFT transforms the signal from the time domain into the frequency domain.
- Requires that the signal be stationary.



The discrete Fourier transform

- The DFT transforms the signal from the time domain into the frequency domain.
- Requires that the signal be stationary.



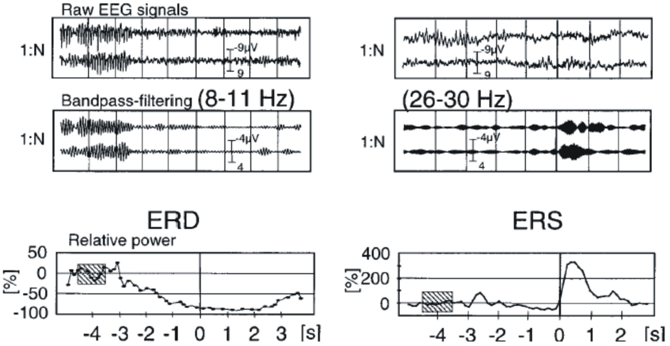
The discrete Fourier transform

- The DFT transforms the signal from the time domain into the frequency domain.
- Requires that the signal be stationary.

- Non-stationary signals:
  - When does the 10 Hz oscillation occur?
  - DFT does not give time information.
  - Time information is not necessary for stationary signals
  - Frequency contents do not change — all frequency components exist all the time.
  - How to investigate event–related spectral changes in brain signals?

Event–related synchronisation / desynchronisation

- Cut the signal in two time windows and assume stationarity in each half.
- $ERD/ERS^1 = \frac{poststimulus\ \ power - baseline\ \ power}{baseline\ \ power} * 100$



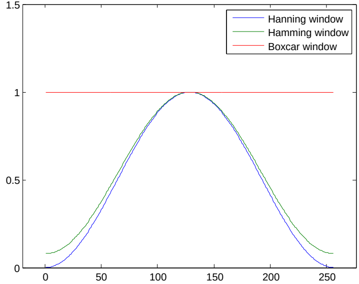
- But why not use even smaller windows?

⇒ Windowed FFT / Short term Fourier transform.

[1]Pfurtscheller & Lopes da Silva (1999). Clin Neurophysiol

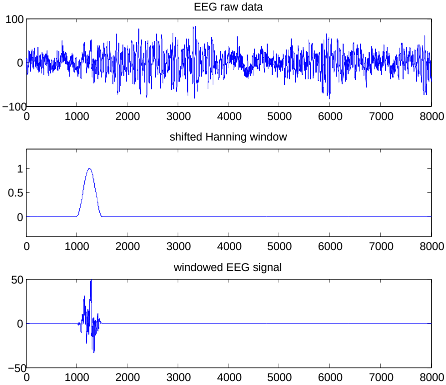
The short term Fourier transform (STFT) I

- Assume that some portion of a non–stationary signal is stationary.
- Important parameters:
    - window function (Hamming, Hanning, Rectangular, etc.)
    - window overlap
    - window length: width should correspond to the segment of the signal where its stationarity is valid.



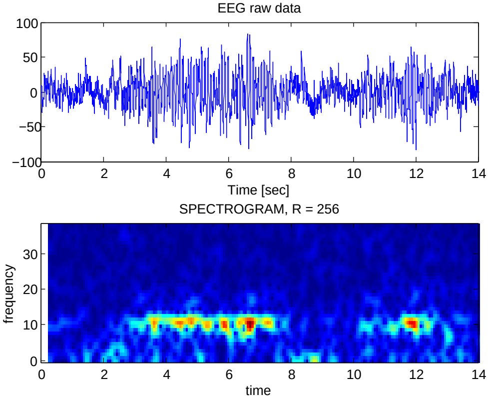
The short term Fourier transform (STFT) I

- Assume that some portion of a non–stationary signal is stationary.
- Important parameters:
  - window function (Hamming, Hanning, Rectangular, etc.)
  - window overlap
  - window length: width should correspond to the segment of the signal where its stationarity is valid.



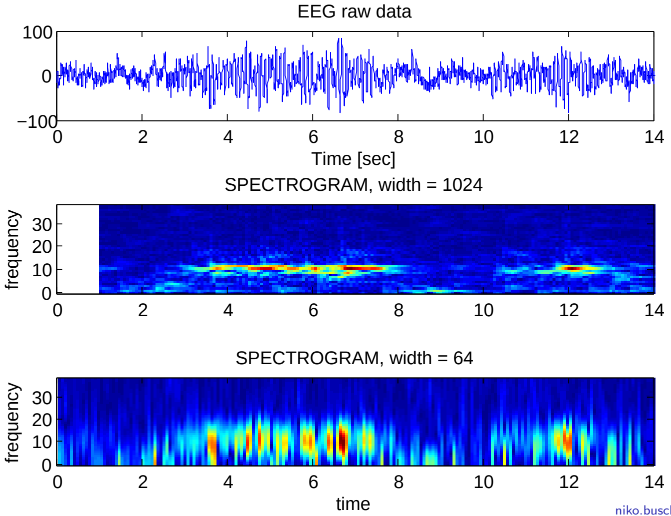
The short term Fourier transform (STFT) I

- Assume that some portion of a non–stationary signal is stationary.
- Important parameters:
    - window function (Hamming, Hanning, Rectangular, etc.)
    - window overlap
    - window length: width should correspond to the segment of the signal where its stationarity is valid.



The short term Fourier transform (STFT) II

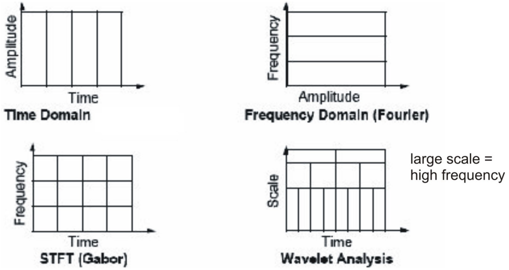
- Window length affects resolution in time and frequency
  - short window: good time resolution, poor frequency resolution.
  - long window: good frequency resolution, poor time resolution.



Uncertainty principle

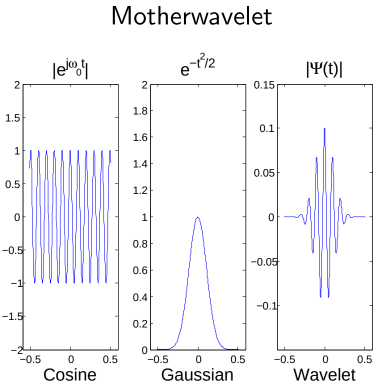
- Werner Heisenberg (1901—1976):
  - Energy and location of a particle cannot be both known with infinite precision.
  - a result of the wave properties of particles (not the measurement).
- Applies also to time–frequency analysis:
  - We cannot know what spectral component exists at any given time instant.
  - What spectral components exist at any given interval of time?
- Spectral/temporal resolution trade off cannot be avoided — but it can be optimised.
  - Good frequency resolution at low frequencies.
  - Good time resolution at high frequencies.

From STFT to wavelets



- STFT: fixed temporal & spectral resolution
  - Analysis of high frequencies ⇒ insufficient temporal resolution.
  - Analysis of low frequencies ⇒ insufficient spectral resolution.
- Wavelet analysis:
  - Analysis of high frequencies ⇒ narrow time window for better time resolution.
  - Analysis of low frequencies ⇒ wide time window for better spectral resolution.

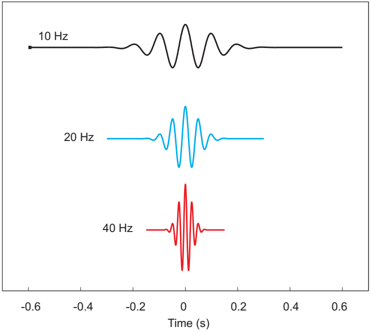
What is a wavelet?

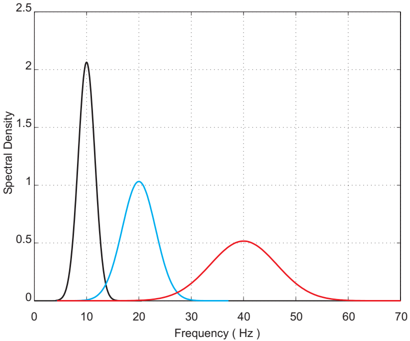


- Zero mean amplitude.
- Finite duration.
- Mother wavelet: prototype function (f = sampling frequency).
- Wavelets can be scaled (compressed) and translated.

What is a wavelet?

Motherwavelet

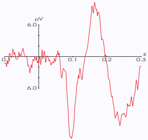




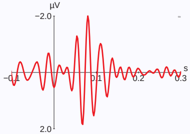
- Zero mean amplitude.
- Finite duration.
- Mother wavelet: prototype function (f = sampling frequency).
- Wavelets can be scaled (compressed) and translated.

Wavelet transform of ERPs

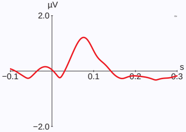
ERP



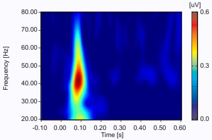
Bandpass–filtered ERP



Wavelet transformed ERP



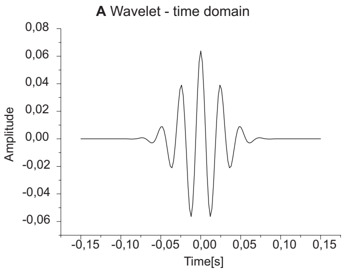
Gamma–Band: ca. 30 – 80 Hz



... but be careful:

- any signal can be represented as oscillations w. time-frequency analysis
- but it does not imply that the signal is oscillatory!

Important parameters of a wavelet



Length how many cycles does a wavelet have?

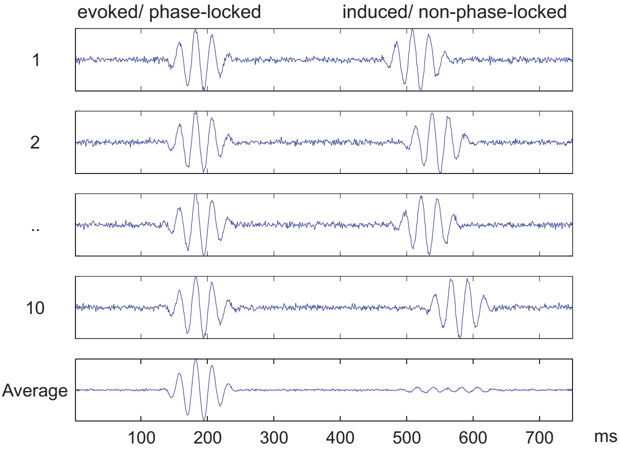
e.g. 40 Hz wavelet (25 ms/cycle), 12 cycles $\Rightarrow$ 250 ms length

σ_t standard deviation in time domain: $\sigma_t = \frac{m}{2\pi * f_0}$

σ_f standard deviation in frequency domain: $\sigma_f = \frac{1}{2\pi * \sigma_t}$

time resolution increases with frequency, whereas frequency resolution decreases with frequency.

Evoked and induced oscillations I

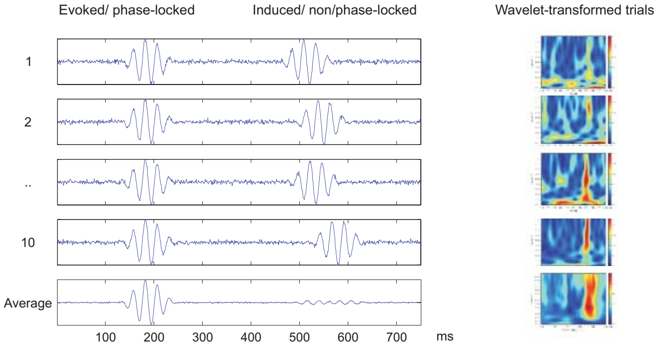


Evoked time-frequency representation of the average of all trials (ERP).

Induced average of time-frequency transforms of single trials.

Evoked and induced oscillations II

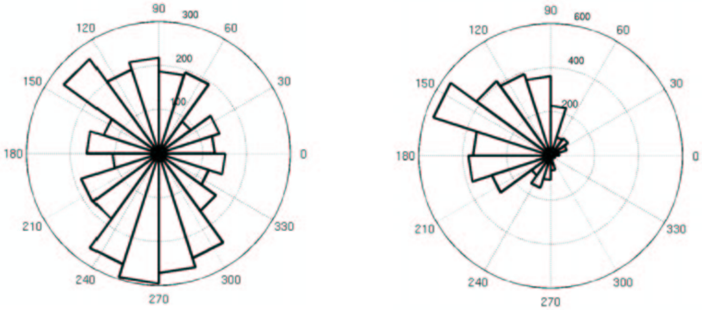
Wavelet analysis of single trials reveals non–phase–locked activity.



Evoked time-frequency representation of the average of all trials (ERP).

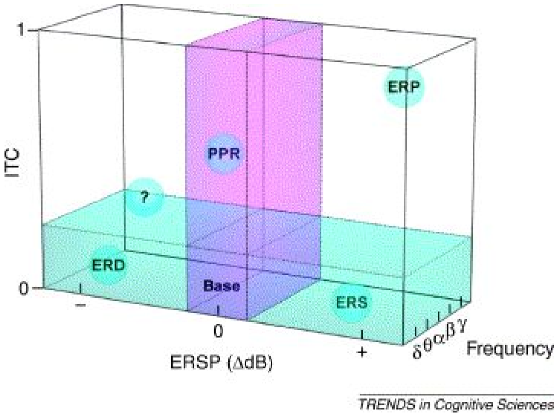
Induced average of time-frequency transforms of single trials.

Phase–locking factor (PLF)



- a.k.a. intertrial coherence (ITC) or phase–locking–value (PLV).
- measures phase consistency of a frequency at a particular time across trials.
- PLF $= 1$: perfect phase alignment.
- PLF $= 0$: random phase distribution.

The EEG state space



- Frequency x phase locking x amplitude changes[2]
- Evoked and induced activity are extremes on a continuum.
- ERPs cover only small part of the EEG space.

[2]Makeig, Debener, Onton, Delorme (2004). TICS

Examples 1: spontaneous EEG

- Stimulus pairs are presented at different phases of the alpha rhythm — sequential or simultaneous?[3]
- If the stimulus pair falls within the same alpha cycle ⇒ perceived simultaneity.
- Does the visual system take snapshots at a rate of 10 Hz?

Simultaneity and the alpha rhythm

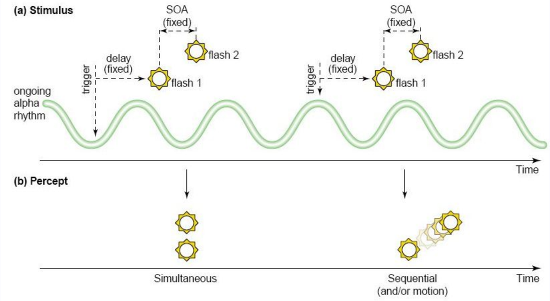


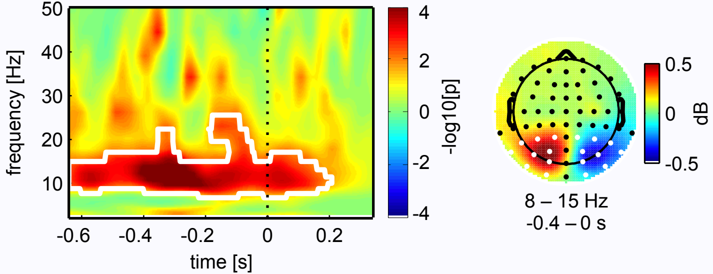
Figure from VanRullen & Koch (2003): Is perception discrete of continuous? TICS

[3] Varela et al. (1981): Perceptual framing and cortical alpha rhythm. Neuropsychologia

Examples 2: pre-stimulus EEG power

- Spatial attention to left or right.
- Stronger alpha power over ipsilateral hemisphere.[4]

Attention: ipsi- vs. contra-lateral

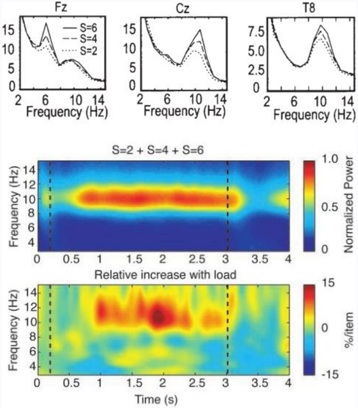


[4] Busch & VanRullen (2010): Spontaneous EEG oscillations reveal periodic sampling of visual attention. PNAS.

Examples 3: analysis of long time intervals

- Sternberg memory task with different set sizes.
- Alpha power increases linearly with set size.[5]

Effect of set size



[5] Jensen et al. (2002): Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. Cereb Cortex.

Recommended reading

WWW:

- EEGLAB's time-frequency functions explained: http://bishoptechbits.blogspot.com/
- FFT explained: http://blinkdagger.com/matlab/matlab-introductory-fft-tutorial/
- Wavelet tutorial http://users.rowan.edu/ polikar/WAVELETS/WTtutorial.html

Books:

- Barbara Burke Hubbard: The World According to Wavelets.
- Steven Smith: The Scientist & Engineer's Guide to Digital Signal Processing (`http://www.dspguide.com/`).
- Herrmann, Grigutsch & Busch: EEG oscillations and wavelet analysis. In: Event-related Potentials: A Methods Handbook.

Papers:

- Tallon-Baudry & Bertrand (1999) Oscillatory gamma activity in humans and its role in object representation. TICS.
- Samar, Bopardikar, Rao & Swartz (1999) Wavelet analysis of neuroelectric waveforms: a conceptual tutorial. Brain Lang.

Thank you...

... for your interest !

Please ask questions!!!