The effects of data filtering on automated ICA classifiers, ERP and multivariate analyses

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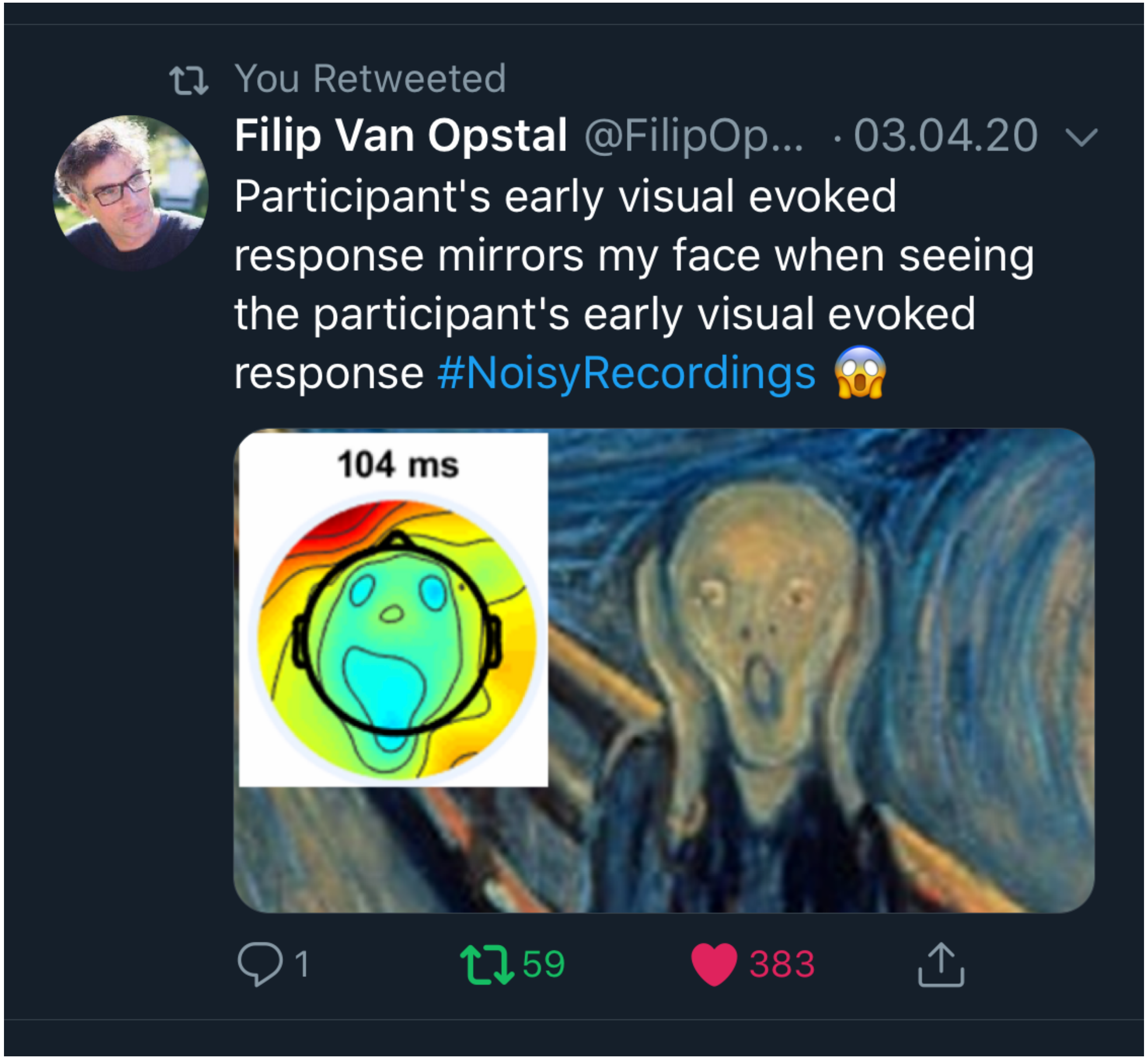
OHBM Educational Course, Virtual Conference June 23rd – July 3rd 2020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Filip Van Opstal @FilipOp... · 03.04.20
Participant's early visual evoked response mirrors my face when seeing the participant's early visual evoked response #NoisyRecordings 😱
104 ms
1
59
383

Overview

- Why do we need to filter?
- Terminology of filters
    - High-pass / low-pass / band-pass / band-stop
    - Filter parameters
        - Cutoff frequencies
        - Roll-off
        - Ripple
        - Delay
        - Non-causal vs. causal filters
        - Finite vs. Infinite Impulse Response (FIR, IIR)
- Effects of low-pass and high-pass filters on ERP analyses
- Interaction of baseline correction and high-pass filters
- Effects of filters on automated ICA classifiers (MARA, IC Label)
- Effects of filters on multivariate analyses
- Standardized preprocessing (Automagic)
- Take home message

Why do we need to filter?

- Artifacts from many different sources can contaminate EEG data and must be removed

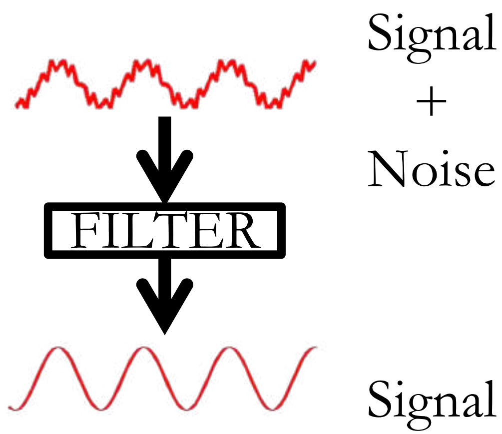
- All EEG analyses require data preprocessing

- Digital filtering is (almost) always used in EEG preprocessing

- Goal: optimize signal-to-noise-ratio (SNR)

- Problem: filtering can produce unintended adverse filter effects and artifacts

- Improve SNR during EEG data acquisition
  - ⇒ proper electrode preparation (lower impedances)
  - ⇒ comfort participants (avoid muscle artifact, sweating, etc.)
  - ⇒ prevention of electromagnetic interference (shielding)
  - ⇒ record sufficient numbers of trials

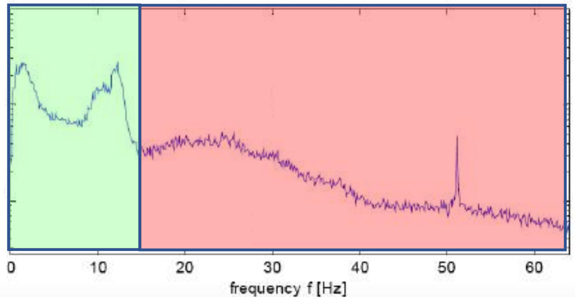


Types of filters

frequency domain response

Low-pass filter

- all frequencies below a defined frequency are passed and all frequencies above this limit are rejected (i.e. attenuating high-frequency bands)



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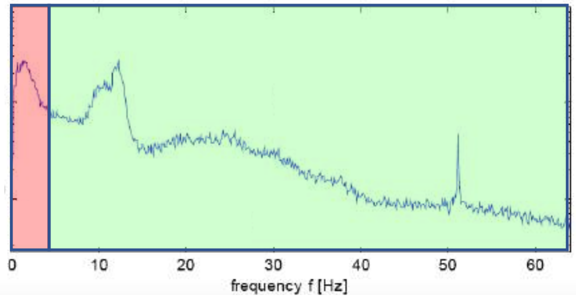
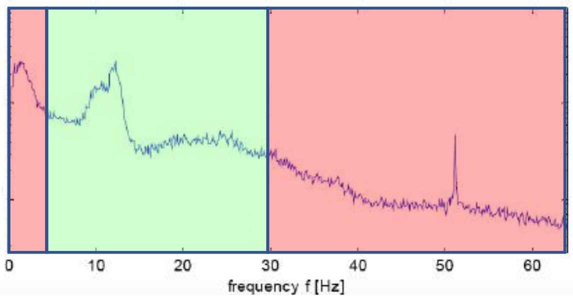


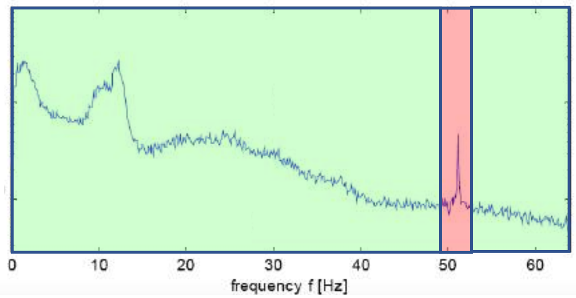
Band-pass filter

- Combine a low-pass and high-pass filter



Notch filter / band-stop filter

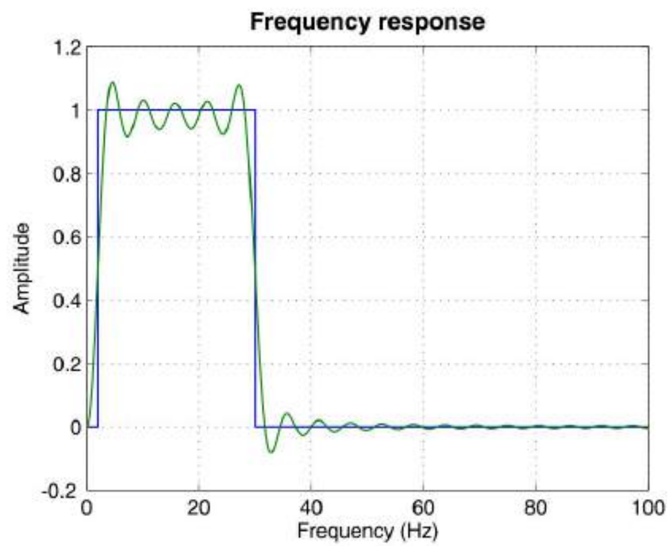
- attenuating specific frequency bands
- in EEG, band-stop filters are almost exclusively used to suppress line noise (50/60 Hz)



Ideal frequency response

Ideal: rectangular window in frequency domain

- Passband
  - Frequencies that are retained
- Stopband
  - Frequencies that are attenuated

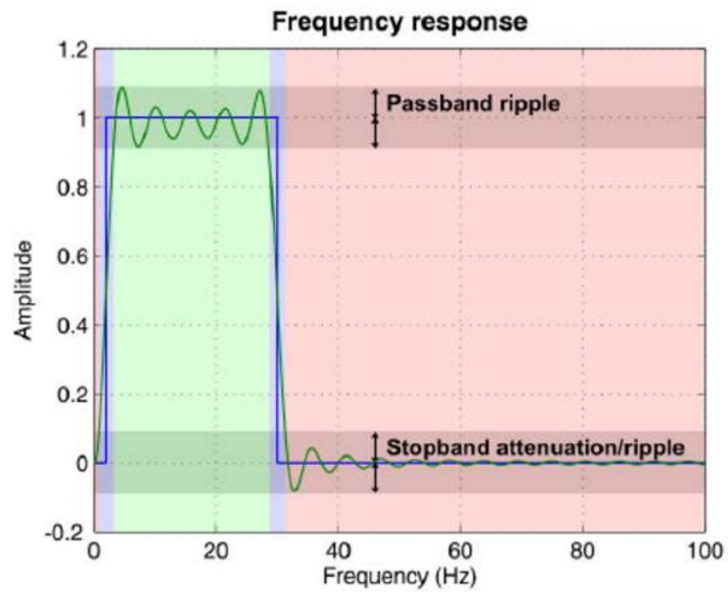


"any abrupt transition in one domain (frequency or temporal) requires an infinite number of components in the other domain"

$\Rightarrow$ the filter would need to be of infinite duration

BUT: finite number of filter coefficients

- Ripples (ringing, Gibbs effect)
  - Deviation from expected frequency response
  - Passband ripple
  - Stopband ripple / stopband attenuation



Widmann et al., 2015

Filter parameters

- Passband (3)
- Stopband (4)

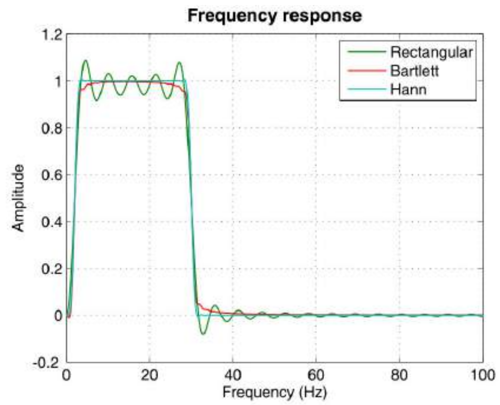
- Transition band width (2)
    - is a function of window type and filter order

- Roll-off / filter order
    - slope of the magnitude response in the transition band
    - narrow transition bands = steep filter roll-off
      wide transition bands = shallow roll-off

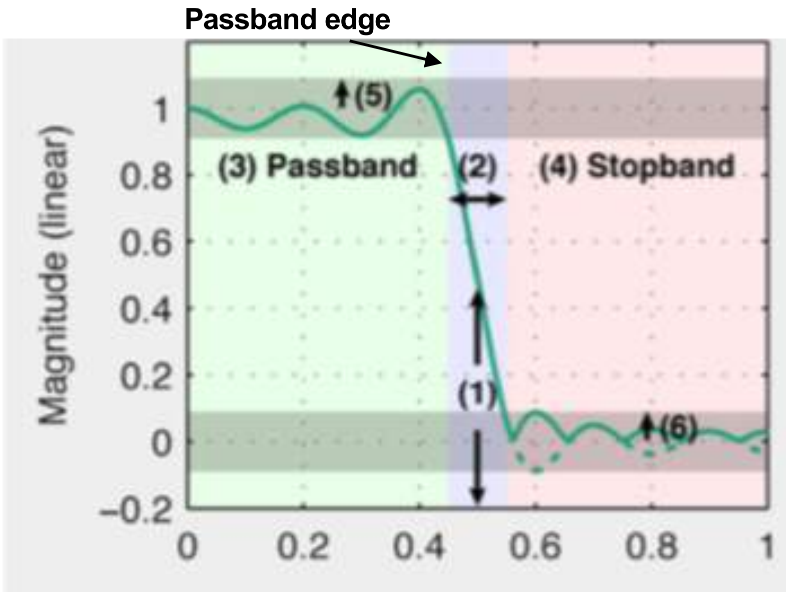
Steep filters produce stronger signal distortions (i.e. wider temporal smearing of distortions and ringing artifacts)

- Cut-off frequency (1)
    - the value that should be reported in a paper
    - for FIR filter: in the center of transition band
    - For FIR filter: half amplitude (–6 dB)
    - For IIR filter: half energy (–3 dB)

Window types



	Max stop-band attenuation (dB)	Max passband ripple	Transition width (normalized freq)
Rectangular	-21	0.00891	0.9/m
Bartlett	-25	0.0562	2.9/m
Hann	-44	0.0663	3.3/m
Hamming	-53	0.0022	5.5/m
Blackman	-74	0.0002	3.6/m
Kaiser	-60	0.001	5.0/m

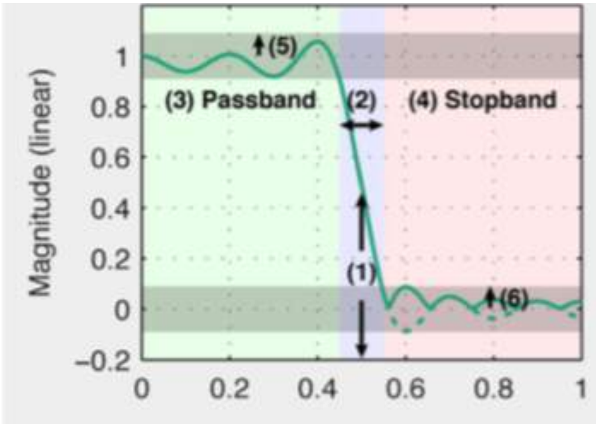


magnitude response (filter gain) for low-pass filter
Passband ripple (5) Stopband attenuation (6)

How the effects of filters are measured: filter responses

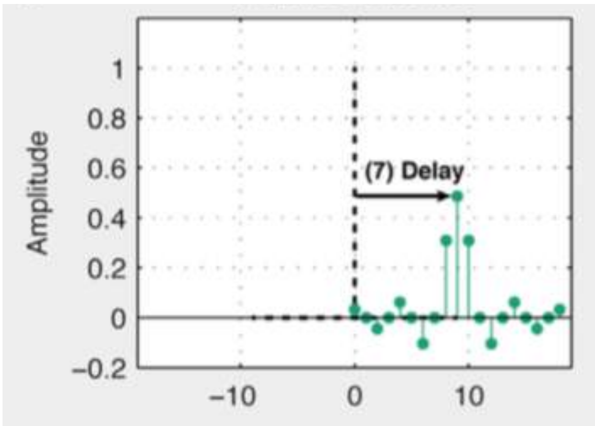
Frequency domain responses

Magnitude response (filter gain)

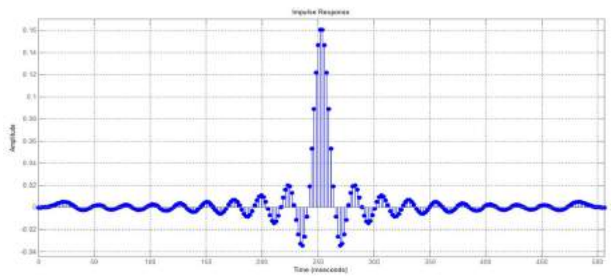


Time domain responses

Impulse response



Low-pass filter



low-pass and high-pass filters smear the signal in the time domain

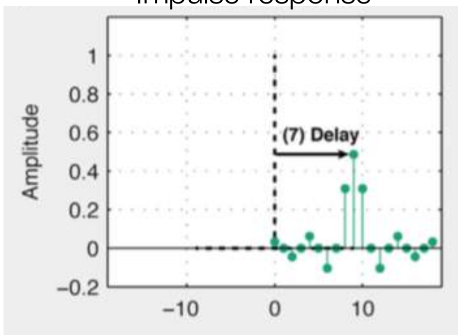
Widmann et al., 2015

Other filter parameters

Zero-phase[1] filters (non-causal filters)

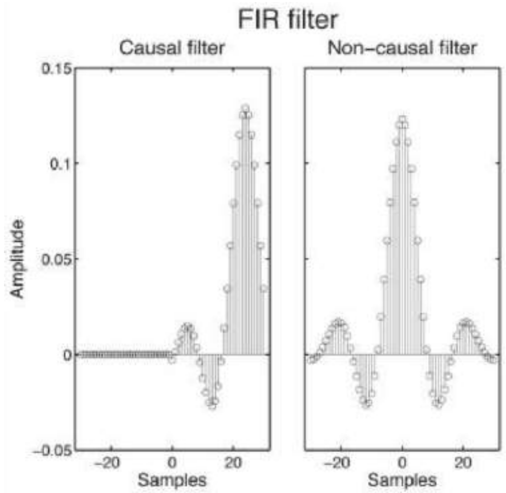
- Zero-phase: every frequency is delayed by the same amount
- Non-causal: output signal is computed from preceding (past) and following (future) samples
  - ⇒ introduce a symmetric change in the signal around a step
- Non-causal filters might smear the signal of interest (ERP) into the baseline interval (see baseline correction discussion)

Impulse response



Minimum phase[1] filters (causal filter)

- Minimum phase: introduce different delays in different frequency bands.
  - ⇒ disturb cross-frequency phase relationships. Problematic for phase-phase or phase-amplitude coupling in time-frequency analysis
- Causal filter computes the filter in the forward direction.
  - ⇒ A causal filter can be preferable in some specific cases (as causal filter don't smear effects back in time)



Impulse response

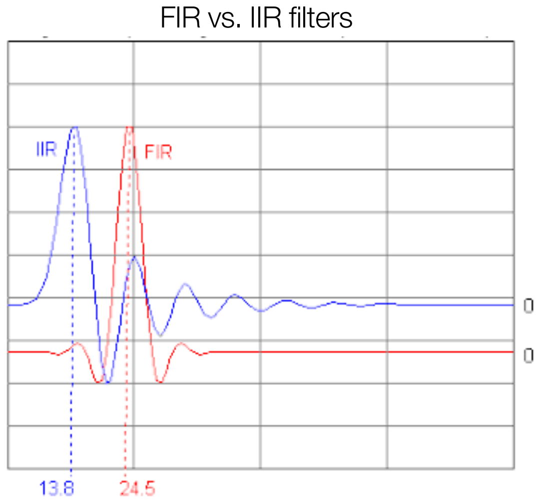
most filters are either zero-phase + non-causal OR minimum-phase + causal

[1] zero phase = linear phase; minimum phase = non-linear phase

FIR vs. IIR filters

Finite Impulse Response (FIR filter):

- impulse response for a finite duration
- typical: Hamming, Kaiser
- “one-pass” (calculated forward only): zero-phase
- easier to control & always stable
- filtering is implemented as convolution (step-wise multiply-add)
- only odd-length FIR filters can be corrected to zero-phase delay
- cutoff frequency is usually specified as half amplitude (–6 dB) cutoff.



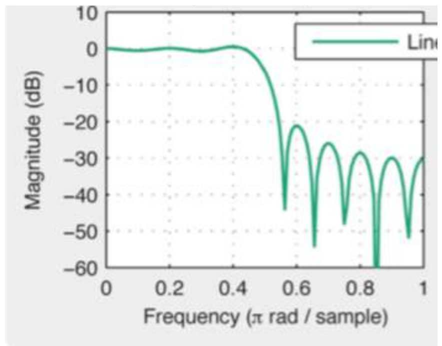
Infinite Impulse Responses (IIR) filters (recursive filters):

- infinite impulse response
- typical: Butterworth, Chebyshev, Elliptic
- asymmetric impulse responses
- if calculated “one-pass”: minimum phase. if “two-pass” (forward and reverse) it is zero-phase
- can be instable (by accumulated rounding errors). IIR filtering should be performed with double precision
- main advantage computationally more efficient (and higher throughput). Thus, frequently preferred for online processing (despite non-linear phase)
- cutoff frequency is usually specified as half energy (–3 dB) cutoff
- IIR filters considered for sharp cutoffs and when a causal filter is needed

FIR filters recommended for most EEG analyses

Widmann et al., 2015

- filter orders of IIR and FIR filters cannot be compared due to the recursive implementation of IIR filters

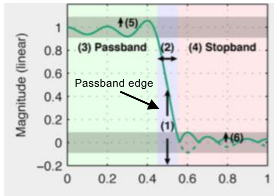


Different definitions of cutoff frequency are used:
- –3 dB (half-energy) cutoff (IIR filters)
- –6 dB (half amplitude) cut-off (FIR filters)

Filters in different EEG software

EEGLab:

- *pop_eegfiltnew* *(default):* non-causal zero phase Hamming-windowed sinc basic FIR filter
    - Importantly, the passband edges are to be specified rather than the cut-off frequencies
- *pop_firws:* other windowed sinc FIR filters available (Kaiser, hann)
    - causal non-linear minimum-phase filters available
- *iirfilt:* (IIR Filter) (available as plugin; elliptic and not Butterworth)



FieldTrip:

- uses a zero-phase (two-pass) Butterworth filter (IIR) as default[1]
- windowed sinc FIR filters available

correct reporting of pop_eegfiltnew:

EEG = pop_eegfiltnew(EEG, 0.1,0);
EEG = pop_eegfiltnew(EEG,0,40);

"0.05 Hz high-pass and 35 Hz low-pass cutoff zero-phase Hamming windowed sinc FIR filters (-6 dB)"

optimally add order & transition band width (is reported in console output)

MNE Python:

- default: hamming non-causal, zero phase FIR filters (IIR available)
- for FIR filters, the lower pass-band edge; for IIR filters, the upper cutoff frequency needs to specified

Brainstorm:

- Low-pass high-pass and band-pass: zero-phase FIR filter (Kaiser window)
- Notch: zero-phase IIR notch filter https://neuroimage.usc.edu/brainstorm/Tutorials/ArtifactsFilter

BrainVision Analyzer:

- zero-phase IIR Butterworth filters of order 2, 4, or 8 (–12, –24, or –48 dB/oct roll-off); zero-phase achieved by applying a filter with half the filter order twice (documentation not found)

[1] see Widmann et al. 2015 for discussion about problems of two-pass filtering (different magnitude outcome for Butterworth IIR filters for different toolboxes; Fig. 3)

Interim Summary

- Sharper filters produce stronger signal distortions (i.e. wider temporal smearing and ringing artifacts). Thus, filters with wider transition bands are preferable where possible

- Low-pass filter: wider transition band can be designed

- High-pass filter: steep high-pass filters are (mostly) needed in ERPs

- Substitute band-pass filter by a separate sharp high-pass and shallow low-pass filter

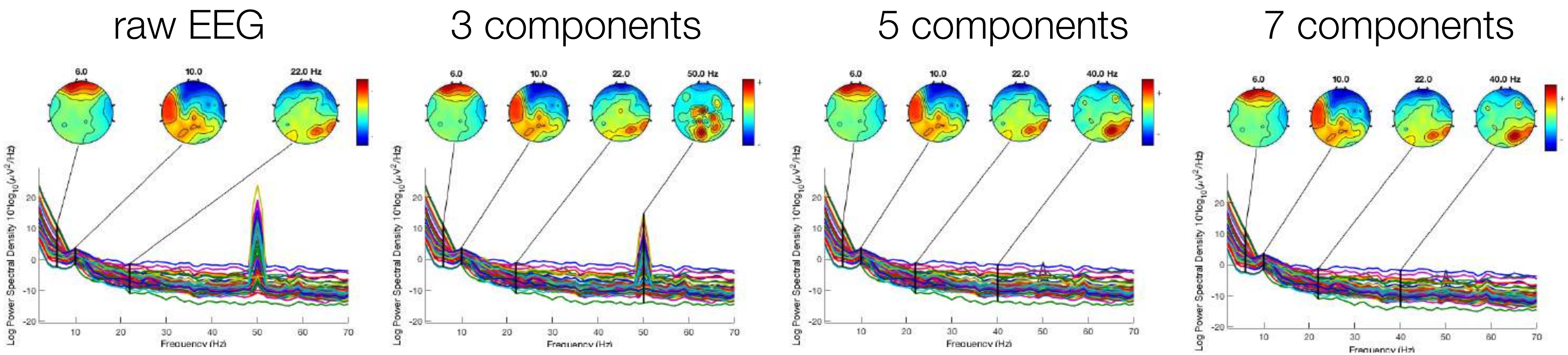
- Notch filter: can produce strong artifacts (see Luck, 2005) & should be replaced by:
  - time domain regression-based approaches (CleanLine) (Mitra and Bokil, 2007, Mullen, 2012)
  - ZapLine (Cheveigné, 2020)

- Report all relevant parameters:

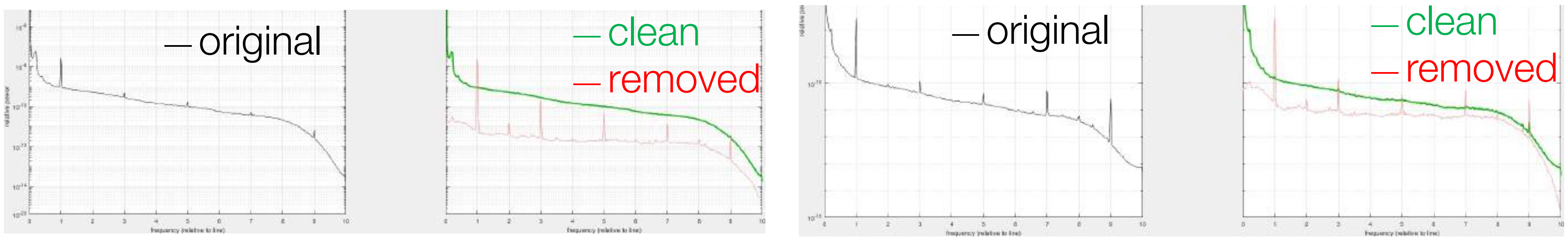
  "0.05 Hz high-pass and 45 Hz low-pass cutoff zero-phase Hamming windowed sinc FIR filters (-6 dB)"

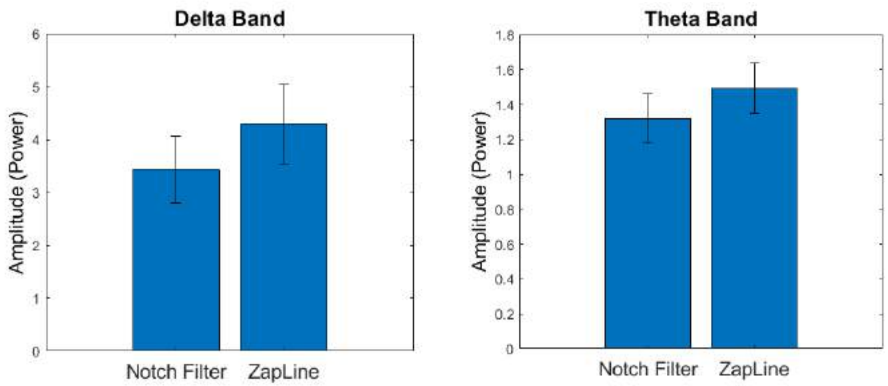
ZapLine – Be cautious

combines benefits of spectral and spatial filtering, minimizes their downsides



The recommended 3 components might not always work => sanity check





Relevant signal is potentially removed (further analyses needed)

https://osf.io/ayhcg/ Cheveigné, 2020

Overview

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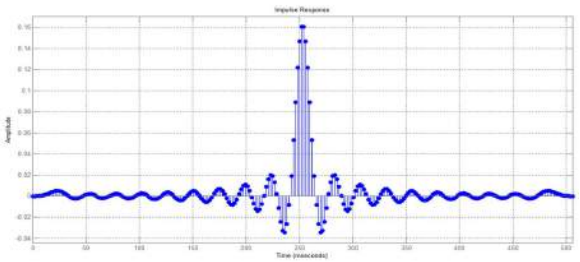
Effects of filters on event related potential (ERP)

"It is important to realize that changes in the frequency spectrum introduced by filtering (i.e. the attenuation of spectral components) must cause changes in the temporal signal, as both representations are coupled by the Fourier transform."

Widmann et al., 2015

Low-pass and high-pass filters (thus also band-pass filter) smear the signal in the time domain

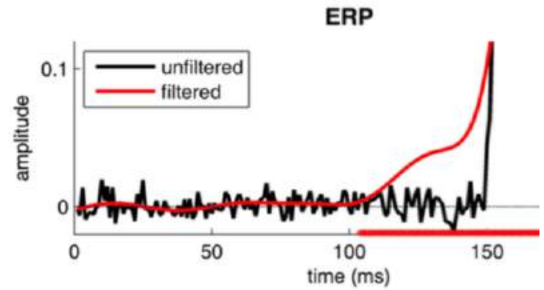


Non-causal low-pass filter

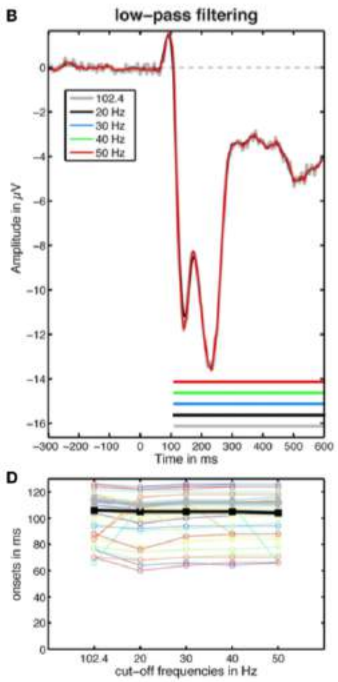
Signal distortion in the time domain also occur if you filter on continuous data!

Effects of low-pass filtering on ERP analyses

- VanRullen study:
  - Simulated data (use of a step function)
  - 30Hz low-pass FIR
  - Smeared data back in time and onset appears to start at 100 ms
  - Conclusion: if low-pass filtered, do not interpret the onsets of ERPs; peak amplitudes and peak latencies ok



- Rousselet study:
  - Real EEG data; 192 face and noise trials using FIR filter
  - low-pass filtering has negligible effects on the onset and time-course on large ERP effects



- Discrepancy because step function is particularly prone to ringing artifacts

- Low amplitude of the higher frequencies in the EEG signal reduces the risk of serious distortion of the ERP waveform when low-pass filters are applied

- Recommendation for ERP analysis: apply (shallow) low-pass filters with cutoff frequencies higher than 40 Hz
  - preserving high-frequency components in the ERPs such as the sharp peak of the short latency components (e.g. P1) (Widmann et al., 2015)

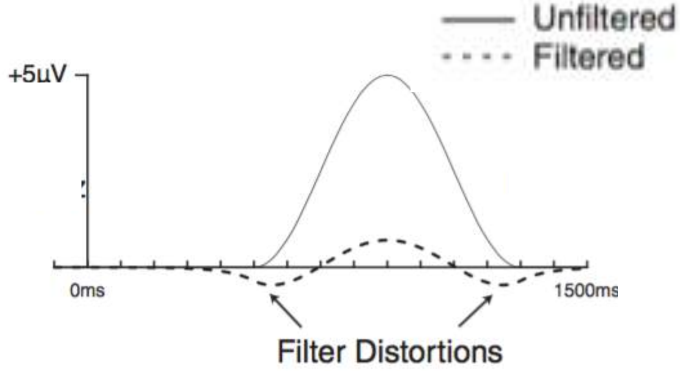
VanRullen, 2011, Rousselet et al., 2011

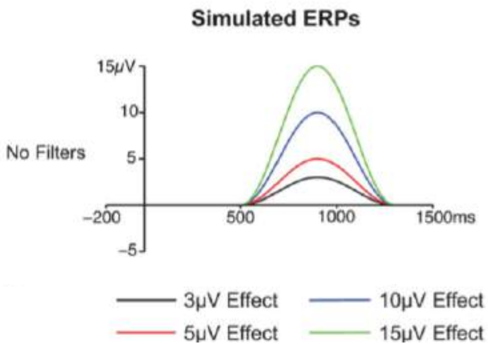
Effects of high-pass filtering on ERP analyses

Many ERP components, in particular slow components (e.g. P300, N400, P600) are affected by high-pass filters

High-pass filters distortion can introduce new peaks into the waveform (“inverted spreading”)

2Hz high-pass filter cut-off 2Hz

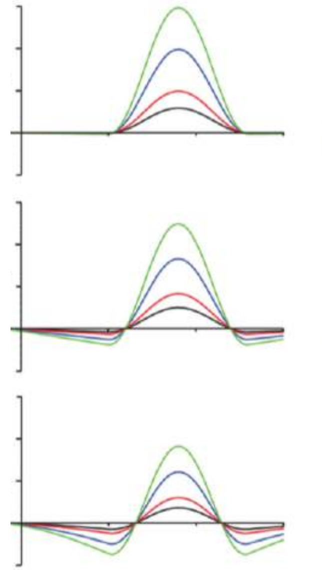




Cut-off: 0.1 Hz

Cut-off: 0.3 Hz

Cut-off: 0.5 Hz



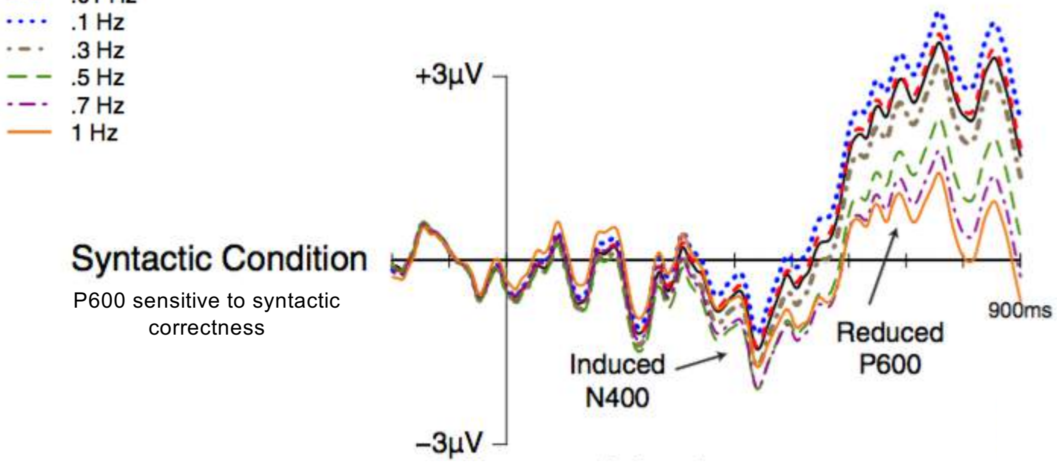
Distortion depends on cut-off of the high-pass filter and the amplitude of the EEG signal

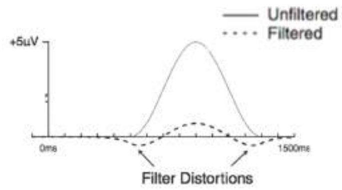
Tanner et al., 2015, Rousselet et al., 2011

Effects of high-pass filtering on ERP analyses

Non-causal
high-pass filters:

ERP difference: syntactic correct – incorrect





High-pass filter ≥ 0.3 Hz induce an
artificially significant effect in N400

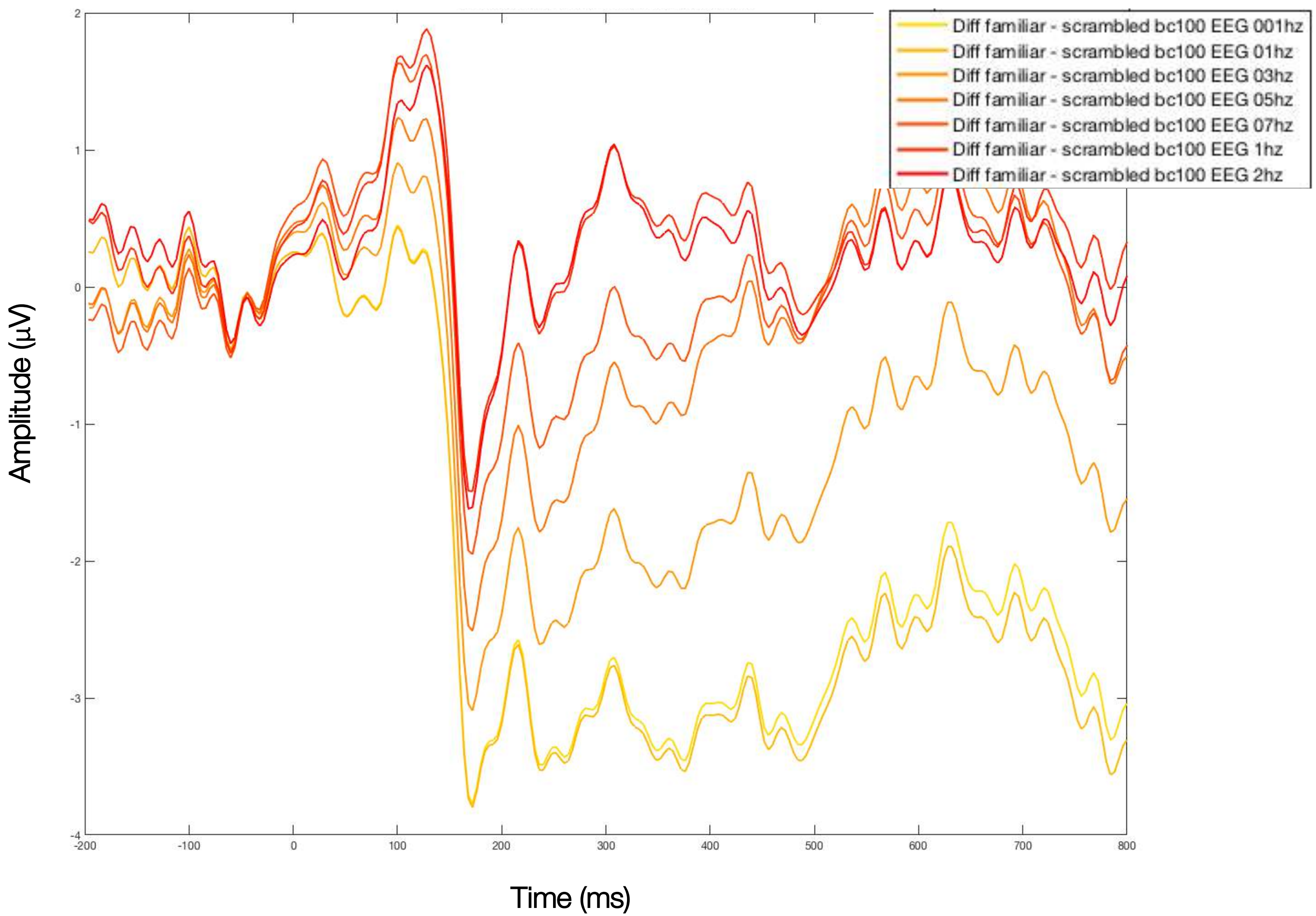
- Potential false conclusions: experimental manipulation is impacting multiple components rather than a single component
- However, low cut-off frequencies (i.e. 0.01 & 0.1 Hz) high-pass filters have only negligible effects on the results

Tanner et al., 2015

Wakeman & Henson (2015) Data Set

Effect of different high-pass filters

Difference ERP “famous faces” – scrambled images



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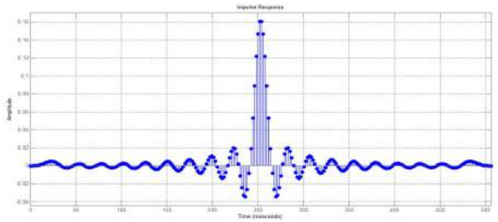
Baseline correction and high-pass filtering

Problems of Baseline Correction:



- (Non-causal) high-pass filters spread post-stimulus effects backward in time, potentially into the baseline interval
- Two conditions may show differences in baseline interval
  (experimental design: systematic preparatory potentials)
- Baseline corrected measures are difference scores!

*no systematic differences" assumption

Comparing two conditions including baseline correction:	$M_1 = P_1 - B_1$ $M_2 = P_2 - B_2$ ➡	$M_2 - M_1 = (P_2 - B_2) - (P_1 - B_1) = (P_2 - P_1) - (B_2 - B_1)$ $if\ B_2 = B_1 \longrightarrow M_2 - M_1 = (P_2 - P_1)$	$Problem\ if\ B_2 \neq B_1$

Extensive Tanner/Luck vs. Maess/Widmann discussion:

- Traditional baseline correction and high-pass filtering suffers many of the same potential pitfalls in terms of artifacts
- Similar tradeoffs: longer baseline intervals and stronger high-pass filters better correct for some types of noise but at increased risk of additional artifacts

Recommendations:

- ERP publication guidelines (Picton et al., 2000): if baseline corrected data are presented, the original ERPs (together with the baseline) must be presented as well
- Include baseline into statistical model (Alday, 2018)

Tanner et al., 2015, Maess et al., 2016, Tanner et al., 2016, Maess et al., 2016, Urbach & Kutas, 2006, Alday, 2018

Regression based baseline correction

Solution: include into statistical analysis

General Linear Model

$$y = \sum_{i \in \text{covariates}} \beta_i x_i + \varepsilon$$

$$y = y_{\text{window}} - y_{\text{baseline}}$$

$$y_{\text{window}} - y_{\text{baseline}} = \sum_{i \in \text{covariates}} \beta_i x_i + \varepsilon$$

$$y_{\text{window}} = \sum_{i \in \text{covariates}} \beta_i x_i + y_{\text{baseline}} + \varepsilon$$

$$y_{\text{window}} = \sum_{i \in \text{covariates}} \beta_i x_i + \bar{x}_{\text{baseline}} + \varepsilon'$$

$$y_{\text{window}} = \beta_0 + \beta_{\text{condition}} x_{\text{condition}} + \beta_{\text{baseline}} x_{\text{baseline}} + \beta_{\text{condition,baseline}} x_{\text{condition}} x_{\text{baseline}} + \varepsilon$$

- Regression based baseline correction explicitly model the influence of the baseline instead of mixing the signals
- Depends not as strongly on the “no systematic differences” assumption
- Does not eliminate the need for appropriate high-pass filtering
- Should be applied on single trial data and regression approaches (e.g. mixed models)

Cyril Pernet mentioned to implement regression based baseline correction in the LIMO EEG pipeline: https://www.hindawi.com/journals/cin/2011/831409/

Alday et al., 2018

Summary: Filtering in ERP analyses

- No general recommendation (data, signal-to-noise ratio (SNR), the noise characteristics, the parameter(s) of interest)
- Goal of filtering:
  - Improve the SNR (i.e. if there is no noise there is no need to filter!)
  - Applied filters must not introduce distortions or artifacts systematically biasing your estimated parameter
- Low-pass filter:
  - Less problematic compared to high-pass filters
  - cutoff frequencies higher than 40 Hz are preferred
- High-pass filter:
  - Lower cut-off values in the range of 0.01-0.05 Hz are preferred
- Detect filter distortions:
  - Systematically explore the effects of filtering (testing different cut-off frequencies) - only in pilot-data
  - Inspect difference between filtered and unfiltered data
- Replace traditional baseline correction with regression-based baseline correction

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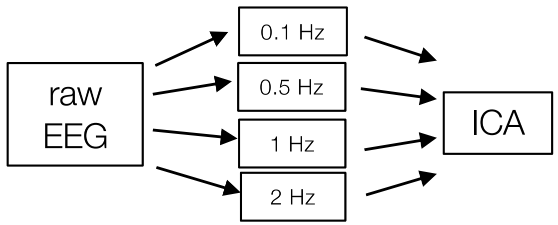
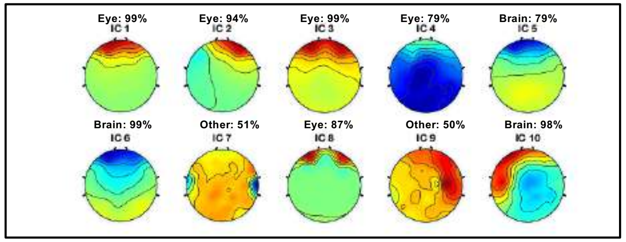
Wakeman & Henson (2015) Data Set

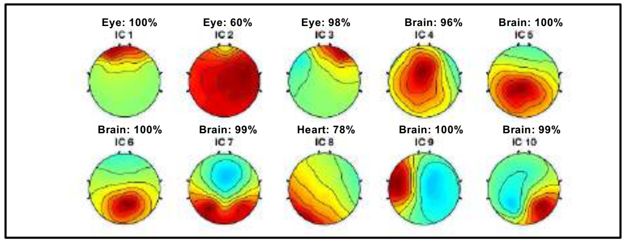
High-pass filter and ICA



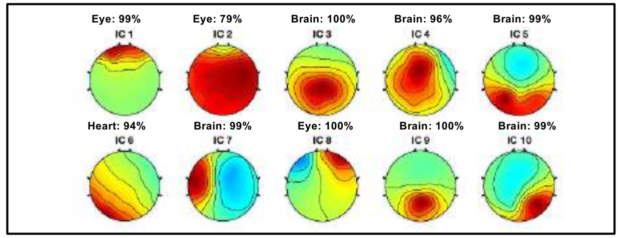
ICA with 0.1 Hz



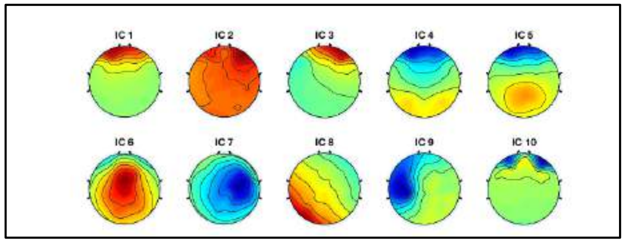
ICA with 1 Hz



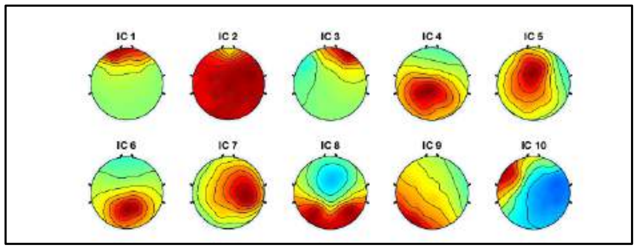
ICA with 2 Hz



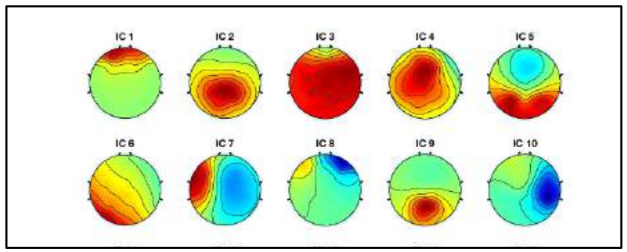
ICA with 0.5 Hz



ICA with 1 Hz high-pass and 45 Hz low pass



ICA with 2 Hz high-pass and 45 Hz low pass



ICA is biased toward high amplitude => low frequencies have most influence on the ICA decomposition results

Recommendation: **Compute ICA on EEG data, which are at least 1 Hz high-pass filtered**

Problem: 1 Hz high-pass filter causes distortion on ERP

Solution: **temporary filtering**

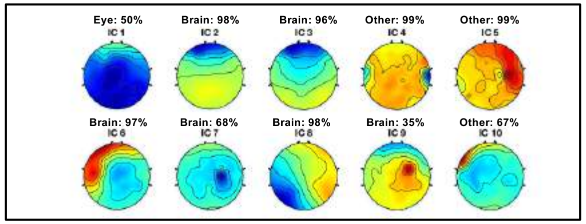
(1. calculate ICA with 1Hz. 2. remove artifactual IC 3. apply ICA weight & sphere matrix of retained IC's to 0.1 Hz high-pass filtered data)

see also: https://sccn.ucsd.edu/wiki/Makoto%27s_preprocessing_pipeline#High-pass_filter_the_data_at_1-Hz_.28for_ICA.2C_ASR.2C_and_CleanLine.29

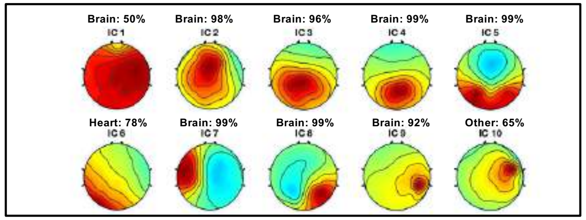
Winkler et al., 2015, Dowding et al. 2015

High-pass filter and ICA artifact removal algorithms (ICLabel & MARA)

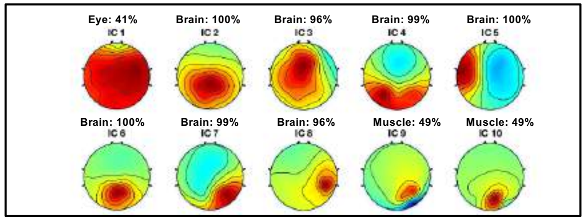
retained IC's with 0.1 Hz



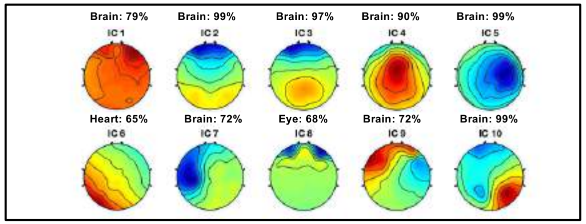
retained IC's with 1 Hz



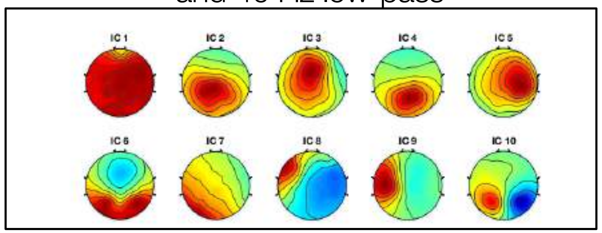
retained IC's with 2 Hz



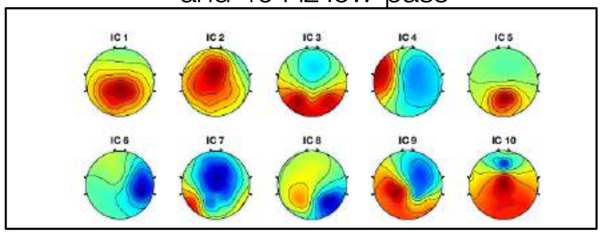
retained IC's with 0.5 Hz



retained IC's with 1 Hz high-pass and 40 Hz low-pass



retained IC's with 2 Hz high-pass and 40 Hz low-pass



Recommendation: Use 2 Hz high-pass and 40 Hz low-pass filtered data for ICLabel (Pion-Tonachini et al., 2019)

Problem: 2 Hz high-pass filter causes distortion on ERP **Solution**: temporary filtering

https://osf.io/ayhcg/

Wakeman & Henson (2015) Data Set

High-pass Filter and ICA artifact removal algorithms (ICLabel & MARA)

raw EEG → **temporary filtering** 2 Hz -40 Hz → ICA → automated artifactual IC removal (ICLabel setting: Muscle, Eye, Heart, Line Noise, Channel Noise, Other, exclude if >80%) → retained ICs

raw EEG → high-pass filtering → 0.1 Hz / 0.5 Hz / 1 Hz

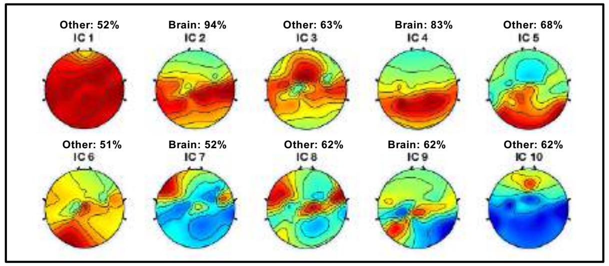
retained ICs → apply ICA weight and sphere matrix → 0.1 Hz / 0.5 Hz / 1 Hz

1 Hz → final ICs

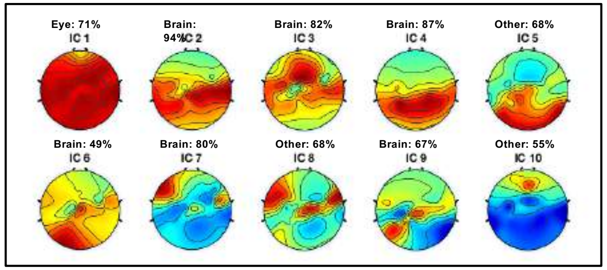
Temporary filtering for IC Label:

1. calculate ICA with 2Hz high-pass and 40 low-pass cut-off filters
2. (automated) removal of artifactual ICs
3. apply ICA weight & sphere matrix of retained IC's to 0.1 Hz high-pass filtered data (*eeg_checkset* function)

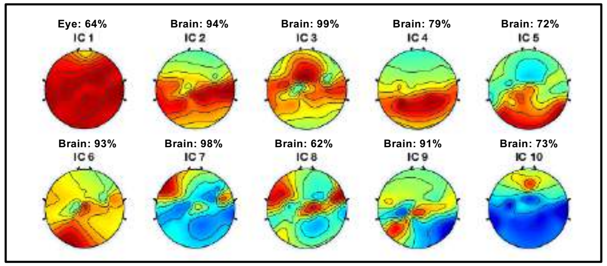
after ICLabel 0.1 Hz (with temp. filtering 2Hz high-pass and 40 Hz low-pass)



after ICLabel 0.5 Hz (with temp. filtering 2Hz high-pass and 40 Hz low-pass)



after ICLabel 1 Hz with temp. filtering 2Hz high-pass and 40 Hz low-pass)



https://osf.io/ayhcg/

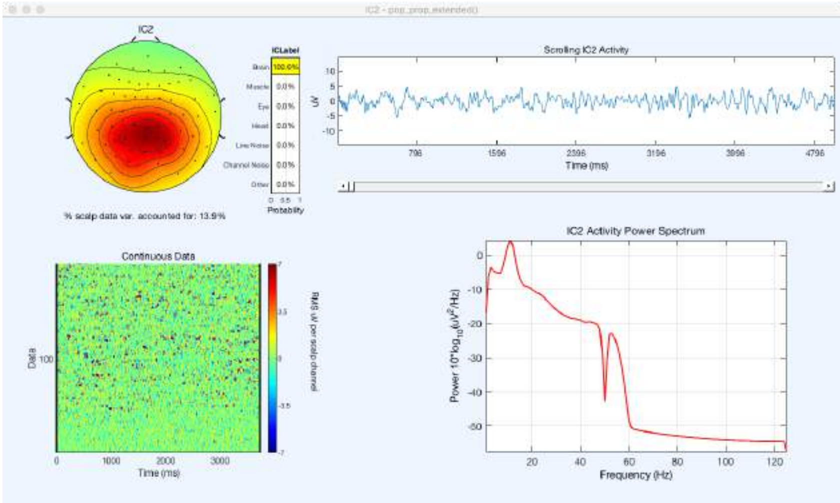
Wakeman & Henson (2015) Data Set

ICLabel

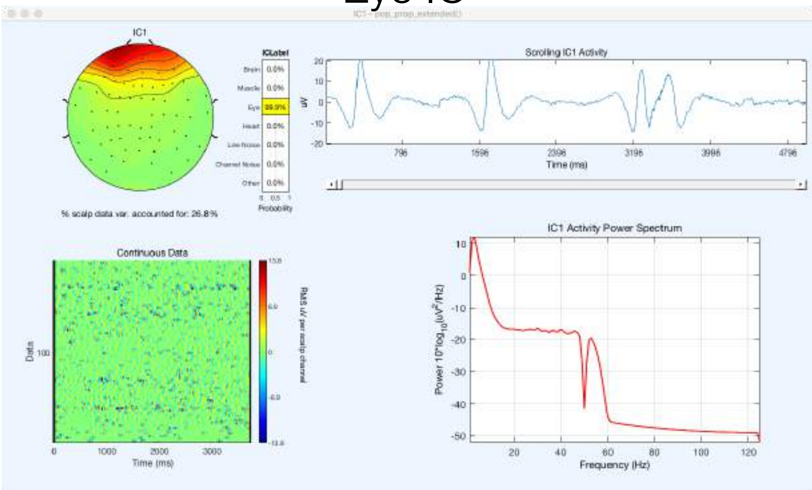
Sanity check: inspect characteristics of ICs

pop_prop_extended()

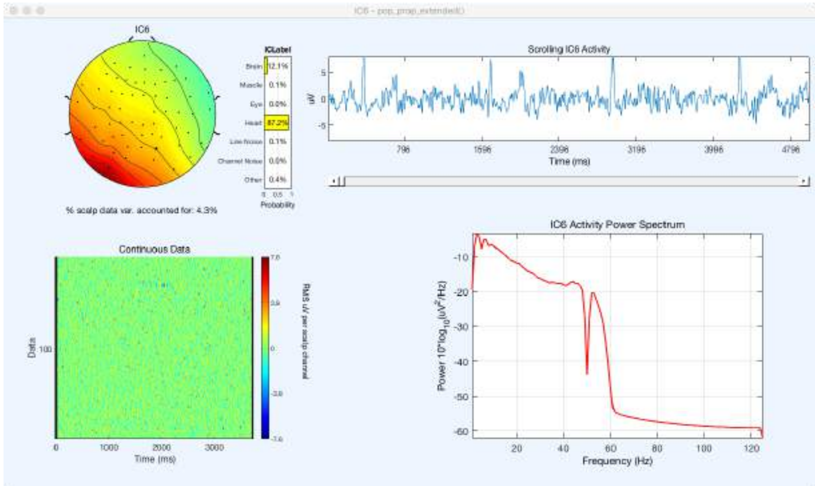
Brain IC



Eye IC

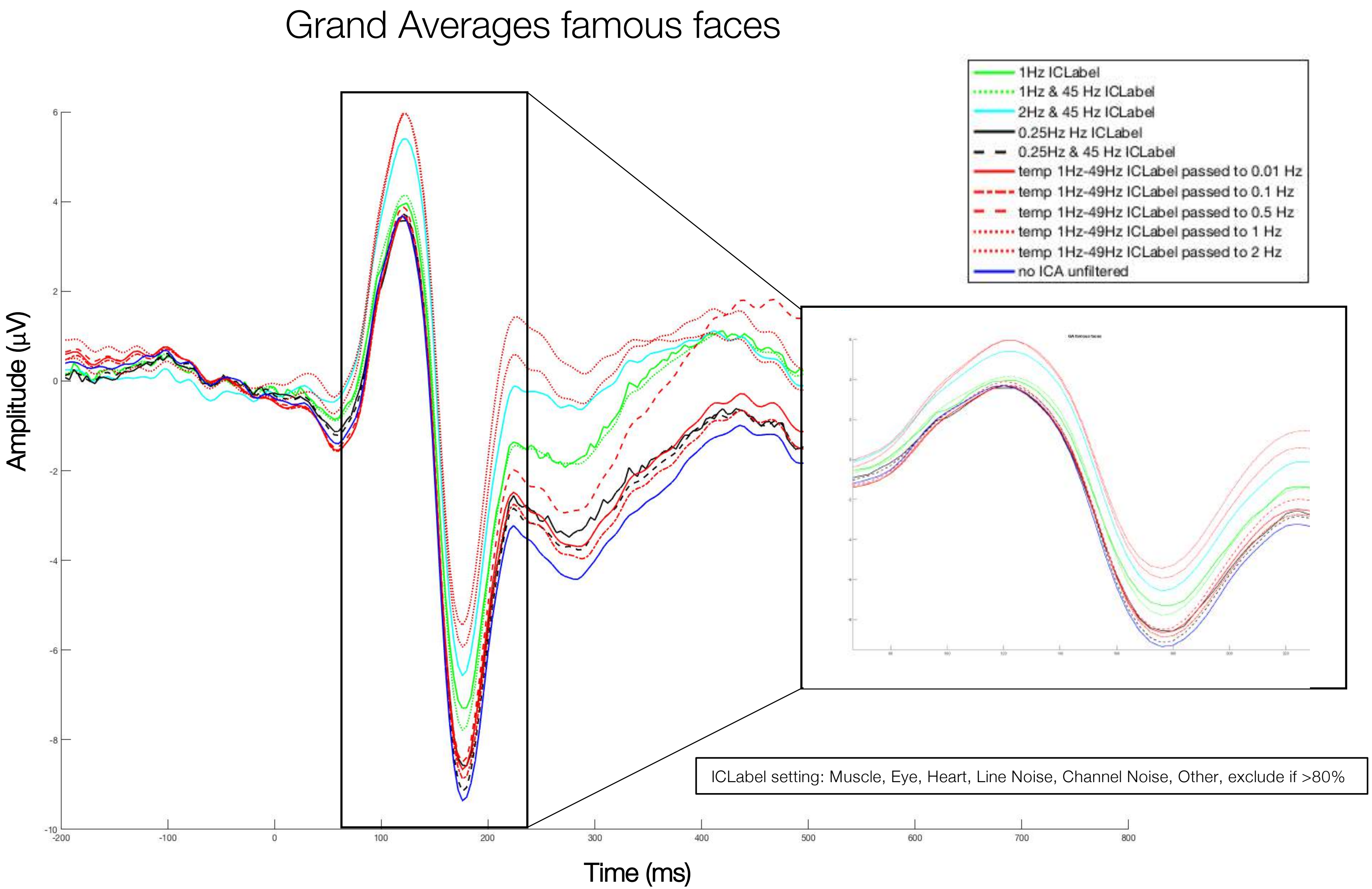


Heart IC



Pion-Tonachini et al., 2019

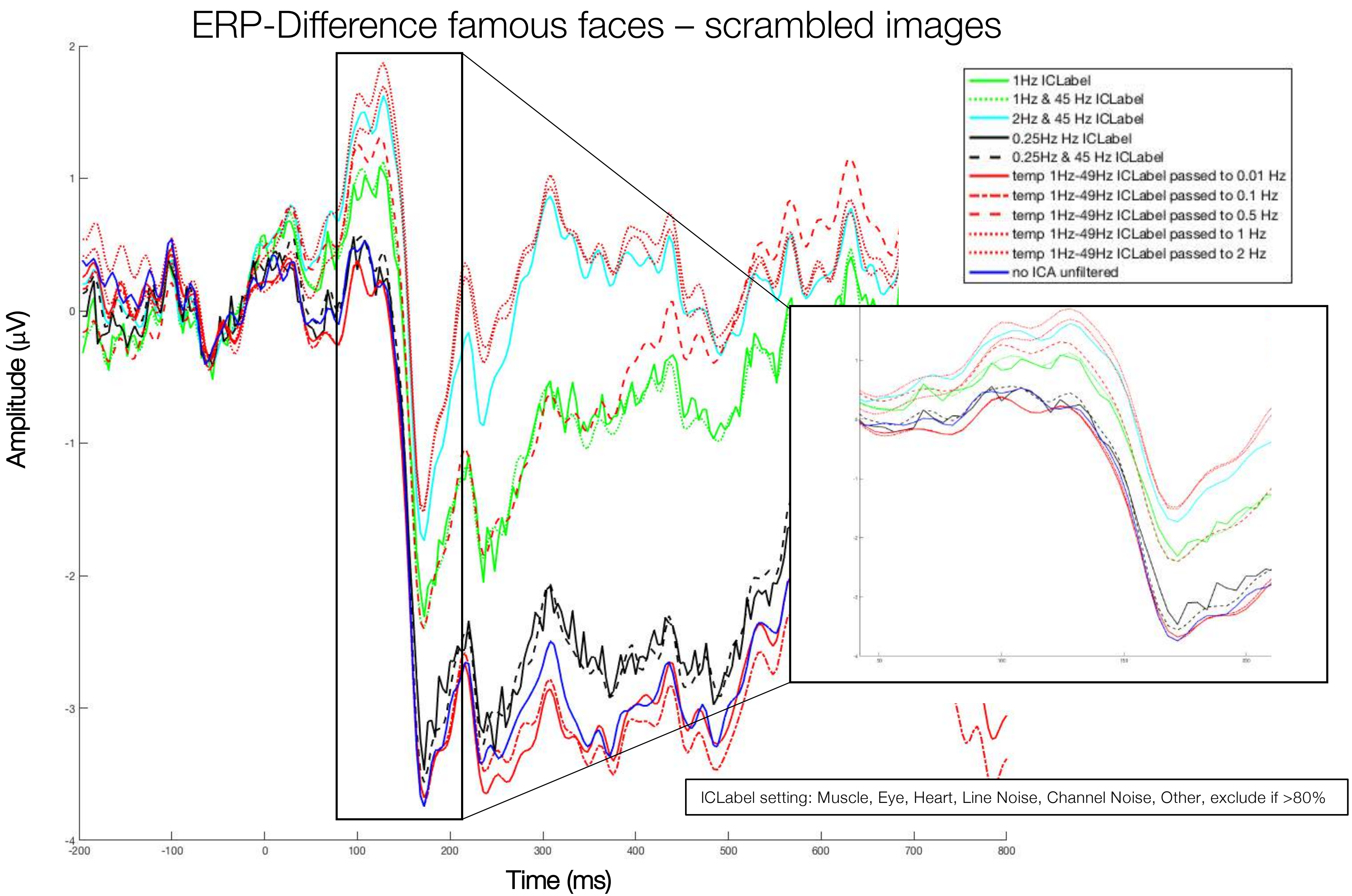
Effects of different high-pass filters on ICA classifiers



https://osf.io/ayhcg/

Wakeman & Henson (2015) Data Set

Effects of different high-pass filters on ICA classifiers



https://osf.io/ayhcg/

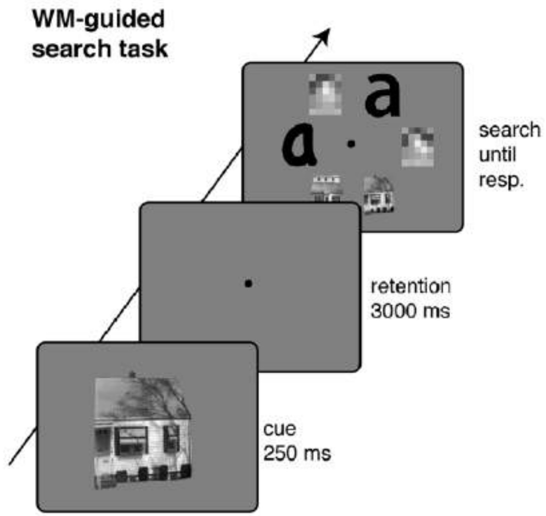
Wakeman & Henson (2015) Data Set

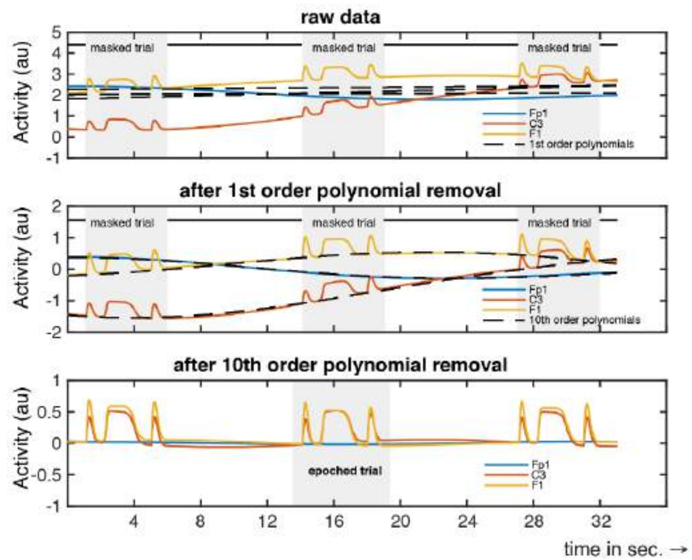
Overview

- Why do we need to filter?
- Terminology of filters
    - High-pass / low-pass / band-pass / band-stop
    - Filter parameters
        - Cutoff frequencies
        - Roll-off
        - Ripple
        - Delay
        - Non-causal vs. causal filters
        - Finite vs. Infinite Impulse Response (FIR, IIR)
- Effects of low-pass and high-pass filters on ERP analyses
- Interaction of baseline correction and high-pass filters
- Effects of filters on automated ICA classifiers (MARA, IC Label)
- **Effects of filters on multivariate analyses**
- Standardized preprocessing (Automagic)
- Take Home Message

High-pass filters and multivariate analyses

- Multivariate pattern classification analyses (MVPA) has become increasingly popular in EEG
- High-pass filtering potentially affects the decoding accuracy
- Particularly problematic in paradigms with long trial durations (e.g. working memory experiments with long retention interval)
- Alternative: robust detrending
  (de Cheveigne & Arzounian, 2018)

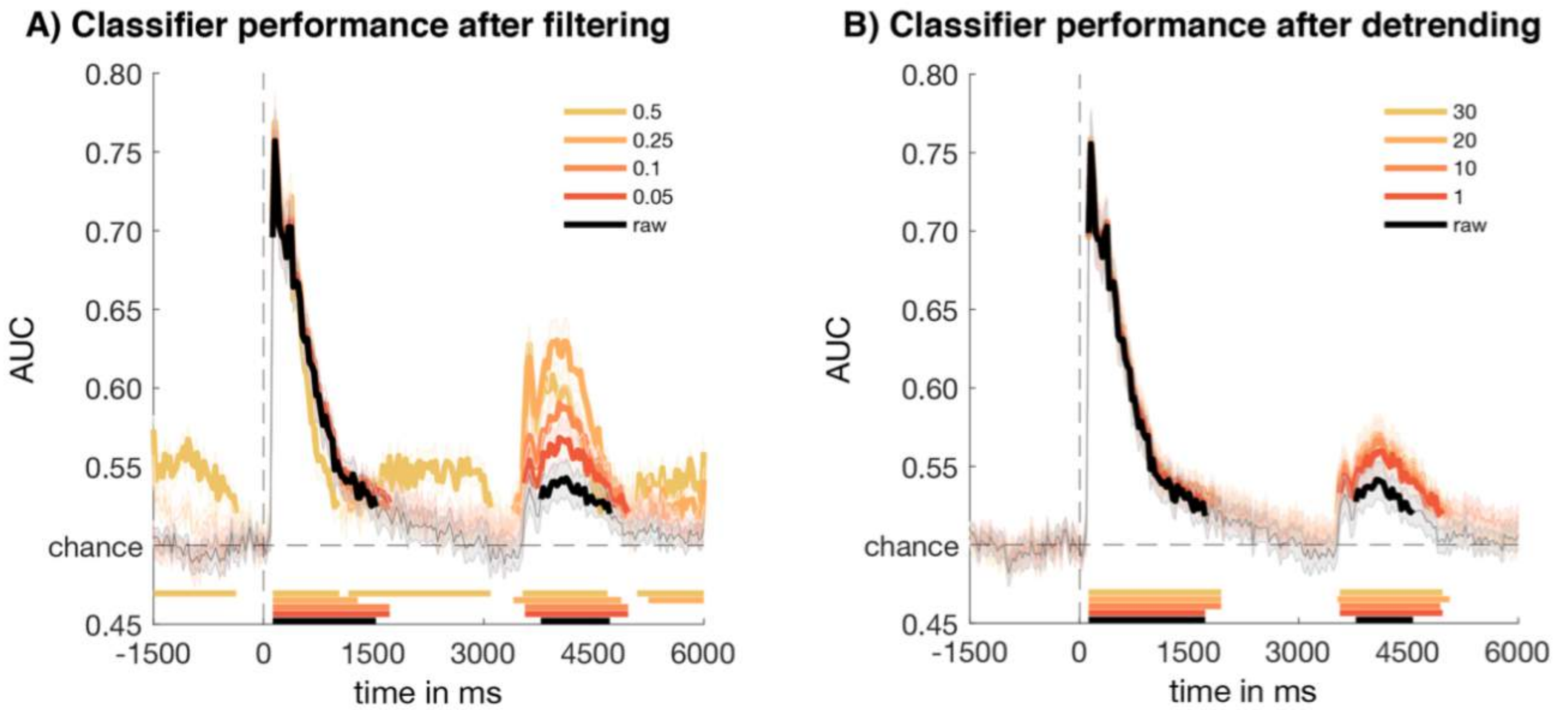




Van Driel et al., 2019

Filters and Multivariate Analyses

Real data



Use high-pass filters with low cut-off frequencies for MVPA analyses

Van Driel et al., 2019

Overview

- Why do we need to filter?
- Terminology of filters
  - High-pass / low-pass / band-pass / band-stop
  - Filter parameters
    - Cutoff frequencies
    - Roll-off
    - Ripple
    - Delay
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- Effects of low-pass and high-pass filters on ERP analyses
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- Effects of filters on automated ICA classifiers (MARA, IC Label)
- Effects of filters on multivariate analyses
- **Standardized preprocessing (Automagic)**
- Take home message

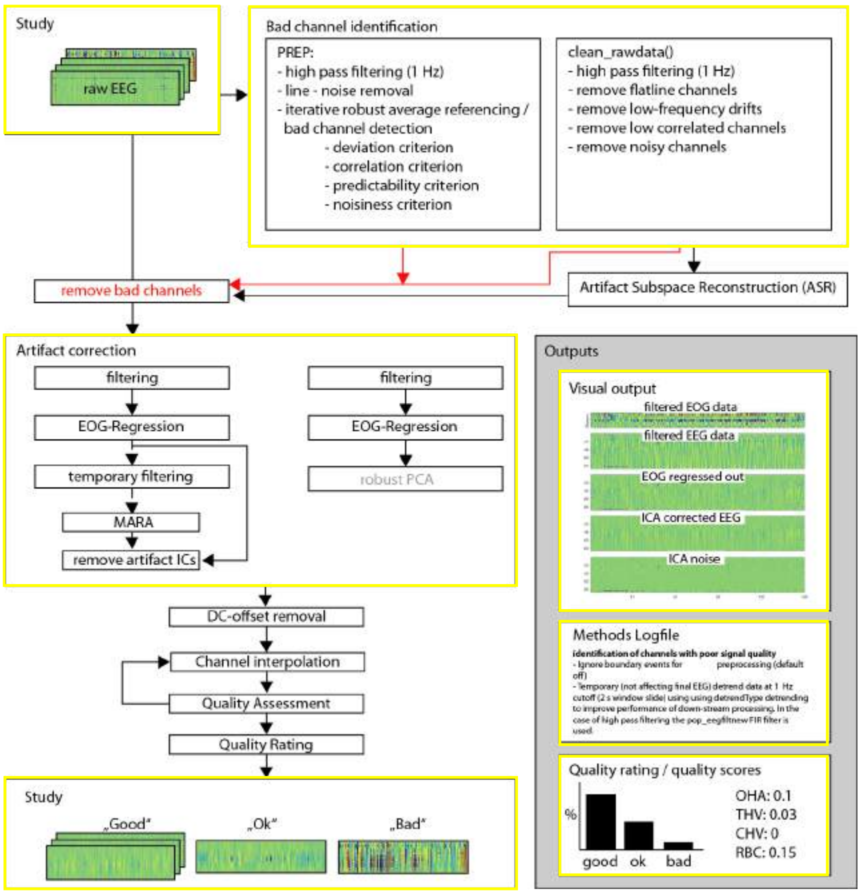
Automagic: Standardized preprocessing toolbox

For small and large scale (growing) studies

Implemented Features:

- Bad channel detection
    - on temporary filtered data
    - PREP (Bigdely-Shamlo et al., 2015)
    - clean_rawdata (Kothe & Makeig, 2013)
- Different types of filters available
    - Low-, high-pass, notch filters (EEGLab)
    - ZapLine (Cheveigné, 2020)
    - CleanLine (Mullen et al., 2012)
- Artifact correction
    - Automated ICA classification
        - MARA (Winkler et al., 2011)
        - ICLabel (Pion-Tonachini et al., 2019)
    - EOG regression (Parra et al., 2005)
    - Robust PCA (Lin et al., 2010)
- Quality Assessment and Rating
- Data visualization (Quality Control)
- Methods Logfile
- BIDS compatible
- available as EEGLab plugin

Workflow Automagic



https://github.com/methlabUZH/automagic

Wiki: https://github.com/methlabUZH/automagic/wiki

Pedroni et al., 2019

Take Home Message

- Filtering results in distortions of the temporal dynamics of the signal
  - ⇒ ERP analysis: high-pass filters systematically bias signal onset latencies and signal amplitudes
  - ⇒ for MVPA analysis: high-pass filters potentially affects the decoding accuracy

- Filter as little as possible
  - ⇒ often not feasible (data contaminated by artifacts) and required (e.g. for ICA decomposition)

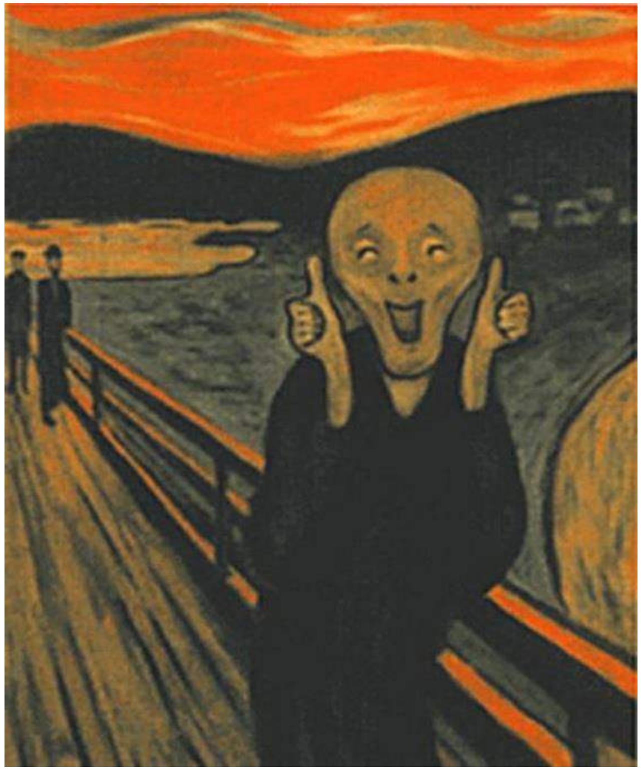
- If filtering is required
  - ⇒ sharp high-pass filter between 0.01 and 0.1 Hz are recommended
  - ⇒ substitute band-pass filters (successive shallow low-pass and sharp high-pass filters)
  - ⇒ substitute notch filter (CleanLine, ZapLine)
  - ⇒ filters should be applied to continuous EEG data, not epoched EEG or averaged ERPs
  - ⇒ systematic comparison (e.g. grand average) of data filtered with different filter parameters (on pilot data)
  - ⇒ Regression-based baseline correction

- Consider temporary filtering (for bad channel detection and ICA automated classifiers)

- Report correct accurate filter parameters & report quality measures (Automagic)

> "Filters are like sharp knives – a very useful tool but to be handled with care"
>
> Widmann et al., 2015

THANK YOU FOR YOUR ATTENTION



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