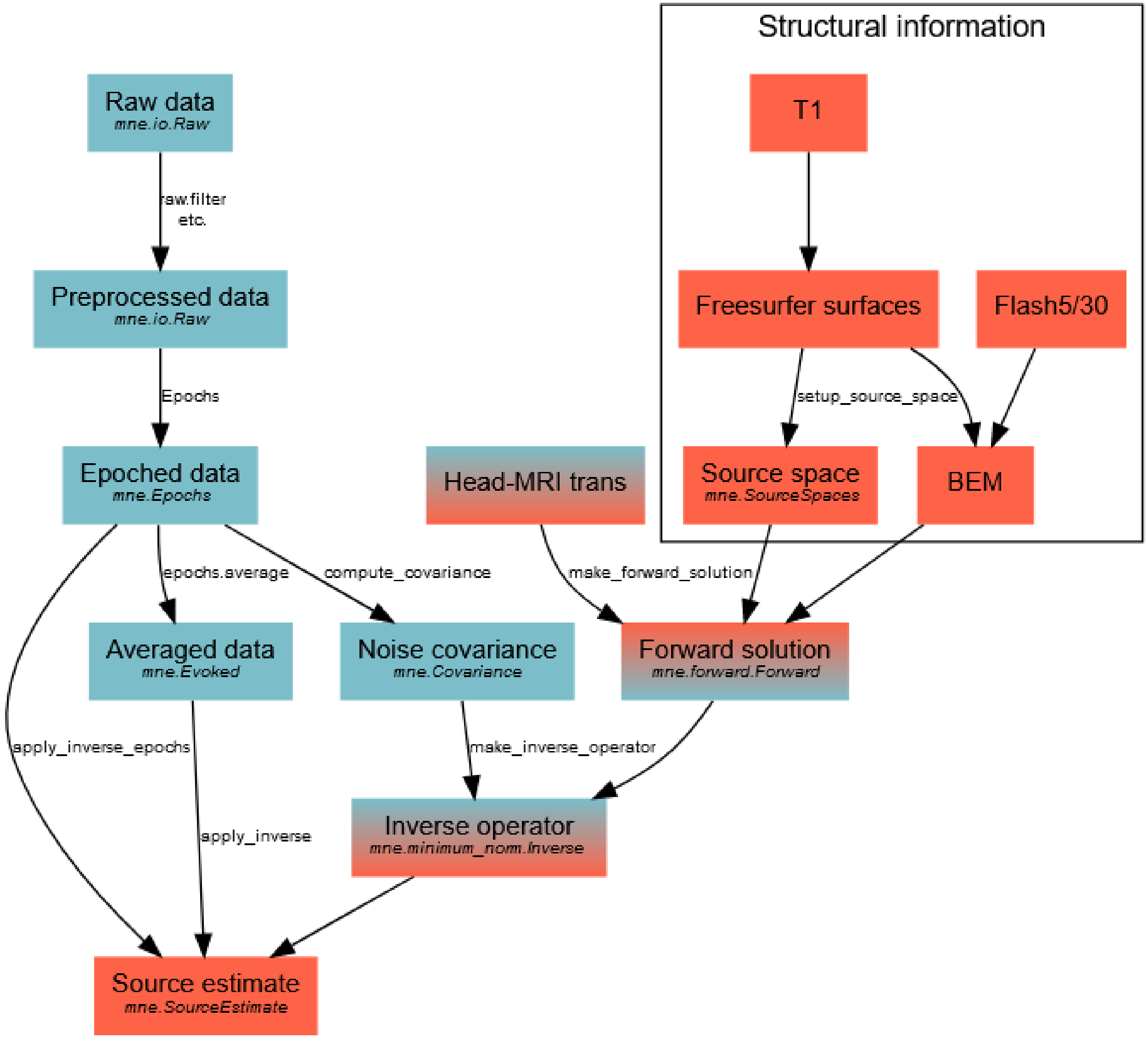
EEG/MEG 1:

Pre-processing – spectral and spatial filtering

Olaf Hauk

olaf.hauk@mrc-cbu.cam.ac.uk

Typical EEG/MEG Analysis Pipeline



https://mne.tools/stable/overview/cookbook.html

Data Pre-Processing - Artefacts

Artefacts

- **non-physiological,** i.e. from outside the body (sensor-intrinsic noise, line noise, moving objects, vibrations)
  => Maxfilter (SSS), Frequency-Filtering, SSP, PCA/ICA

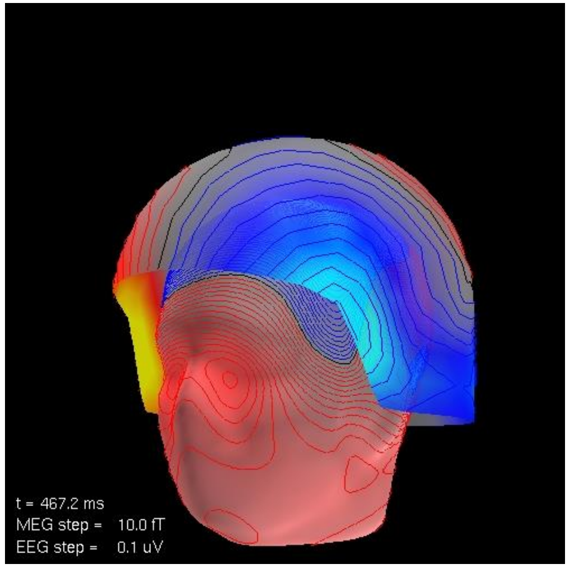
- **Physiological but non-brain**, e.g. eye movements, muscles
  => SSP, PCA/ICA, H/L-Filtering

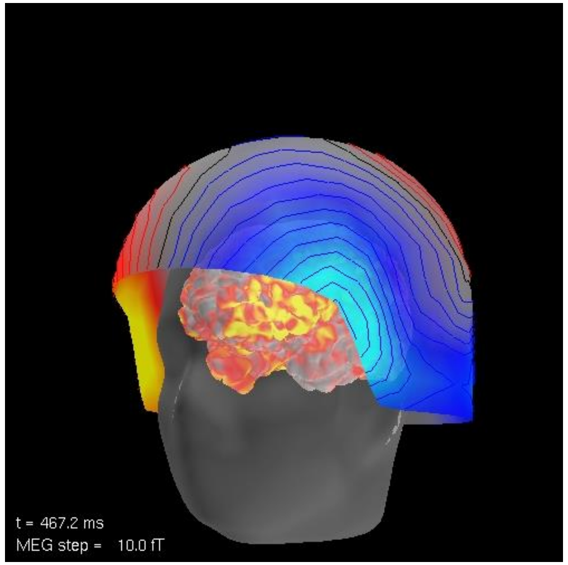
- **Physiological from the brain,** i.e. brain sources that are not of interest or not included in your source model
  => choose appropriate source estimation, regularisation

Wisdoms:
"Some people's signal is other people's noise."
Unfortunately, you cannot just choose what's signals and what's noise.
It's always better to avoid artefacts than to correct them.

Artefacts in EEG and MEG Will End Up in Source Space

Eye Blink





This will affect all source estimation methods –
get rid of your artefacts beforehand.

Separating Signal and Noise Components - “Decompositions”

You can decompose your signal in any way you want – the question is whether it can separate “interesting” from “non-so-interesting” parts of your data, either in space or time.

1) Define a set of “basis functions”, e.g.
    a) A priori: sines/cosines, wavelets, polynomials.
    b) Data driven: PCA/SVD/ICA, empirical modes.
2) Fit these basis functions to your data to explain (most of) its variance.
3) Select (or remove) those basis functions that you are (not) interested in, e.g. signal vs noise.
4) Reconstruct your signal with the components of interest.

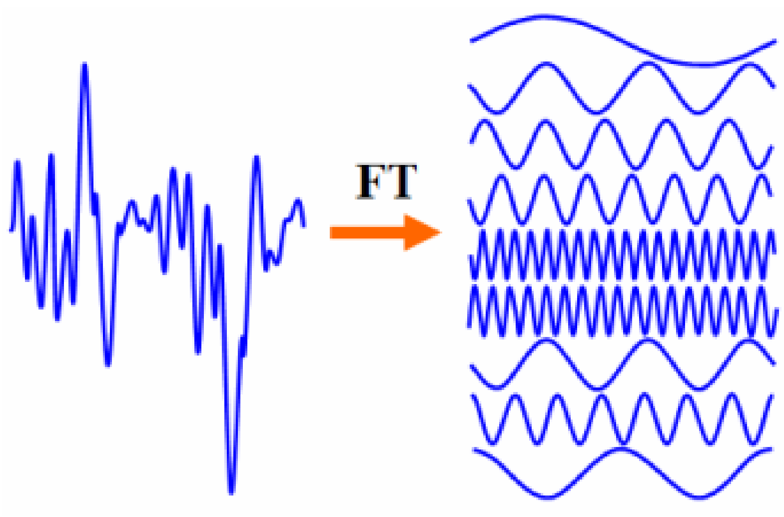
If the basis functions are meaningful, you may be successful: cleaner data.
If the basis functions do not correspond to signal and noise parts of your data – you will get a result, but it will be distorted.

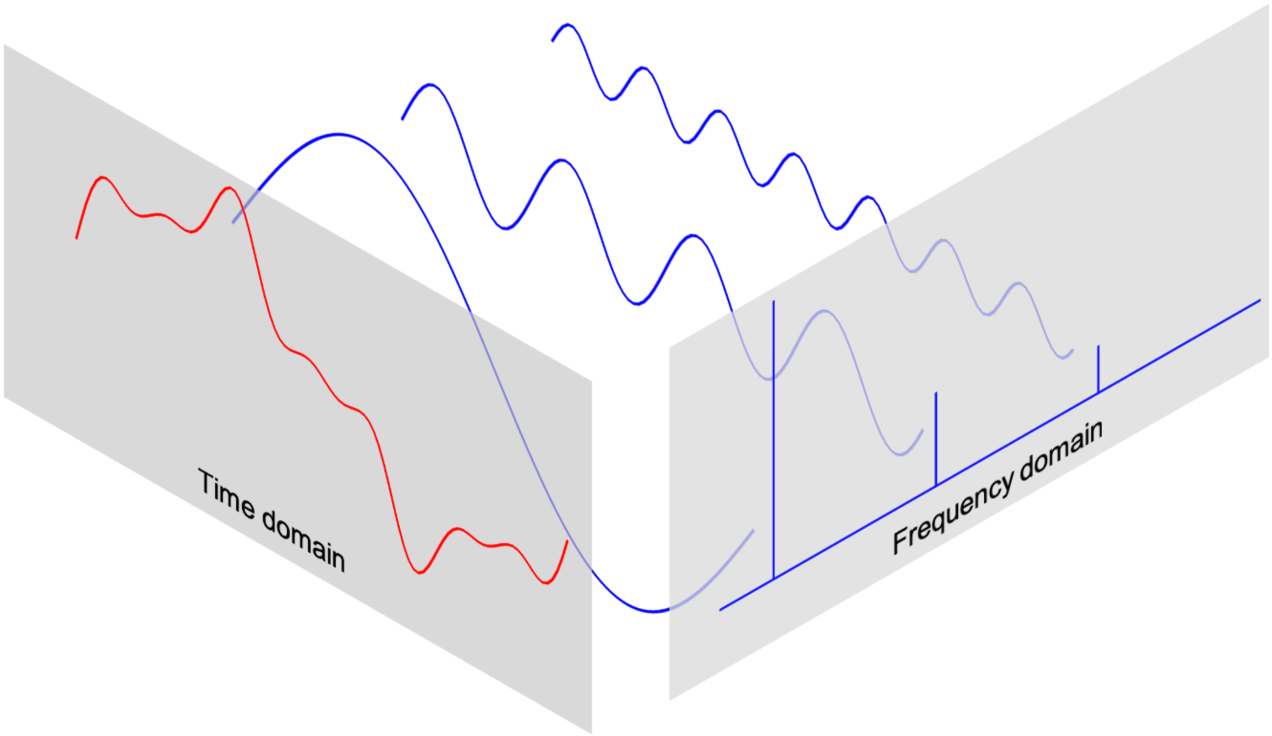
Think about what artefacts are the most relevant in your data, then decide which method is best to remove them:

1. How frequent?
2. How large? Time course and topography?
3. Are they related to your variables of interest?

Time-Domain Signals Can Be Represented in the Frequency Domain - and Vice Versa

Decomposing signals
into sine/cosine terms





https://pythonnumericalmethods.studentorg.berkeley.edu/notebooks/chapter24.02-Discrete-Fourier-Transform.html

Basic Principals of Frequency Filtering

Filtering changes the time course of your data. Thus:

“Filter as much as necessary but as little as possible.”

Common types of filters:

“High-pass”: Lets higher frequencies pass, suppresses lower frequencies (incl. “detrending”)

“Low-pass”: Lets lower frequencies pass, removes higher frequencies

“Band-pass”: Lets frequencies within a frequency band pass, suppresses frequencies above and below the band

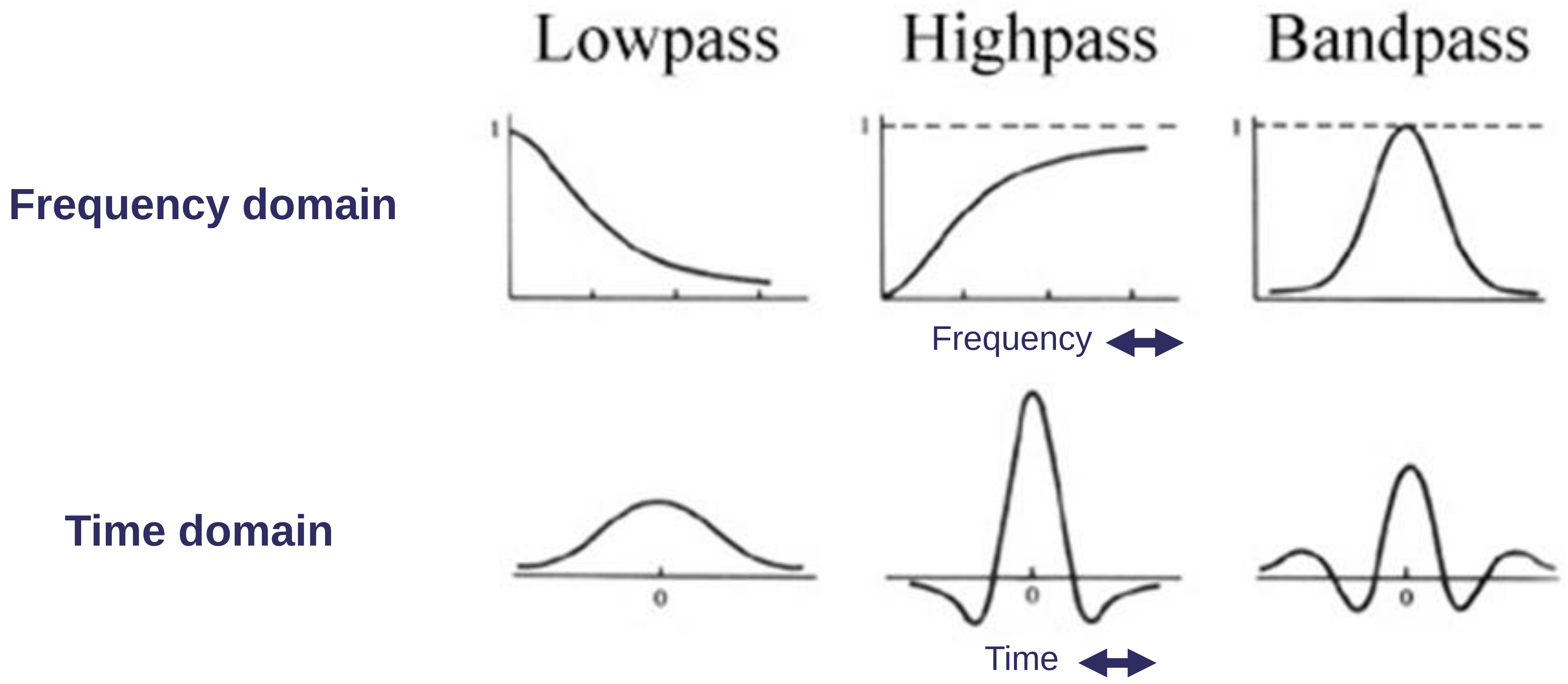
“Notch” filter: A very sharp band-pass filter, e.g. for 50 or 60 Hz line noise

(e.g. Cheveigen & Nelken, Neuron 2019, https://www.sciencedirect.com/science/article/pii/S0896627319301746), Widmann et al., Journal of Neuroscience Methods 2015, https://www.sciencedirect.com/science/article/pii/S0165027014002866, Tanner et al., Psychophysiology 2016, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4506207/).

Basic Principals of Frequency Filtering

Time-domain and frequency-domain filtering are two sides of the same coin:

One type of frequency-domain filtering corresponds to one type of time-domain filtering.

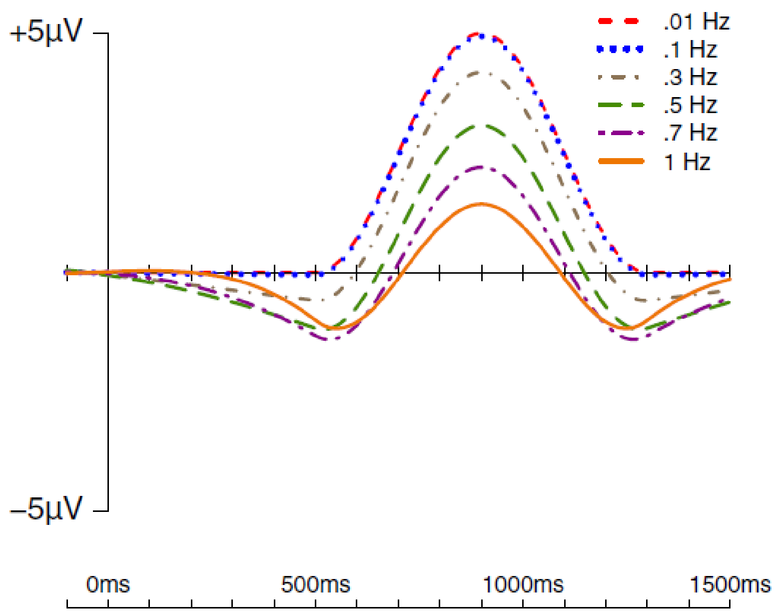


https://uk.mathworks.com/matlabcentral/fileexchange/51155-time-domain-filtering-vs-frequency-domain-filtering-in-images

Filtering can affect both signal and artefact

High-pass filtering:

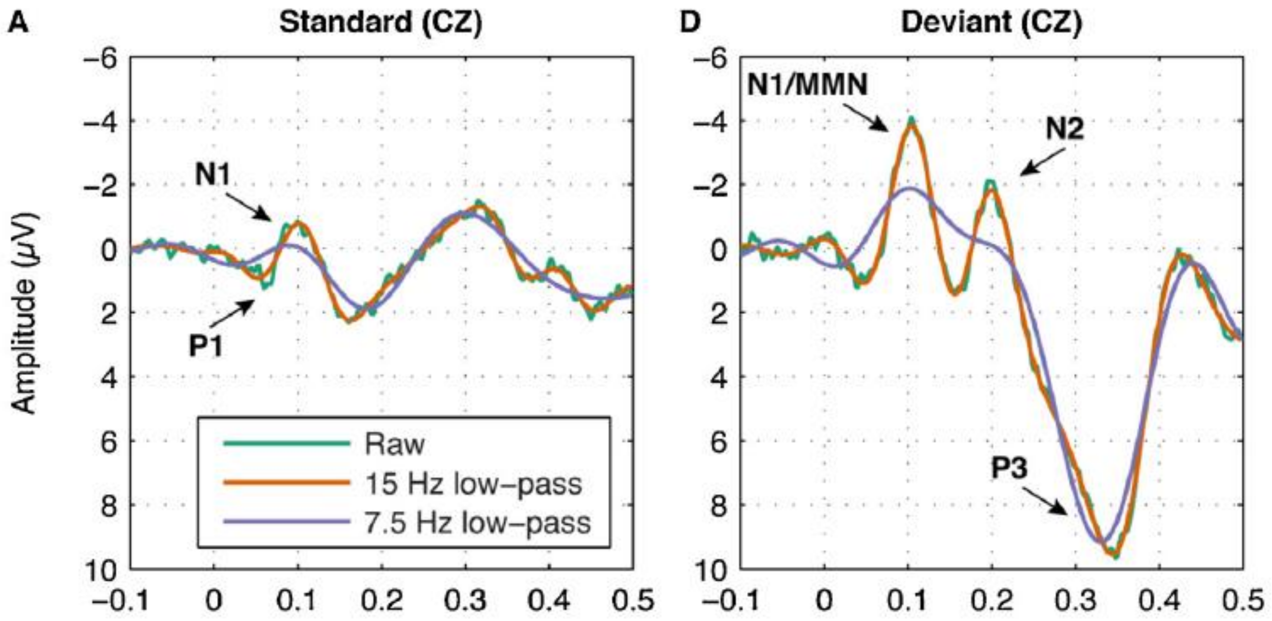
"(linear/polynomial) Detrending"
"Removing slow drifts"



Tanner et al., Psychophysiology 2016,
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4506207

Low-pass filtering:

"Smoothing"

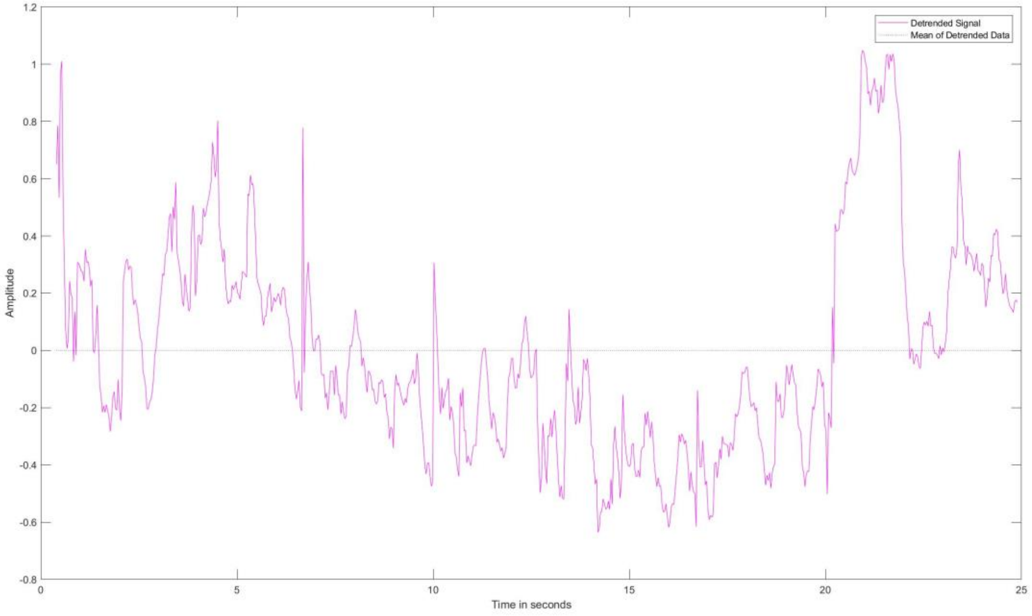


Widmann et al., Journal of Neuroscience Methods 2015,
https://www.sciencedirect.com/science/article/pii/S0165027014002866

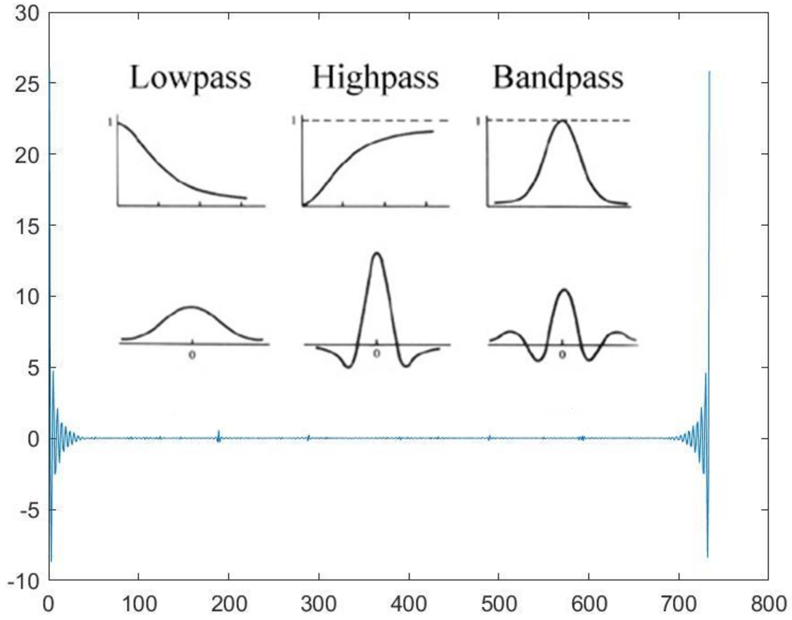
Edge Artefacts of Filters

- Filtering artefacts occur at signal discontinuities, e.g. at the beginning and the end of the data.
- Thus, filter the “longest possible data segment”, ideally the raw data as early as possible.
- If you have to filter epochs, consider filtering longer epochs than you actually need.
- Be careful with “effects” close to the border of epochs.

Raw signal



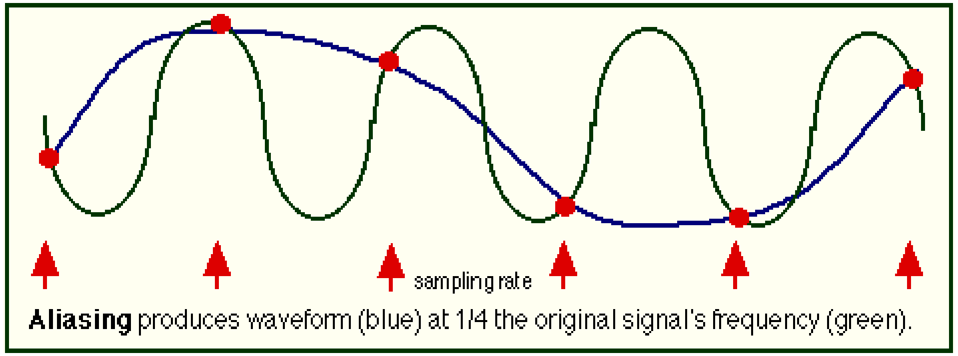
High-pass filtered signal



Filtering and Downsampling: “Aliasing”

- Downsampling can lead to “aliasing” if the data are not filtered appropriately (Nyquist theorem): Filter at least below half of the sampling frequency before downsampling.

Aliasing



Also watch:
https://www.youtube.com/watch?v=R-IVw8OKjvQ
Thanks to Alessandro.

Spatial Data Decompositions: Spatial Filtering

Spatial Data Decompositions: SSP and ICA

If artefacts have characteristic topographies, several methods can be applied to remove (some) noise or extract signals:

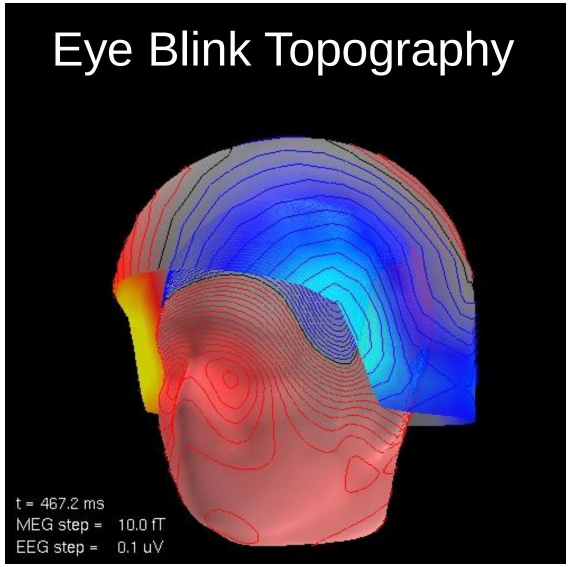
• **SSP: Signal Space Projection** (needs pre-defined topographies)

The following often go under the term “blind source separation”, because the topographies are not pre-defined, and found by the methods themselves (under certain assumptions):

• PCA: Principal Component Analysis

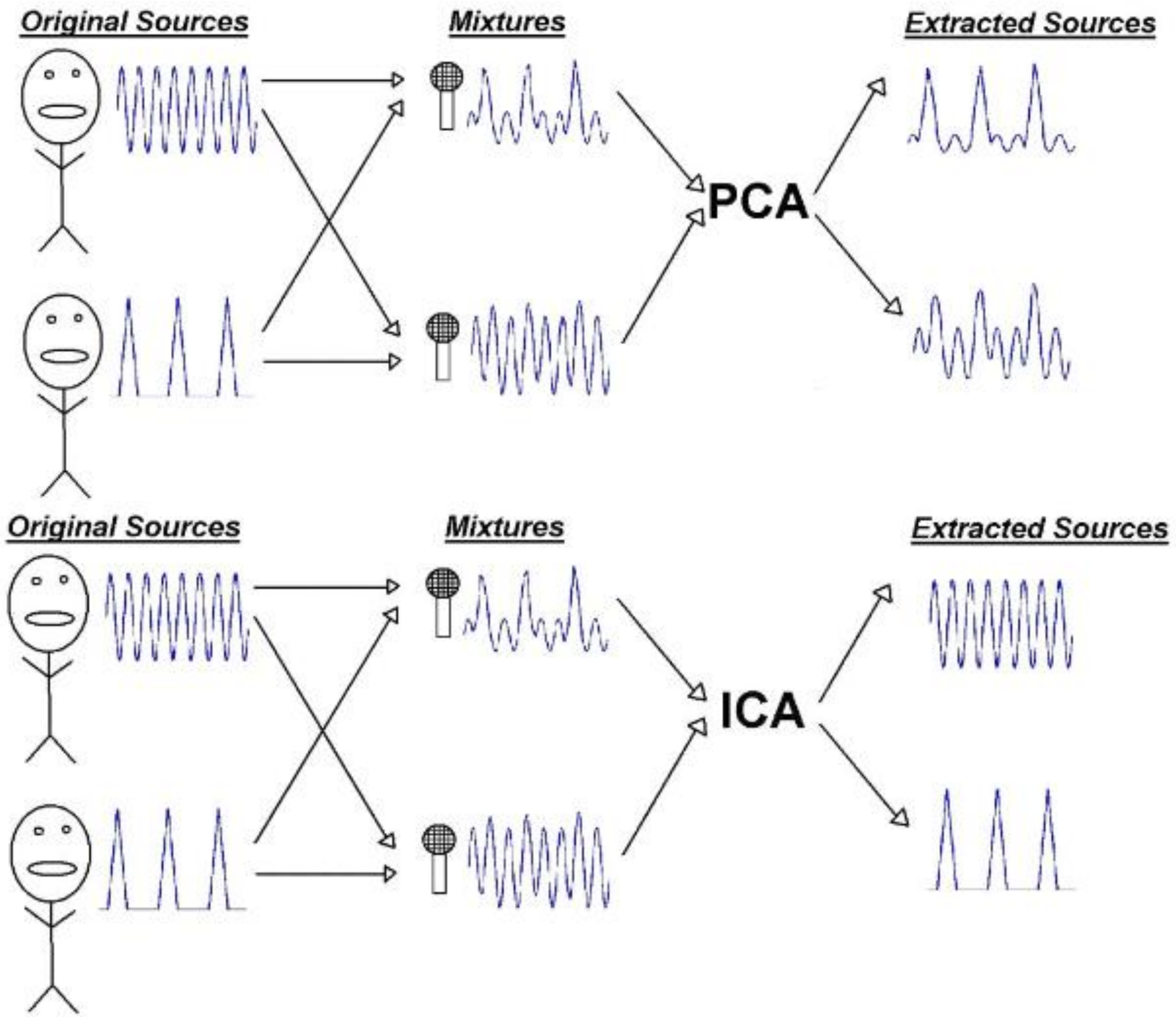
• SVD: Singular Value Decomposition

• **ICA: Independent Component Analysis**



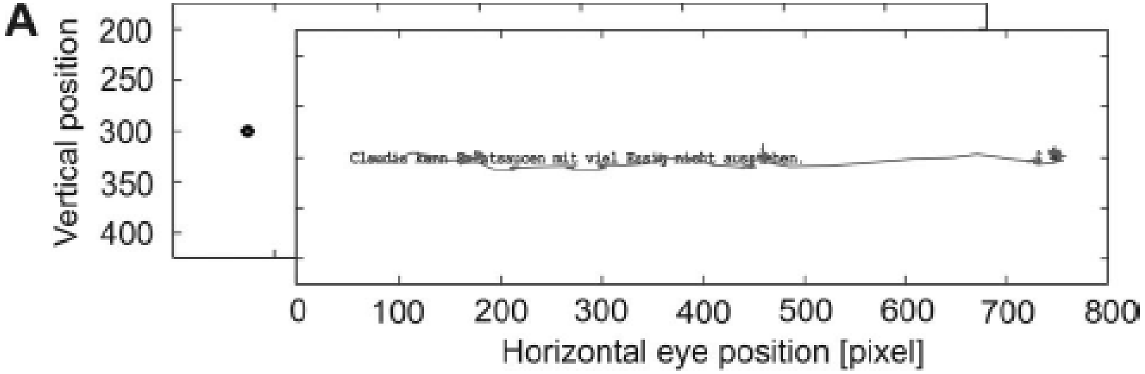
Independent Component Analysis

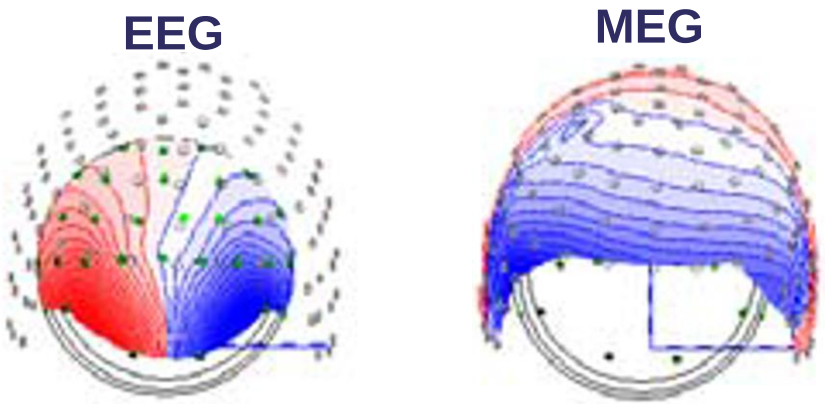
Goal: (De-)mixing of sources in the cocktail party effect

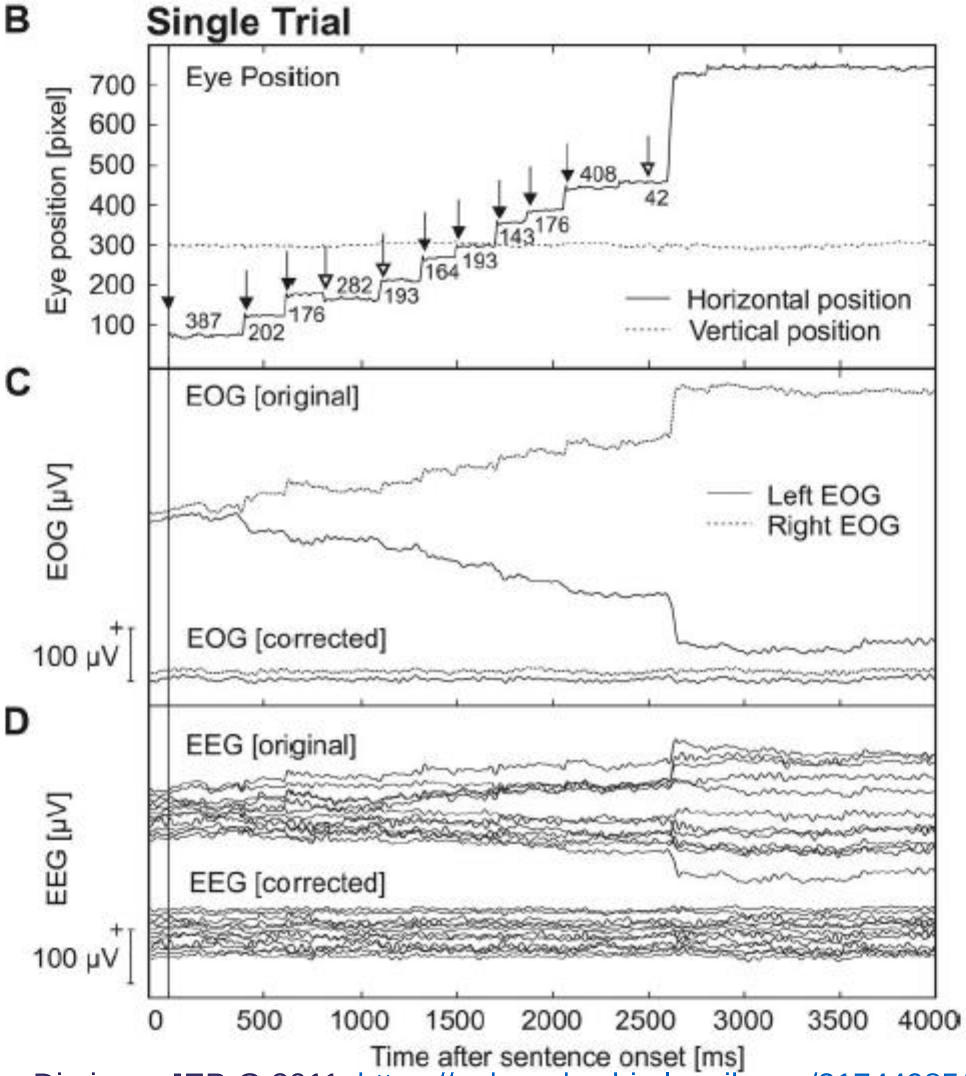


http://www.tqmp.org/Content/vol06-1/p031/p031.pdf

Tricky Example: Saccade Artefacts







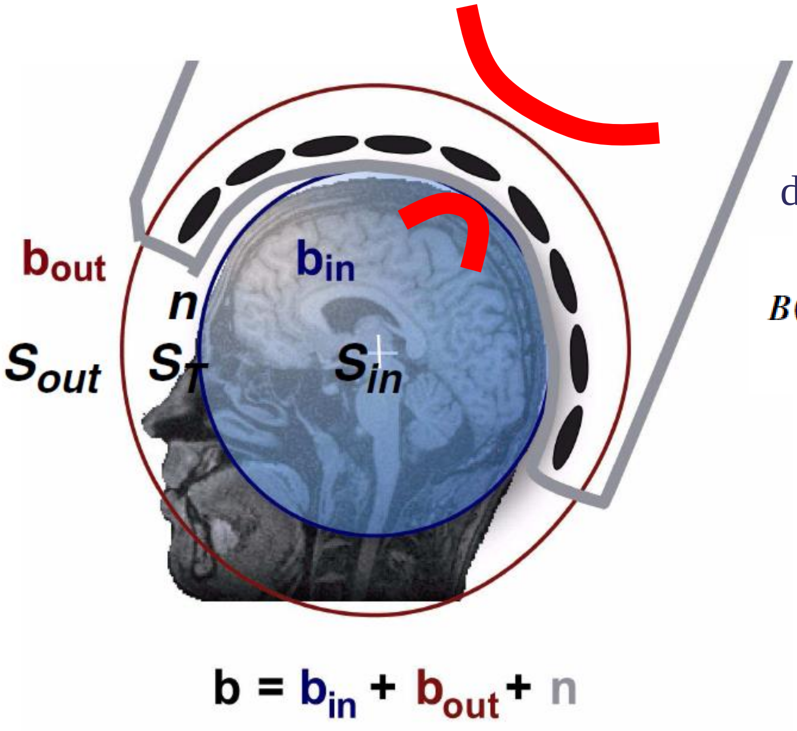
Dimigen, JEP-G 2011, https://pubmed.ncbi.nlm.nih.gov/21744985/

“Optimizing the ICA-based removal of ocular EEG artifacts from free viewing experiments”

Dimigen, Neuroimage 2020, https://www.sciencedirect.com/science/article/pii/S1053811919307086

“Maxfilter” – Maxwell Filtering

Suppressing Signals From Distant Sources (MEG only)



The mathematical basis of Maxfilter:

decomposition of magnetic fields into spherical harmonics

$$B(r) = -\mu_o \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \alpha_{nm} \frac{\nu_{nm}(\theta, \varphi)}{r^{n+2}} - \mu_o \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \beta_{nm} r^{n-1} \omega_{nm}(\theta, \varphi).$$

$$\nu_{nm}(\theta, \varphi) = -(n+1) Y_{nm} e_r + \frac{\partial Y_{nm}}{\partial \theta} e_\theta + \frac{im Y_{nm}}{\sin\theta} e_\varphi,$$

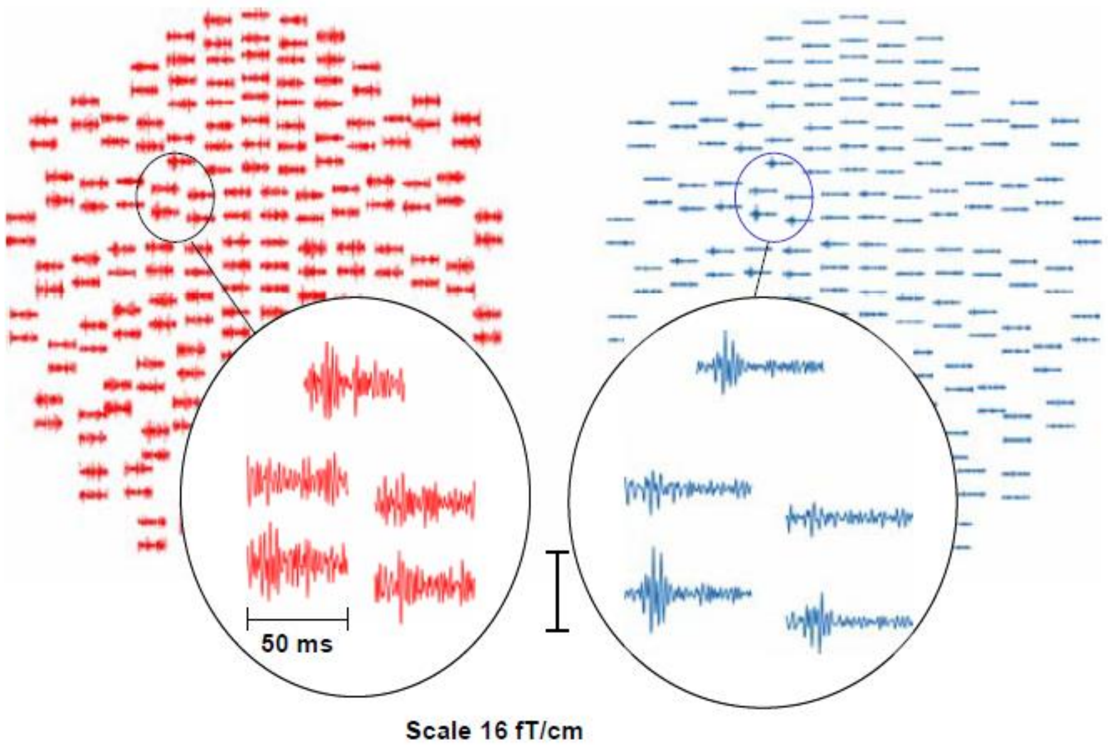
$$\omega_{nm}(\theta, \varphi) = n Y_{nm} e_r + \frac{\partial Y_{nm}}{\partial \theta} e_\theta + \frac{im Y_{nm}}{\sin\theta} e_\varphi,$$

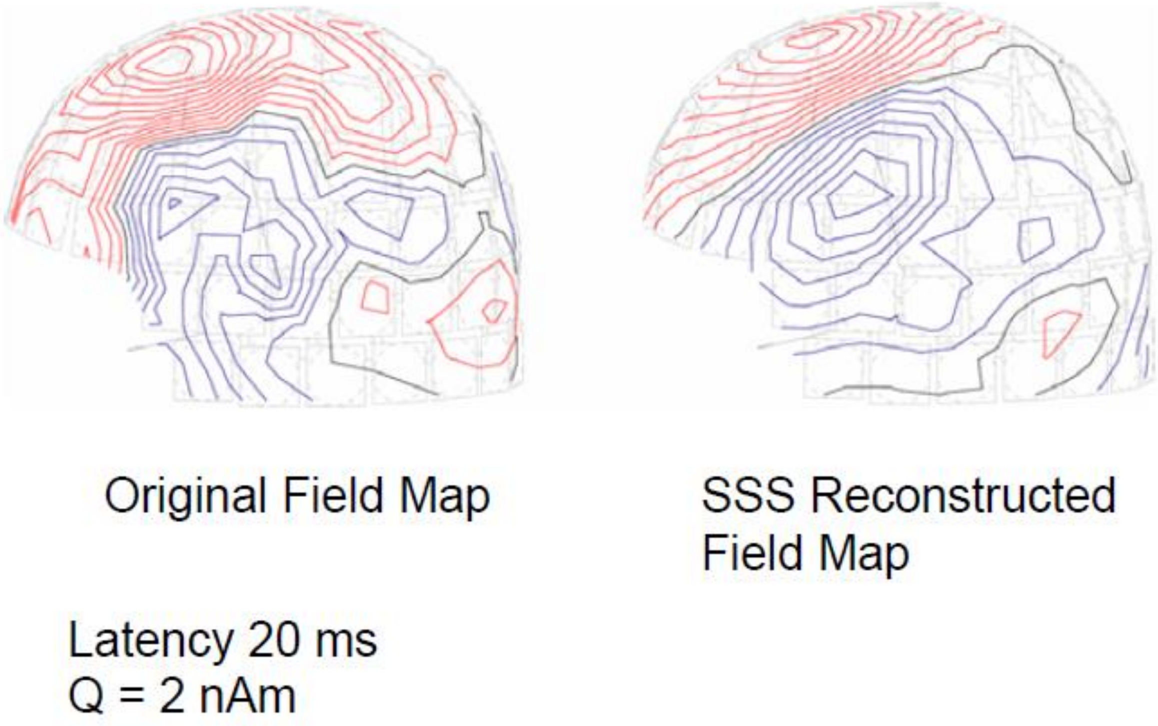
The measured magnetic field distribution is decomposed into “inside” (the helmet) and “outside” components, and the outside components are removed.

Taulu & Kajola, Journal of Applied Physics 2005

Maxfilter – Signal Space Separation (SSS)

Without | With | Without | With





Taulu & Kajola, Journal of Applied Physics 2005

Maxfilter Software

Software shielding (Signal Space Separation, SSS)
By subtracting the outer SSS components from measured signals, the program suppresses artifacts from distance sources.

Automated detection of bad channels
By comparing the reconstructed sum with measured signals, the program can automatically detect if there are MEG channels with bad data that need to be excluded from Maxwell-filtering.

Spatio-temporal suppression of artifacts ("-st")
By correlation the time courses of SSS artefact components with the cleaned signal, the program can identify and suppress further artefacts that arise close to the sensor array.

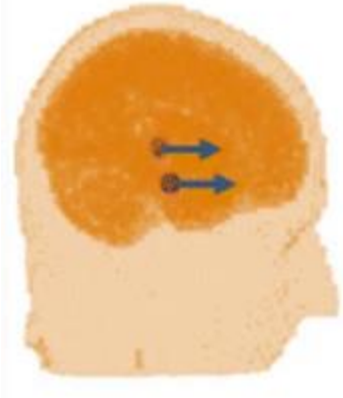
Notch Filter to remove 50/60 Hz line noise.

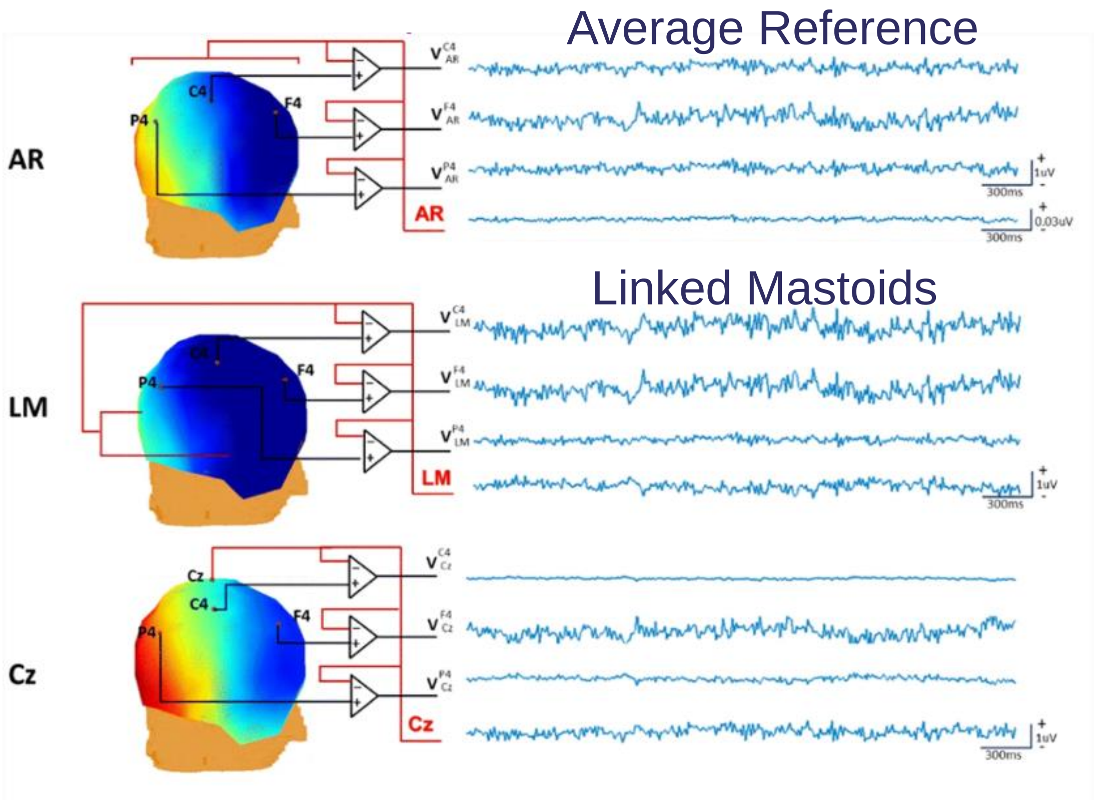
Transformation of MEG data between different head positions ("-trans")
By transforming the inner components into harmonic amplitudes (i.e. virtual channels), MEG signals in a different head position can be estimated easily.

Compensation of disturbances caused by head movements ("-movecomp")
By extracting head position indicator (HPI) signals applied continuously during a measurement, the data transformation capability is utilized to estimate the corresponding MEG signals in a static reference head position.

EEG only: Choice of reference site

Data from
two simulated dipoles





The choice of reference changes time course and topography. For high-density recordings (> 65 channels), average reference is recommended. Note: Source estimates do not depend on the reference.

Yao et al., Brain Topography 2019

Thank you