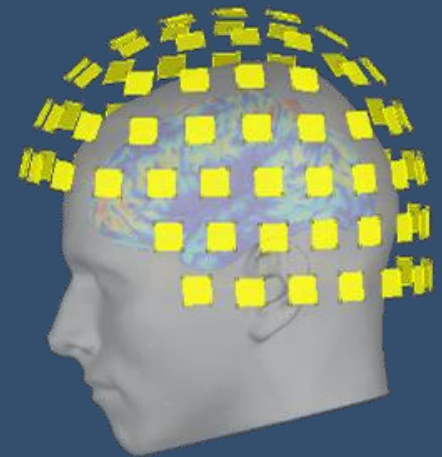


MEG and EEG analysis using
Brainstorm
<http://neuroimage.usc.edu/brainstorm>



Cutting
Gardens



USC University of
Southern California
USC Viterbi
School of Engineering

LOS ANGELES GARDEN



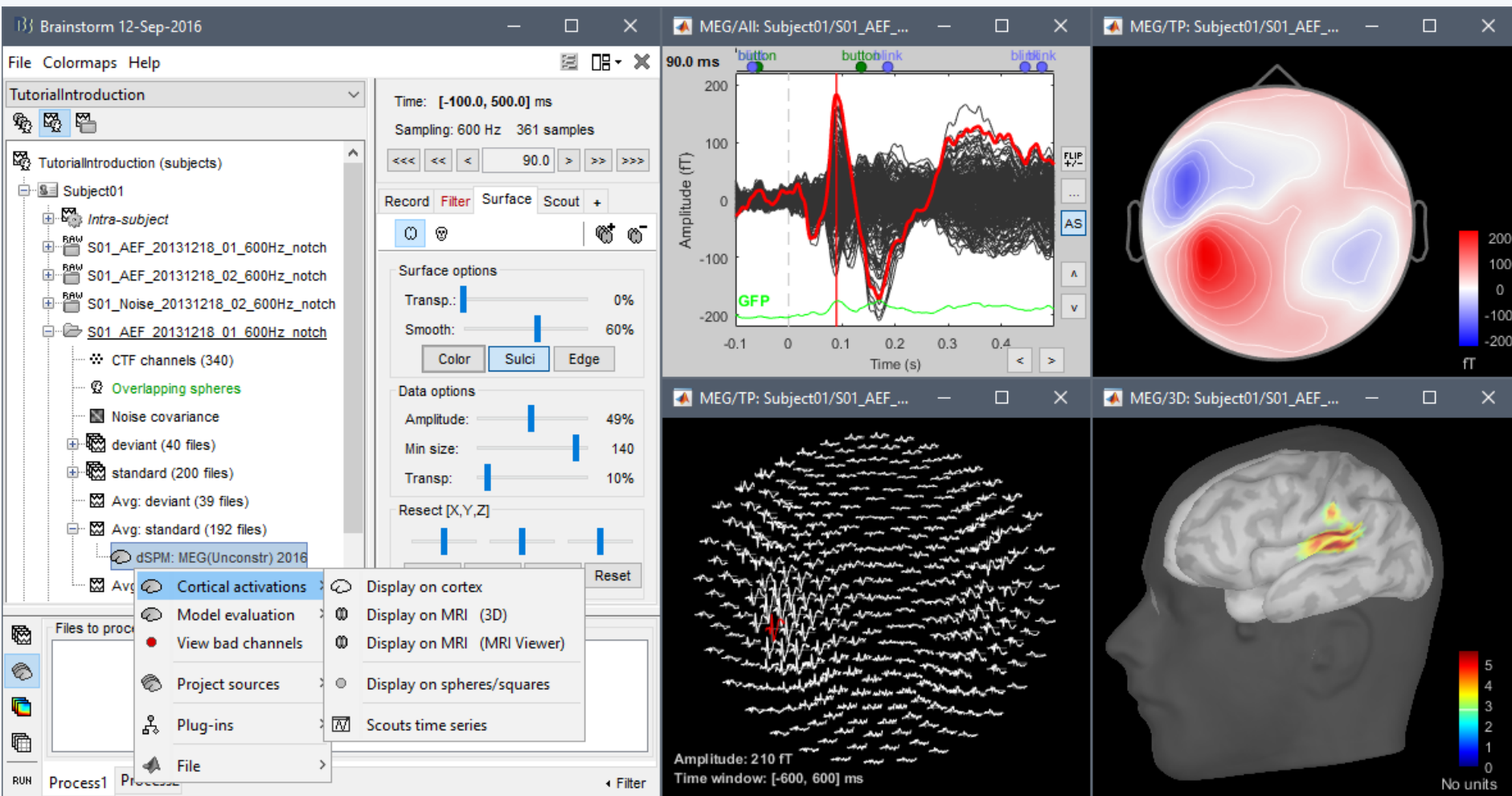
October 2023

Brainstorm

- Free and open-source application
- Matlab & Java: Platform-independent
- Designed for Matlab
- Stand-alone version available
- Interface-based: click, drag, drop
- No programming experience required
- Daily updates of the software
- Supports most common file formats

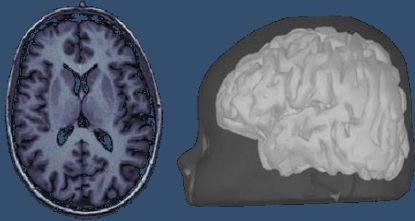


Graphic interface

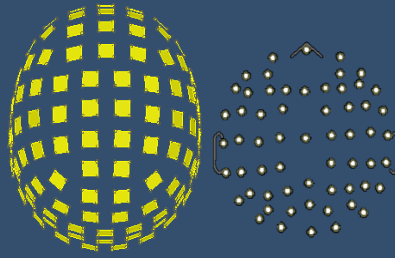


Workflow

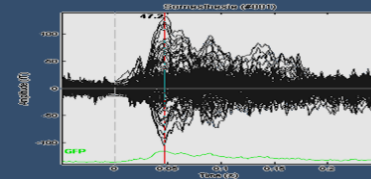
Anatomy



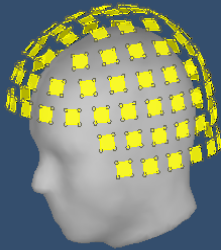
Sensors



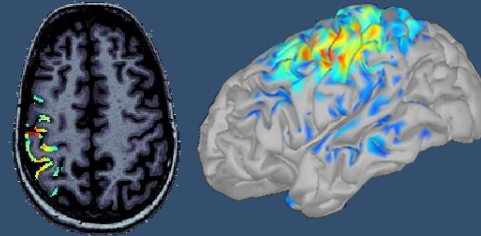
EEG/MEG



Co-registration



Source estimation



Analysis

Averages
Contrasts
Group analysis
Time-frequency
Connectivity

Single subject

Anatomy
Link recordings
MRI registration

Importing

PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

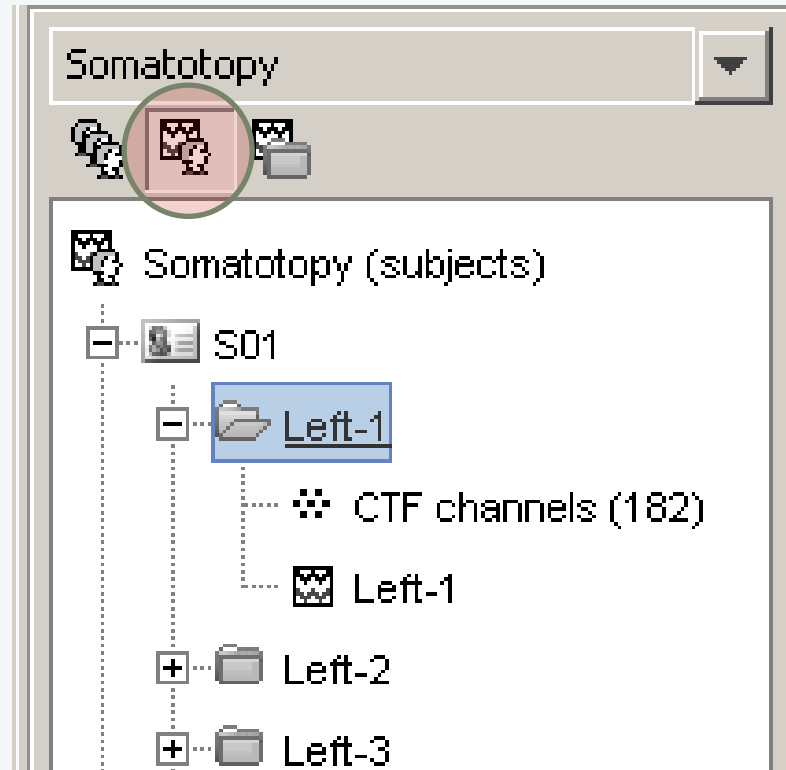
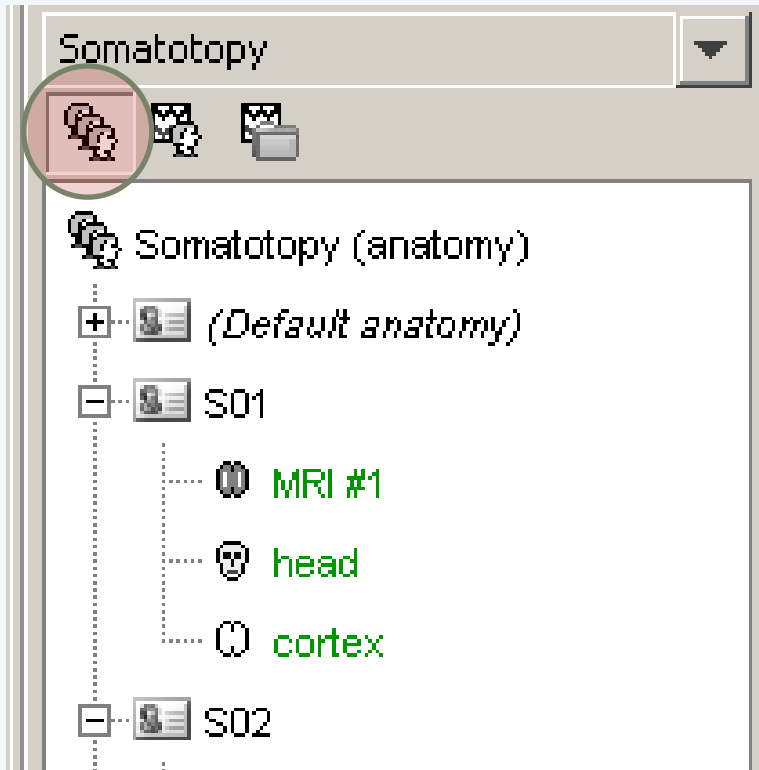
Pre-processing

Events
Epoching
Averaging
Sources
Time-frequency

Analysis of the
experimental data

Loop:
all acquisition runs
all subjects

Database



- Three levels:
 - Protocol
 - Subject
 - Condition
- Popup menus
- All files saved in Matlab .mat
- Same architecture on the disk

Import

Anatomy

Link recordings

MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

Markers

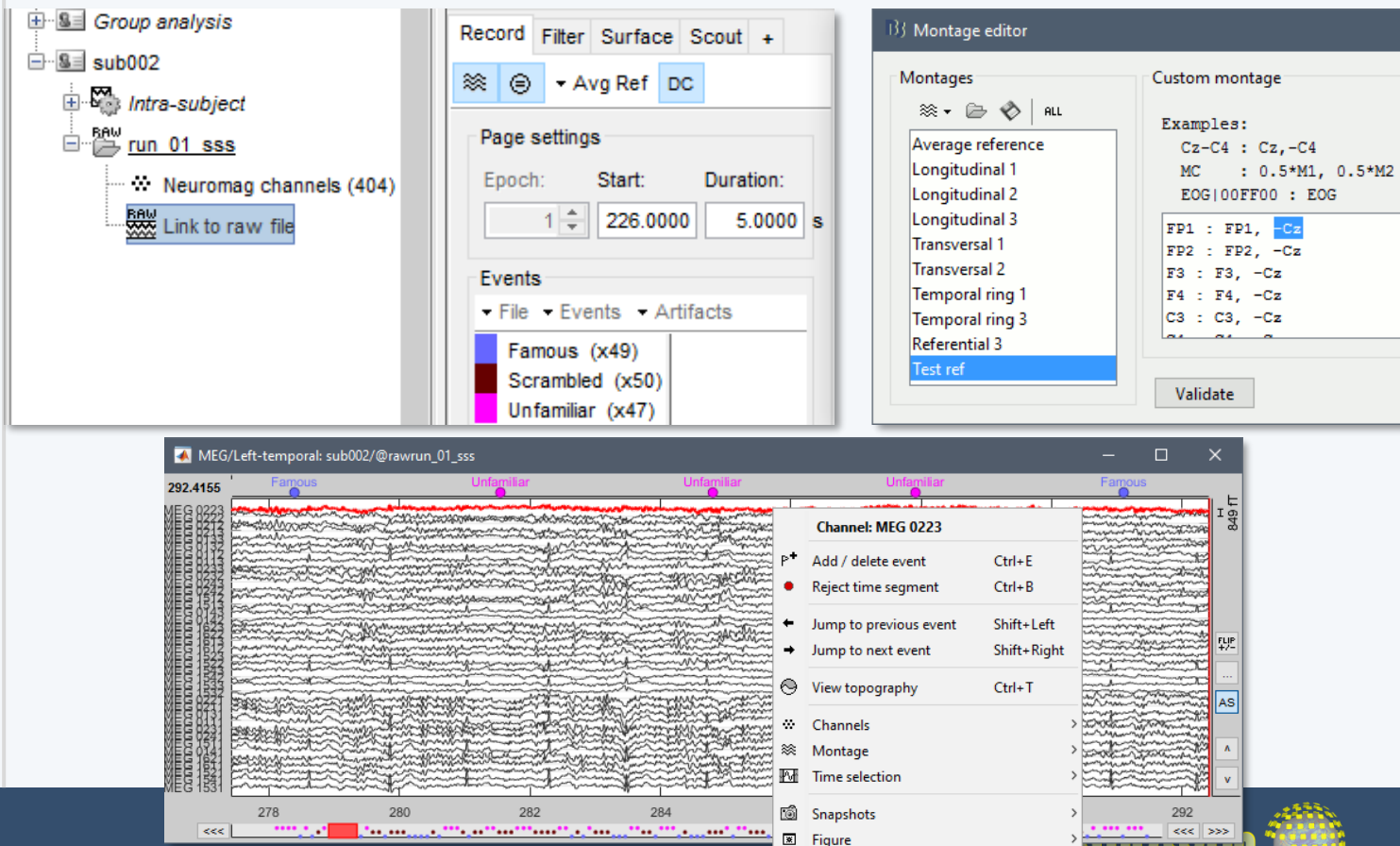
Epoching

Averaging

Sources

Time-frequency

- Original files linked to the database (no copy)
- Rich data viewer with flexible montage editor
- Optimized reading functions



Co-registration MEEG / MRI (I)

Anatomy

Link recordings

MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

Markers

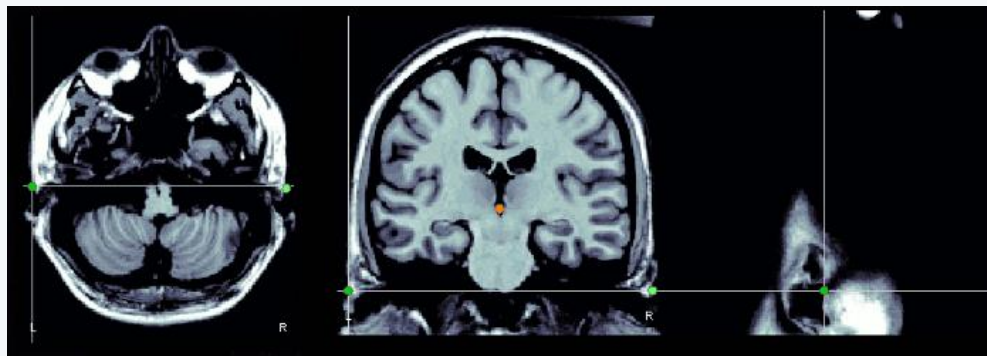
Epoching

Averaging

Sources

Time-frequency

- Basic estimation based on three points: Nasion (NAS), Left ear (LPA), Right ear (RPA)
- MRI: Marked in the volume with the MRI Viewer
- MEEG: Obtained with a tracking system (Polhemus)



Co-registration MEEG / MRI (2)

Anatomy

Link recordings

MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

Markers

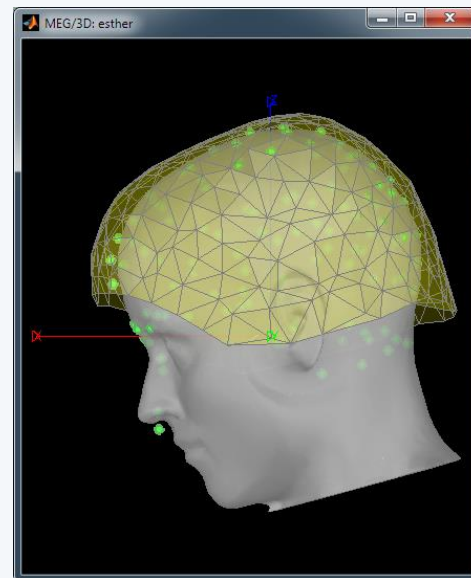
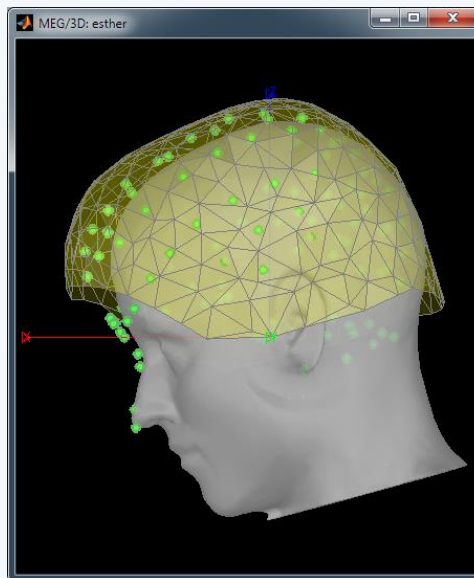
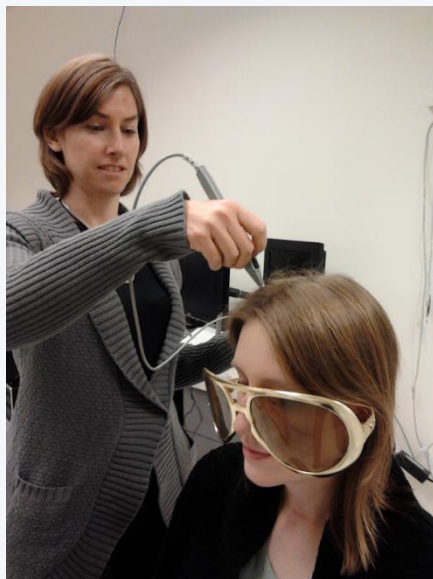
Epoching

Averaging

Sources

Time-frequency

- Automatic adjustment based on head shape: Fitting Polhemus points on the MRI head surface
- Final registration must be checked manually
- Polhemus driver included in Brainstorm



Quality control

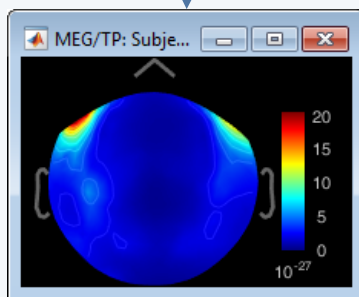
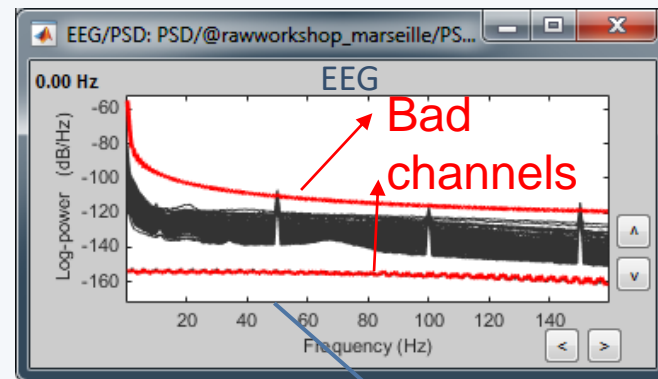
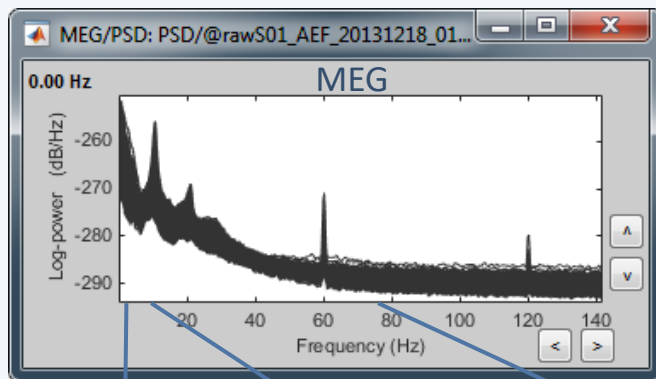
Anatomy
Link recordings
MRI registration

PSD

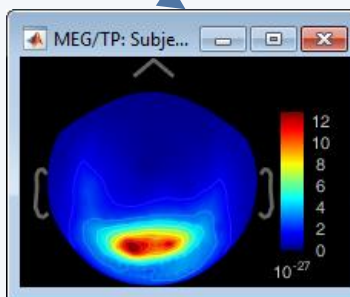
Filters
Bad channels
Artifacts
Correction
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

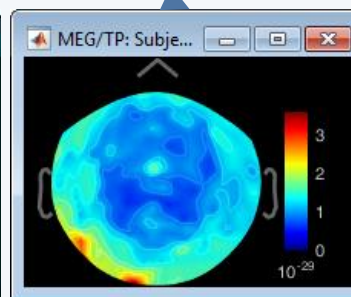
- Power spectrum density for quality control



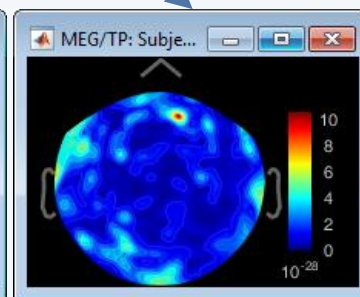
< 3Hz: Eyes



10Hz: Alpha



> 40Hz: Muscle



50/60Hz

Pre-processing

Anatomy
Link recordings
MRI registration

PSD

Filters

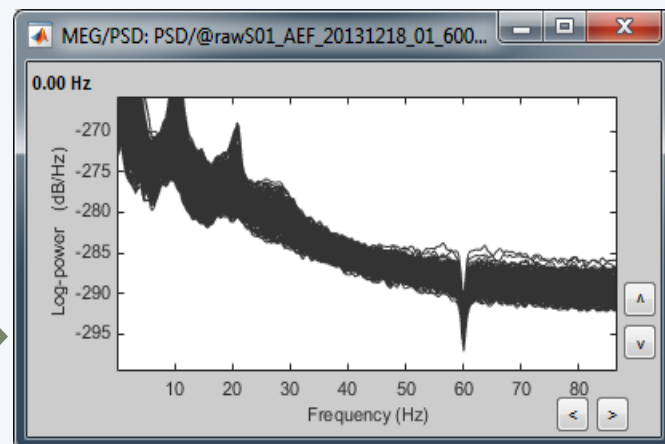
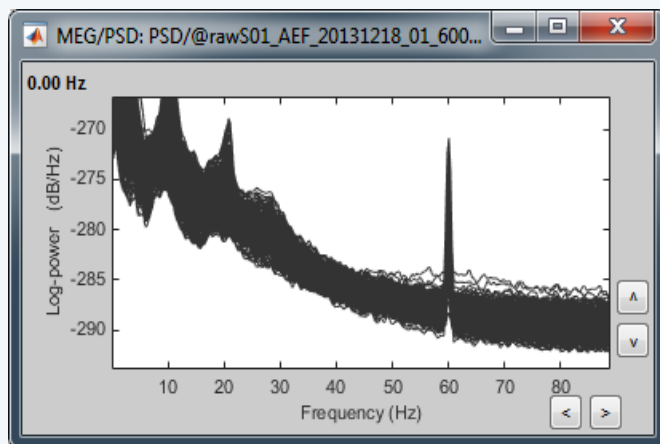
Bad channels
Artifacts
Correction
Bad segments

Markers

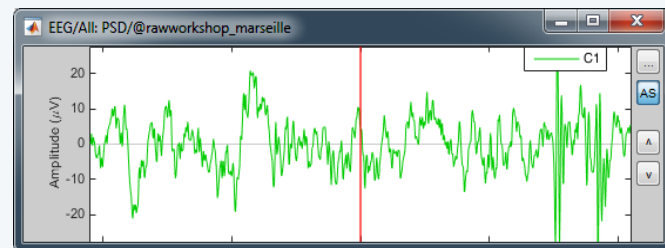
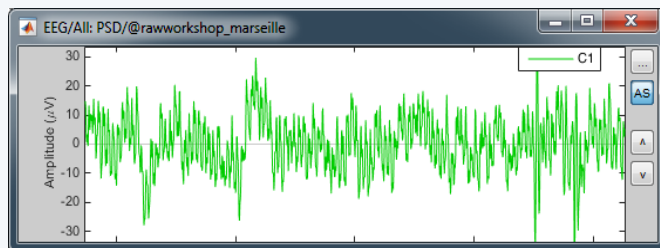
Epoching
Averaging
Sources
Time-frequency

- Notch filter: Removes 50Hz/60Hz power line noise (and harmonics)

PSD



Signal



Pre-processing

Anatomy
Link recordings
MRI registration

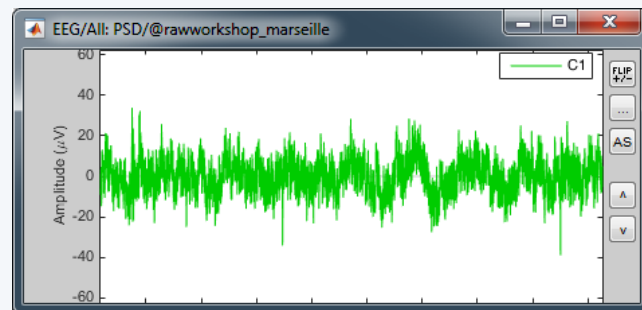
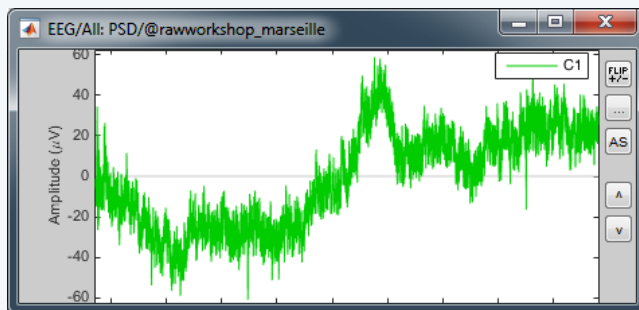
PSD

Filters

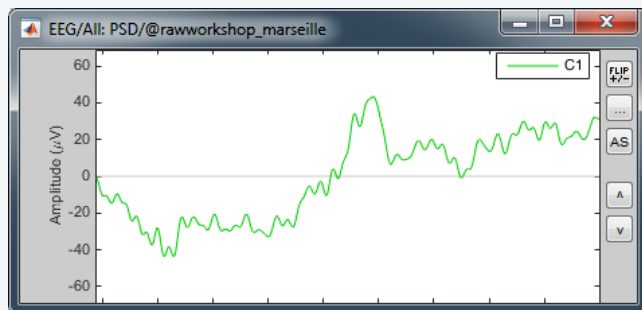
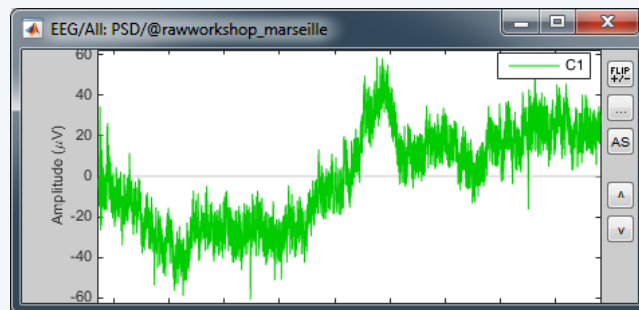
Bad channels
Artifacts
Correction
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

- High-pass filter: Removes slow components (eye movements, breathing, sensor drifts...)



- Low-pass filter: Remove high-frequencies



Pre-processing

Anatomy
Link recordings
MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

Markers

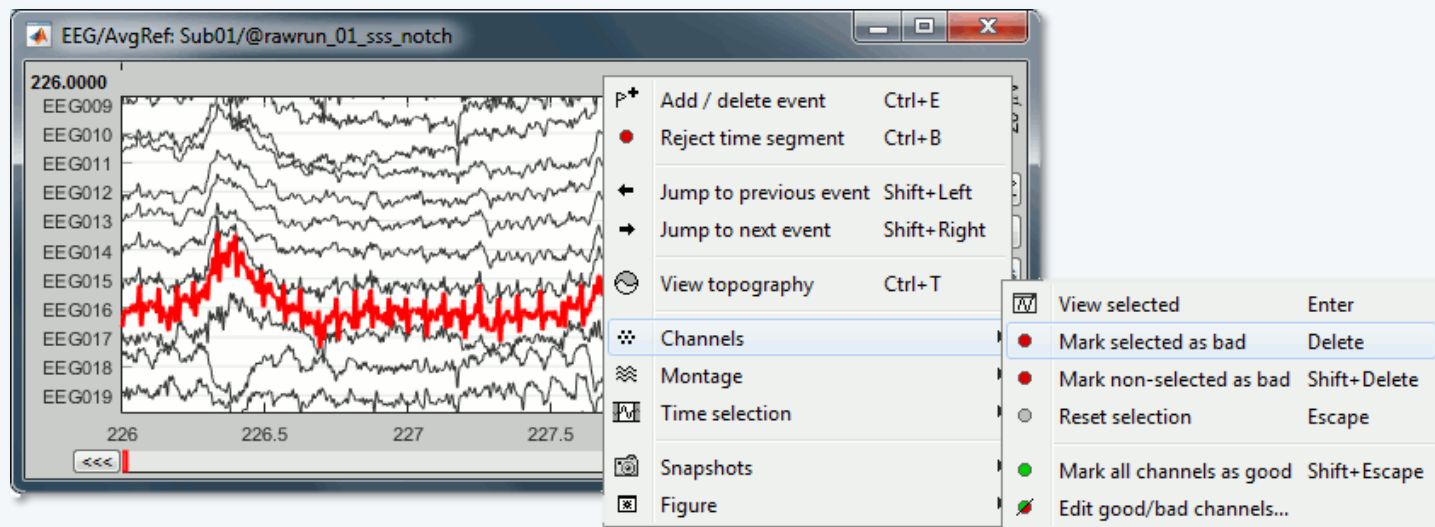
Epoching

Averaging

Sources

Time-frequency

- Manual inspection of the recordings
- Interactive selection of bad channels
- Re-reference the EEG if necessary (Average ref)



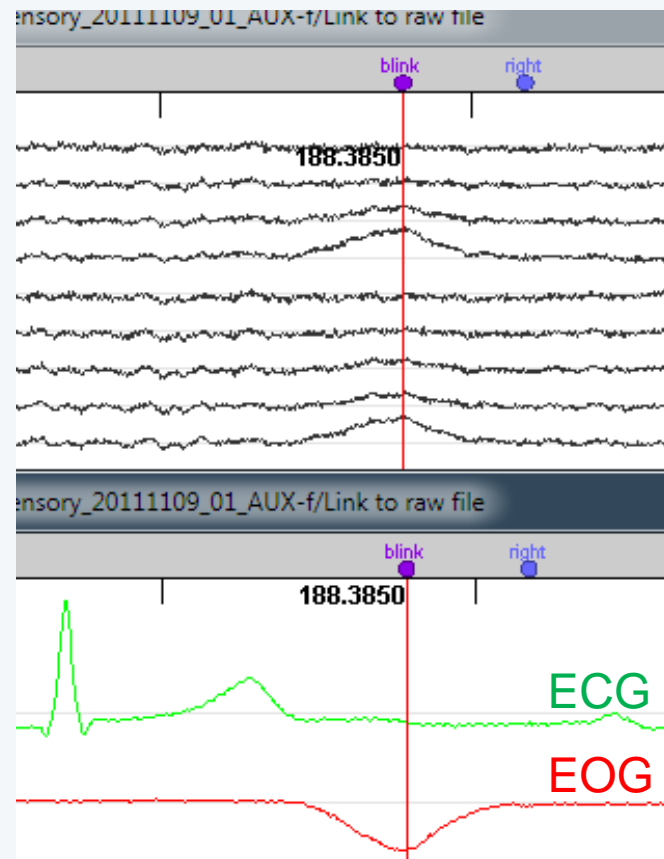
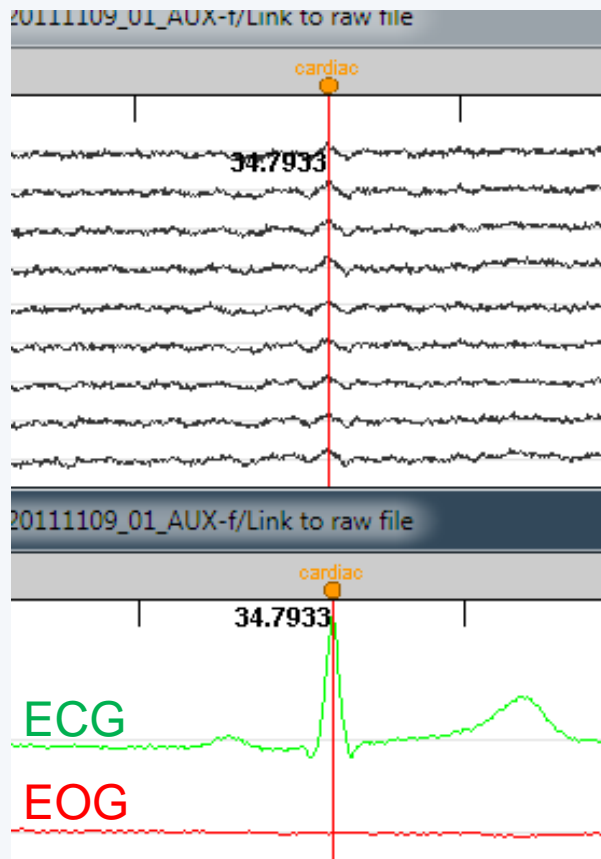
Pre-processing

Anatomy
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PSD
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Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

- Automatic detection of blinks and heartbeats (peak detection, or explicit amplitude threshold)



Artifact correction

- Two categories of artifacts:
 - Well defined, reproducible, short, frequent:
 - Heartbeats, eye blinks, eye movements, some stimulators
 - Unavoidable and frequent: we cannot just ignore them
 - Can be modeled and removed from the signal efficiently
 - All the other events that can alter the recordings:
 - Movements, building vibrations, metro nearby...
 - Too complex or not repeated enough to be modeled
 - Safer to mark them as bad segments, and ignore them

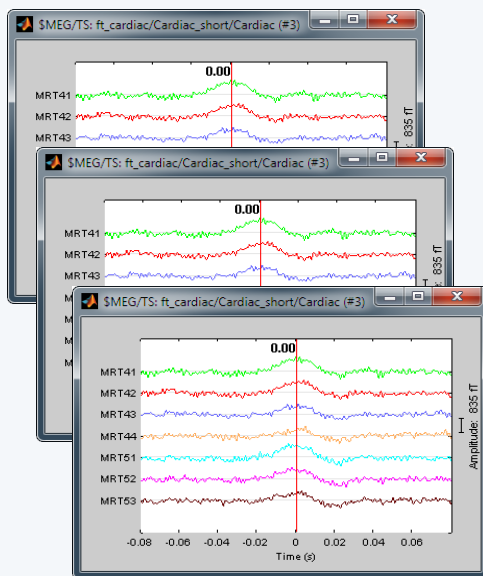
Anatomy
Link recordings
MRI registration

PSD
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Bad segments

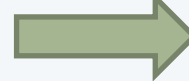
Markers
Epoching
Averaging
Sources
Time-frequency

- Correction with Signal Space Projections (SSP)

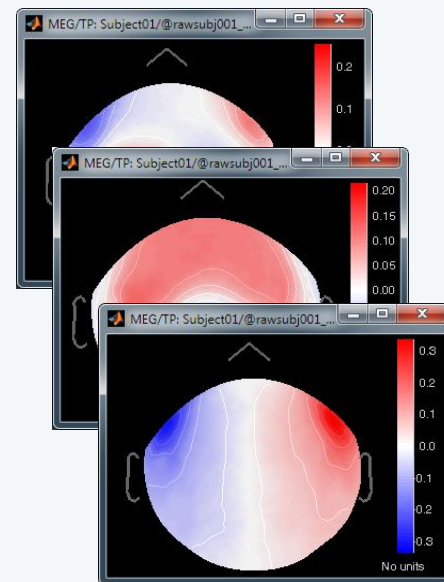
Detect artifacts



PCA



Spatial components



Select components and compute a linear projector to remove their contribution from the recordings

Pre-processing

Anatomy
Link recordings
MRI registration

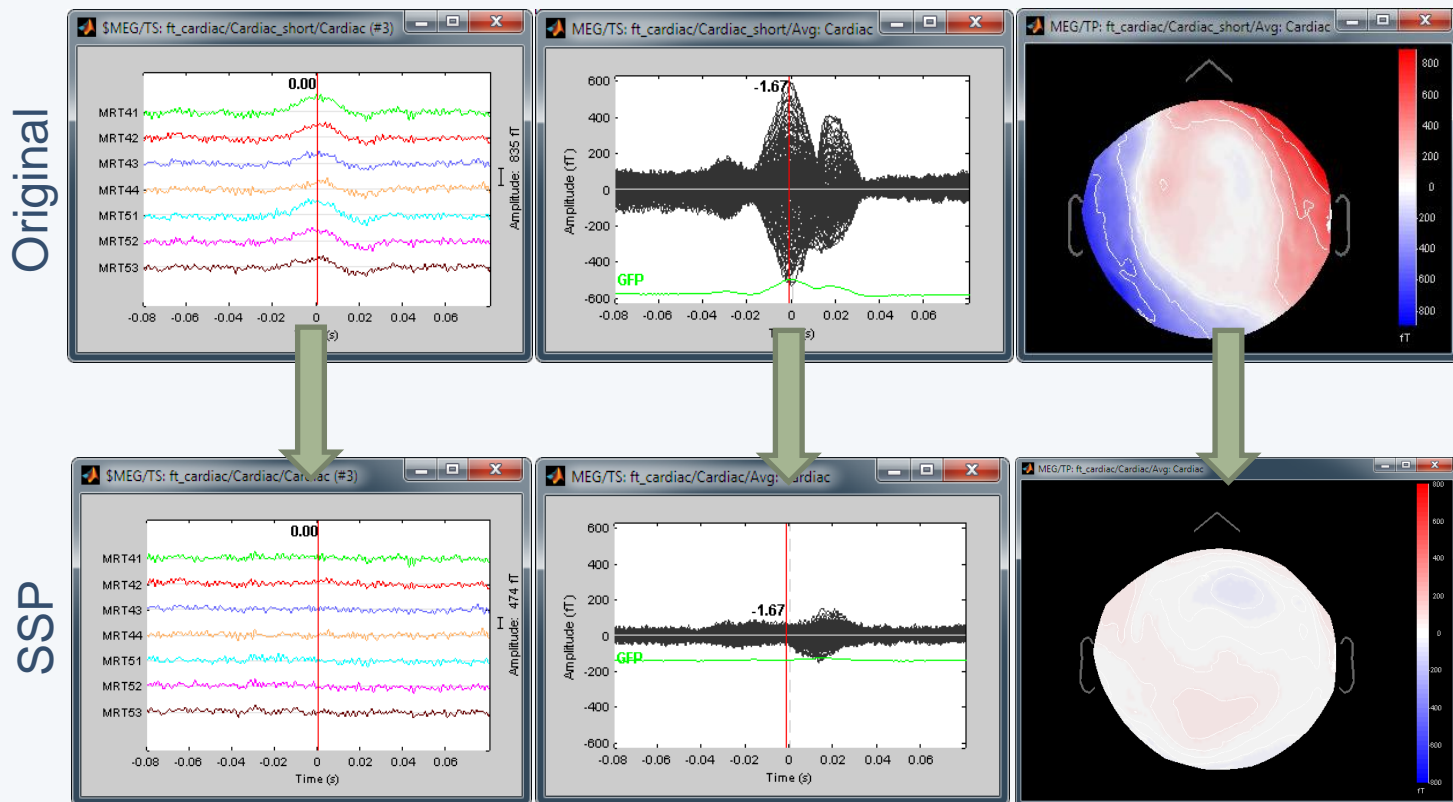
PSD
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Artifacts

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Bad segments

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Epoching
Averaging
Sources
Time-frequency

- Example: Cardiac artifact



Pre-processing

Anatomy
Link recordings
MRI registration

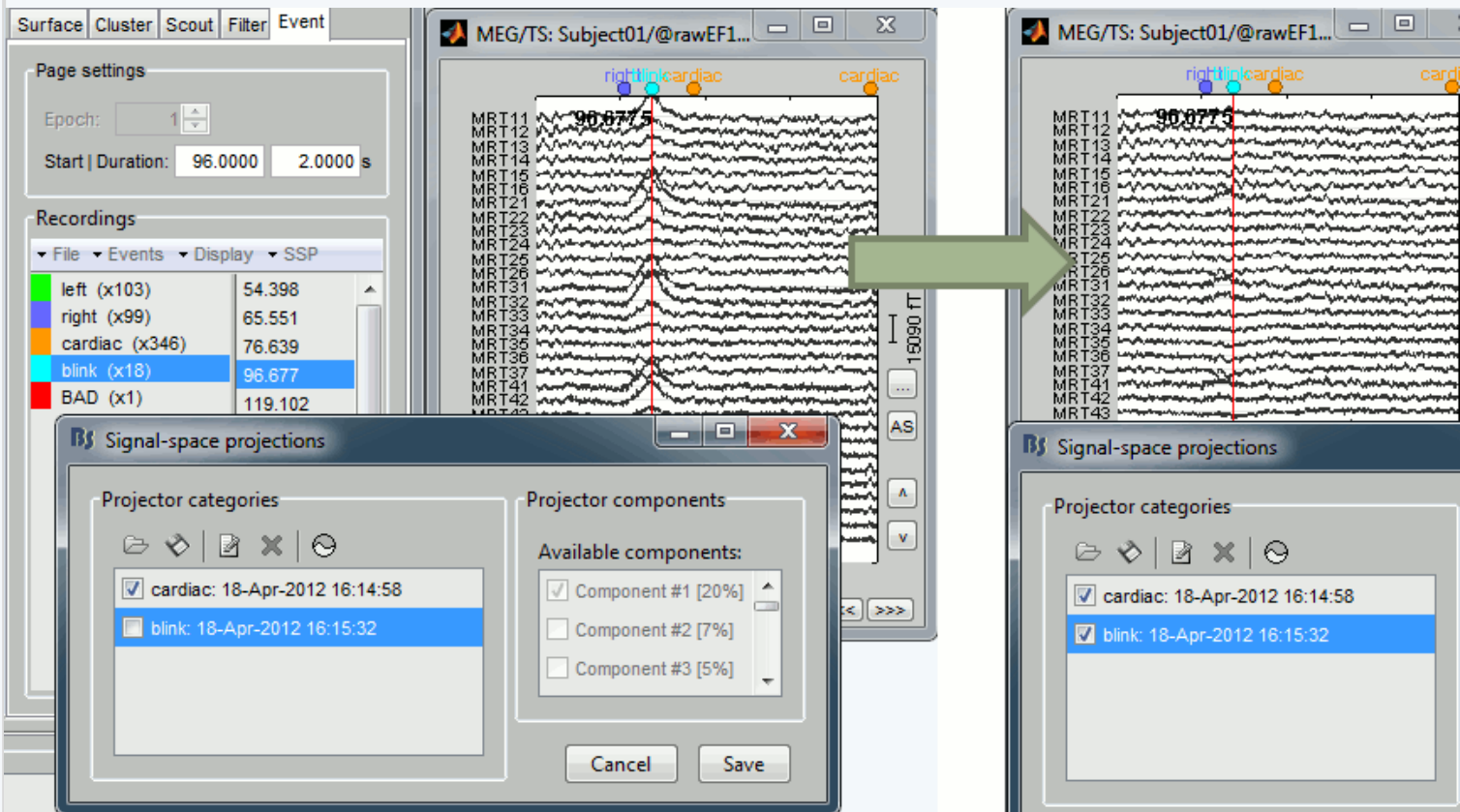
PSD
Filters
Bad channels

Correction

Bad segments

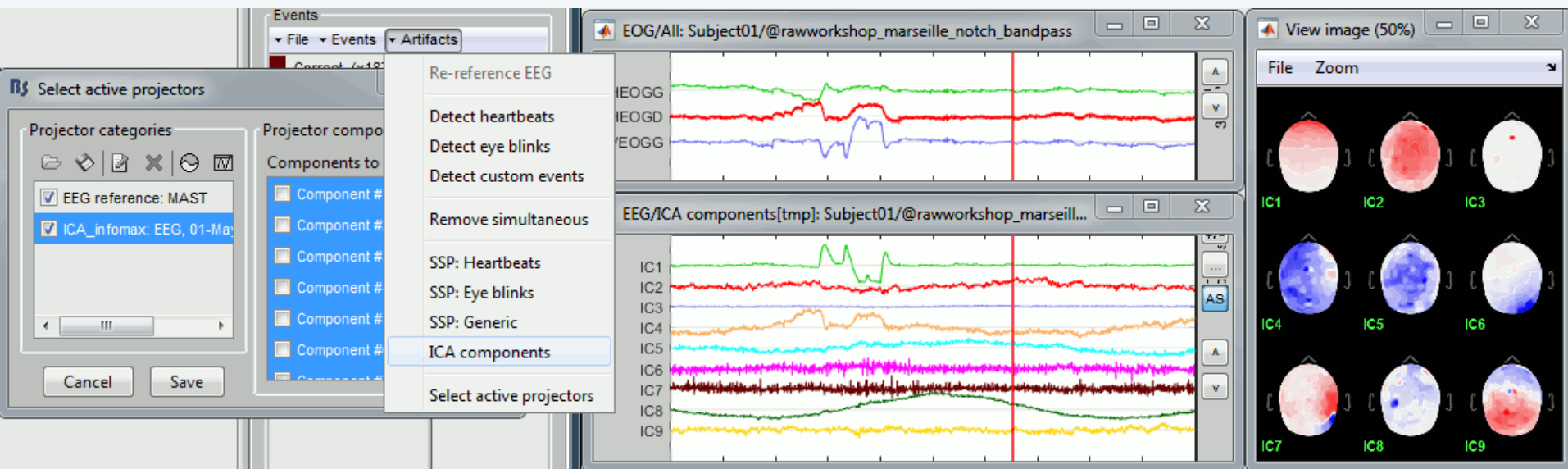
Markers
Epoching
Averaging
Sources
Time-frequency

- Example: Blink



Pre-processing

- Independent component analysis (ICA):
 - Popular in the EEG literature
 - Alternative to SSP for low number of sensors
 - Already implemented: Infomax and JADE (EEGLAB)



Pre-processing

Anatomy
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PSD

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Markers

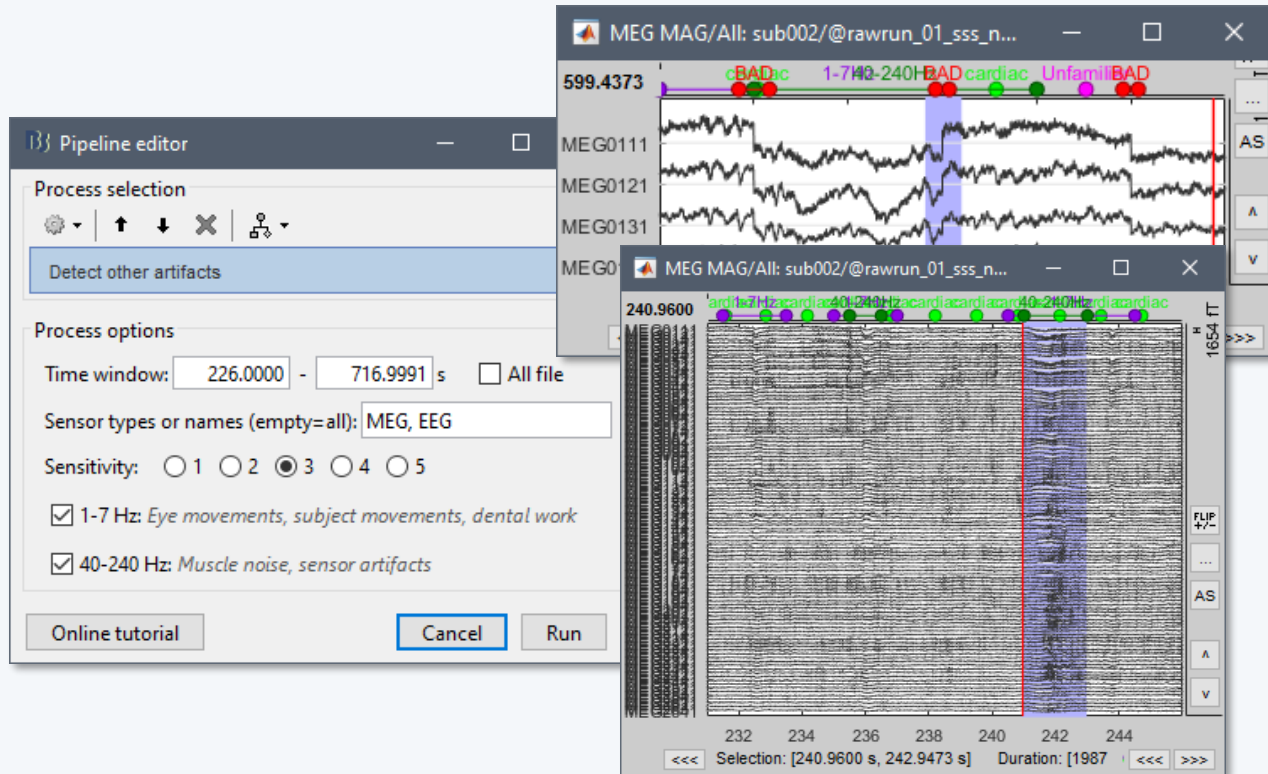
Epoching

Averaging

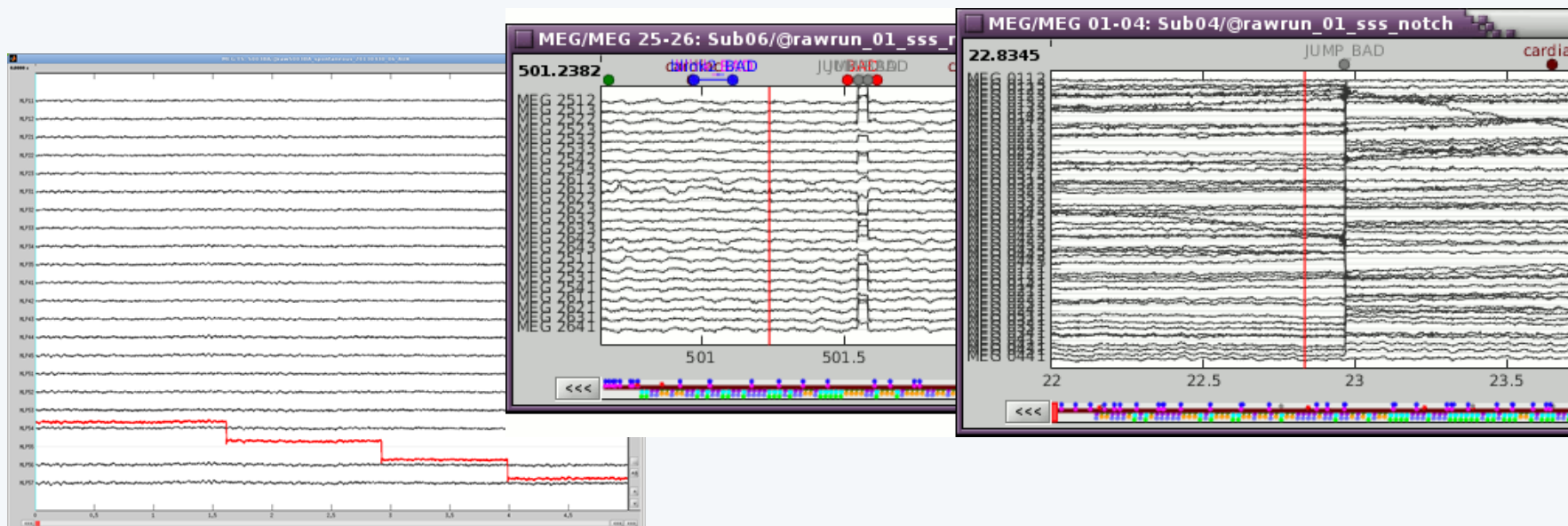
Sources

Time-frequency

- Automatic detection of artifacts (RMS-based)
- Manual screening of all the recordings is advised (scroll all the sensors by pages of 10-20s)
- Exclude: Blinks, movements, SQUID jumps



- Sharps steps followed by a change of baseline value
- Mark the channels as bad before running MaxFilter
- Or mark the segments as bad in Brainstorm



Epoching

Anatomy
Link recordings
MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

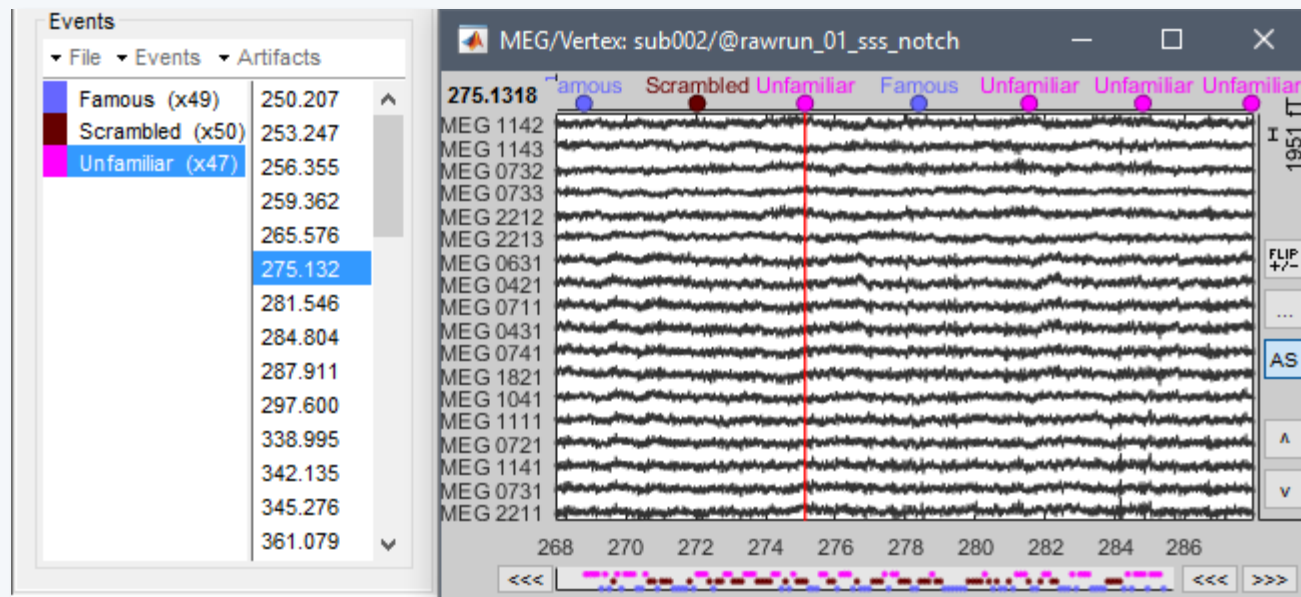
Markers

Presentation

Sensor

Manual

- Two types of experiments:
 - Steady-state or resting-state (ongoing activity)
 - Event-based (stimulus, response, spike...)
- How to get event markers in the recordings?



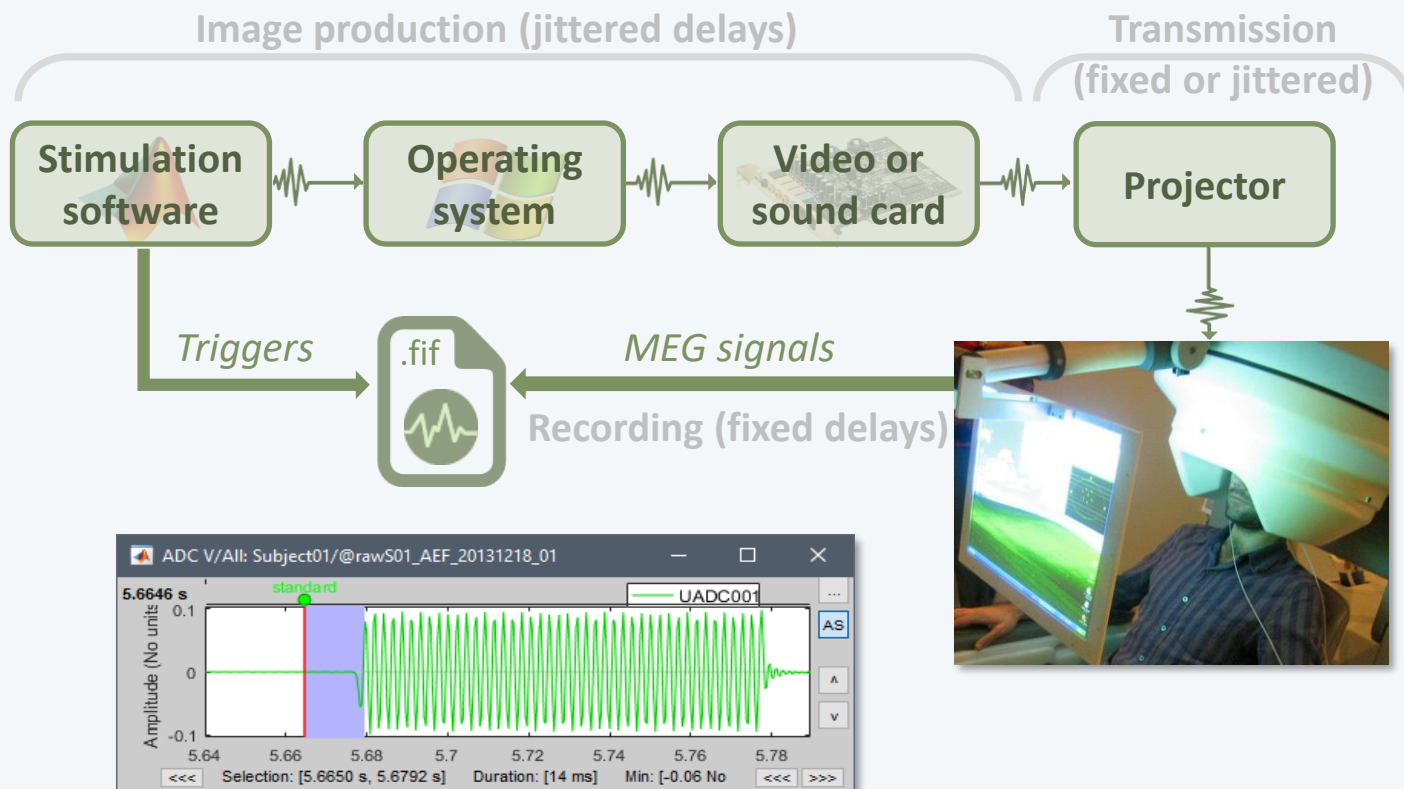
Epoching

Anatomy
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MRI registration

PSD
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Bad segments

Markers
Presentation
Sensor
Manual

- Reading the triggers saved by the presentation software (includes jittered OS delays)



- File triggers are never aligned with the real stim

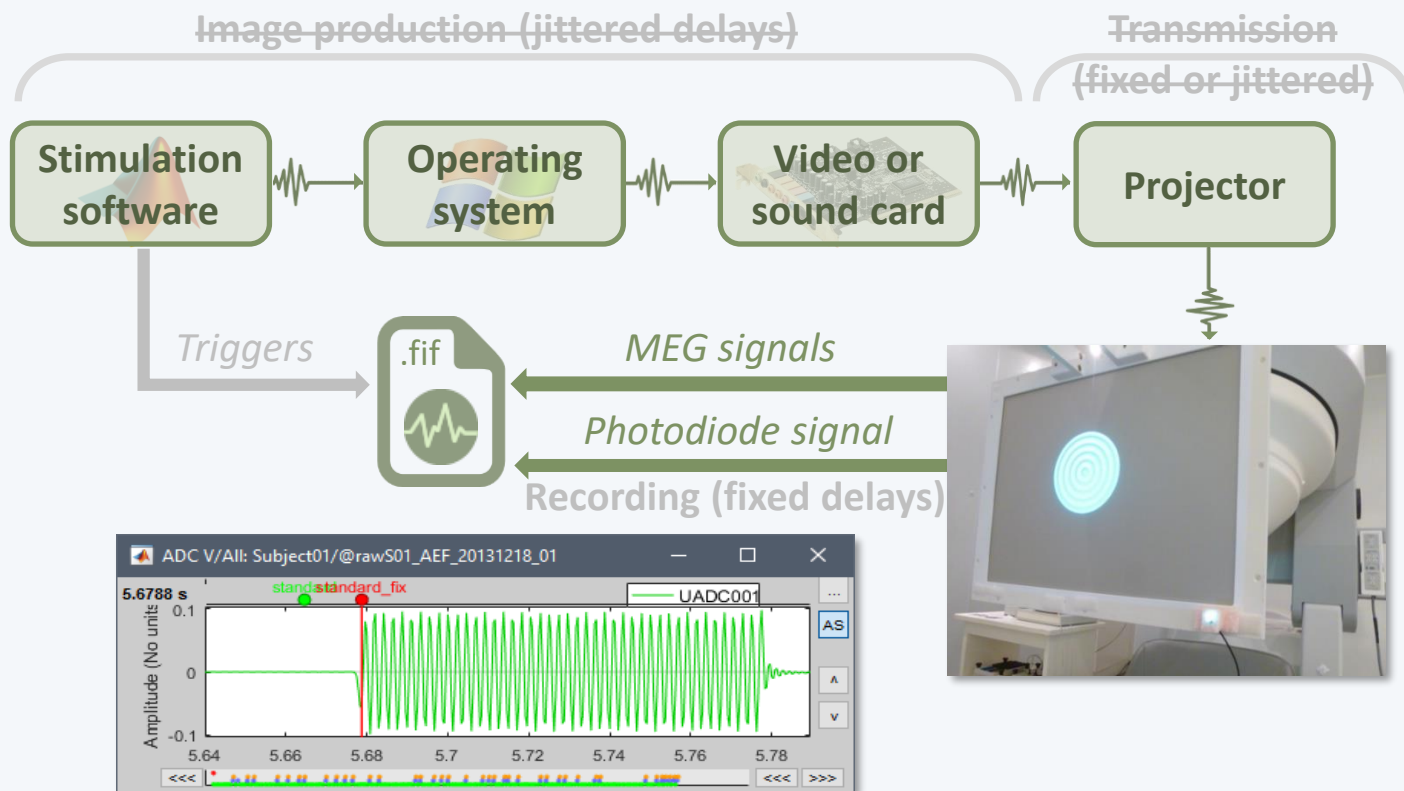
Epoching

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Markers
Presentation
Sensor
Manual

- Reading information recorded on the subject side (photodiode, microphone, response box...)



- Avoids most uncontrollable jittered delays

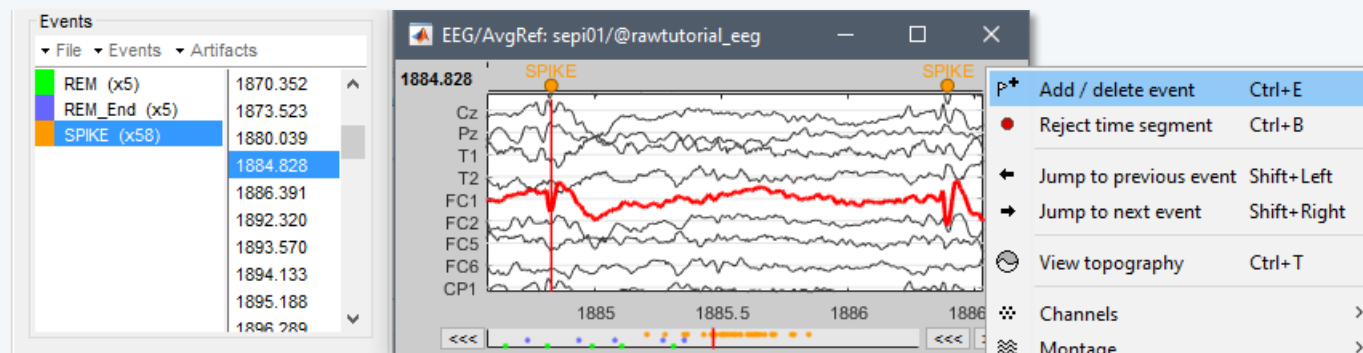
Epoching

Anatomy
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Bad channels
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Bad segments

Markers
Presentation
Sensor
Manual

- Reading the triggers save by the presentation software (includes jittered OS delays)
- Reading information recorded on the subject side (photodiode, microphone, response box)
- Manual or automatic marking of biological or behavioral events, post-acquisition (epileptic spikes, sleep spindles, rat position in a box...)
- Optimized workflow for clinicians (keyboard and mouse shortcuts, workspace...)



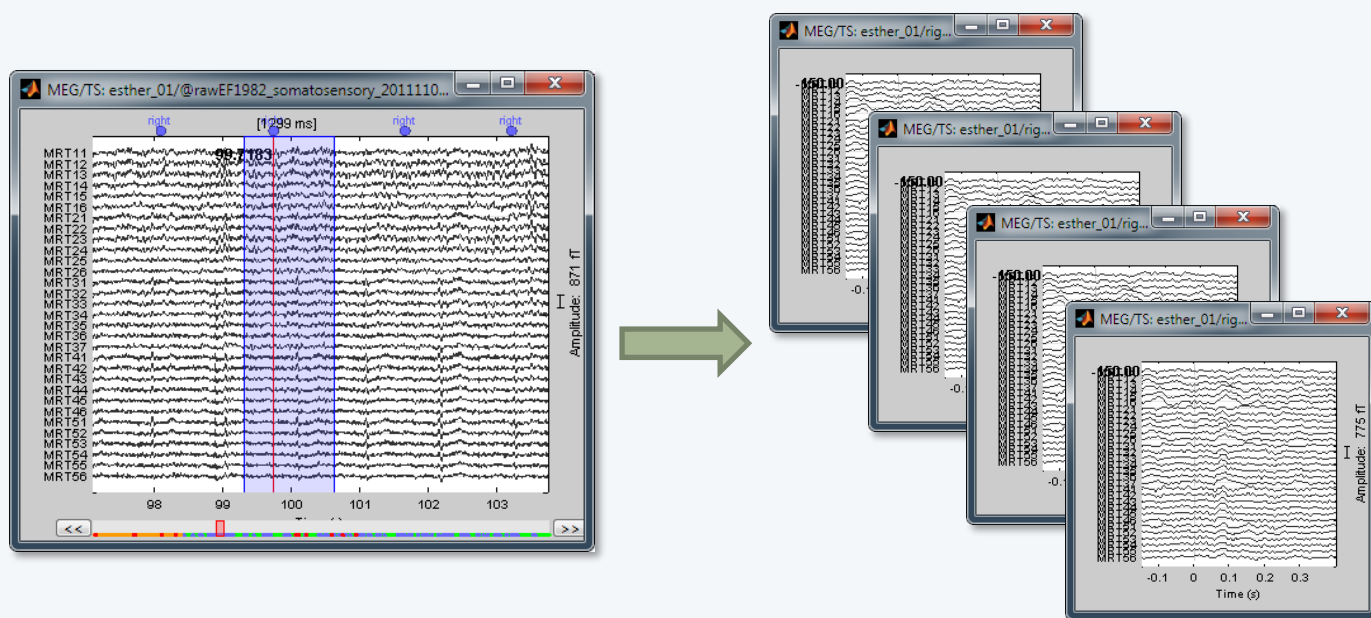
Epoching

Anatomy
Link recordings
MRI registration

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Correction
Bad segments

Markers
Epoching
Combine
Extract
Length
Process

- Epochs = Trials = Short blocks of recordings around an event of interest.
- Epoching = Extracting epochs from the continuous recordings and saving them.



Epoching

Anatomy
Link recordings
MRI registration

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Markers

Epoching

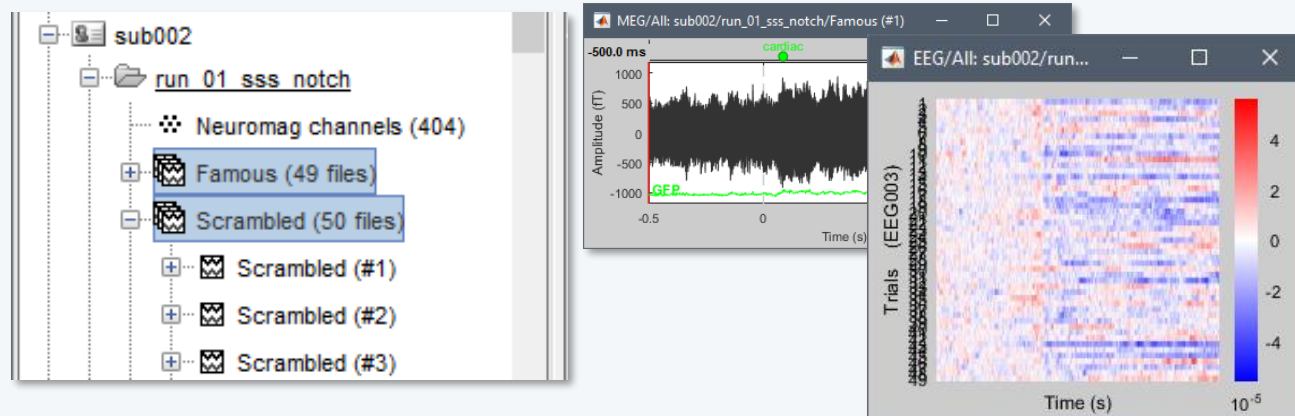
Combine

Extract

Length

Process

- In Brainstorm, each imported epoch is an independent file in the database.
- Accessible by event type or individually.



- In other programs, all the epochs from one run are saved in one single file (one file per event type, or one file with all the events).

Epoching

Anatomy
Link recordings
MRI registration

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Markers

Epoching

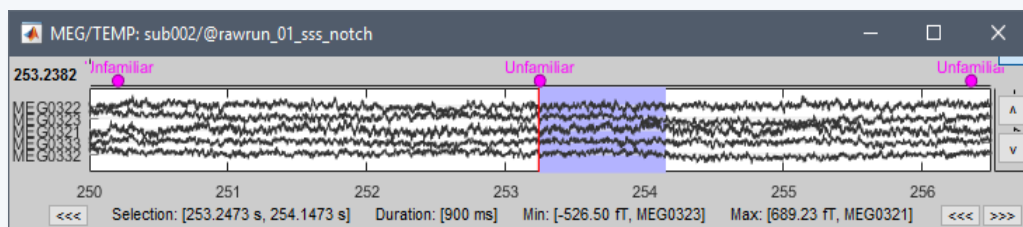
Combine

Extract

Length

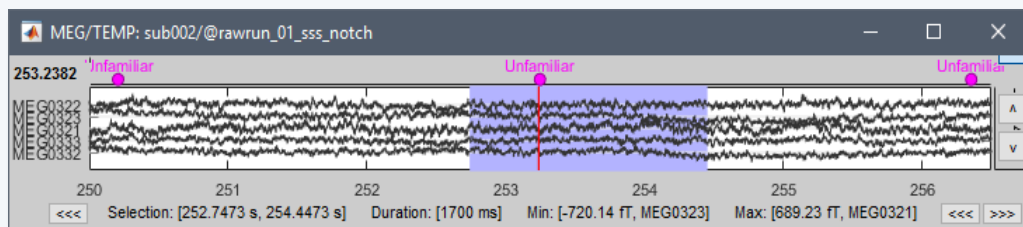
Process

- How to define the optimal epoch length ?
- Experimental design:
Expected effect duration, inter-stimulus interval



[0,900] ms

- Analysis: Frequency filters and amplitude normalizations may require longer epochs



+ 200ms baseline
+ 300ms filters
= [-500, 1200] ms

- Computational limitations: Size and time

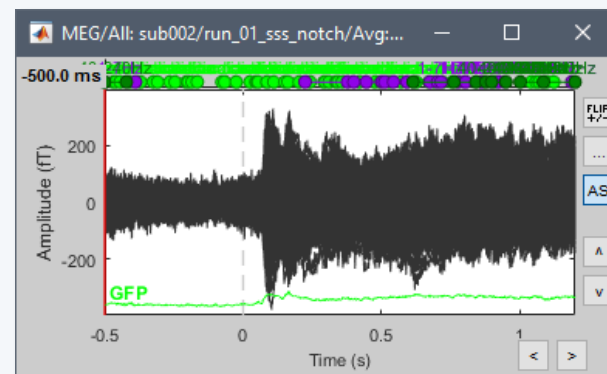
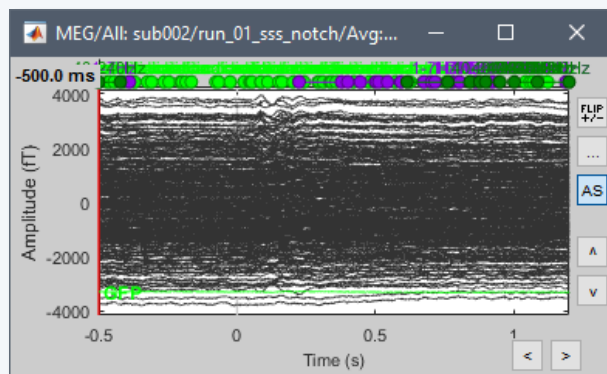
Epoching

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- Processing steps that can be applied on epochs:
 - **DC offset correction:** Subtract the average estimated over a baseline period
 - **Detrending:** Subtract a linear trend estimated over a reference period
 - **Resampling:** Decrease the sampling rate
- This dataset: DC correction, baseline= $[-500,0]$ ms



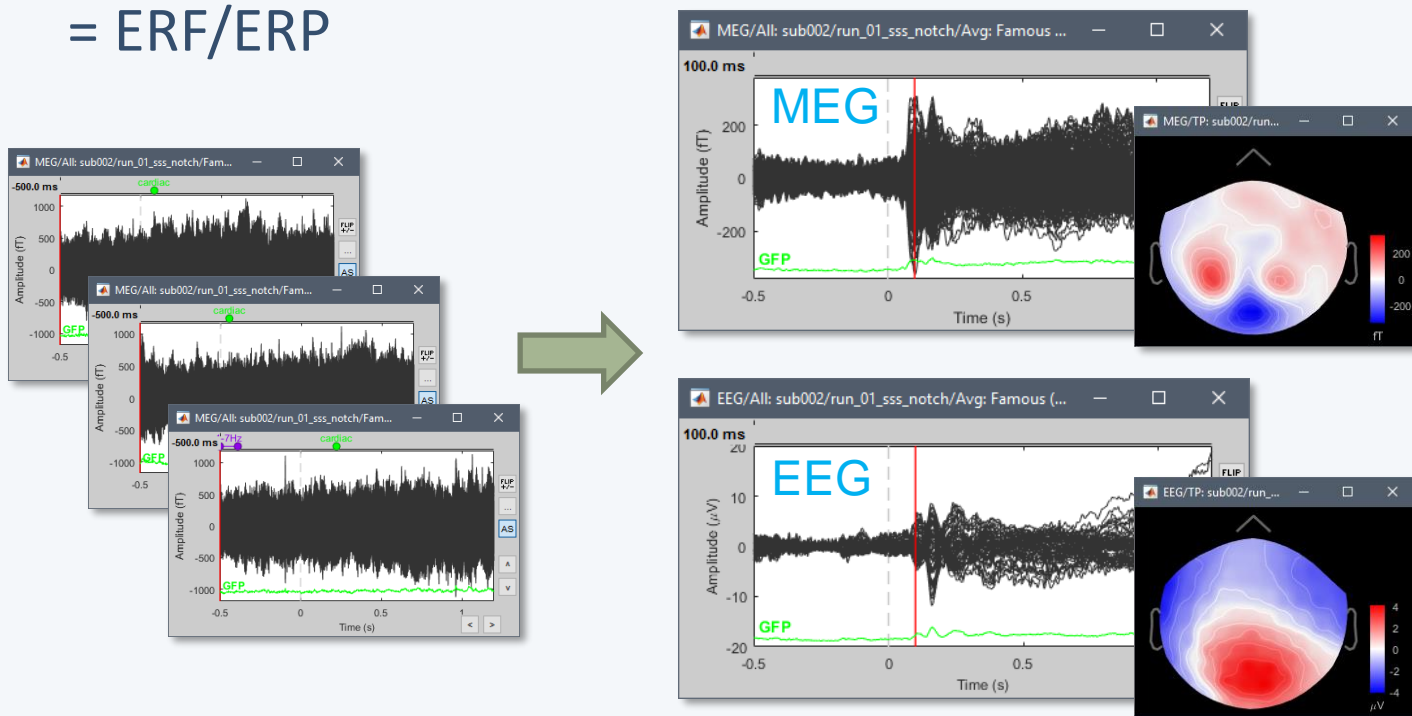
Single subject

Anatomy
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Epoching
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Sources
Time-frequency

- Averaging the trials: Reveals the features of the signals that are locked in time to a given event
 - = Event-related field / potential
 - = Evoked response
 - = ERF/ERP



Single subject

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- **EEG:** Averaging data across runs and subjects OK.
- **MEG:** Averaging across runs is not always accurate
 - Head shapes differ between subjects.
 - Head positions different between runs.
 - One sensor does not record the same thing in two different runs.
 - Coregistration of runs with Elekta MaxFilter helps but modifies a lot the recordings.
Never use this to average across subjects.
 - Recommended: Estimate the sources for each run separately, then average in source space.

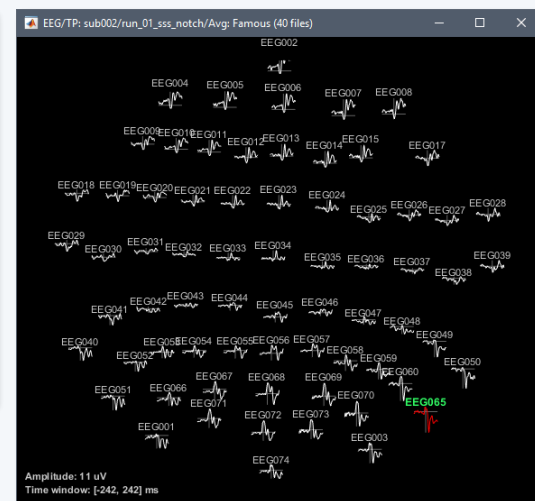
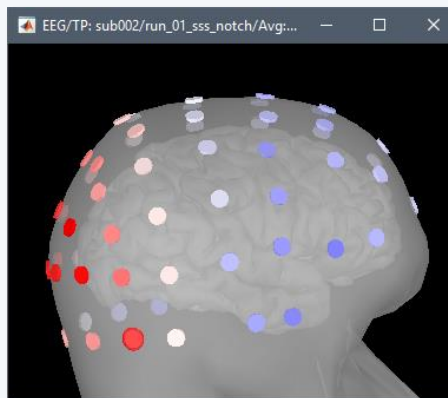
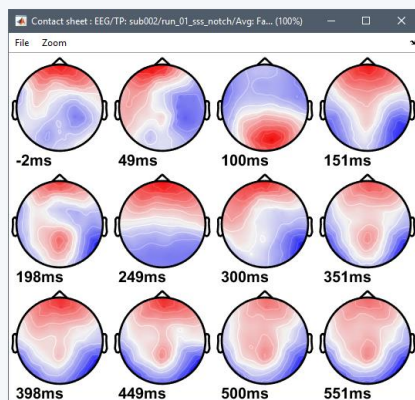
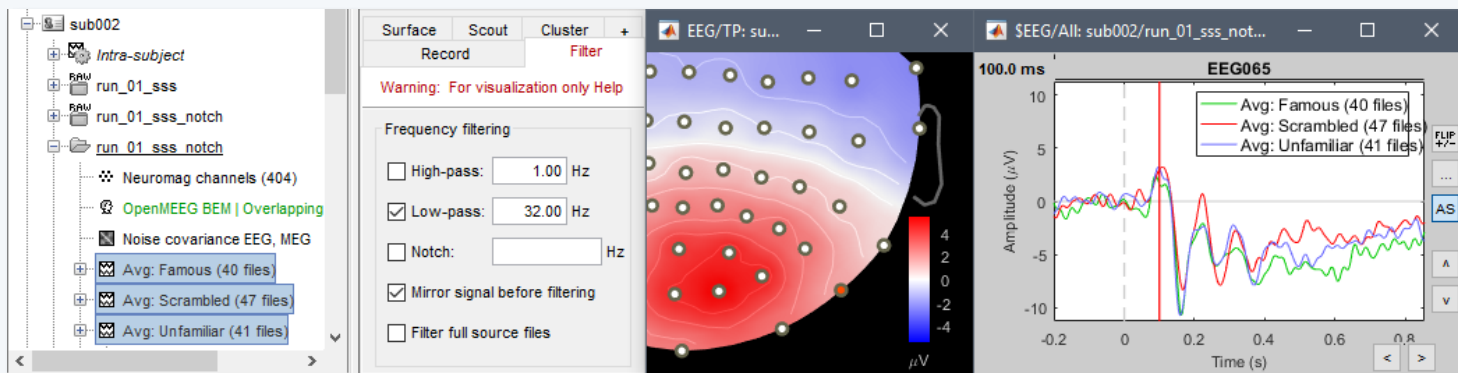
Single subject

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Sources
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- EEG ERP: Famous faces



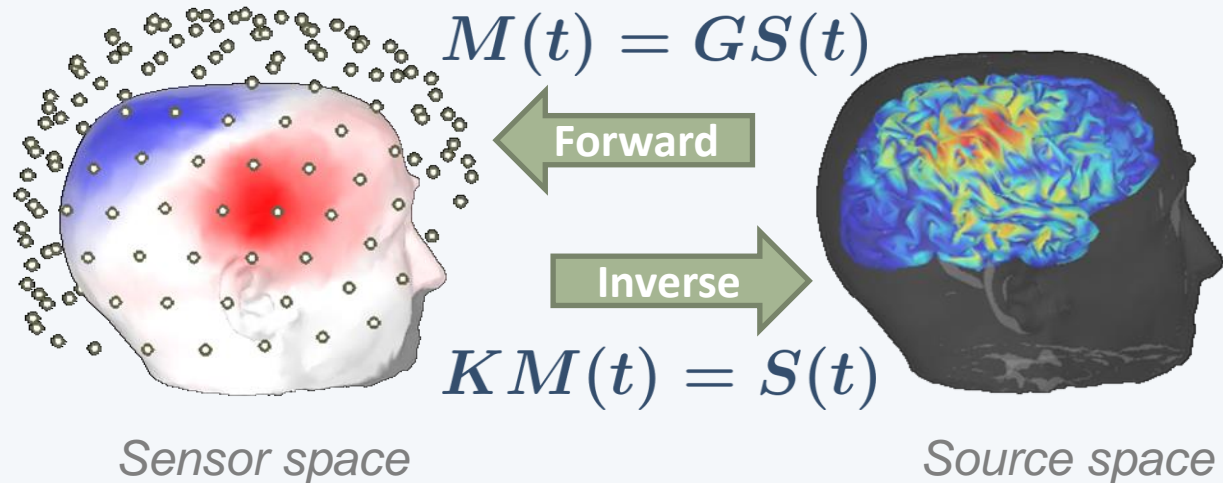
Single subject

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$M(t)$ Sensor space: EEG or MEG sensors
 $S(t)$ Source space: Cortex or full head volume
 G Forward model: Overlapping spheres (MEG)
OpenMEEG BEM/DUNEuro FEM (EEG)
 K Inverse model: **Minimum norm estimates**
Beamformers
Separately for MEG and EEG



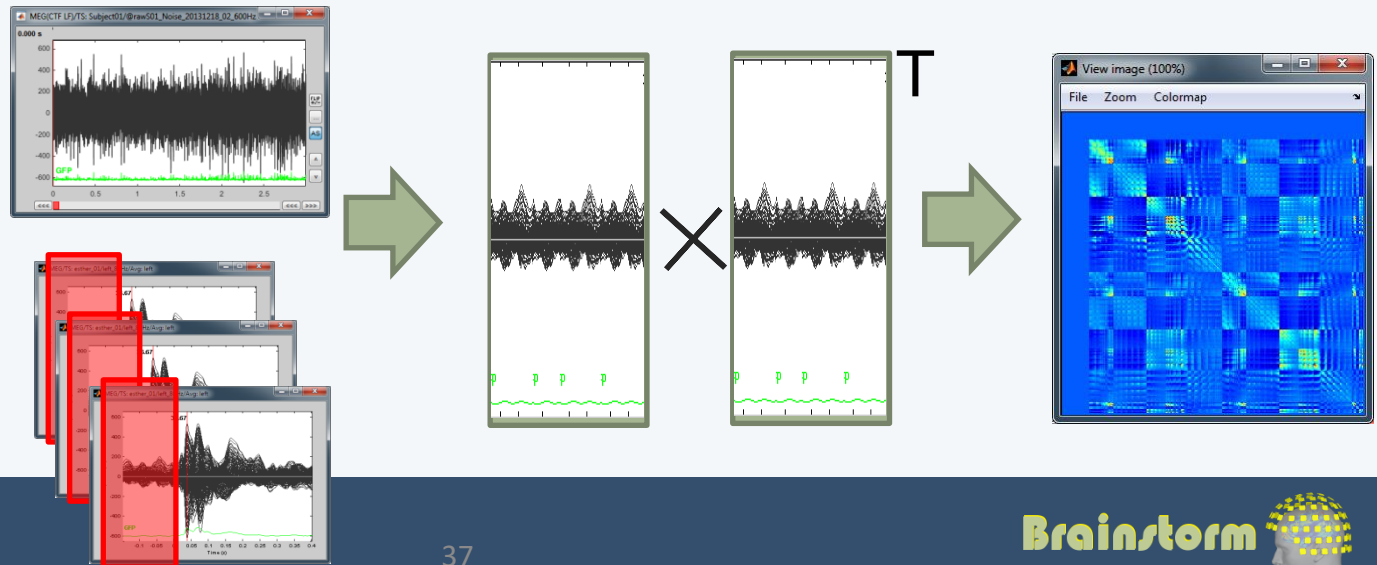
Single subject

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- The MNE model requires an estimation of the level of noise of the sensors
- Noise covariance matrix = covariance of segments that do not contain any “meaningful” data
- Empty room, pre-stim baseline, resting



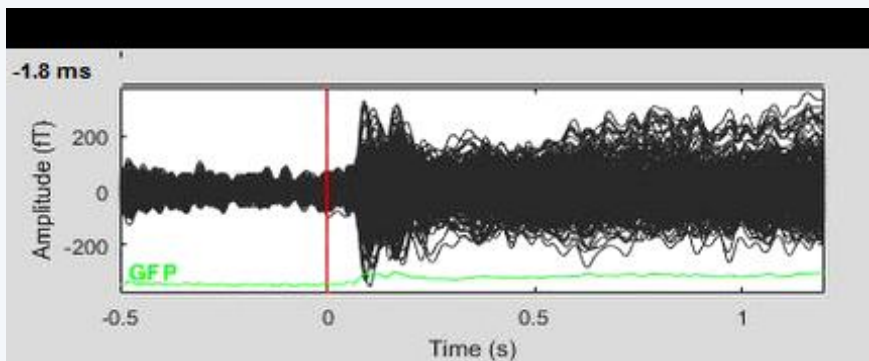
Single subject

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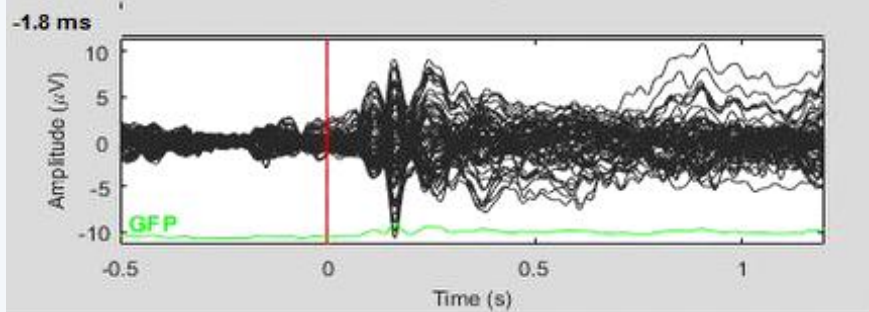
PSD
Filters
Bad channels
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

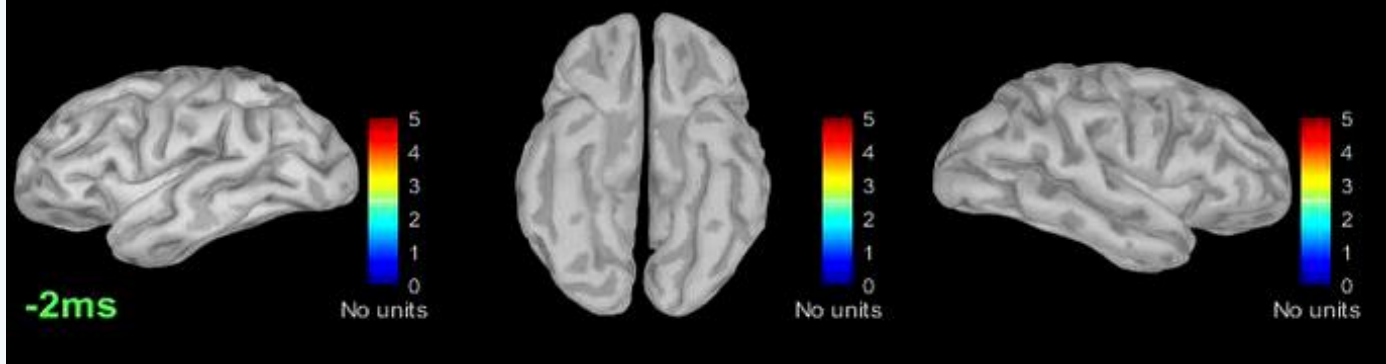
MEG



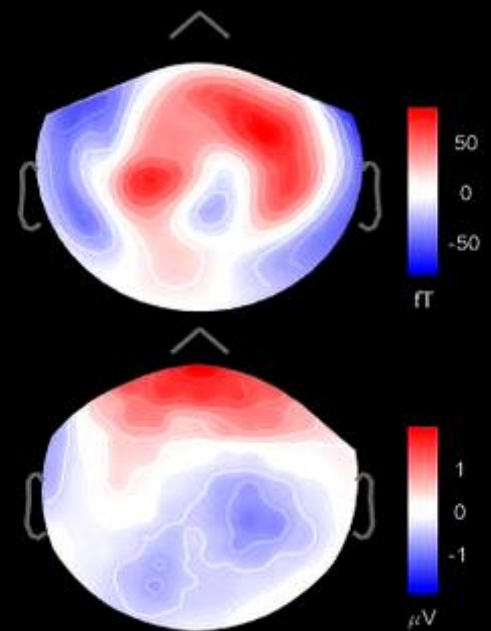
EEG



MEG sources



Famous faces



Single subject

Anatomy
Link recordings
MRI registration

PSD

Filters

Bad channels

Artifacts

Correction

Bad segments

Markers

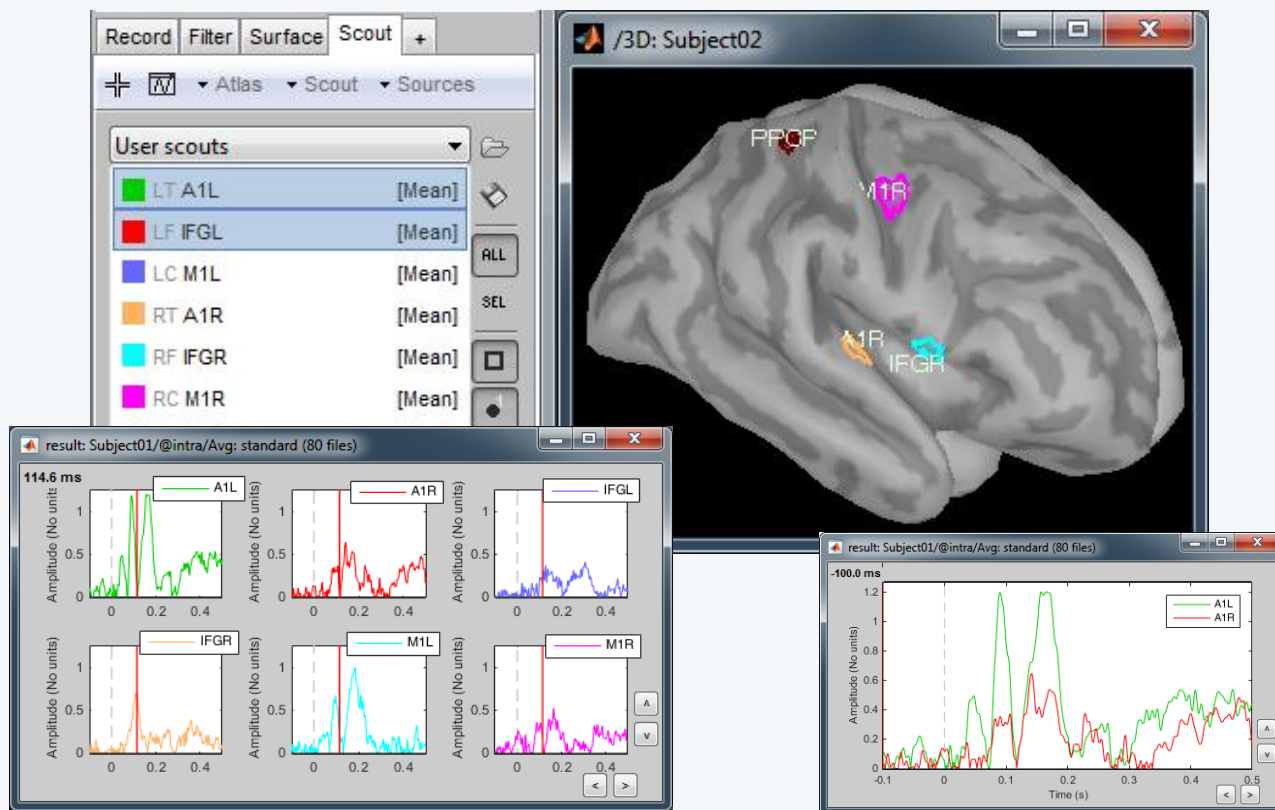
Epoching

Averaging

Sources

Time-frequency

- Regions of interest at cortical level (scouts)
= Subset of a few dipoles in the brain
= Group of vertices of the cortex surface

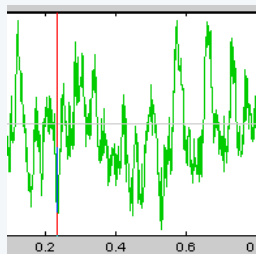


Single subject

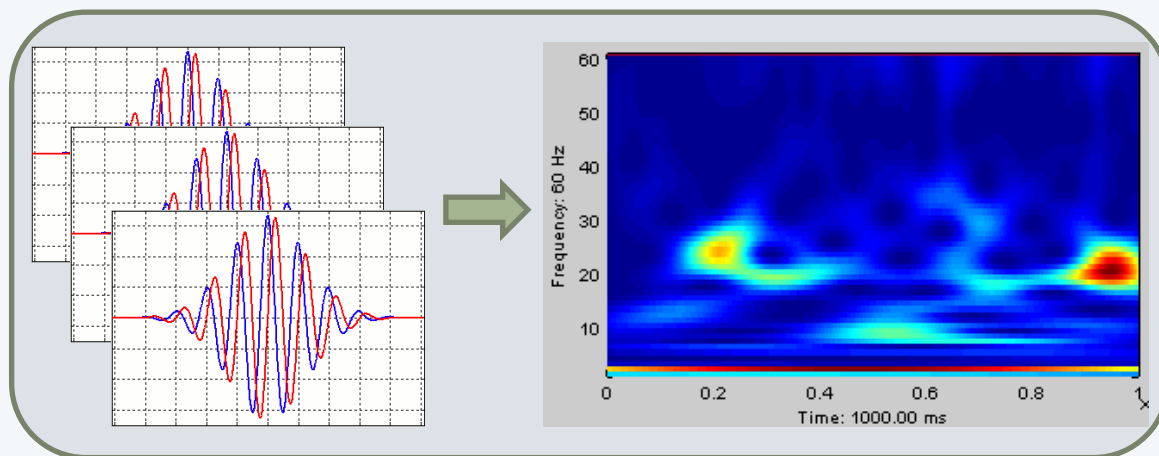
Anatomy
Link recordings
MRI registration

PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

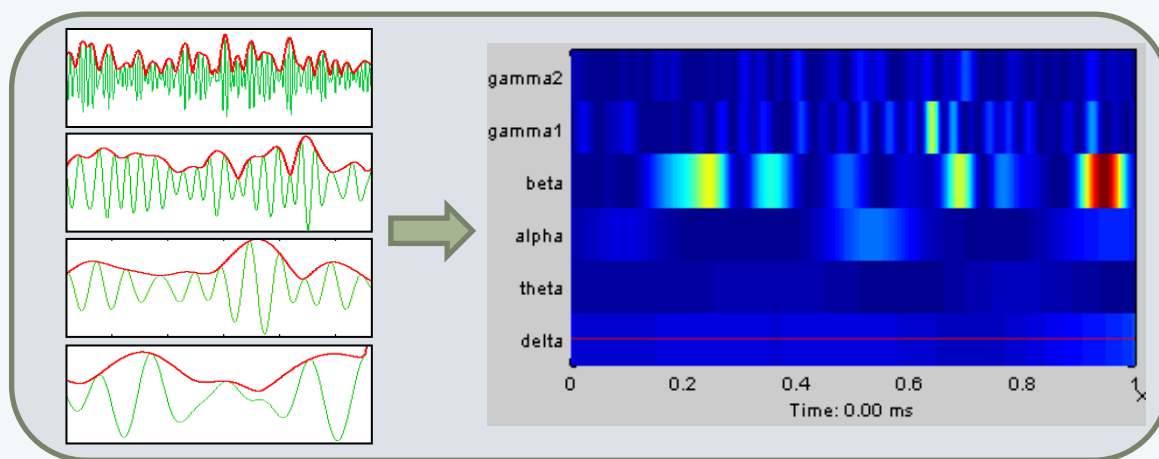
Markers
Epoching
Averaging
Sources
Time-frequency



Morlet wavelets



Hilbert transform + band-pass filter



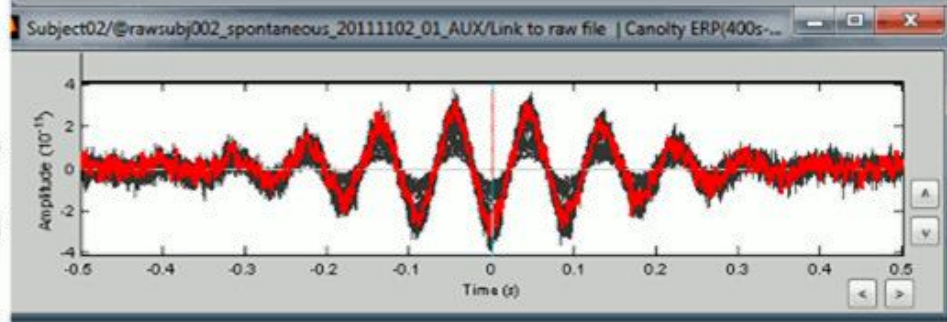
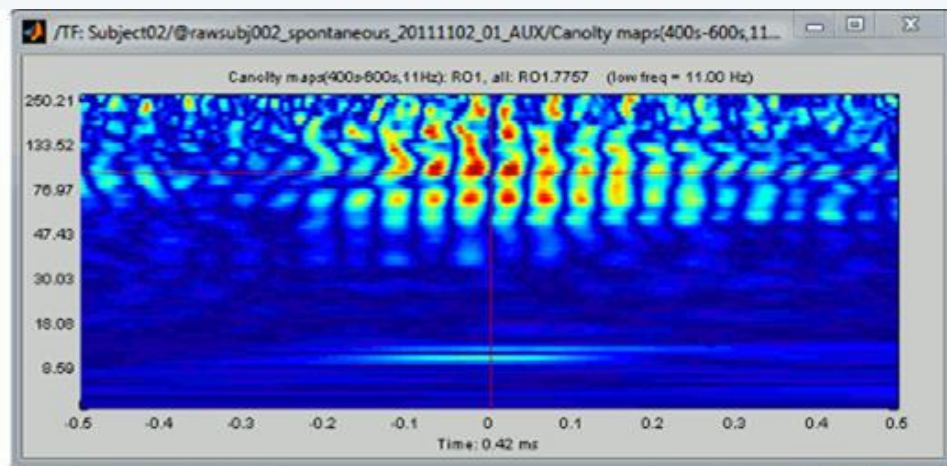
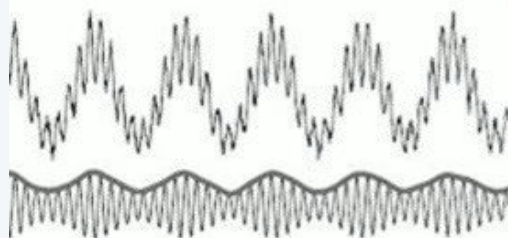
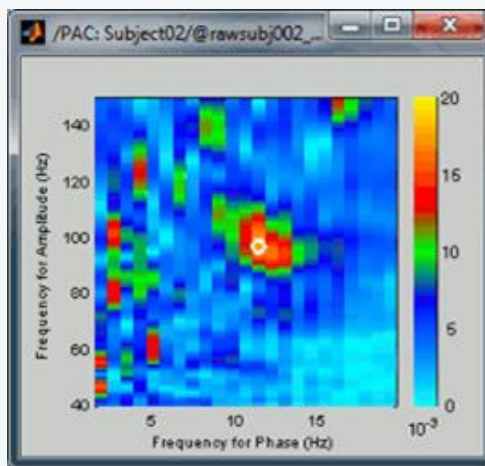
Single subject

Anatomy
Link recordings
MRI registration

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Averaging
Sources
Time-frequency
Other measures

- Phase-amplitude coupling



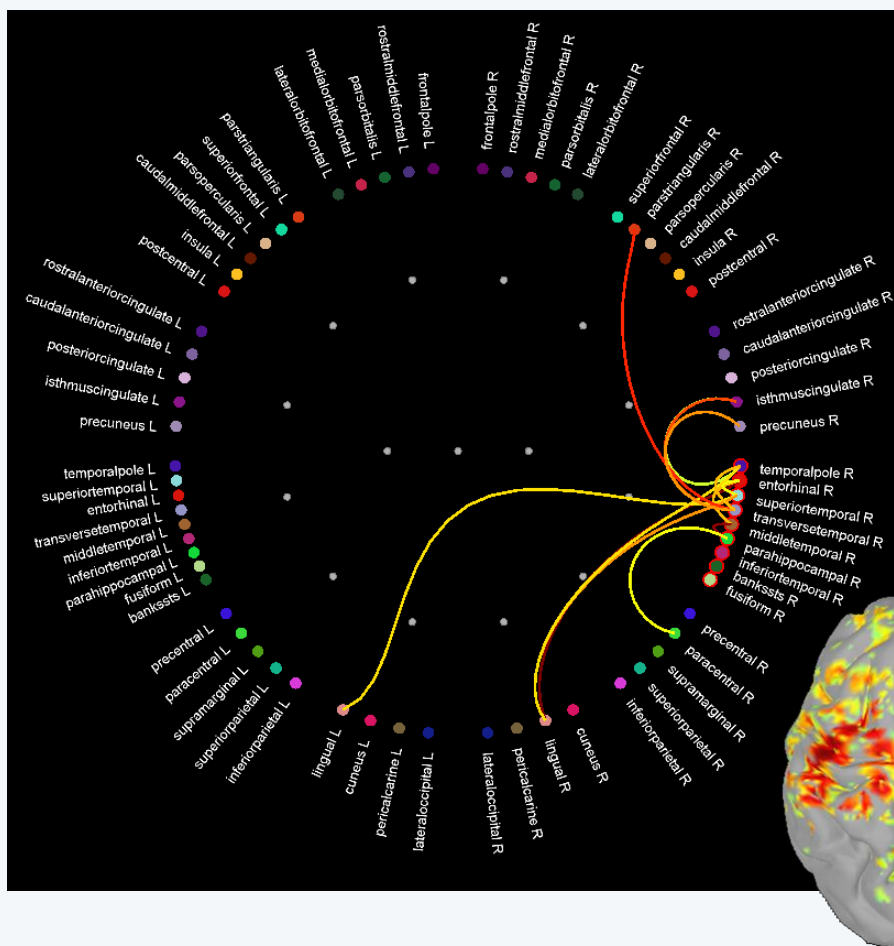
Single subject

Anatomy
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Bad segments

Markers
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Sources
Time-frequency
Other measures

- Connectivity measures



- Correlation
- Coherence
- Phase locking value
- Granger causality

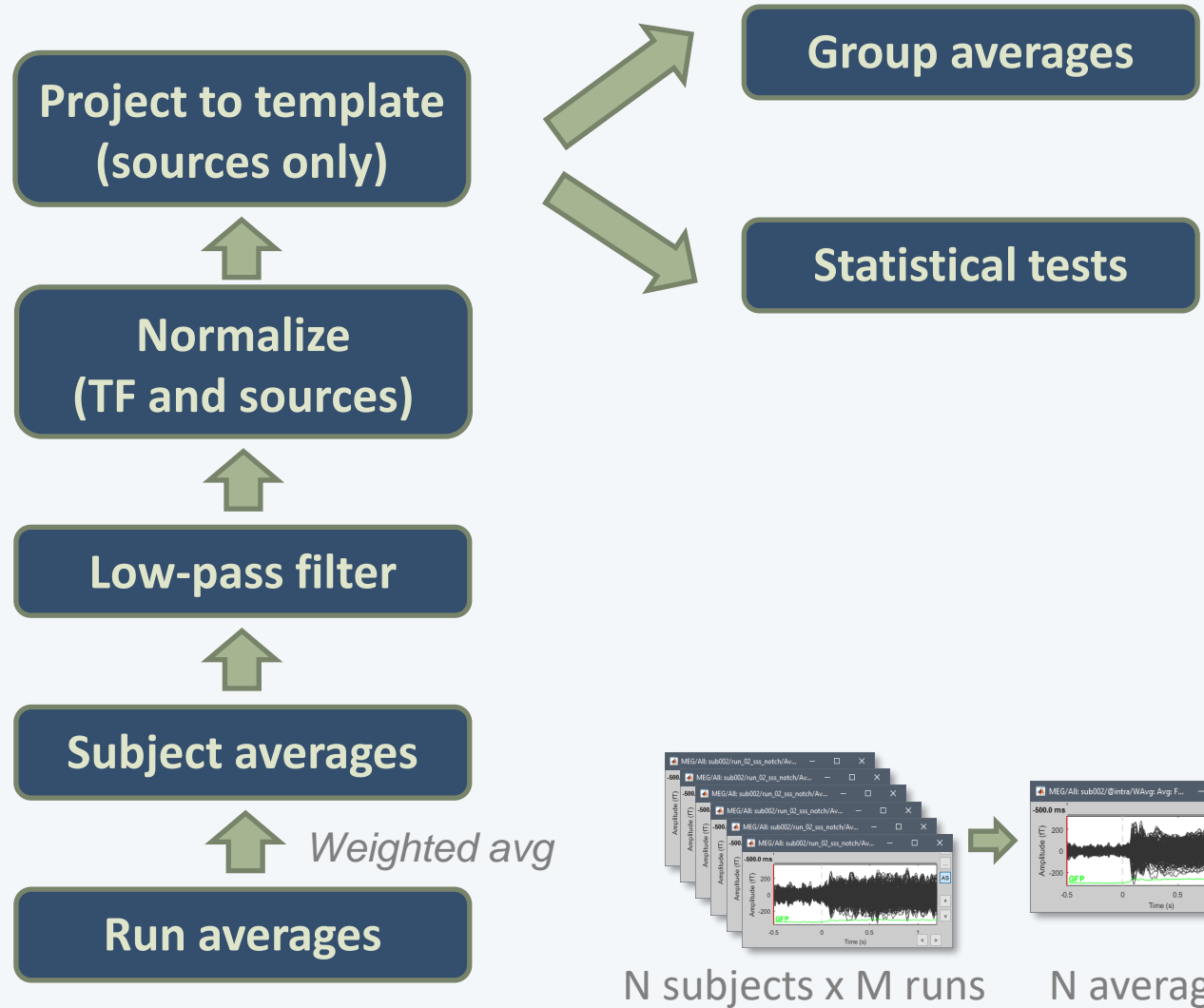


Group analysis

Anatomy
Link recordings
MRI registration

PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency



Group analysis

Subject averages

Low-pass

Normalize

Project

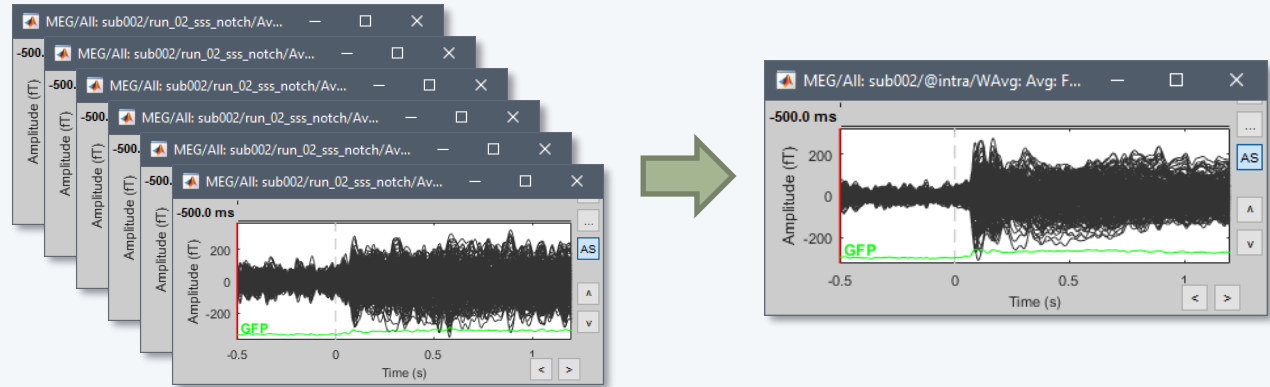
Group averages

Group statistics

Quality control

Workflow

- Weighted average of 6 runs per subject (recordings, sources MEG/EEG, time-frequency)



- Sources: Compute within-subject differences
 - (Faces - Scrambled) and (Famous - Unfamiliar)
 - The sign of the MNE source amplitude is ambiguous, we will apply an absolute value before comparing between subjects

Group analysis

Subject averages

Low-pass

Normalize

Project

Group averages

Group statistics

Quality control

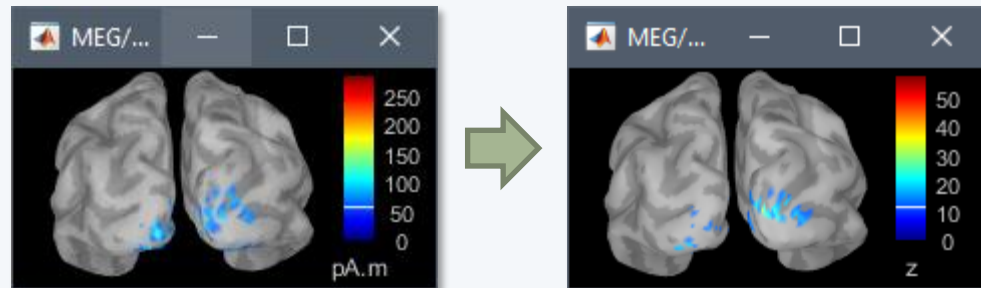
Workflow

- Amplitude normalization before group analysis

Baseline = [-200,0]ms

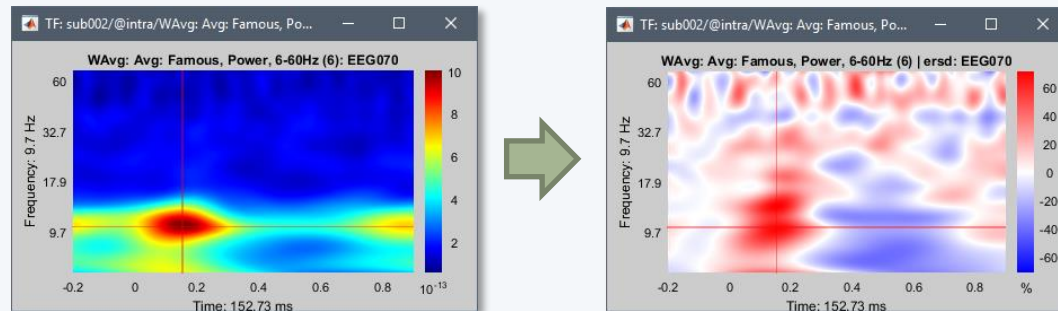
- Sources: Z-score normalization wrt baseline

$$S = (S - \text{mean}(\text{baseline})) / \text{std}(\text{baseline})$$



- Time-frequency: Event-related sync/desync

$$TF = (TF - \text{mean}(\text{baseline})) / \text{mean}(\text{baseline}) * 100$$



Group analysis

Subject averages

Low-pass

Normalize

Project

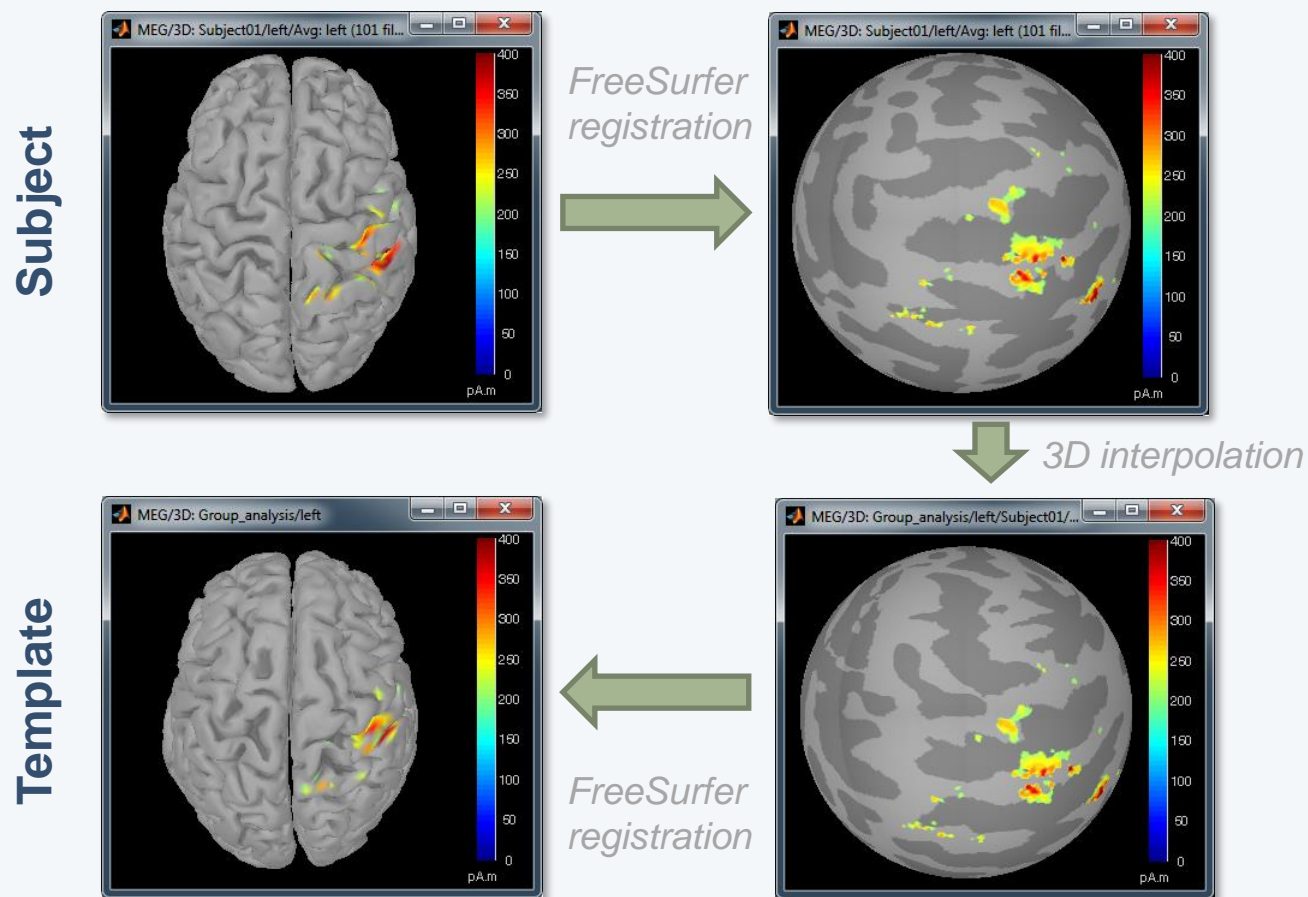
Group averages

Group statistics

Quality control

Workflow

- Using FreeSurfer registration



Group analysis

Subject averages

Low-pass

Normalize

Project

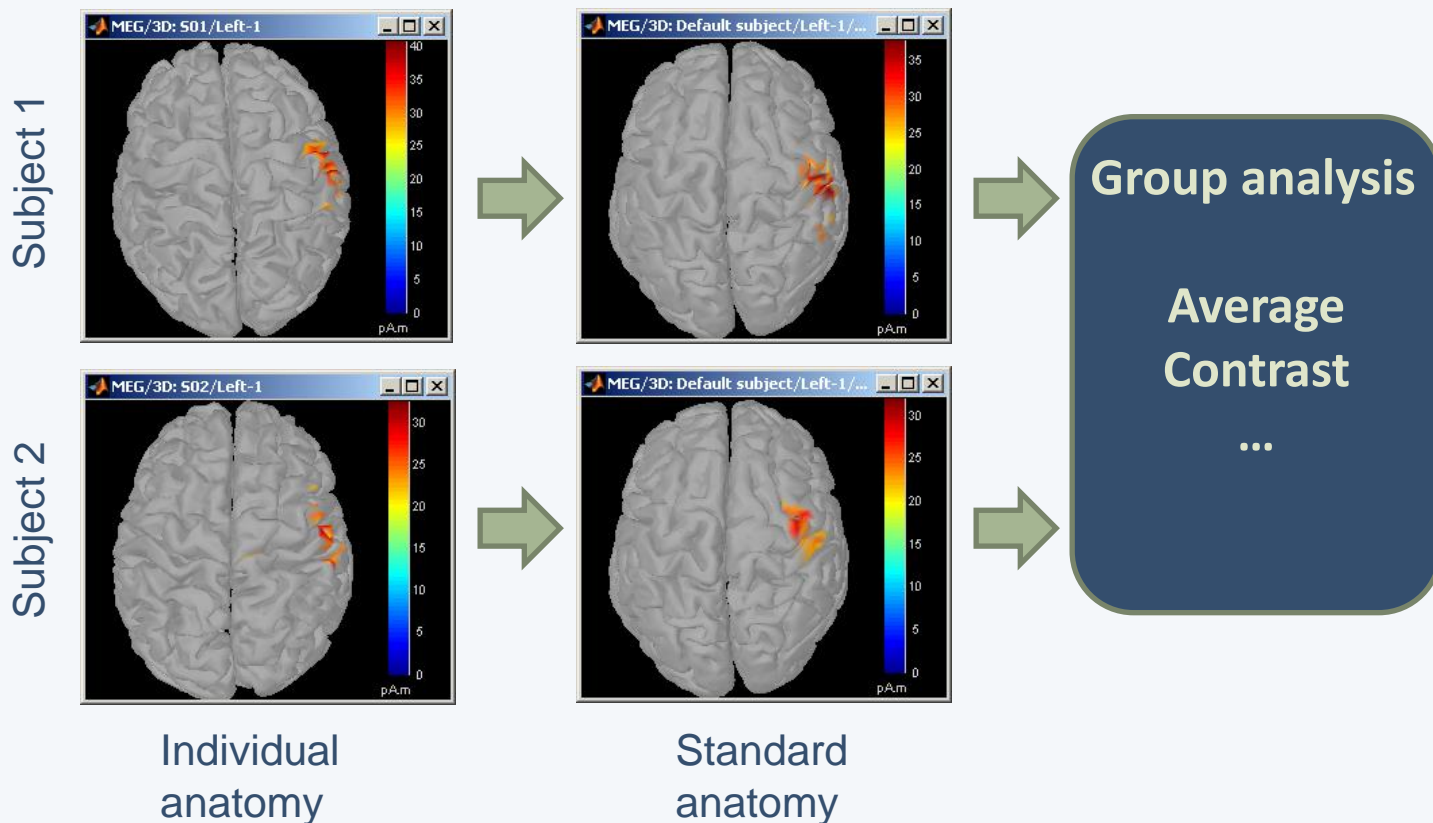
Group averages

Group statistics

Quality control

Workflow

- Registration of individual sources on a template (ICBM152, Colin27, DNI, infants...)



Group analysis

Subject averages

Low-pass

Normalize

Project

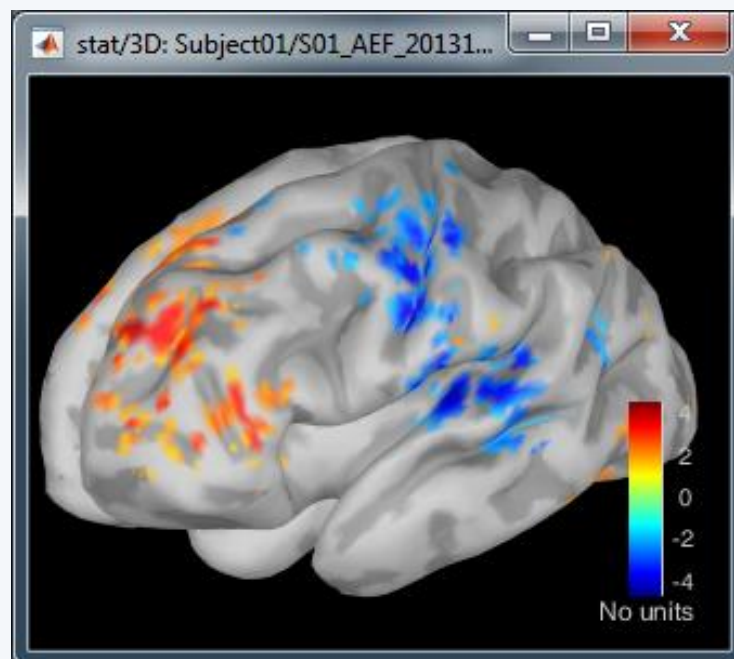
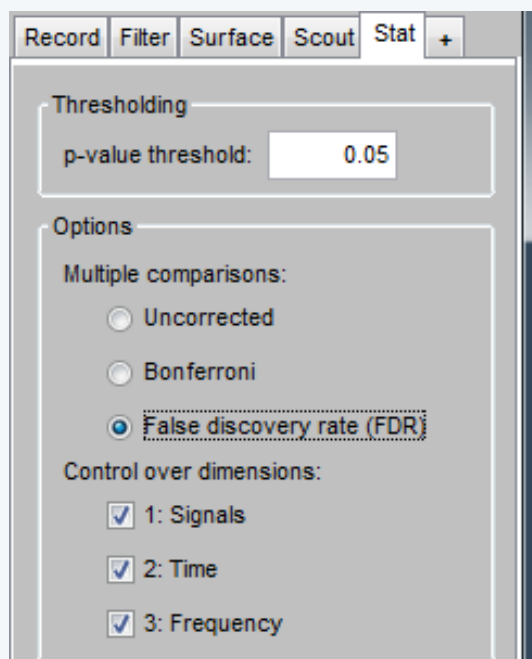
Group averages

Group statistics

Quality control

Workflow

- Contrasts between subjects or conditions
- Parametric t-test
- Cluster-based non-parametric tests
- Export to: **SPM**, R, Excel, SPSS, Matlab...



Group analysis

Subject averages

Low-pass

Normalize

Project

Group averages

Group statistics

Quality control

Workflow

- Execution reports with snapshots saved in HTML

The screenshot shows the 'TutorialGroup' interface with a tree view of analysis steps. The tree is expanded to show 'Intra-subject' analysis. The steps listed are:

- Group analysis
 - Common files
 - Intra-subject
 - Avg: WAvg: Avg: Faces (16 files) | low(32Hz) | tim
 - Avg: WAvg: Avg: Famous (16 files) | low(32Hz) | ti
 - Avg: WAvg: Avg: Scrambled (16 files) | low(32Hz)
 - Avg: WAvg: Avg: Unfamiliar (16 files) | low(32Hz) |
 - Faces - Scrambled
 - Famous - Unfamiliar
 - mean(|Faces-Scrambled) | MEG
 - mean(|Faces-Scrambled) | EEG
 - mean(|Faces)-mean(|Scrambled) | MEG
 - mean(|Faces)-mean(|Scrambled) | EEG
 - Faces - Scrambled: Cluster t-test EEG
 - Famous - Unfamiliar: Cluster t-test EEG
 - Faces - Scrambled: Parametric t-test
 - Faces - Scrambled: Permutation t-test
 - Famous - Unfamiliar: Parametric t-test
 - |Faces-Scrambled|=0: Parametric Chi2 test | MEG
 - log(|Faces-Scrambled)=0: Parametric Chi2 test | ME
 - |Faces|=Scrambled: Parametric t-test | MEG
 - |Faces-Scrambled|=0: Parametric Chi2 test | EEG
 - log(|Faces-Scrambled)=0: Parametric Chi2 test | ME
 - |Faces|=Scrambled: Parametric t-test | MEG

The screenshot shows an execution report window titled 'Report: C:\Users\francois\brainstorm\reports\report_TutorialScript_130125_1735.mat'. The report shows '0 errors and 3 warnings'. The warnings are:

- process_import_freesurfer: warning [No input] Errors detected in the events of the AUX file (markers at the beginning of a trial): Removed 1 x "left": 82.500, Removed 1 x "right": 276.000
- process_sin_remove: warning Subject01@[rawsubj001_somatosensory_20111109,...] Cannot overwrite native files.
- process_evt_detect_eog: info Subject01@[rawsubj001_somatosensory_20111109,...] EEG058: 30 events detected in 2 categories

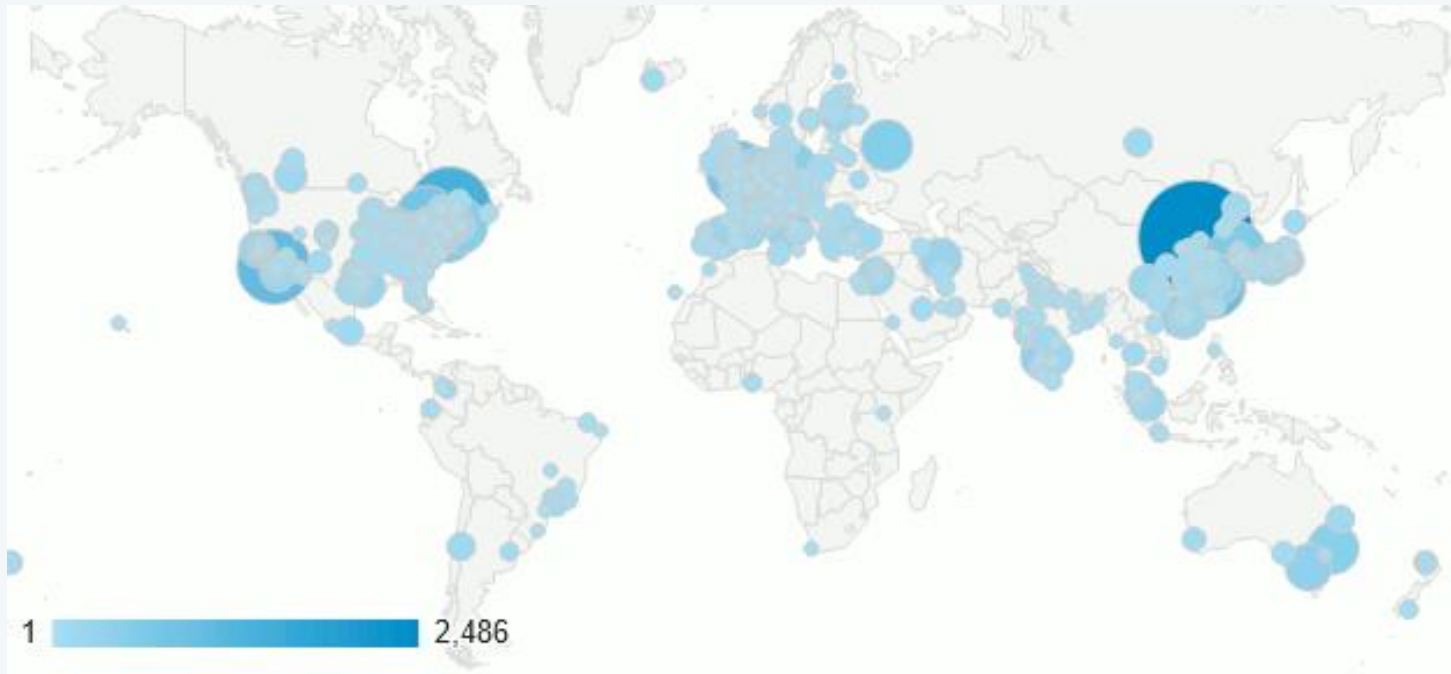
The report also lists 'Initial files' (None) and 'Intermediate files' (various .mat files, some deleted). Below the report, there are two windows showing 'Snapshots'. The top window shows a 3D brain model with a red region of interest. The bottom window shows two time-series plots of 'Amplitude (T)' vs 'Time (s)' for 'Subject01/left/data_average_130125_1254.mat' and 'Subject01/right/data_average_130125_1254.mat'. Both plots show a sharp peak around 0.05s, with a green line indicating the 'GFP' (Global Field Power) component.

Add your code to Brainstorm

- Direct manipulation of the files in Matlab
- Use the menu “Run Matlab command”
- Write a plugin:
 - Well documented API
 - Lots of example (170 functions written as plugins)
 - Open-source GitHub repository
- Examples of recent external contributions:
 - MVPA decoding (Oliva, MIT)
 - Microstate segmentation (Cacioppo, UChicago)
 - Eyetracker/EEG synchronization (Uni Freiburg)

User community (2023)

- 40,000+ users registered on the website



Find users next to you

Location:

Users found: 847

User support

- Online tutorials: 30-hour self-training program
- Active user forum: 150 posts/month
- Daily updates: 1500 downloads/month



Brainstorm Edit Search

Get started

- Software**
 - Introduction
 - Gallery
 - Download
 - Installation
- Users**
 - Tutorials
 - Forum
 - Courses
 - Community
 - Publications
- Development**
 - What's new

Starting a new study

1. Create a new protocol [9]
2. Import the subject anatomy [8]
3. Explore the anatomy [13]

Reviewing

4. Channel file / MRI registration [11]
5. Continuous recordings [9]
6. Multiple windows [5]
7. Event markers [10]

Pre-processing

8. Stimulation delays [9]
9. Select files / Run processes [11]
10. Power spectrum / Frequency filters [15]
11. Bad channels [6]
12. Artifact detection [8]
13. Artifact cleaning with SSP [16]
14. Additional bad segments [7]

Epoching and averaging

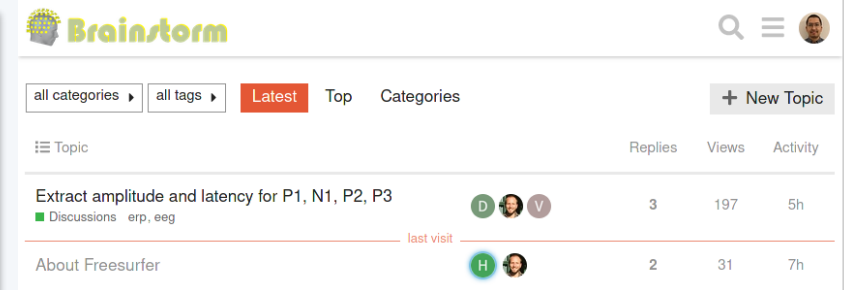
15. Import epochs [9]
16. Average response [7]
17. Visual exploration [10]
18. Colormaps [5]
19. Clusters of sensors [4]

Source modeling

20. Head model [9]
21. Noise/data covariance
22. Source estimation [28]
23. Scouts [17]

Advanced processing

24. Time-frequency [33]
25. Difference [13]
26. Statistics [30]
27. Workflows [10]
28. Scripting [31]



Brainstorm Search

all categories all tags Latest Top Categories + New Topic

Topic	Replies	Views	Activity
Extract amplitude and latency for P1, N1, P2, P3 Discussions erp, eeg	3	197	5h
About Freesurfer	2	31	7h



@BrainstormSoftware



@brainstorm2day



@brainstorm-tools

Contributors

Investigators



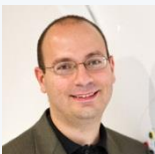
Sylvain Baillet
MNI



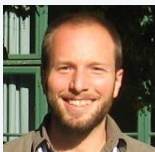
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Cleveland Clinic



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MIT



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Raymundo Cassani
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Marc Lalancette
MEG manager, MNI

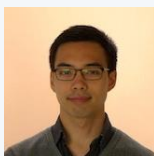
McGill



Konstantinos Nasiotis
Post-doc

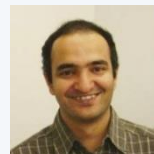


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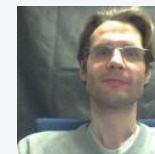


Juan García-Prieto
Martinos Ctr, MGH

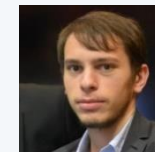
NIRSTORM



Christophe Grova
Concordia



Thomas Vincent
Montreal Heart Inst.

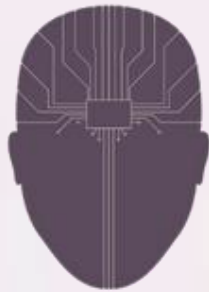


Edouard Delaire
Concordia

Next Brainstorm Workshop

2nd International Conference on

Artificial Intelligence in Epilepsy and Neurological Disorders



April 1st – 4th 2024

Park city, ut, usa

www.AIEPILEPSY-NEURO.com

Algorithms, machine learning, deep learning and artificial intelligence in epilepsy and neurological disorder clinical care, practice and research with special emphasis on devices, wearables, apps and platforms

This year on April 1st we will also hold a special Workshop on the Brainstorm Platform for Clinicians and Scientists and its use in Stereotactic EEG and Epilepsy Surgery

Organizing Committee:

Sam Lhatoo MD, Philippe Ryvlin, Michael Sperling, Sandor Beniczky

For any information: Aiepilepsy-neuro@ant-congres.com

Team today



**Raymundo
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**Takfarinas
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**Woojae
Jeong**



**Chinmay
Chinara**



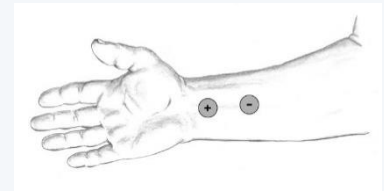
**John
Mosher**



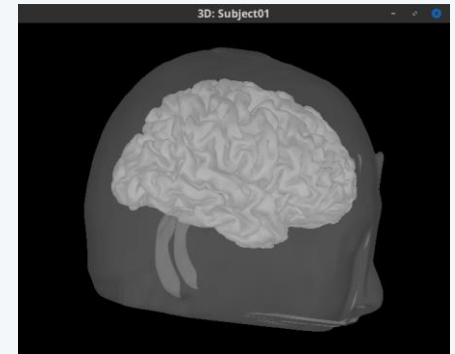
**Richard
Leahy**

Median nerve stimulation

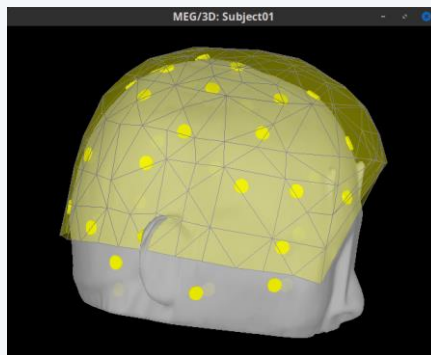
- Right arm stimulation: monophasic square-wave duration 0.3 ms at 2.8 Hz
- 1 participant / 1 run / 336 stimuli
- Individual MRI, processed with CAT12
- MEG: Yokogawa 160 axial gradiometers @ 2000 Hz
- EEG: Nihon Kohden 41 electrodes @ 2000 Hz



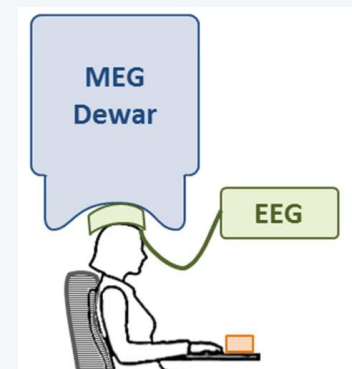
Median nerve percutaneous stimulation



Scalp and cortical surface



EEG electrodes and MEG helmet



Simultaneous MEG and EEG acquisition