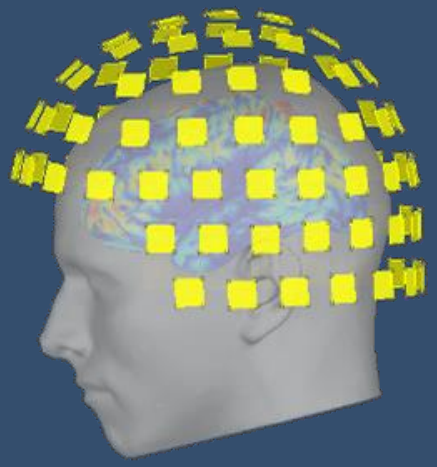
MEG and EEG analysis using

Brainstorm

http://neuroimage.usc.edu/brainstorm



USC University of Southern California

Cleveland Clinic

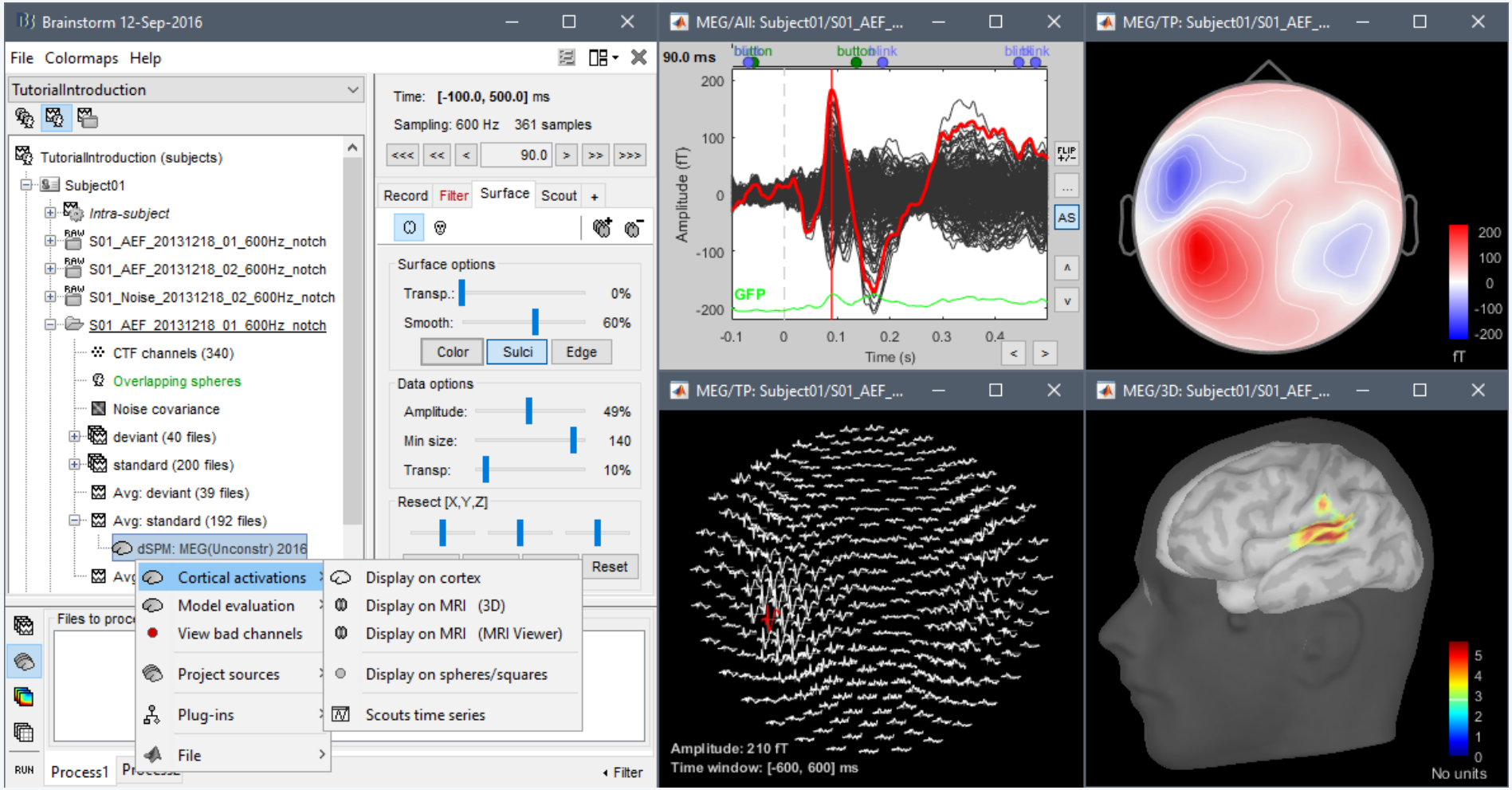
McGill

neuro

Cambridge, June 2017

Francois Tadel
Sylvain Baillet

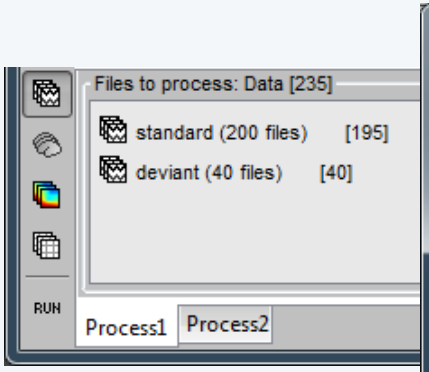
Graphic interface

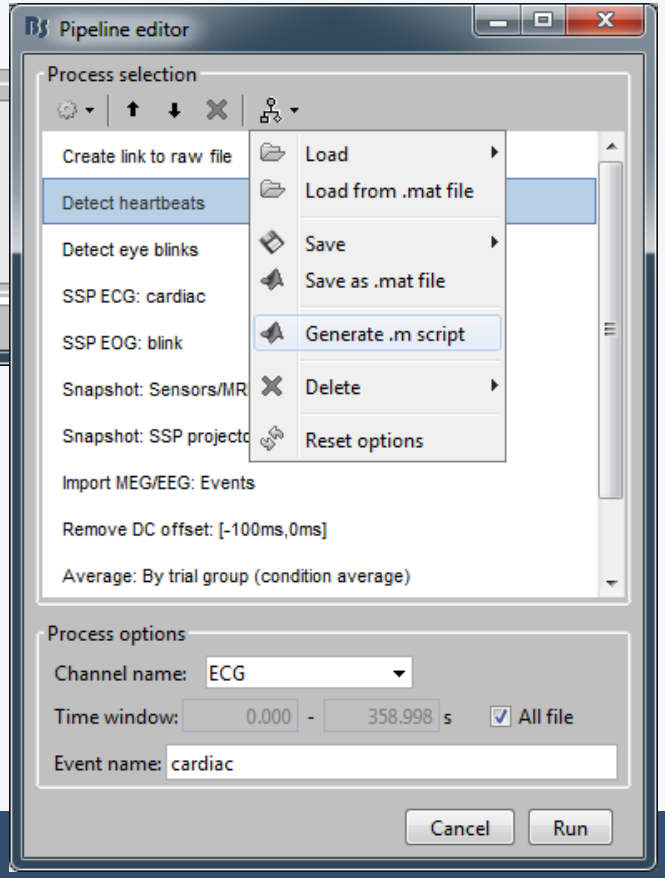


Brainstorm

Scripting environment

- Rapid selection of files and processes to apply
- Automatic generation of Matlab scripts
- Plug-in structure: easy to add custom processes






```
% Script generated by Brainstorm v3.1 (17-Dec-2010).
FileNamesA = {'Subject01\Left\data_average_101213_1558.mat', ...
              'Subject01\Right\data_average_101213_1559.mat'};
FileNamesB = [];

% Process: Detect bad trials: Peak-to-peak  MEGGRAD(0-2000)
sFiles = bst_process(...
    'CallProcess', 'process_detectbad', ...
    FileNamesA, FileNamesB, ...
    'timewindow', [-0.0998, 0.3000], ...
    'meggrad', {[0, 2000], 'fT/cm (x 0.04)', 1e-015}, ...
    'rejectmode', 2);

% Process: Remove baseline: [-100ms,-1ms]
sFiles = bst_process(...
    'CallProcess', 'process_baseline', ...
    sFiles, [], ...
    'baseline', [-0.09983, -0.00056], ...
    'overwrite', 1);

% Process: Band-pass filter: 1Hz - 80Hz
sFiles = bst_process(...
    'CallProcess', 'process_bandpass', ...
    sFiles, [], ...
    'f1', 1, ...
    'f2', 80, ...
    'overwrite', 1);

% Process: Average by condition
sFiles = bst_process(...
    'CallProcess', 'process_average', ...
    sFiles, [], ...
    'avgtype', 3, ...
    'isstd', 0);
```

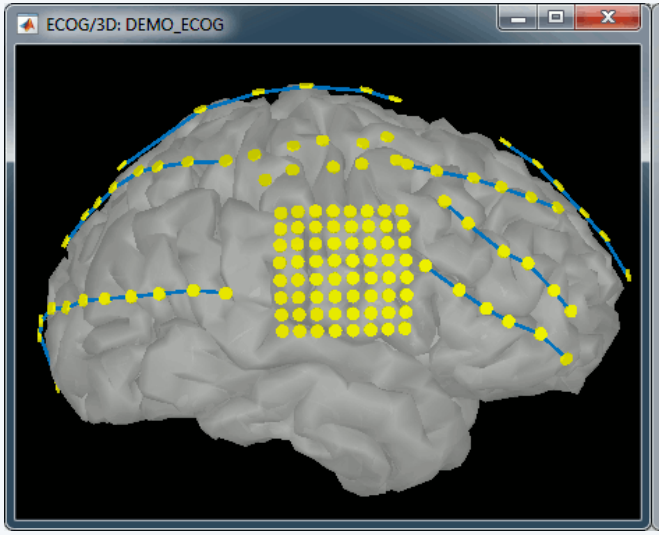
- Free and open-source application
- Matlab & Java: Platform-independent
- Designed for Matlab
- Stand-alone version available
- Interface-based: click, drag, drop
- No programming experience required
- Daily updates of the software
- Supports most common file formats



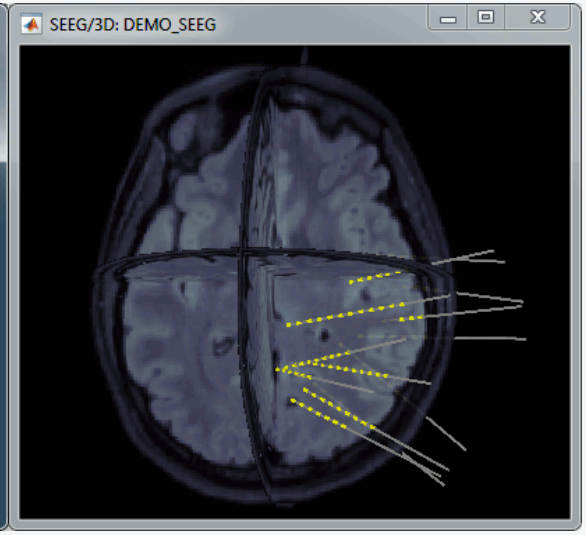


Multi-modal imaging

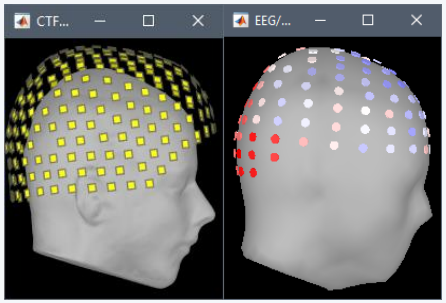
ECoG



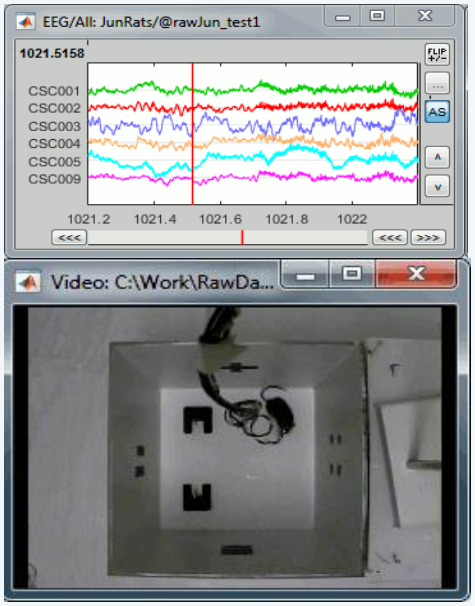
Depth electrodes



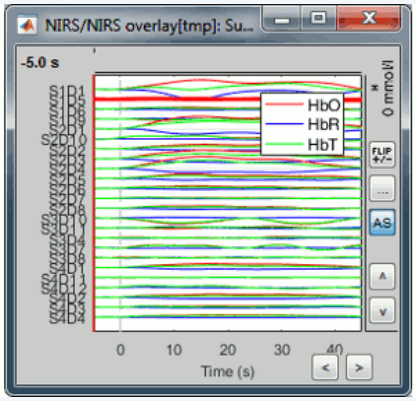
MEG/EEG

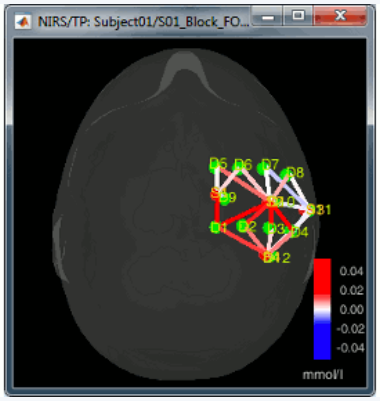


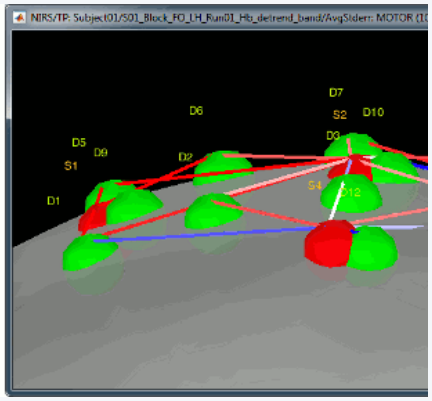
Electrophysiology



fNIRS





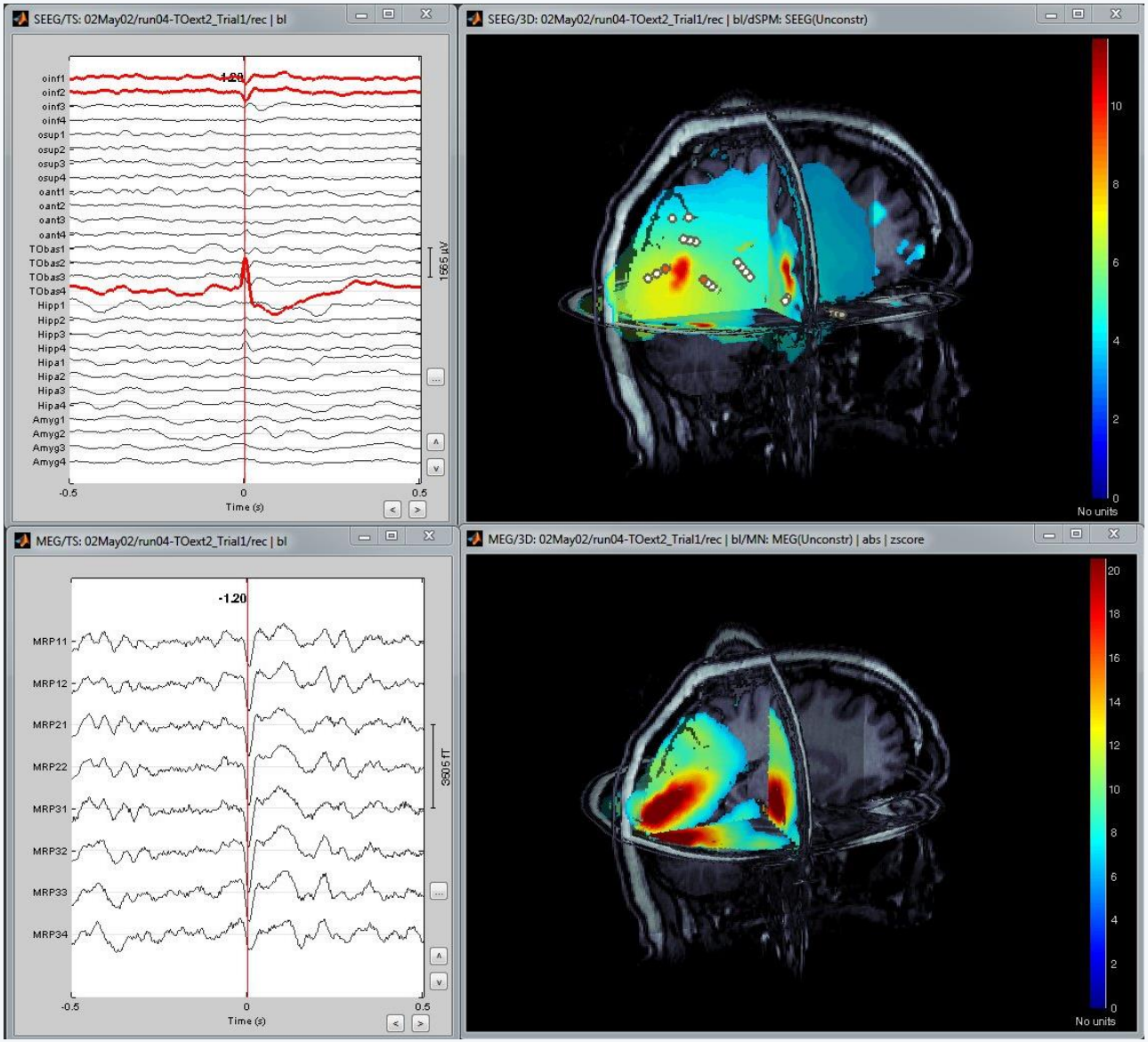


Brainstorm

Multi-modal imaging

Easy integration of:

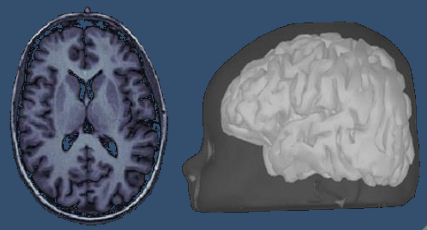
- MEG
- EEG
- ECoG
- SEEG
- Animal LFP
- NIRS



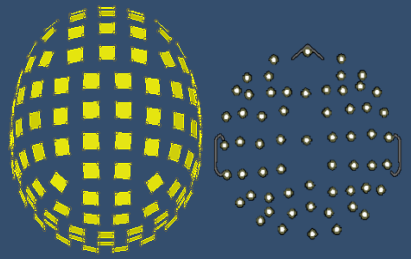
Brainstorm

Workflow

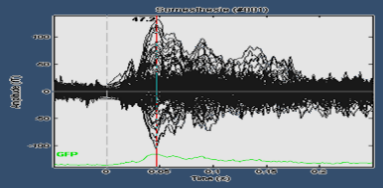
Anatomy



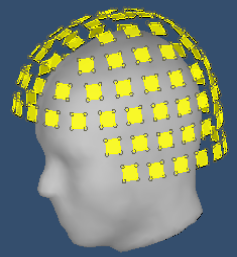
Sensors



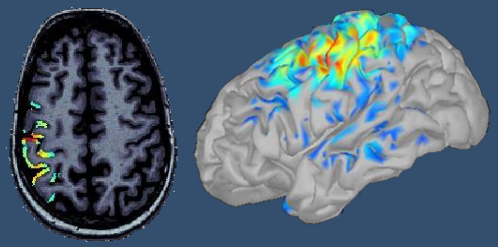
EEG/MEG



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

Markers
Epoching
Averaging
Sources
Time-frequency

Analysis of the experimental data

Loop:
all acquisition runs
all subjects

Import

Anatomy
Link recordings
MRI registration

PSD
Filters
Bad channels
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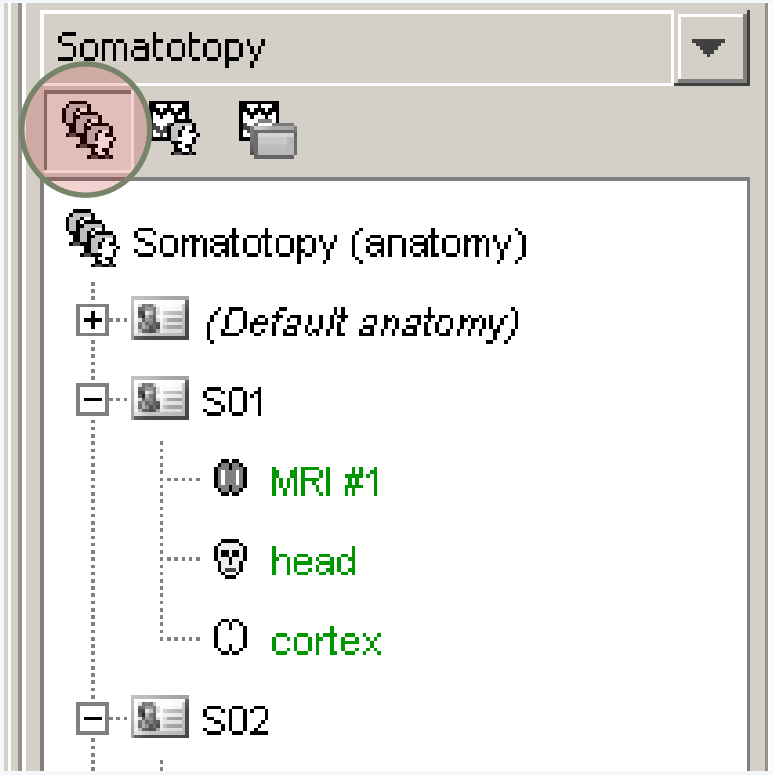
Bad segments

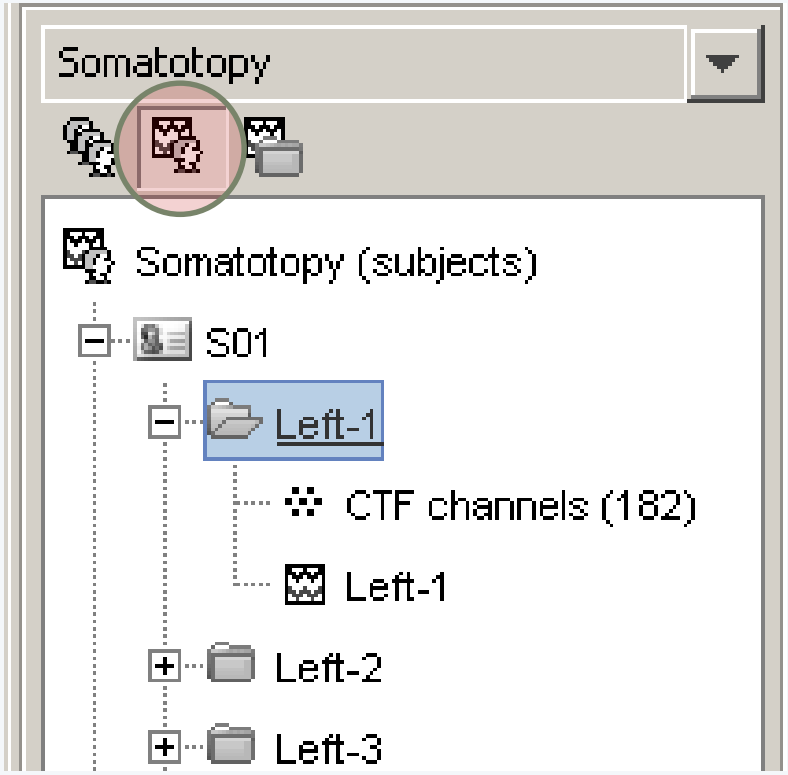
Markers
Epoching
Averaging
Sources
Time-frequency

- One-click import of the T1 segmentation: FreeSurfer, BrainSuite, BrainVISA, CIVET
- Import and place fiducials in the MRI (N,L,R)

Brainstorm

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

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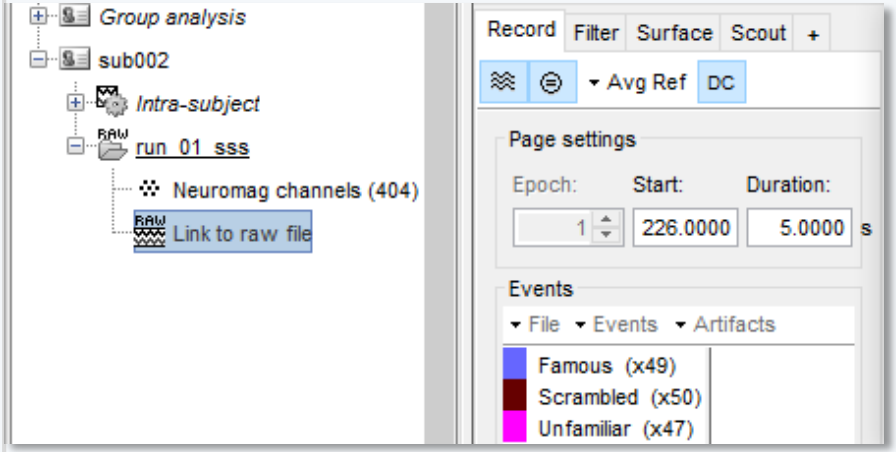
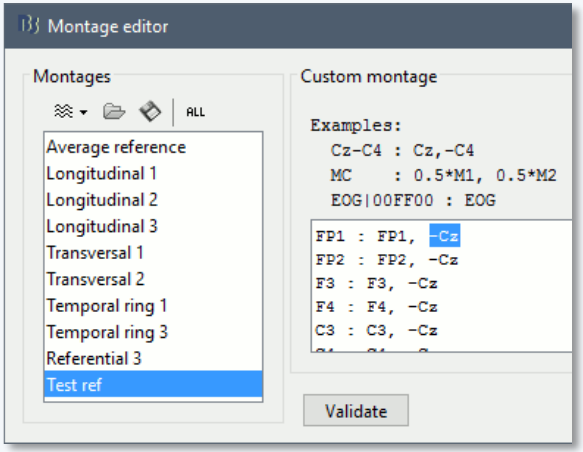
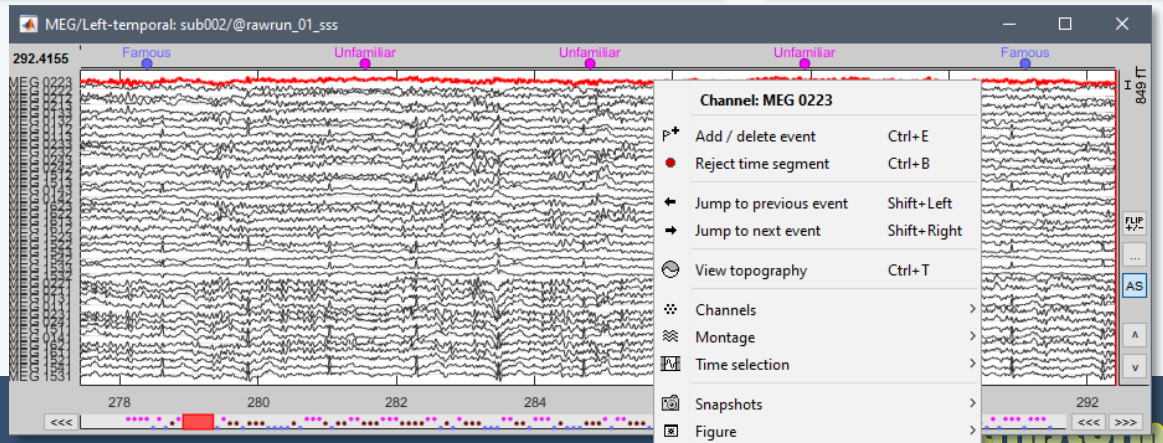
Markers
Epoching
Averaging
Sources
Time-frequency

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

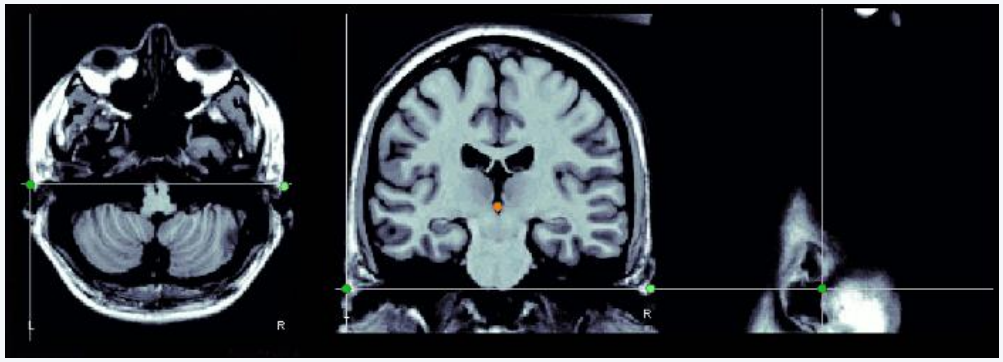






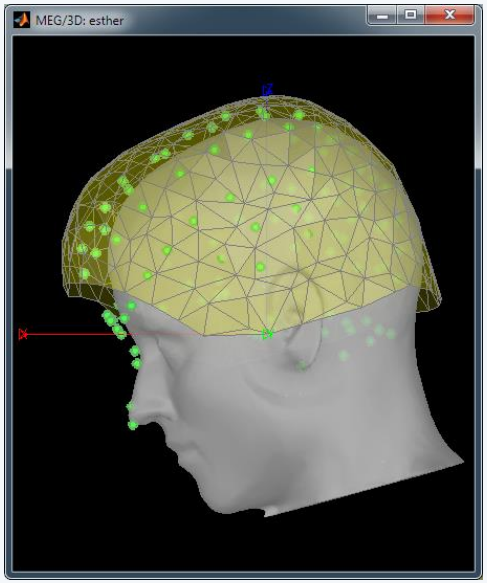
Co-registration MEG / MRI (1)

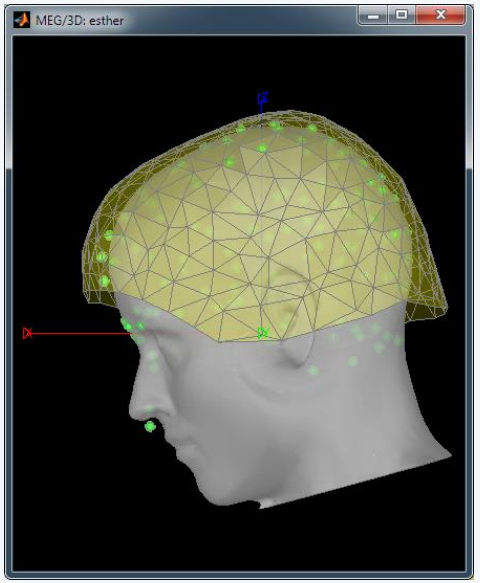
- Basic estimation based on three points:
  Nasion (NAS), Left ear (LPA), Right ear (RPA)
- MRI: Marked in the volume with the MRI Viewer
- MEG: Obtained with a tracking system (Polhemus)



Co-registration MEG / MRI (2)

- 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





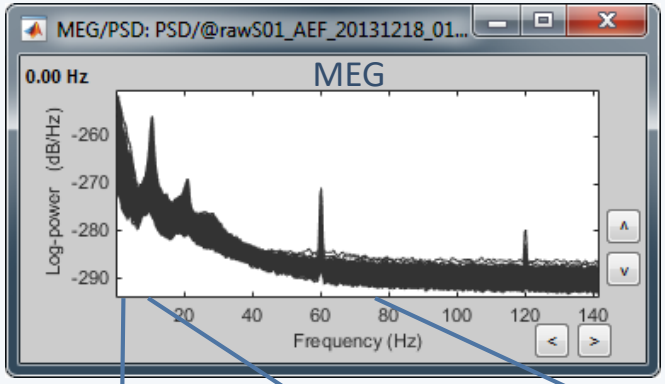
Quality control

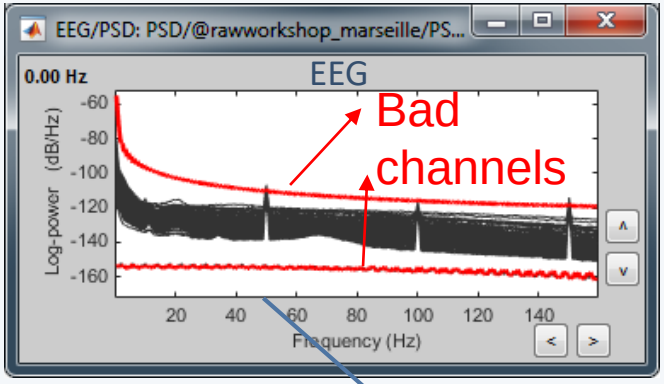
Anatomy
Link recordings
MRI registration

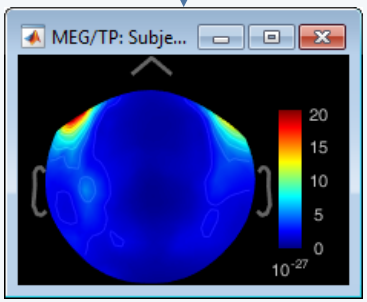
PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

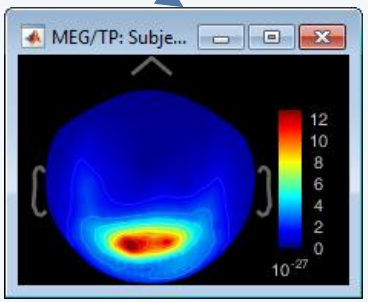
Markers
Epoching
Averaging
Sources
Time-frequency

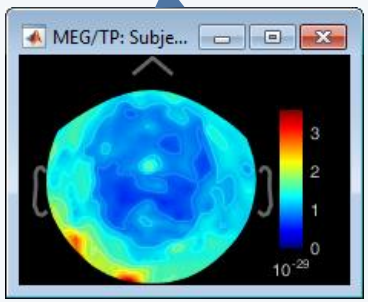
- Power spectrum density for quality control

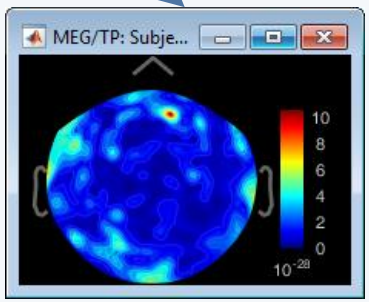












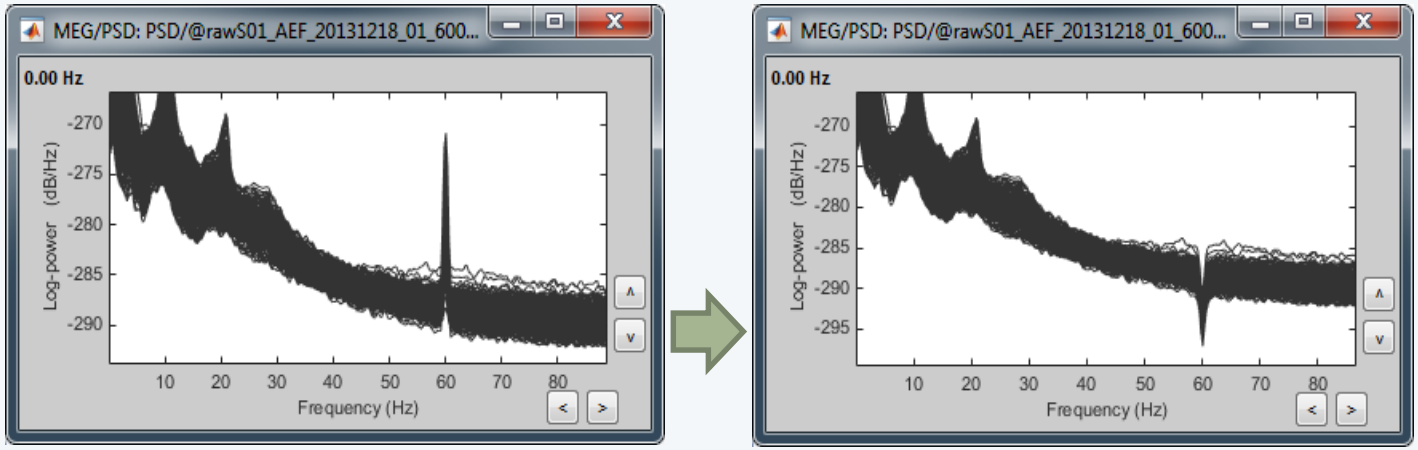
< 3Hz: Eyes | 10Hz: Alpha | > 40Hz: Muscle | 50/60Hz

Brainstorm

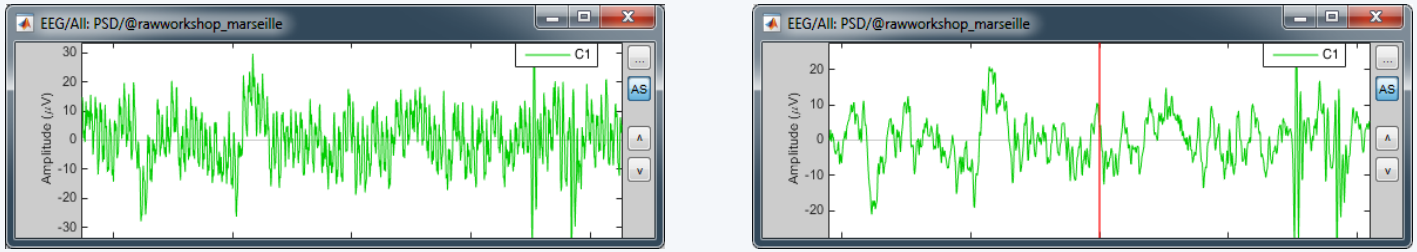
Pre-processing

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

PSD

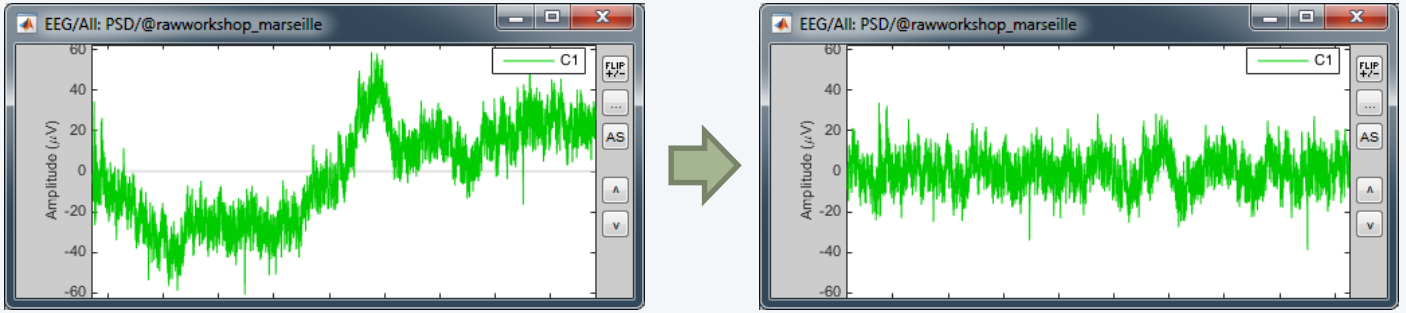


Signal

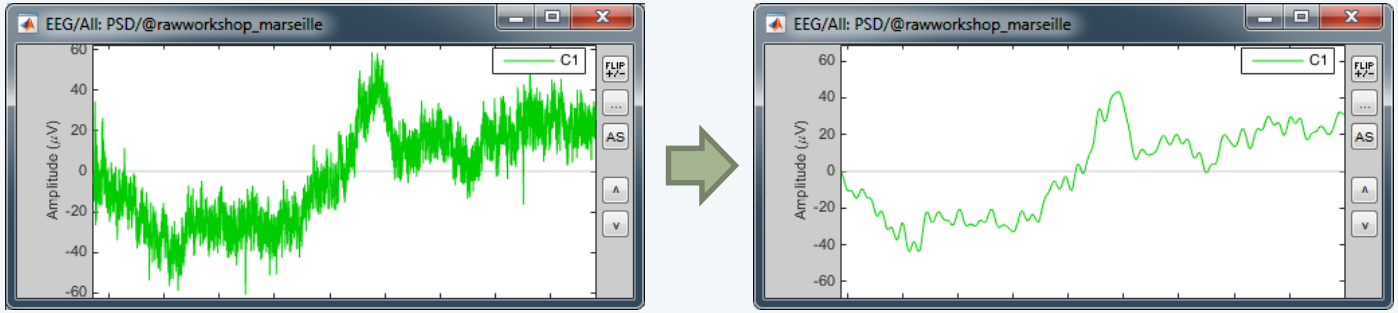


Pre-processing

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

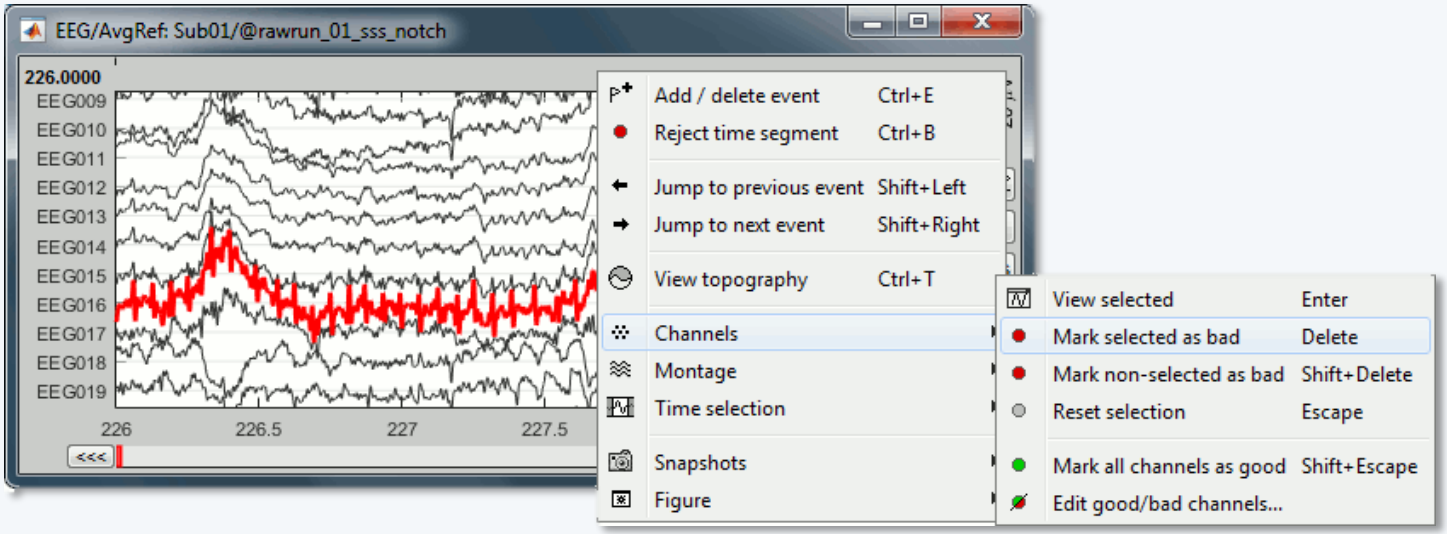


- Low-pass filter: Remove high-frequencies



Pre-processing

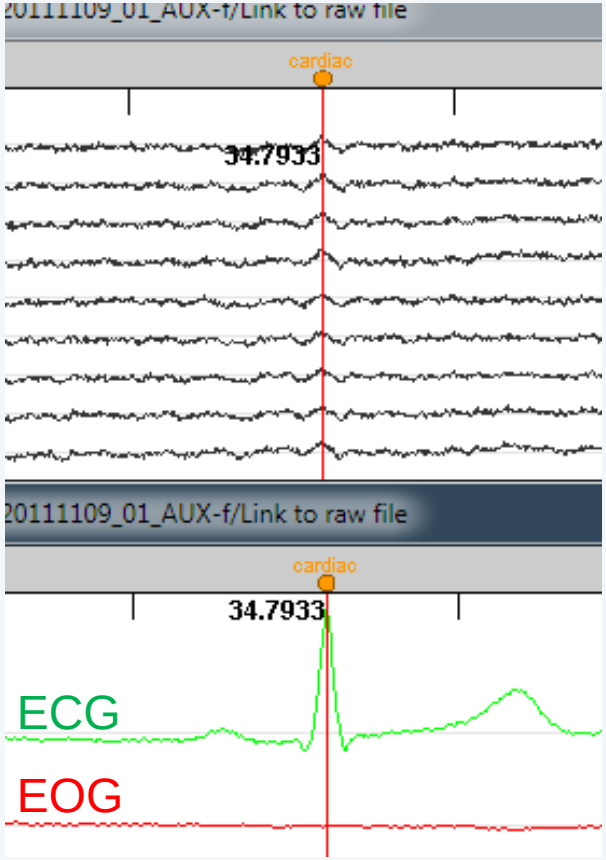
- Manual inspection of the recordings
- Interactive selection of bad channels
- Re-reference the EEG if necessary (Average ref)

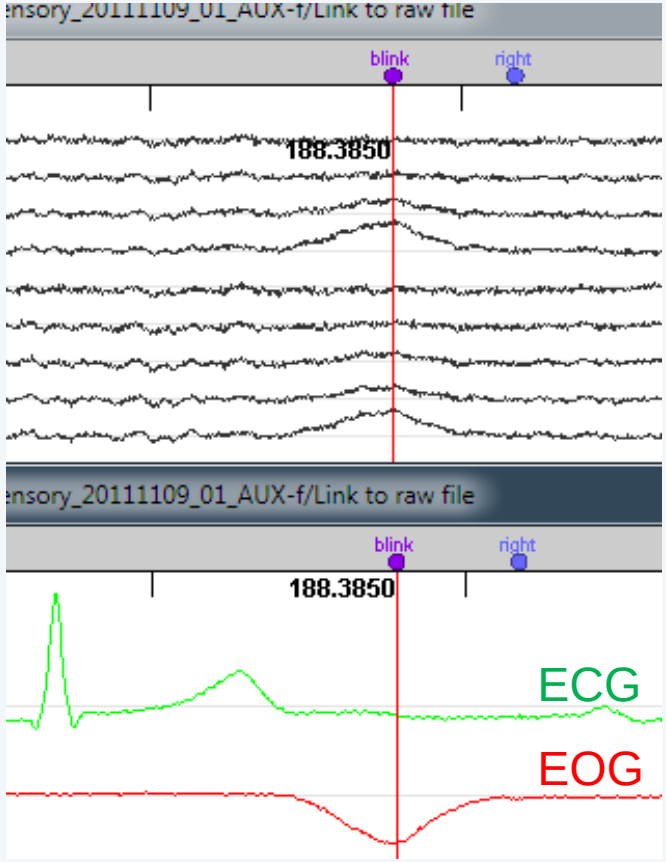


Brainstorm

Pre-processing

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





Brainstorm

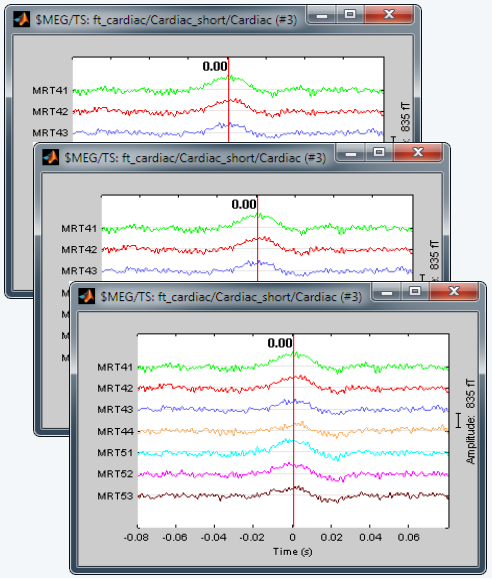
Artifact correction

- 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

Pre-processing

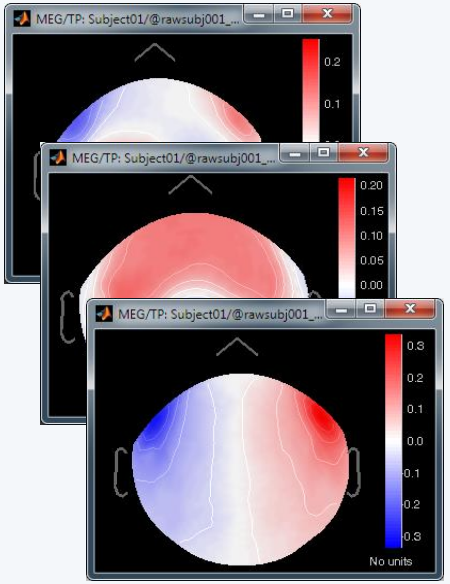
- Correction with Signal Space Projections (SSP)

Detect artifacts



PCA

Spatial components



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

Brainstorm

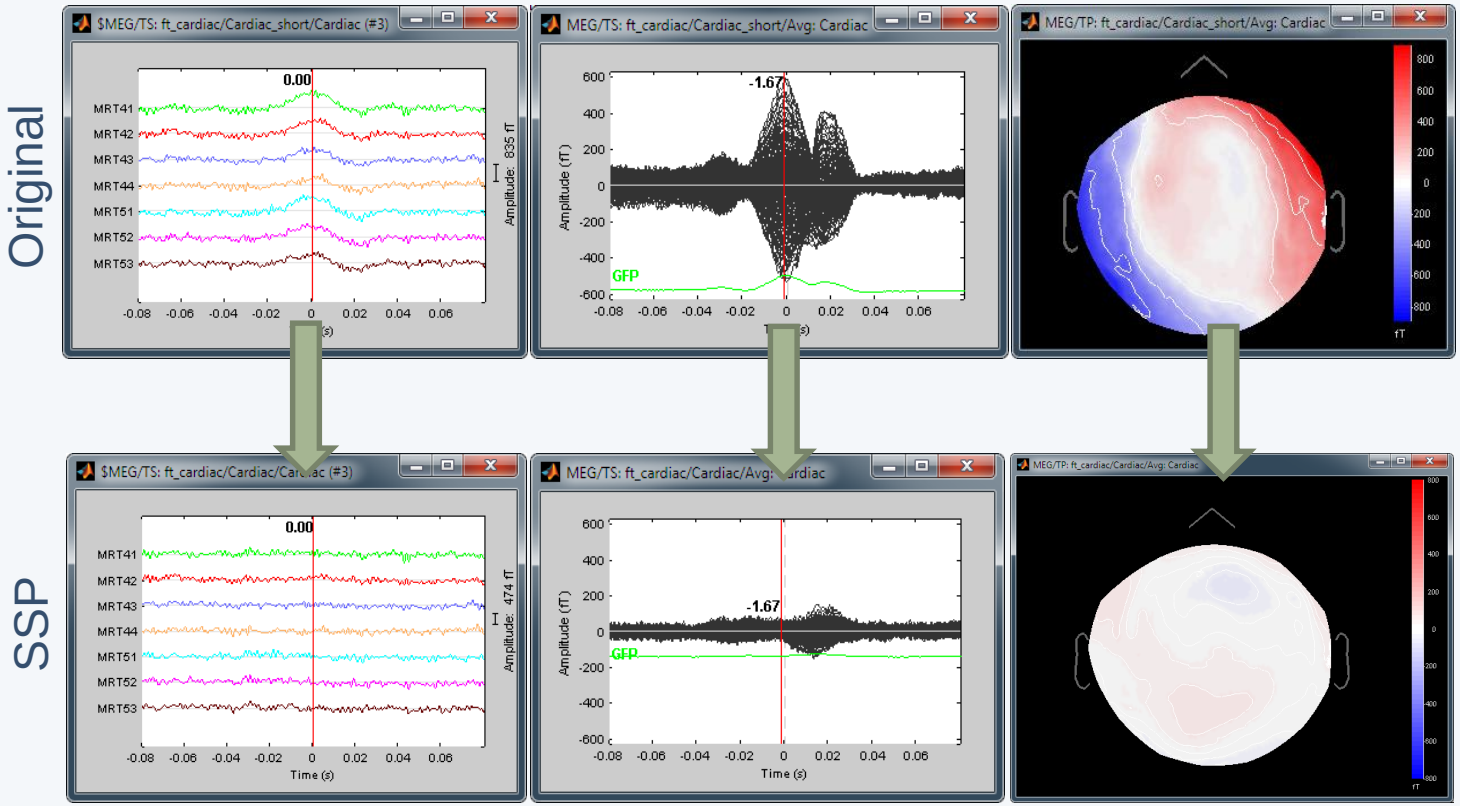
Pre-processing

Anatomy
Link recordings
MRI registration

PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

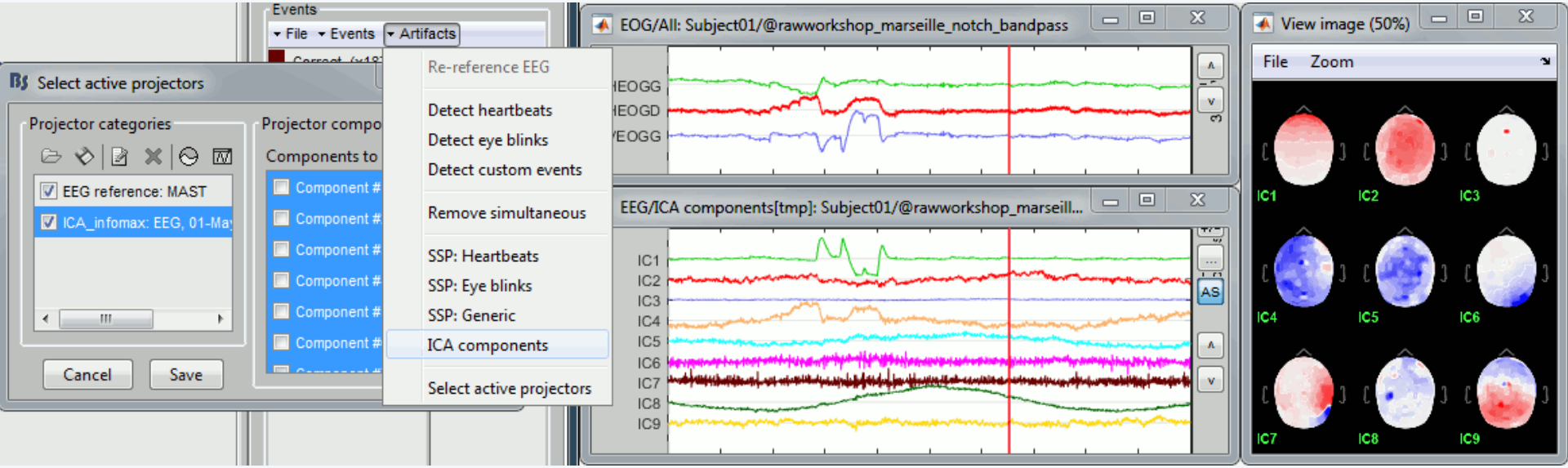
- Example: Cardiac artifact



Brainstorm

Pre-processing

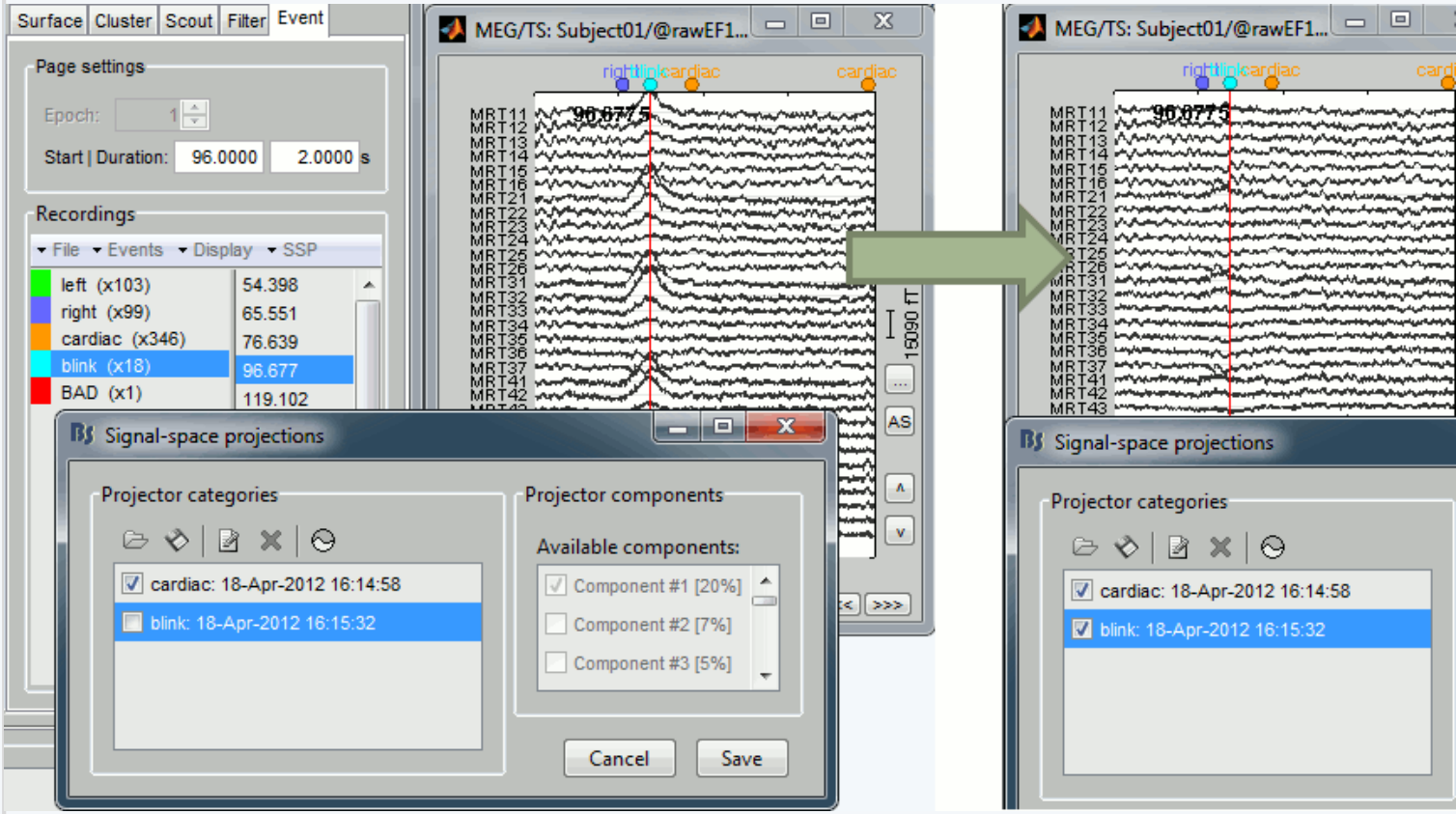
- Independent component analysis (ICA):
  - Popular in the EEG literature
  - Alternative to SSP for low number of sensors
  - Already implemented: Infomax and JADE (EEGLAB)



Brainstorm

Pre-processing

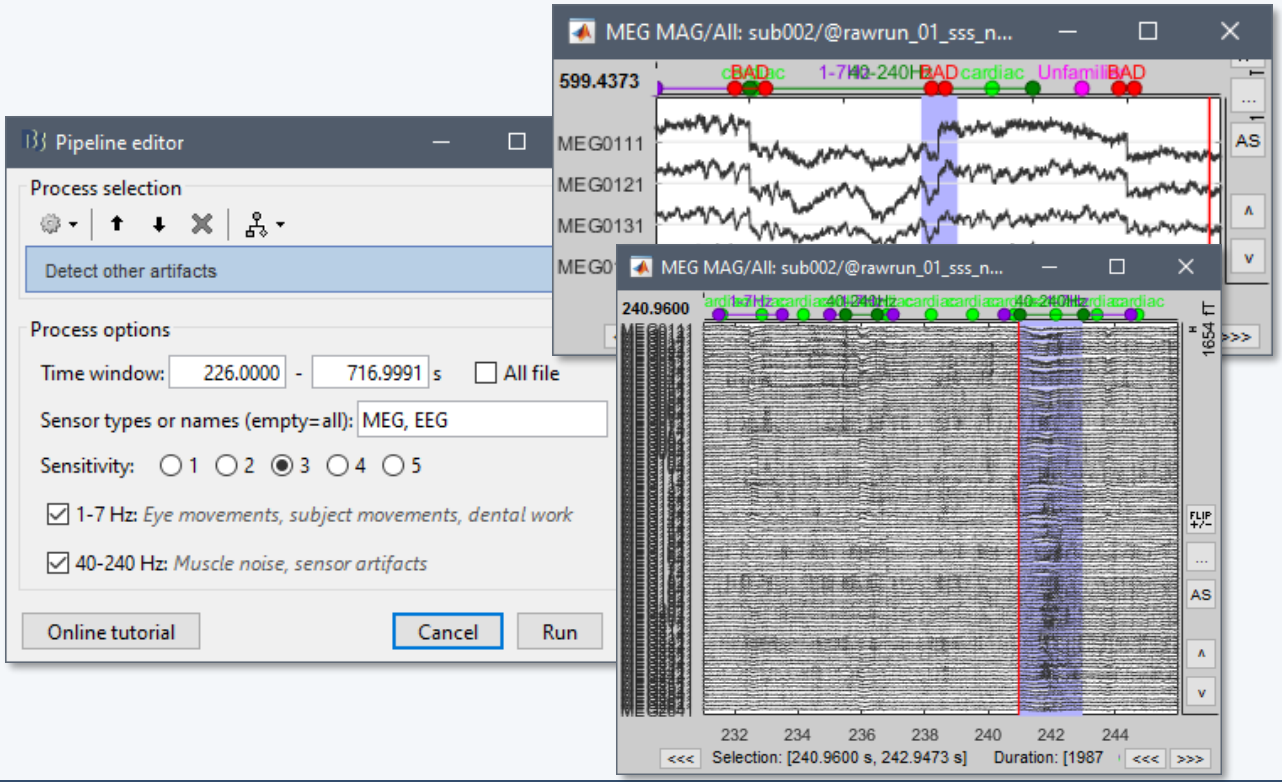
- Example: Blink



Brainstorm

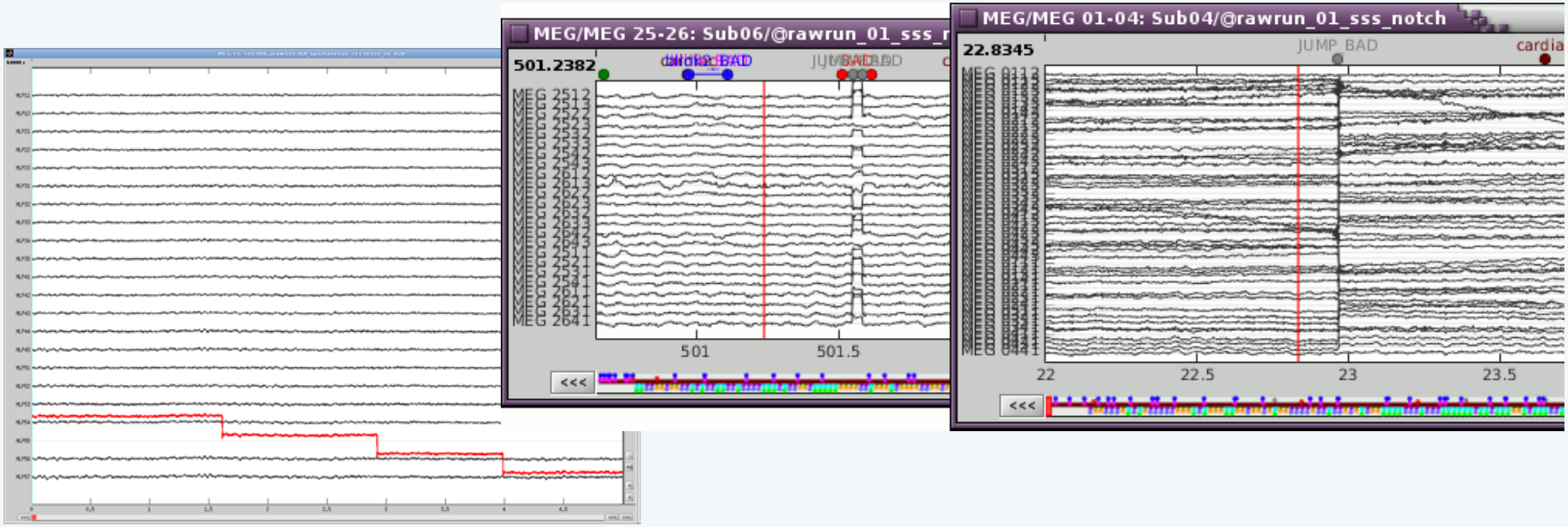
Pre-processing

- 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



Brainstorm

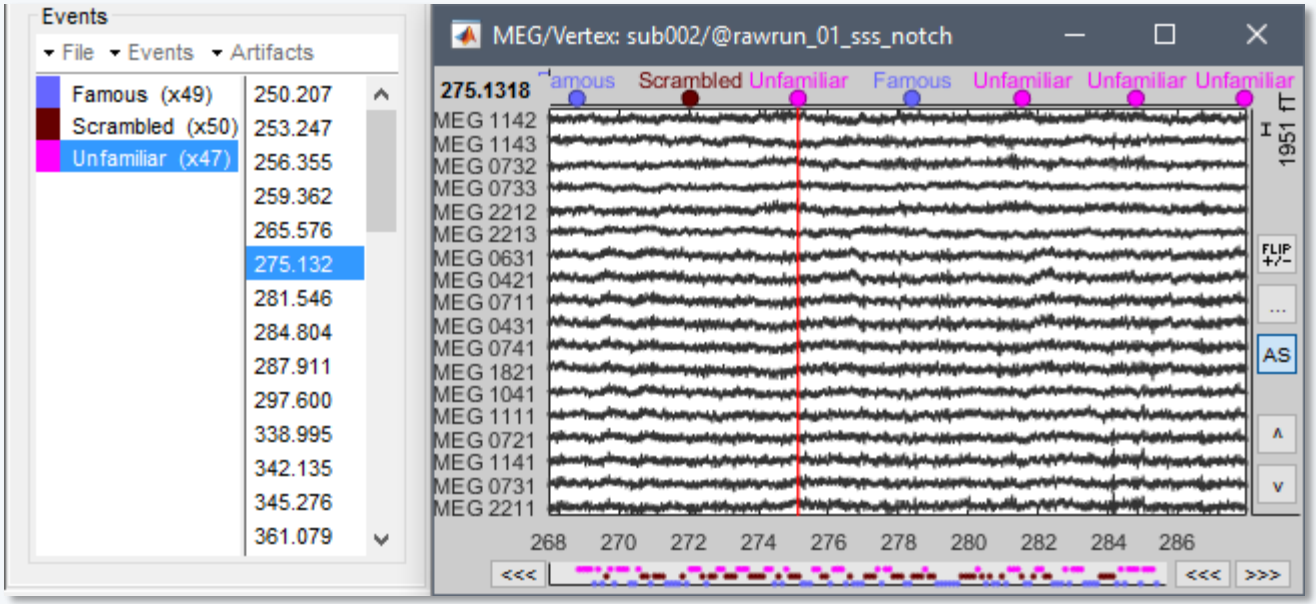
- Sharps steps followed by a change of baseline value
- Mark the channels as bad before running MaxFilter
- Or mark the segments as bad in Brainstorm



Epoching

- Two types of experiments:
  - Steady-state or resting-state (ongoing activity)
  - Event-based (stimulus, response, spike…)

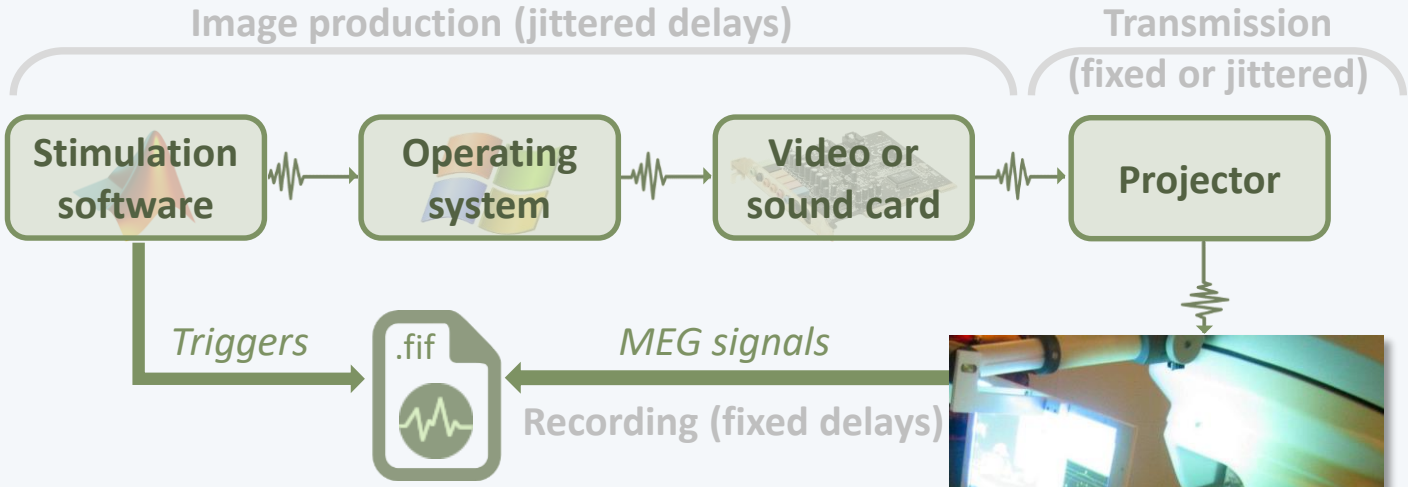
- How to get event markers in the recordings?

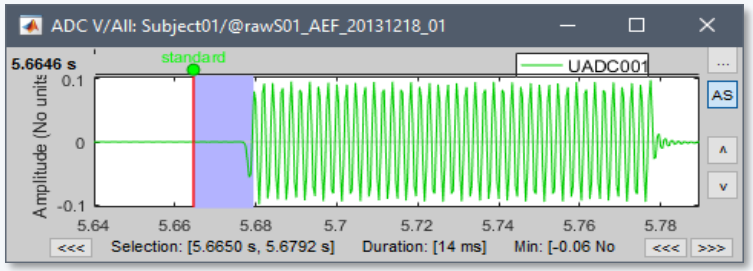


Brainstorm

Epoching

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

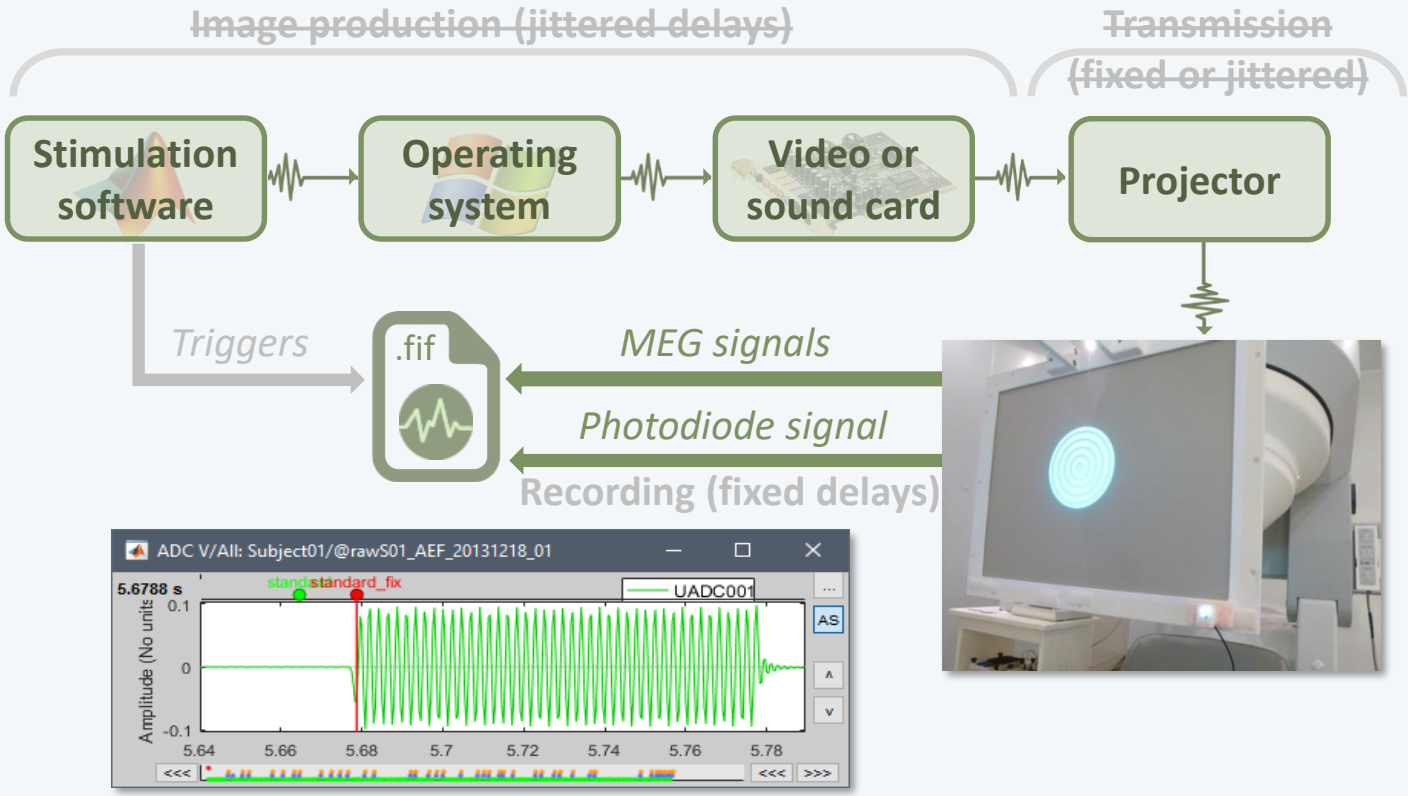




- File triggers are never aligned with the real stim

Epoching

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

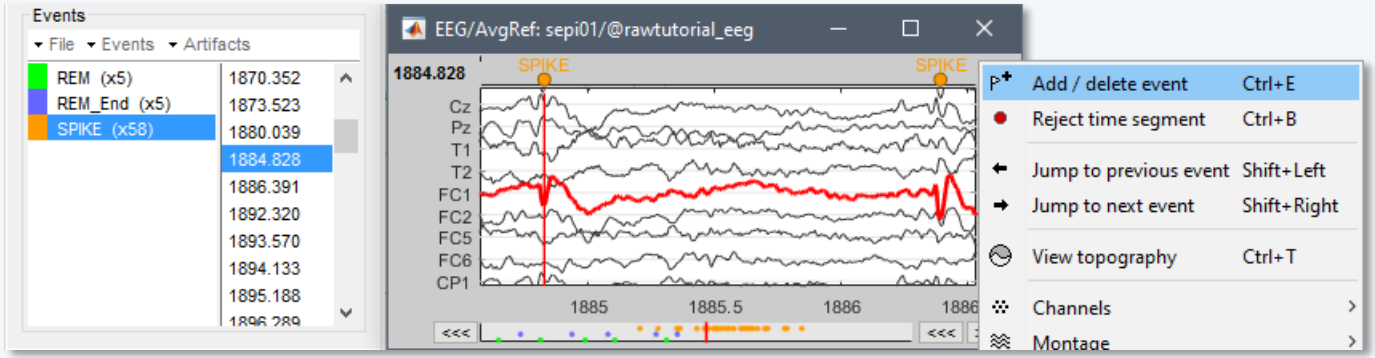


- Avoids most uncontrollable jittered delays

Brainstorm

Epoching

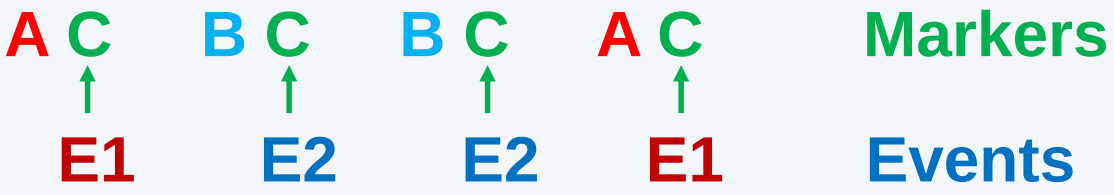
- Reading the triggers saved by the presentation software (includes jittered OS delays)
- Reading information recorded on the subject side (photodiode, microphone, response box…)
- Manual or automatic marking of biological or behavioral events, post-acquisition (epileptic spikes, sleep spindles, rat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



Brainstorm

Epoching

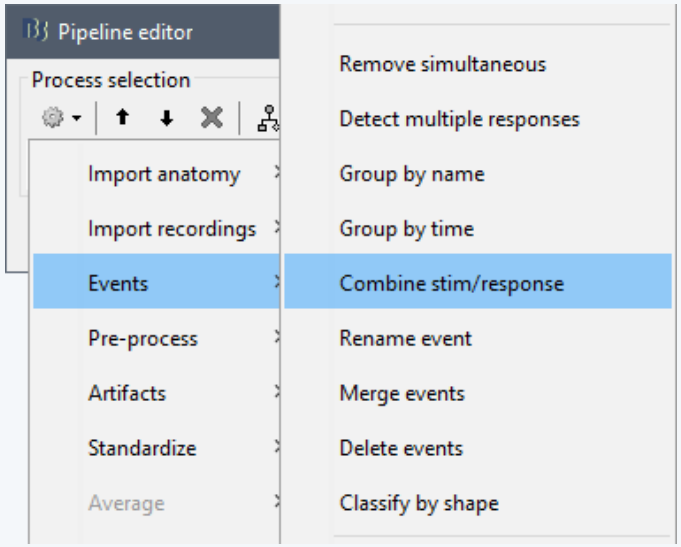
- In some experiments, the event of interest is a combination of presentation markers.
- Example: Priming experiments

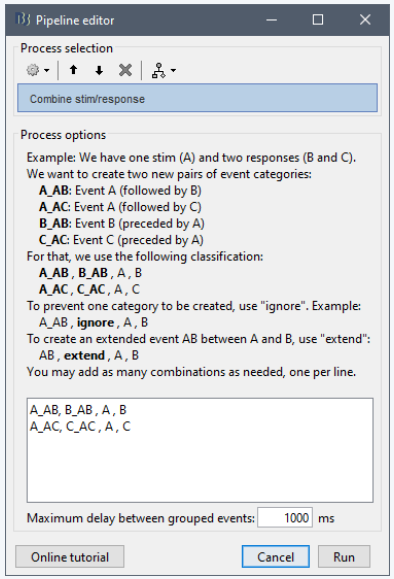


- In Brainstorm, the events of interest are saved as new marker types in the continuous files.
- In other environments, the events are sometimes defined only at the epoching time and not saved in the continuous file.

Epoching

- In Brainstorm, the events of interest are saved as new marker types in the continuous files.

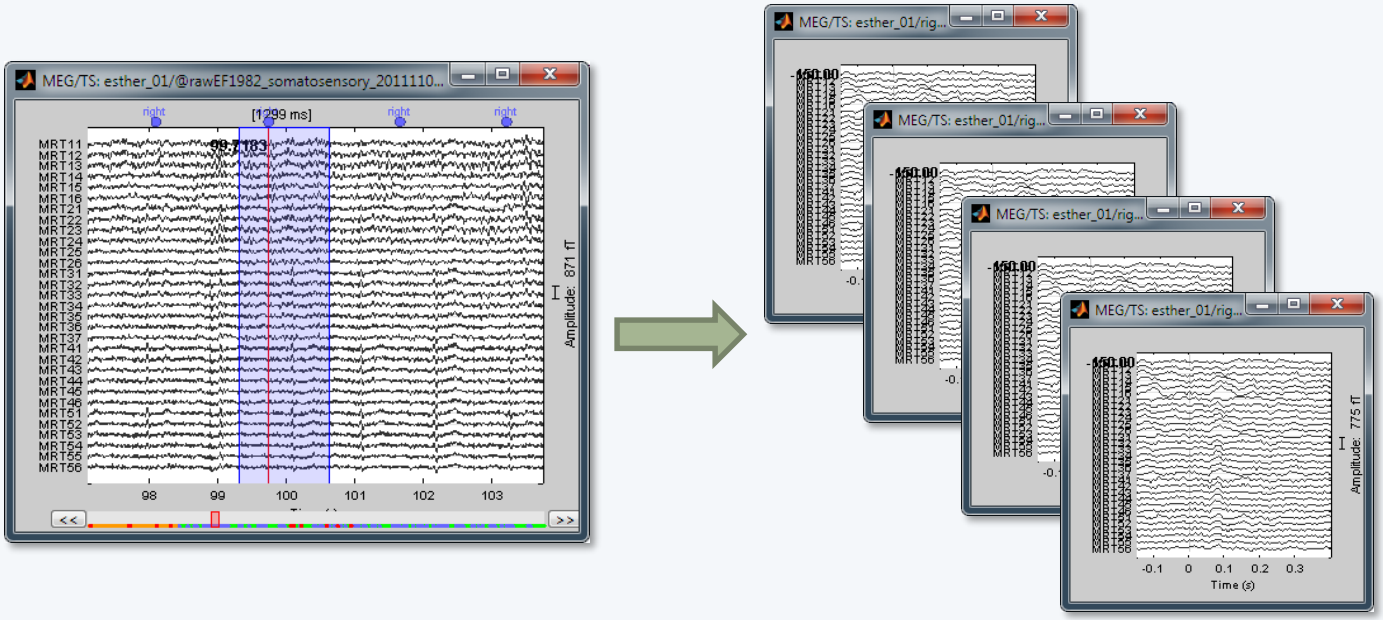




- In other environments, the events are sometimes defined only at the epoching time and not saved in the continuous file.

Epoching

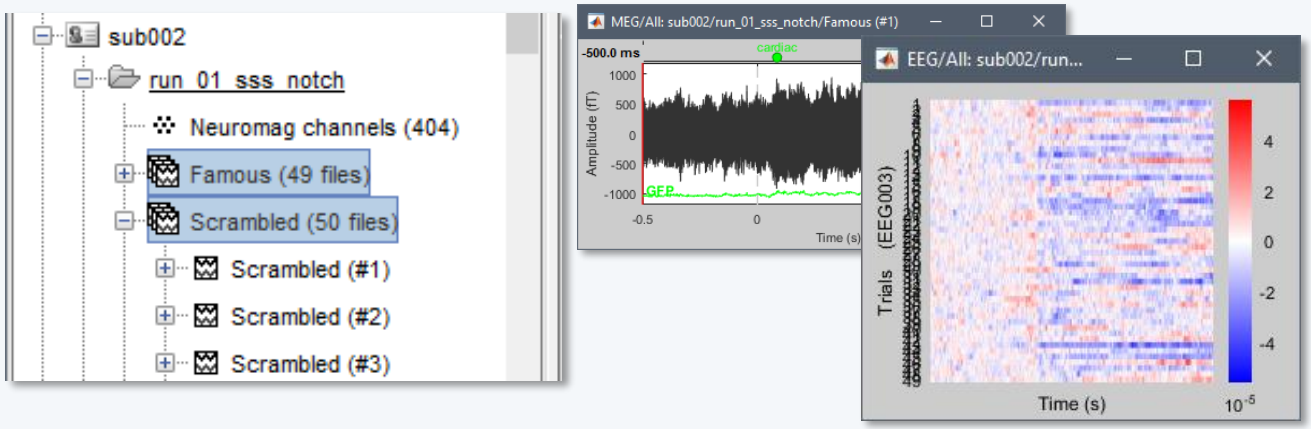
- Epochs = Trials = Short blocks of recordings around an event of interest.
- Epoching = Extracting epochs from the continuous recordings and saving them.



Brainstorm

Epoching

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

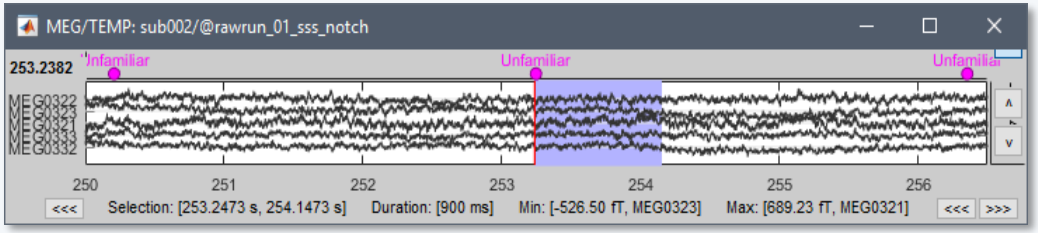


- In other programs, all the epochs from one run are saved in one single file (one file per event type, or one file with all the events).

Brainstorm

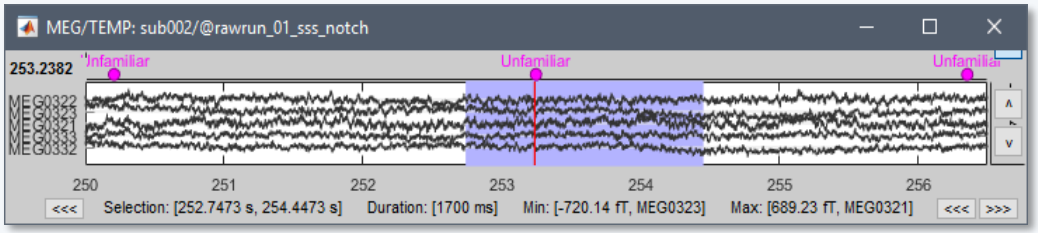
Epoching

- 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



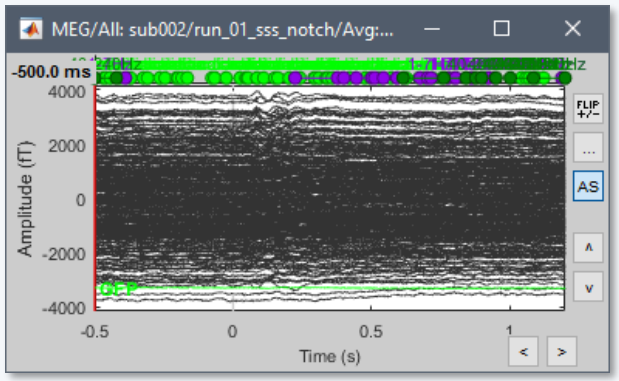
+ 200ms baseline
+ 300ms filters

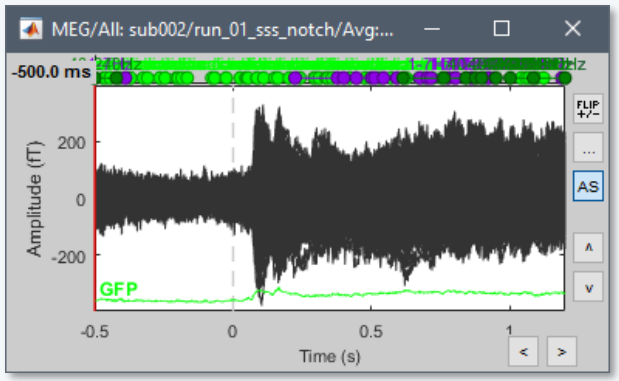
= [-500, 1200] ms

- Computational limitations: Size and time

Epoching

- 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



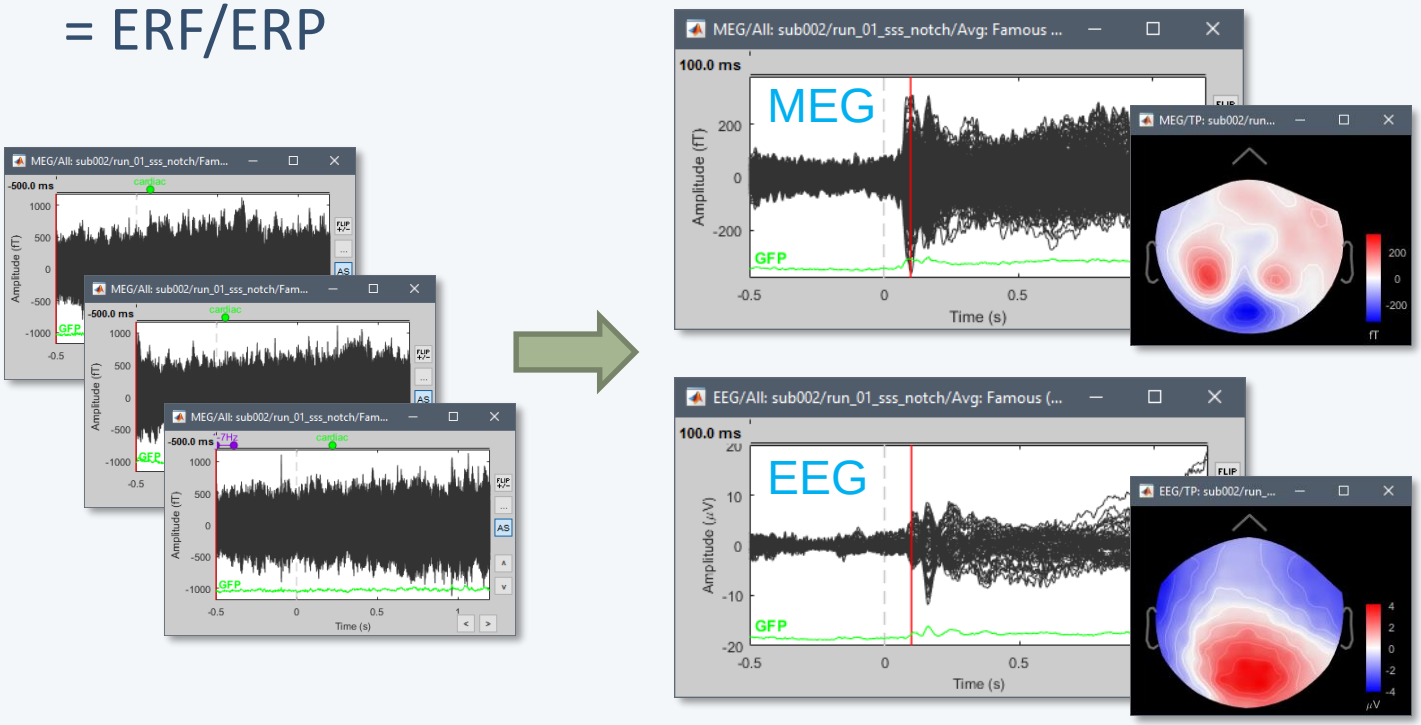


Brainstorm

Single subject

- 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



Brainstorm

Single subject

- **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.

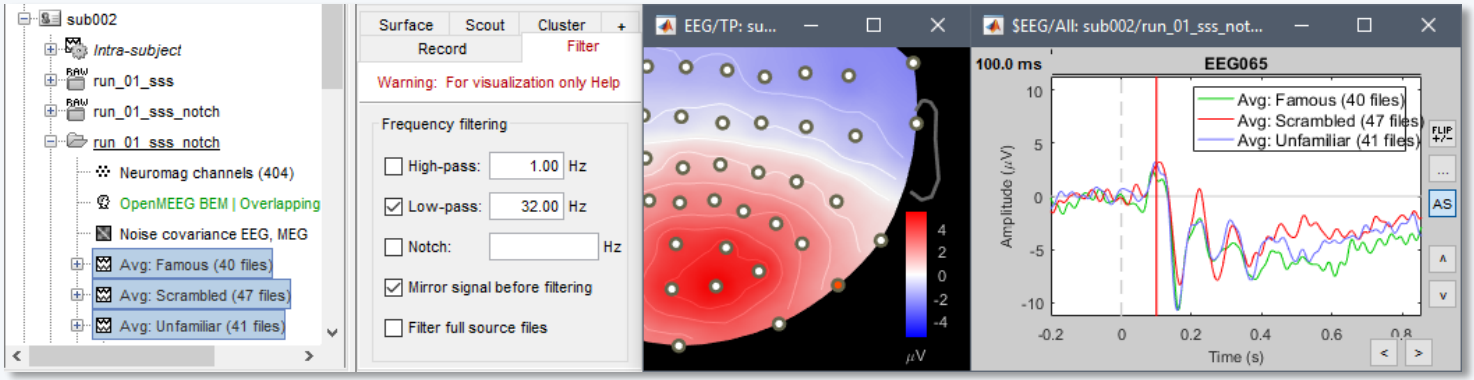
Single subject

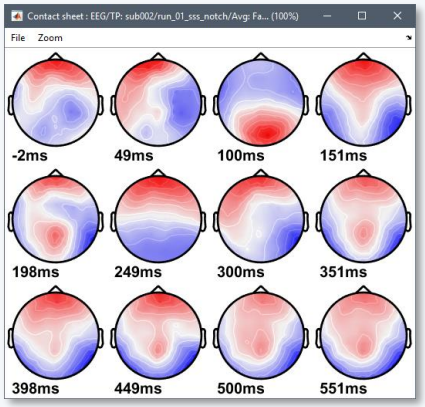
Anatomy
Link recordings
MRI registration

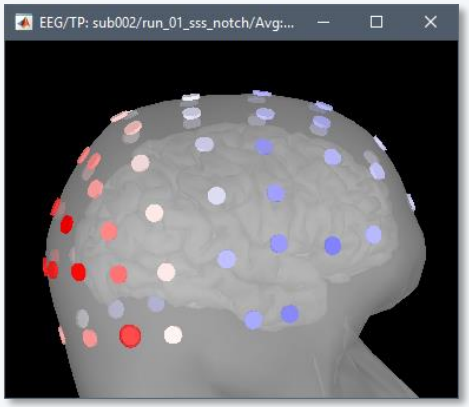
PSD
Filters
Bad channels
Artifacts
Correction
Bad segments

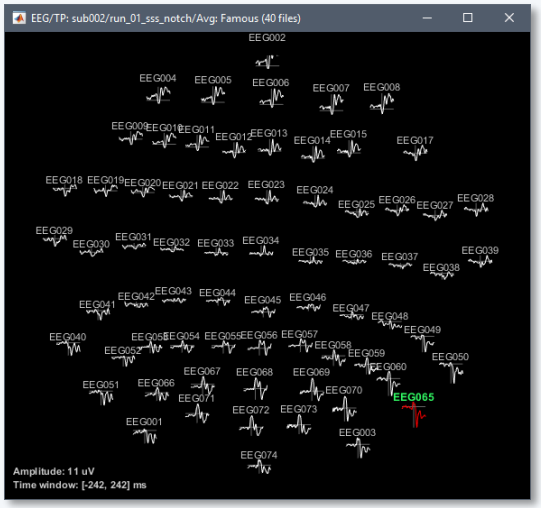
Markers
Epoching
Averaging
Sources
Time-frequency

- EEG ERP: Famous faces





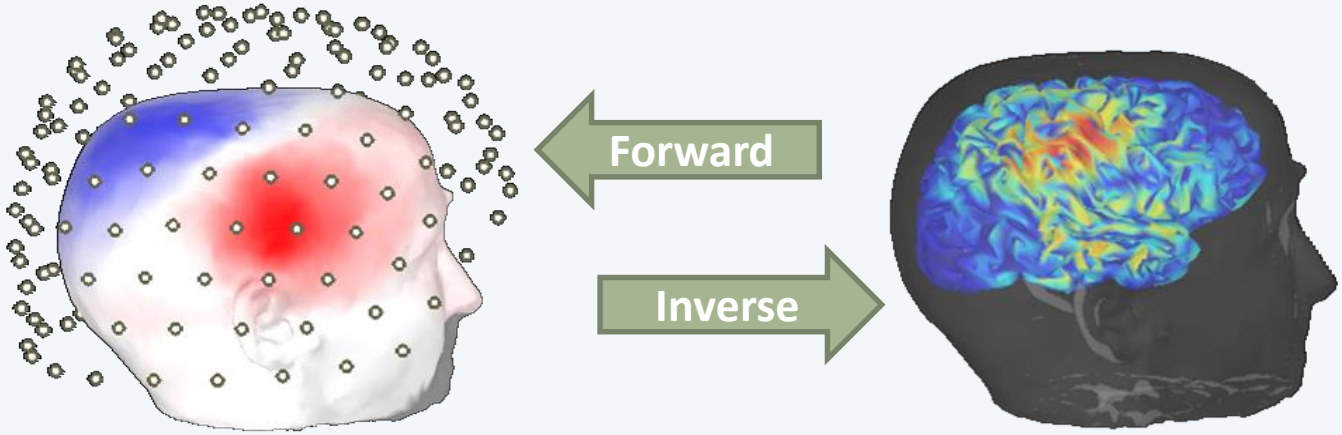




Brainstorm

Single subject

- Source space: Cortex or full head volume
- Forward model: Overlapping spheres (MEG)
  OpenMEEG BEM (EEG)
- Inverse model: **Minimum norm estimates**
  Beamformers
  Separately for MEG and EEG

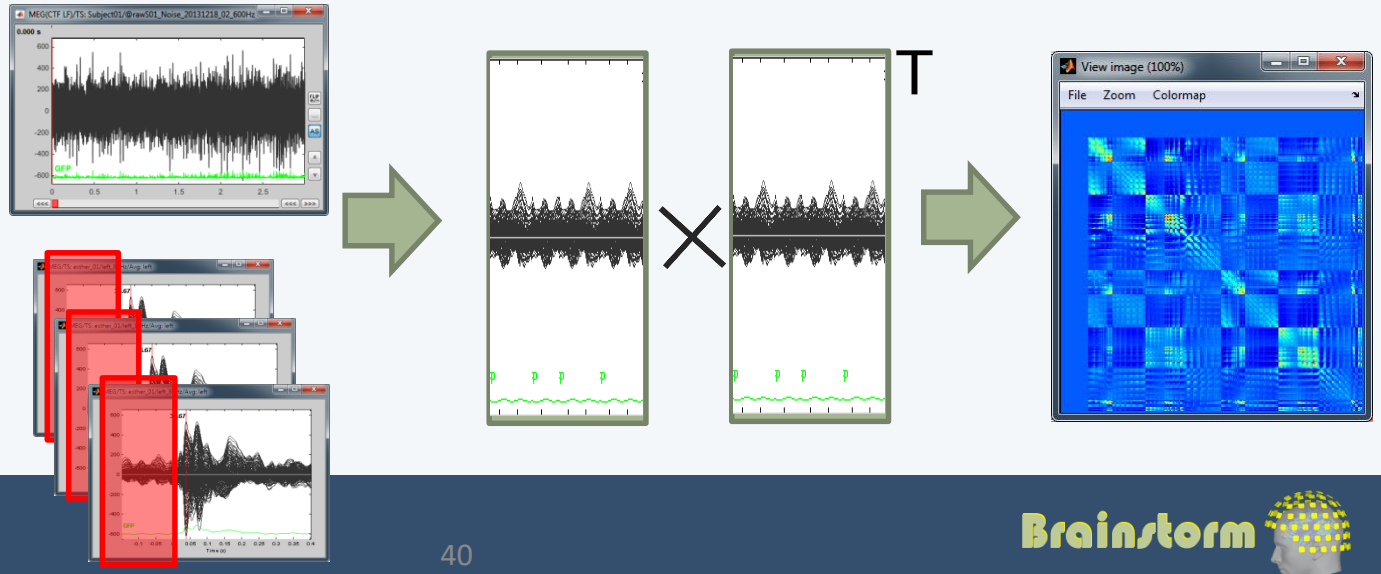


Sensor space *Source space*

Brainstorm

Single subject

- 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



Brainstorm

Single subject

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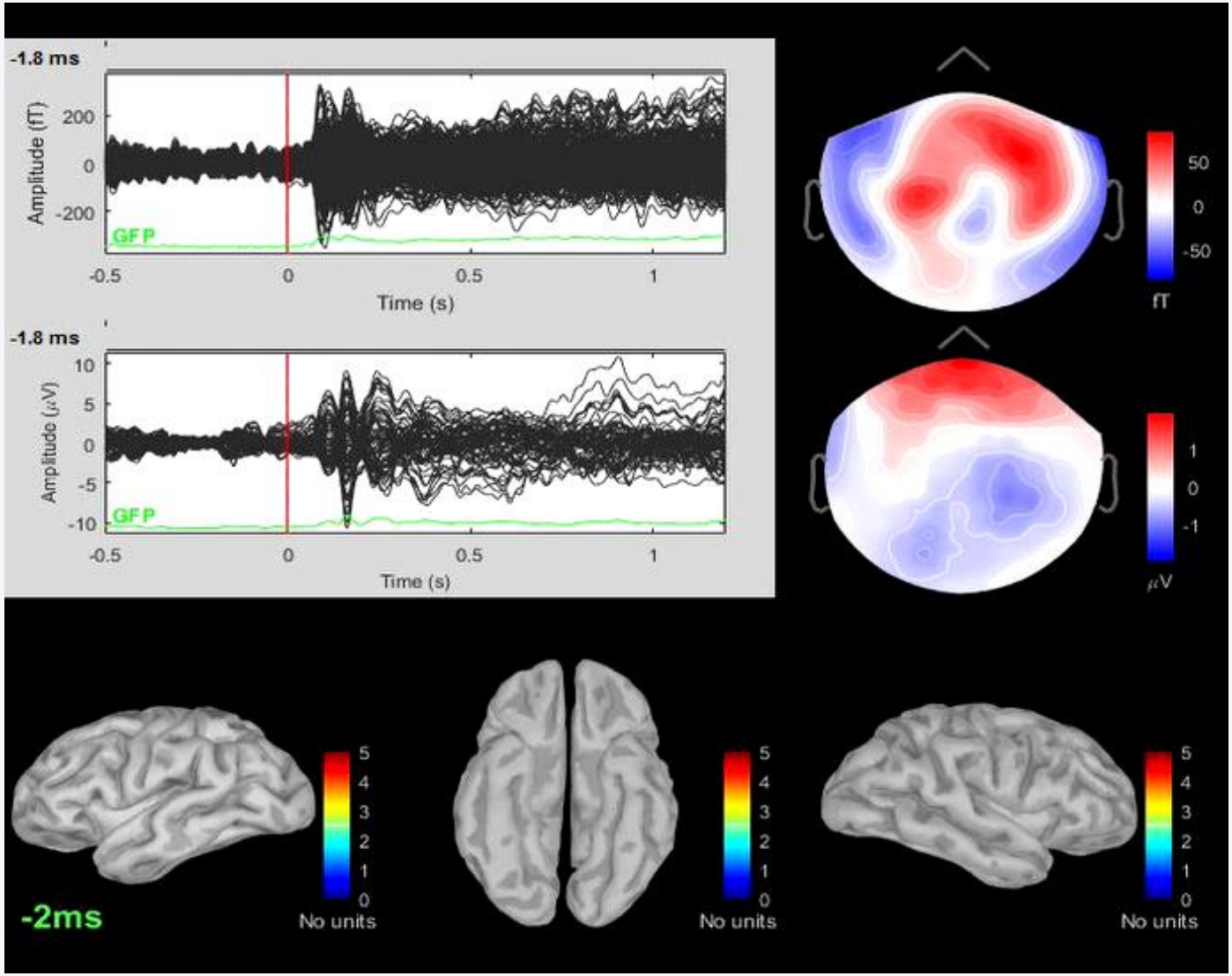
Bad segments

Markers
Epoching
Averaging
Sources
Time-frequency

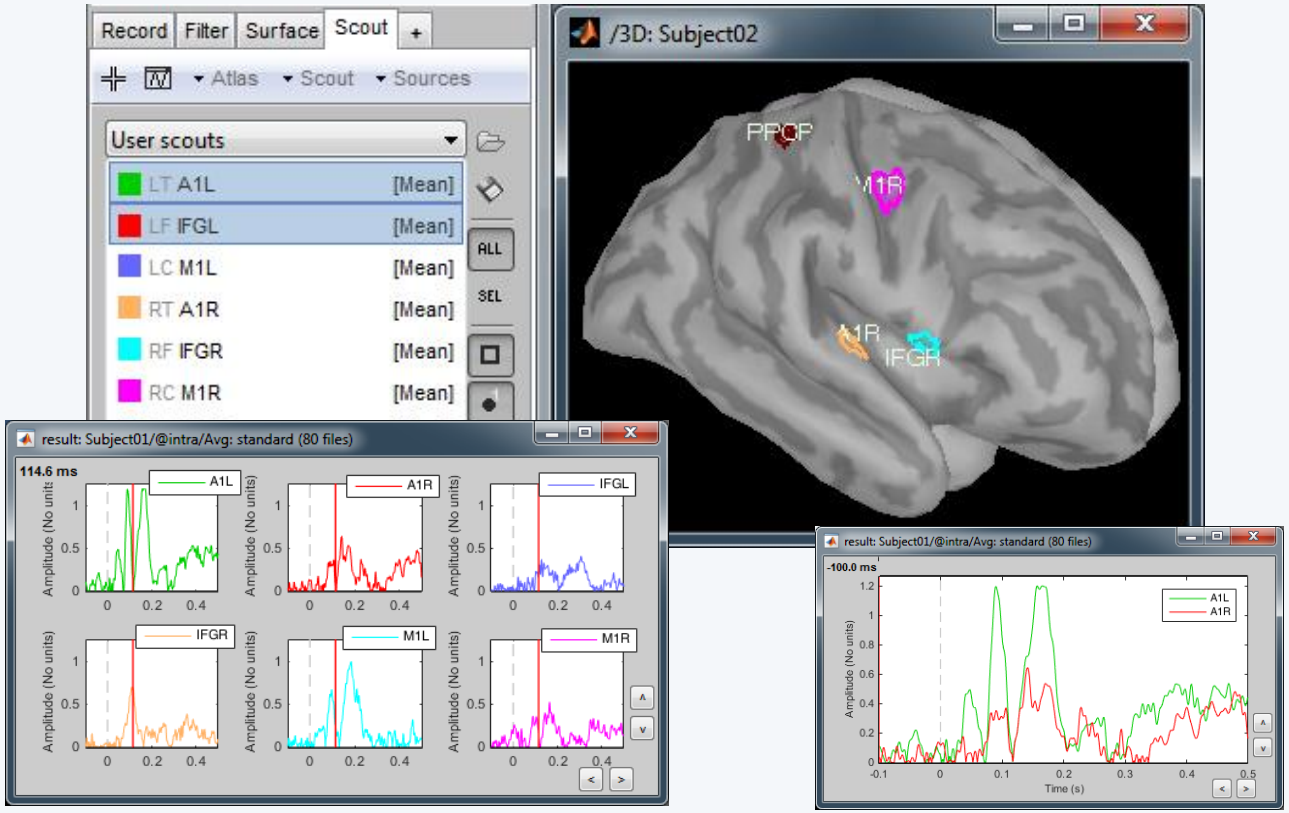
Famous faces



Brainstorm

Single subject

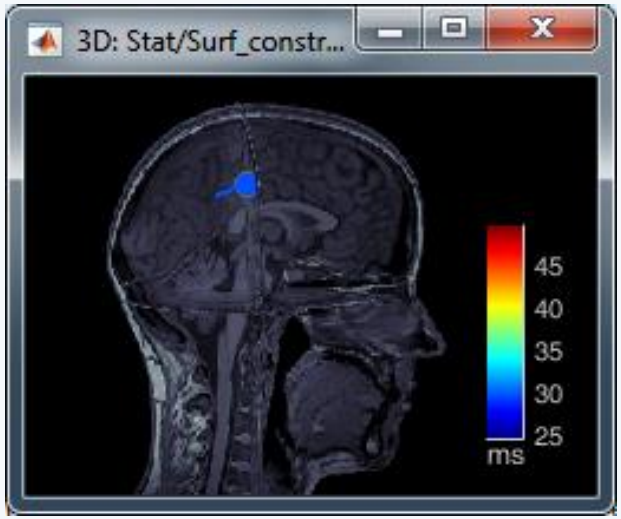
- Regions of interest at cortical level (scouts)
  = Subset of a few dipoles in the brain
  = Group of vertices of the cortex surface

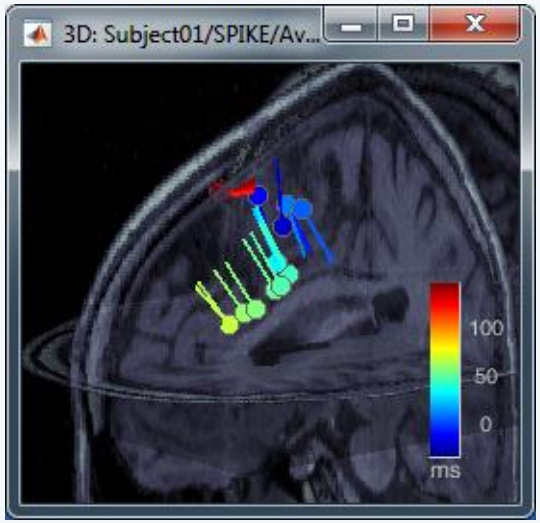


Brainstorm

Single subject

- Dipole scanning
  Compute a distributed source model, then find the most significant dipole at each time sample.
- Dipole fitting (FieldTrip)
  Non-linear search of the dipoles that minimizes the residuals (data explained - recordings)





Brainstorm

Single subject

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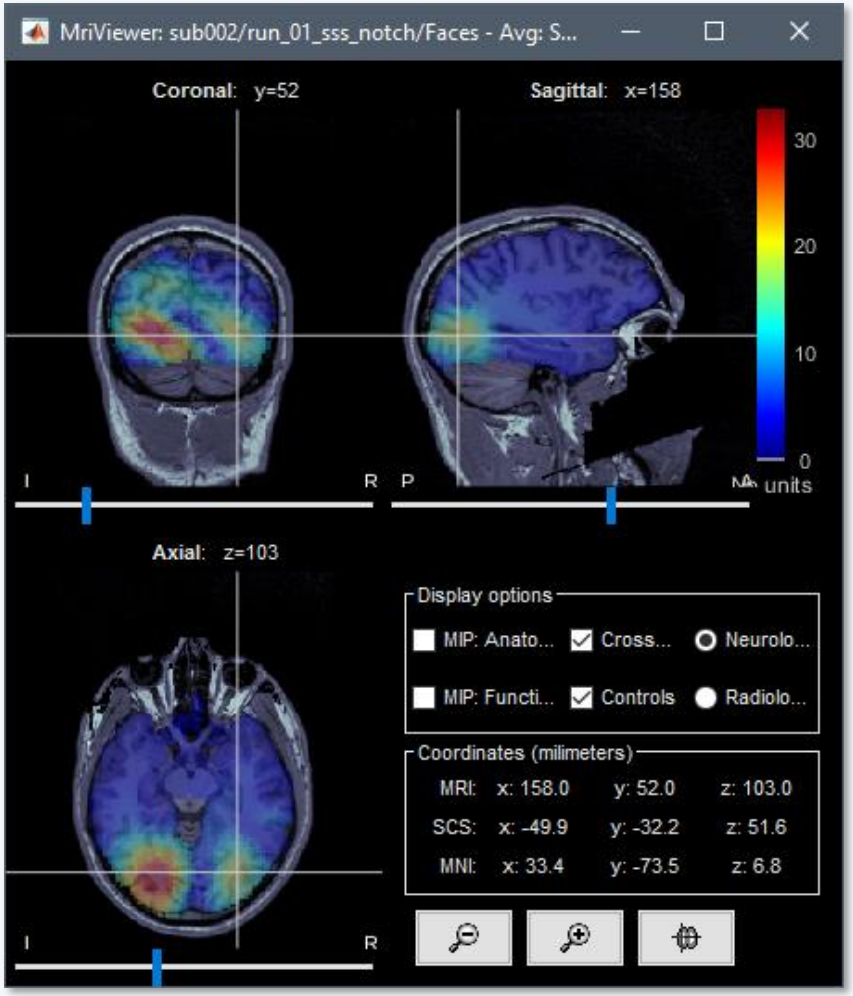
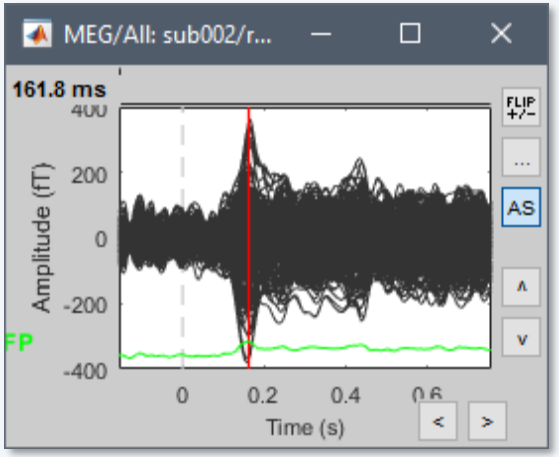
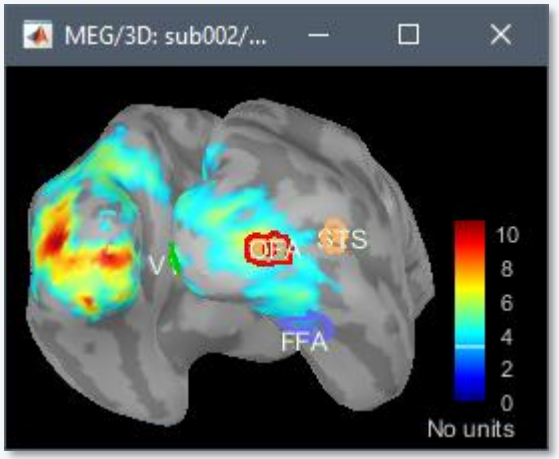
Averaging
Sources
Time-frequency

- Faces – Scrambled, 160ms



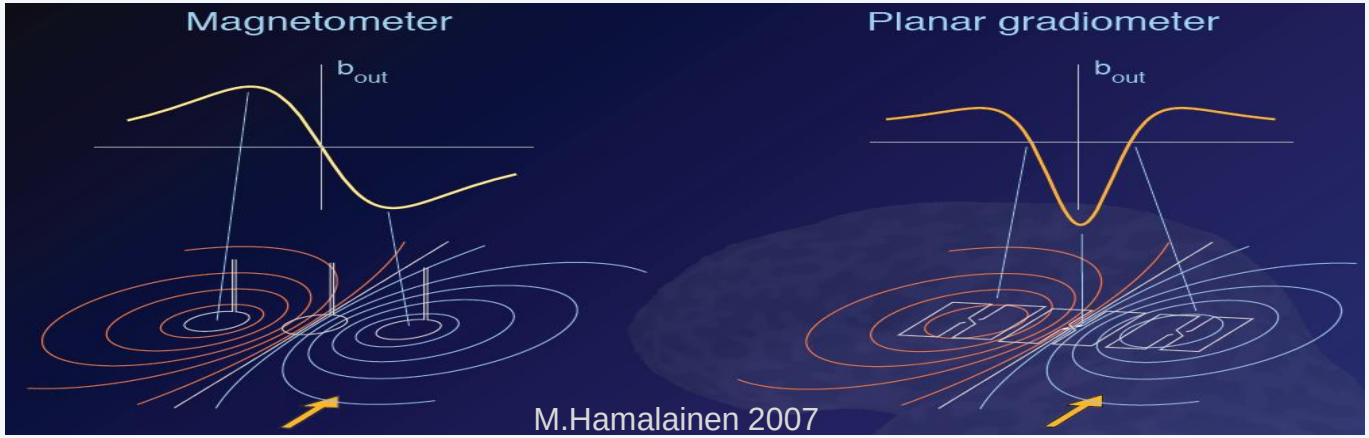




Brainstorm

Source estimation: MEG

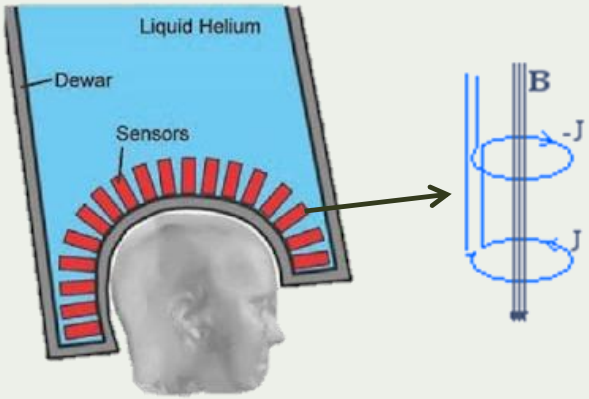
- Recommended in MEG analysis:
  - The subject head can move in the helmet
  - One sensor is not corresponding to one brain region
  - Different types of sensors (magneto / gradiometers)
  - Difficult to read, reproduce or compare
- Converting to source space helps solving those issues



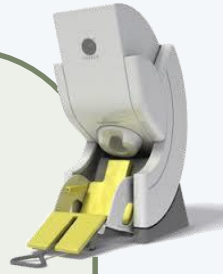
MEG sensors

CTF (MNI)

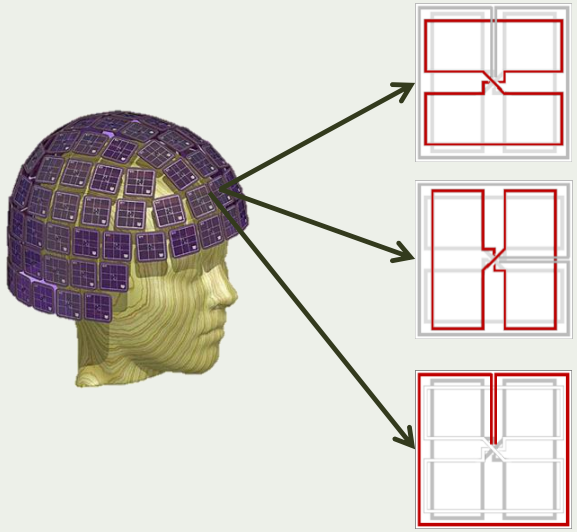
275 axial gradiometers



Elekta (MIT)



204 planar gradiometers
102 magnetometers

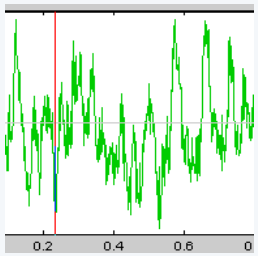


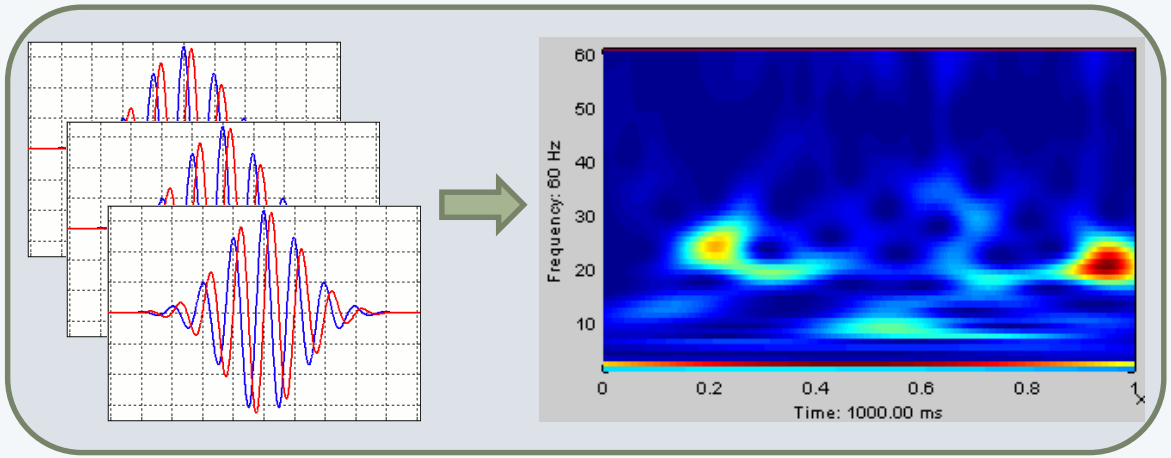
Source estimation: EEG

- In EEG, those problems don't exist:
  - Electrodes positions are fixed and known
  - More reproducible signal shapes and topographies
  - Clinicians are trained to work at the sensor level
- But the source reconstruction is still interesting:
  - Localize the signal generators in the brain (epilepsy and pre-surgical functional mapping)
  - Spatial separation of simultaneous sources

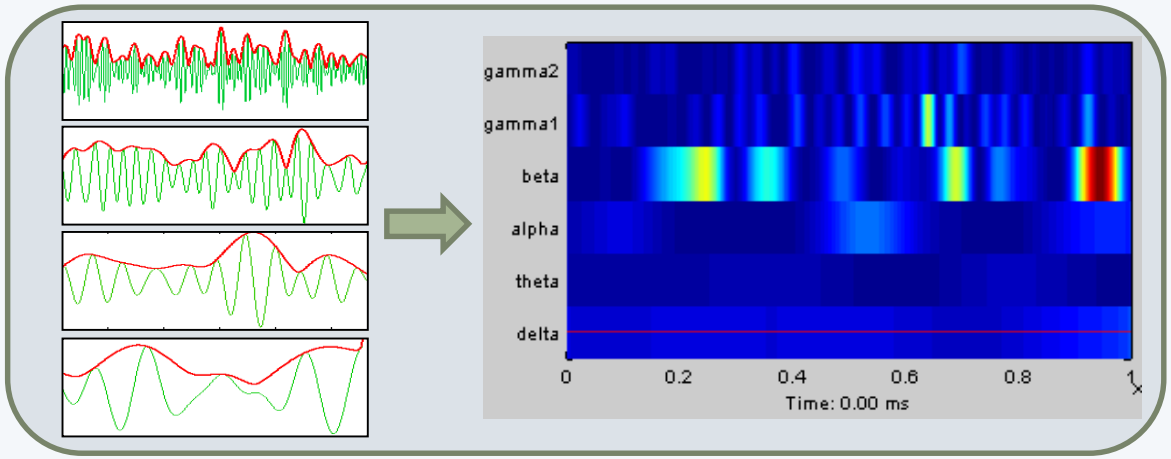
Single subject

Morlet wavelets



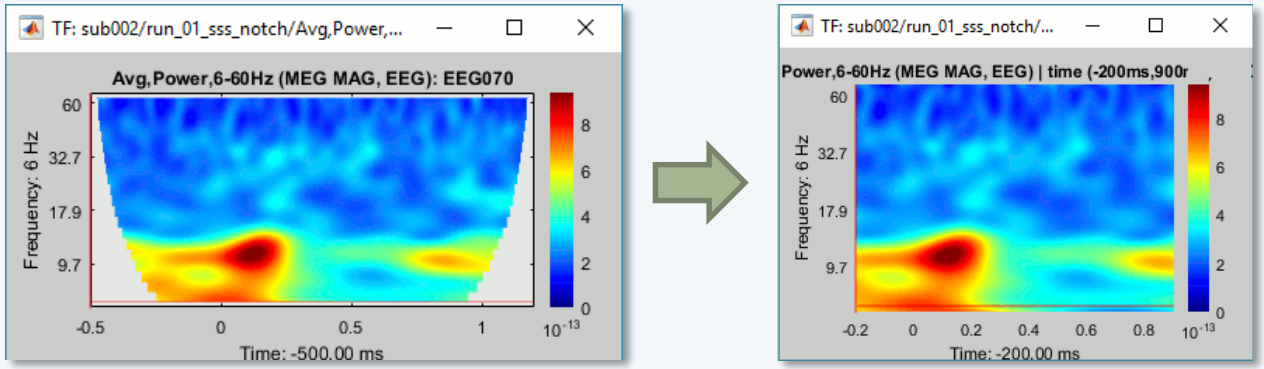


Hilbert transform + band-pass filter

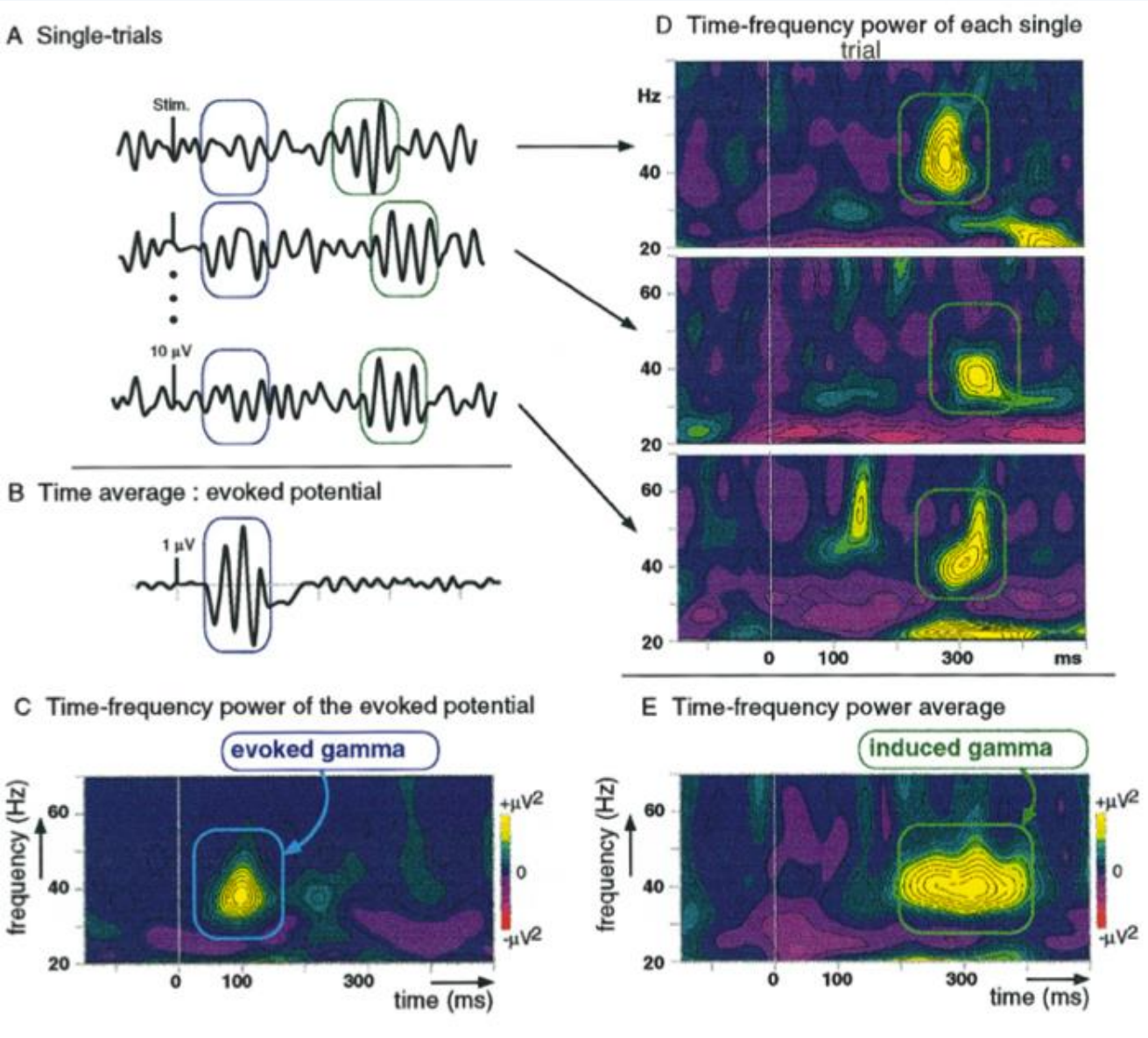


Brainstorm

- Make sure you know the transient periods for all the frequency bins, and do not include them in your analysis.
- An easy solution is to cut them out immediately after the computation.

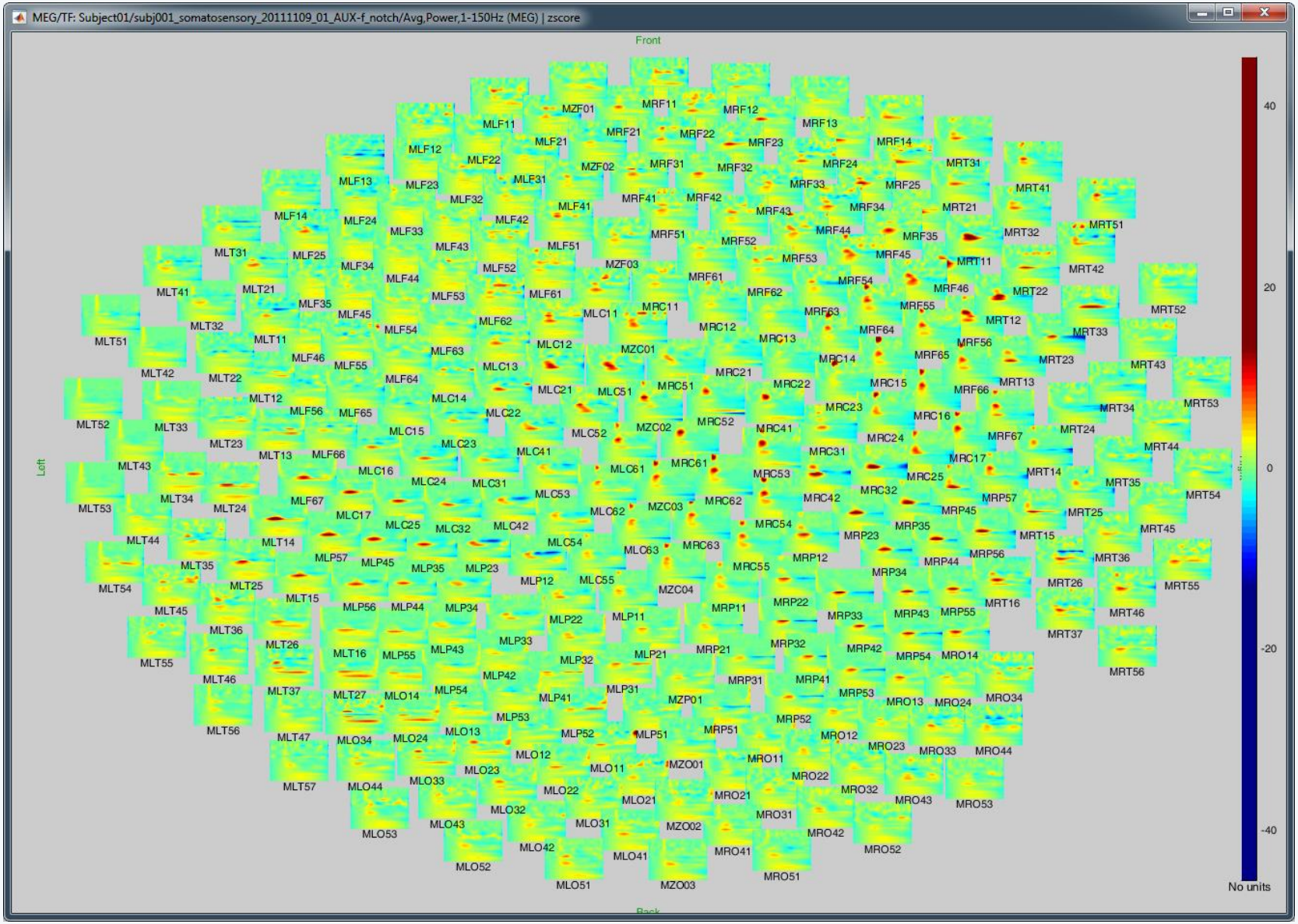


Time-frequency Average



Brainstorm

Time-frequency



Brainstorm

Single subject

Anatomy
Link recordings
MRI registration

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Bad channels
Artifacts
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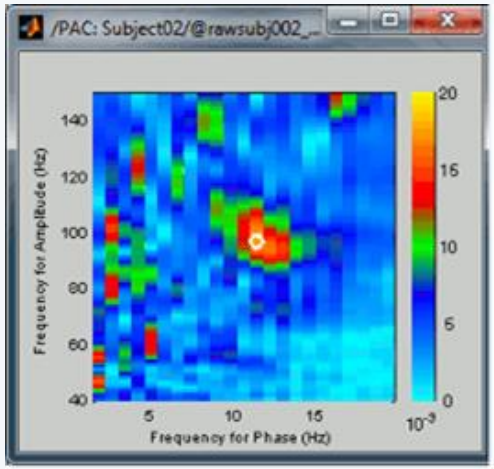
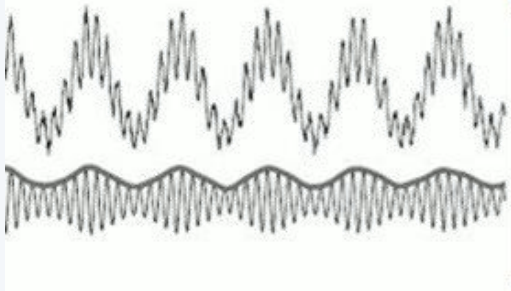
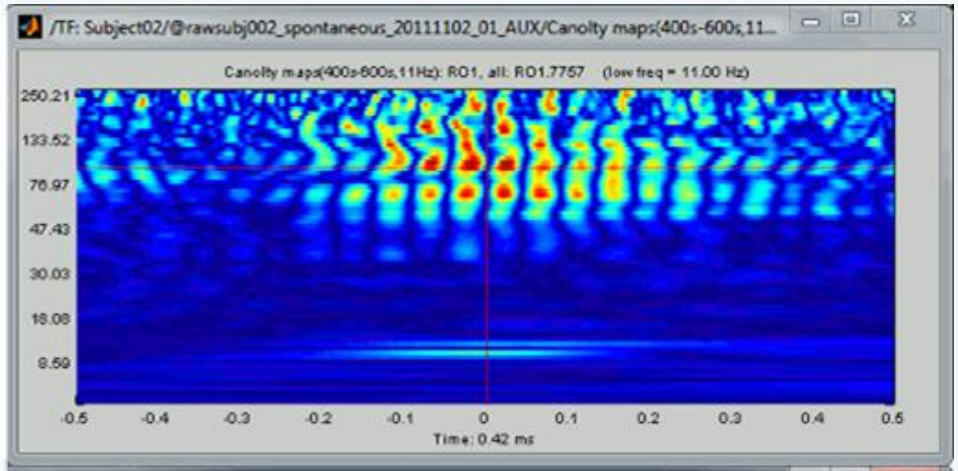
Bad segments

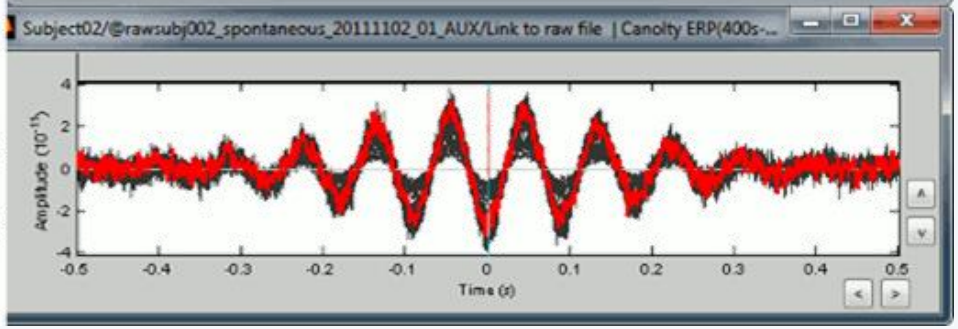
Markers
Epoching
Averaging
Sources
Time-frequency
Other measures

- Phase-amplitude coupling





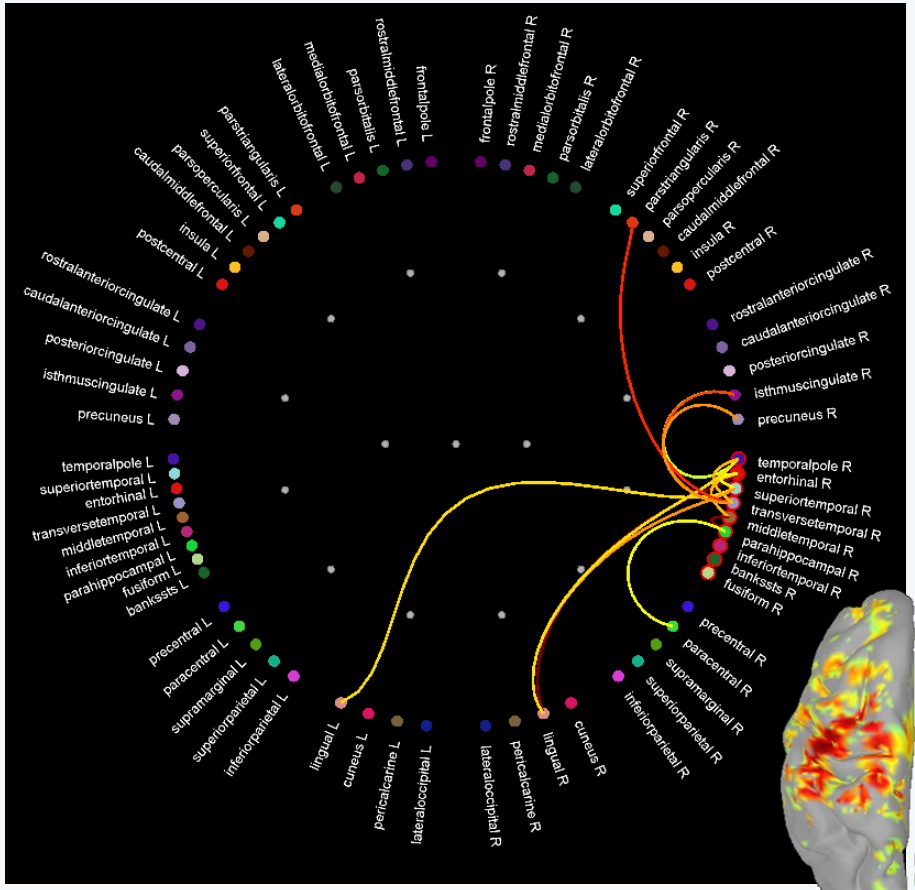




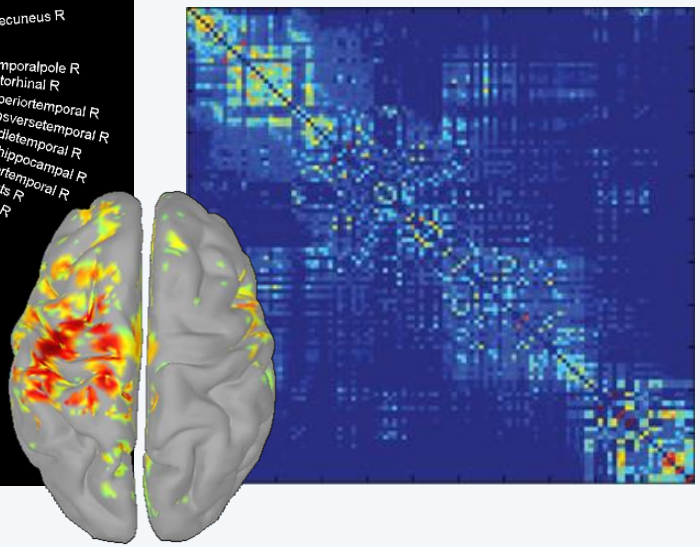
Brainstorm

Single subject

- Connectivity measures



- Correlation
- Coherence
- Phase locking value
- Granger causality



Brainstorm

Group analysis

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Link recordings
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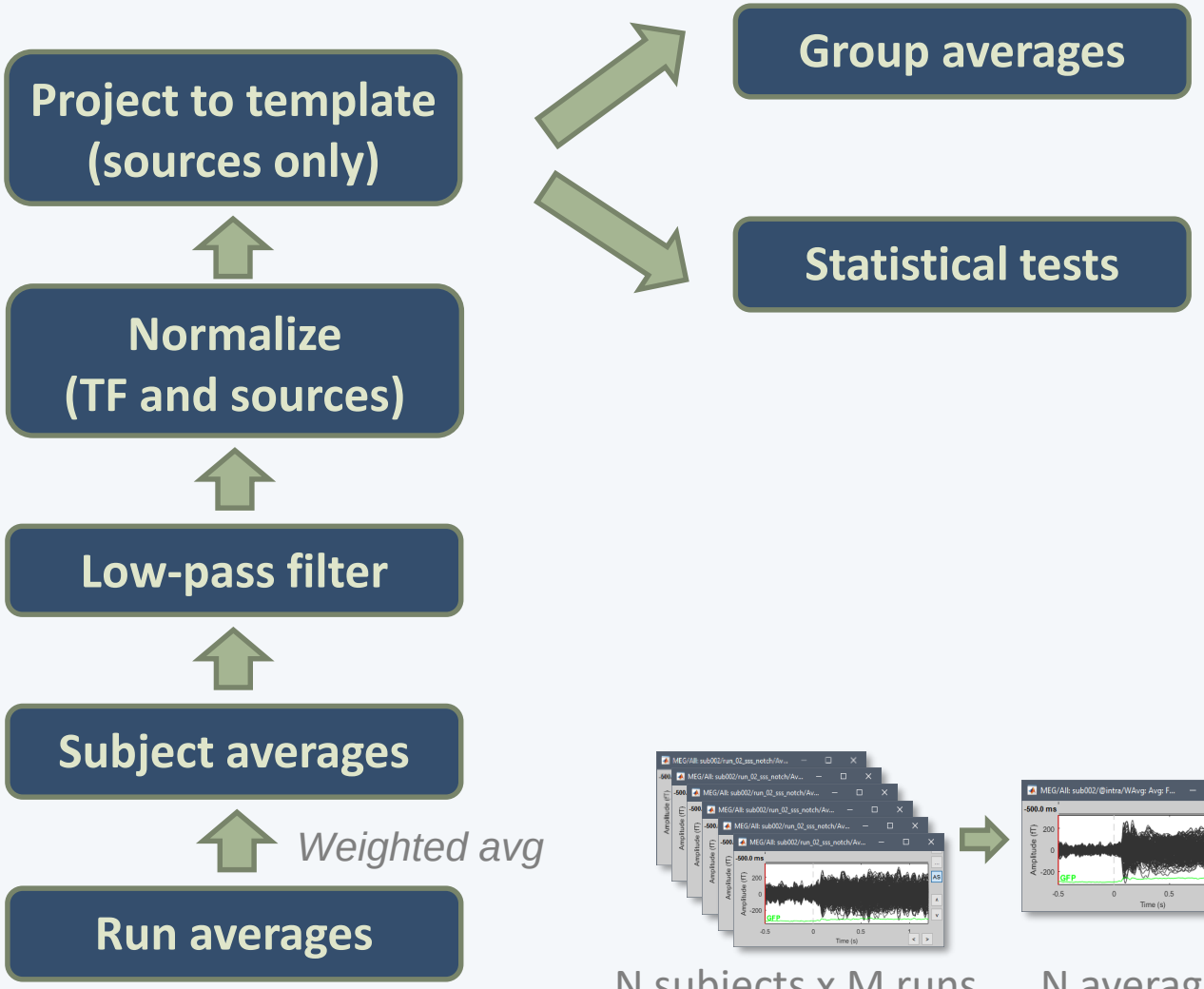
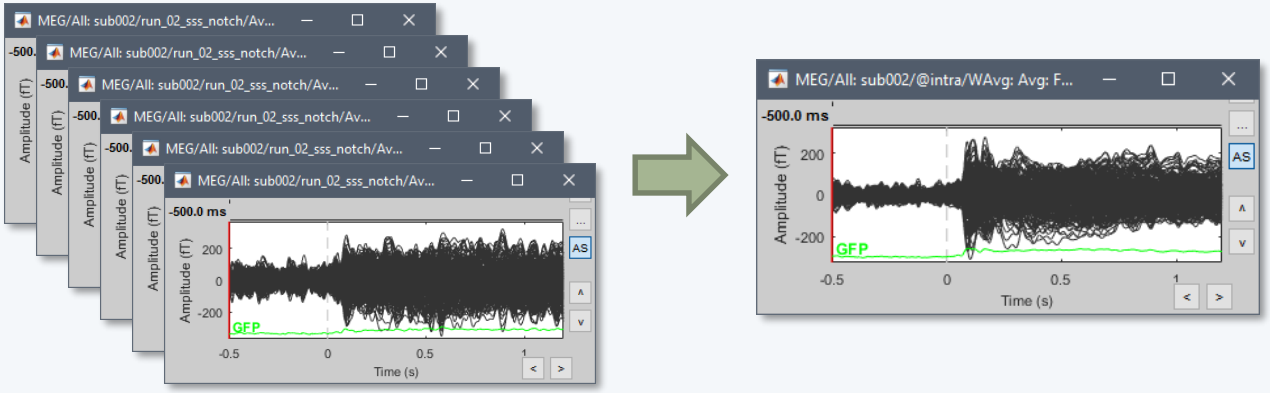


Brainstorm

Group analysis

- 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

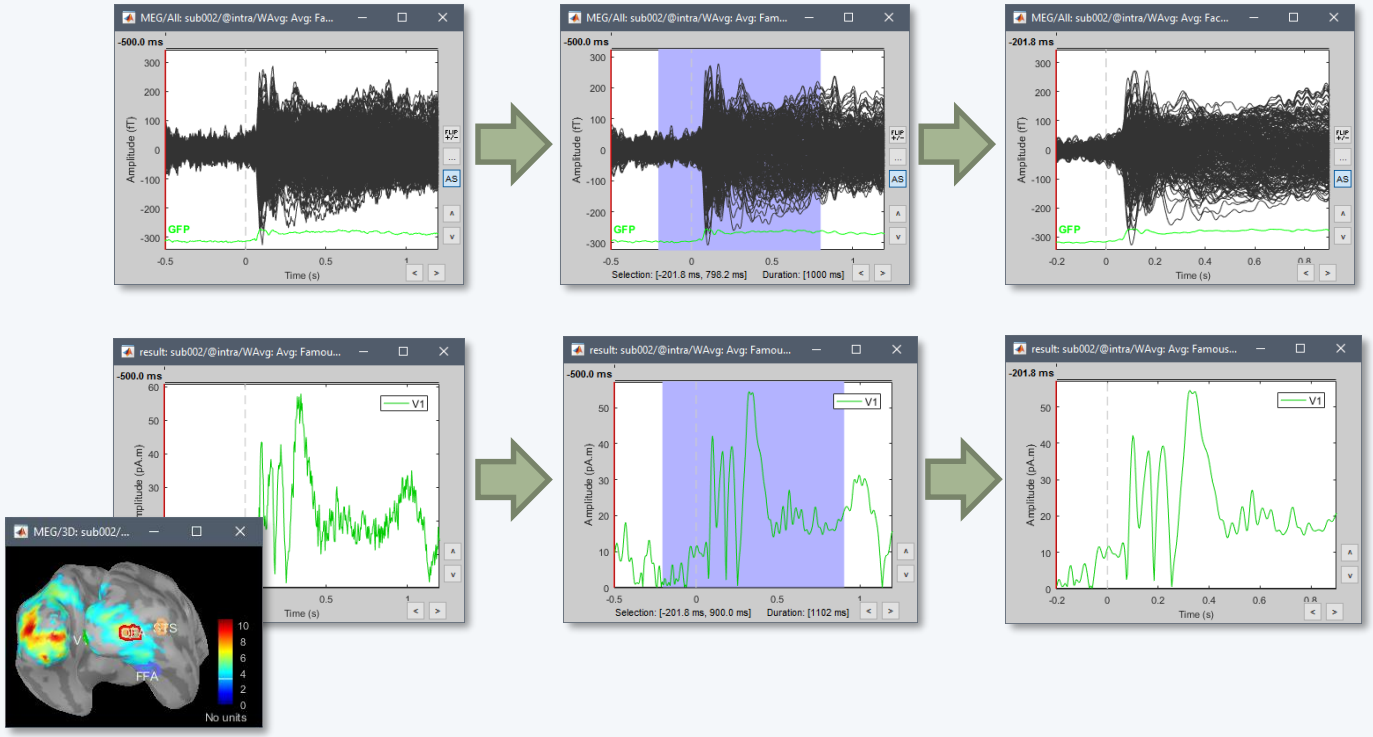
Group analysis

Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

- Low-pass filter the subject averages: 32Hz
- Remove 300ms on each side (edge effects)



Brainstorm

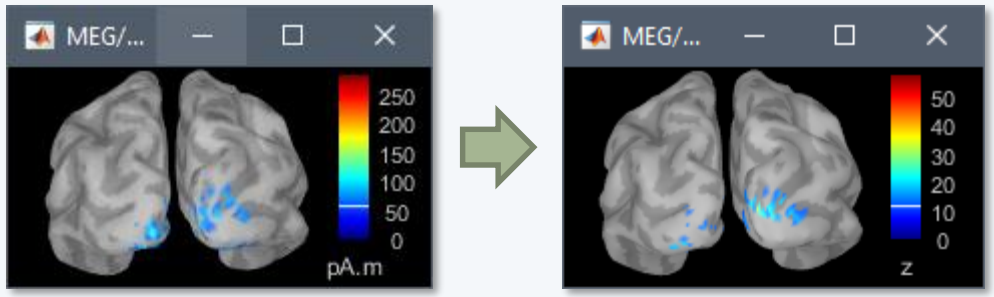
Group analysis

Subject averages
Low-pass
Normalize
Project

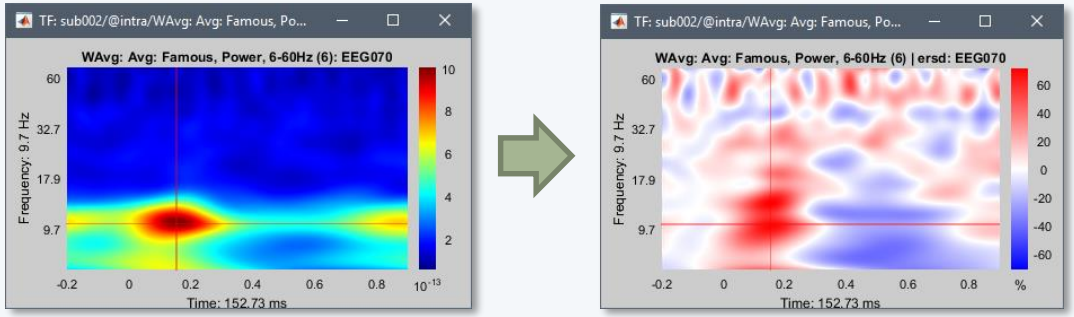
Group averages
Group statistics

Quality control
Workflow

- Amplitude normalization before group analysis
  Baseline = [-200,0]ms
- Sources: Z-score normalization wrt baseline
  S = (S – mean(baseline)) / std(baseline)



- Time-frequency: Event-related sync/desync
  TF = (TF – mean(baseline)) / mean(baseline) * 100



Brainstorm

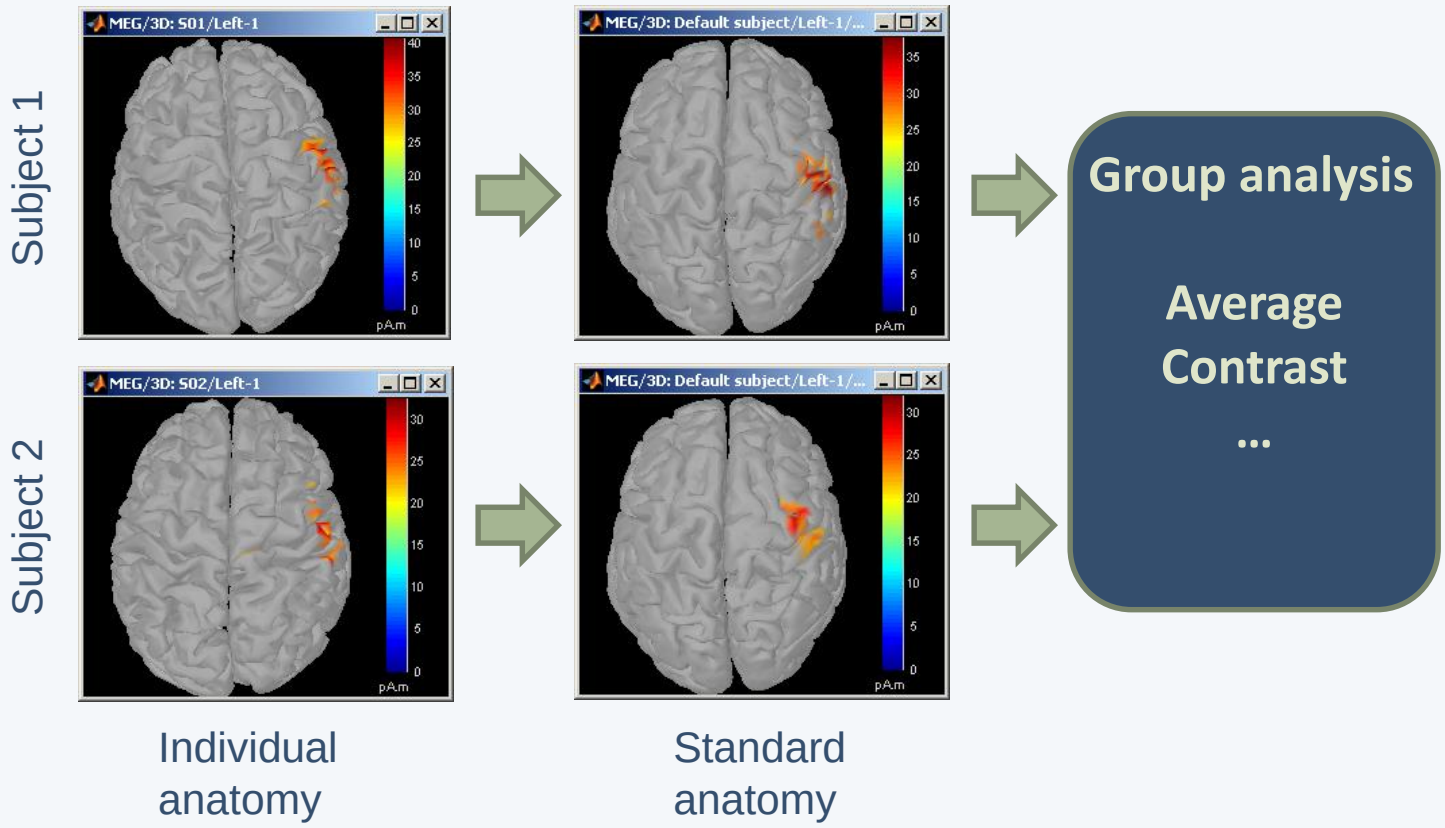
Group analysis

Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

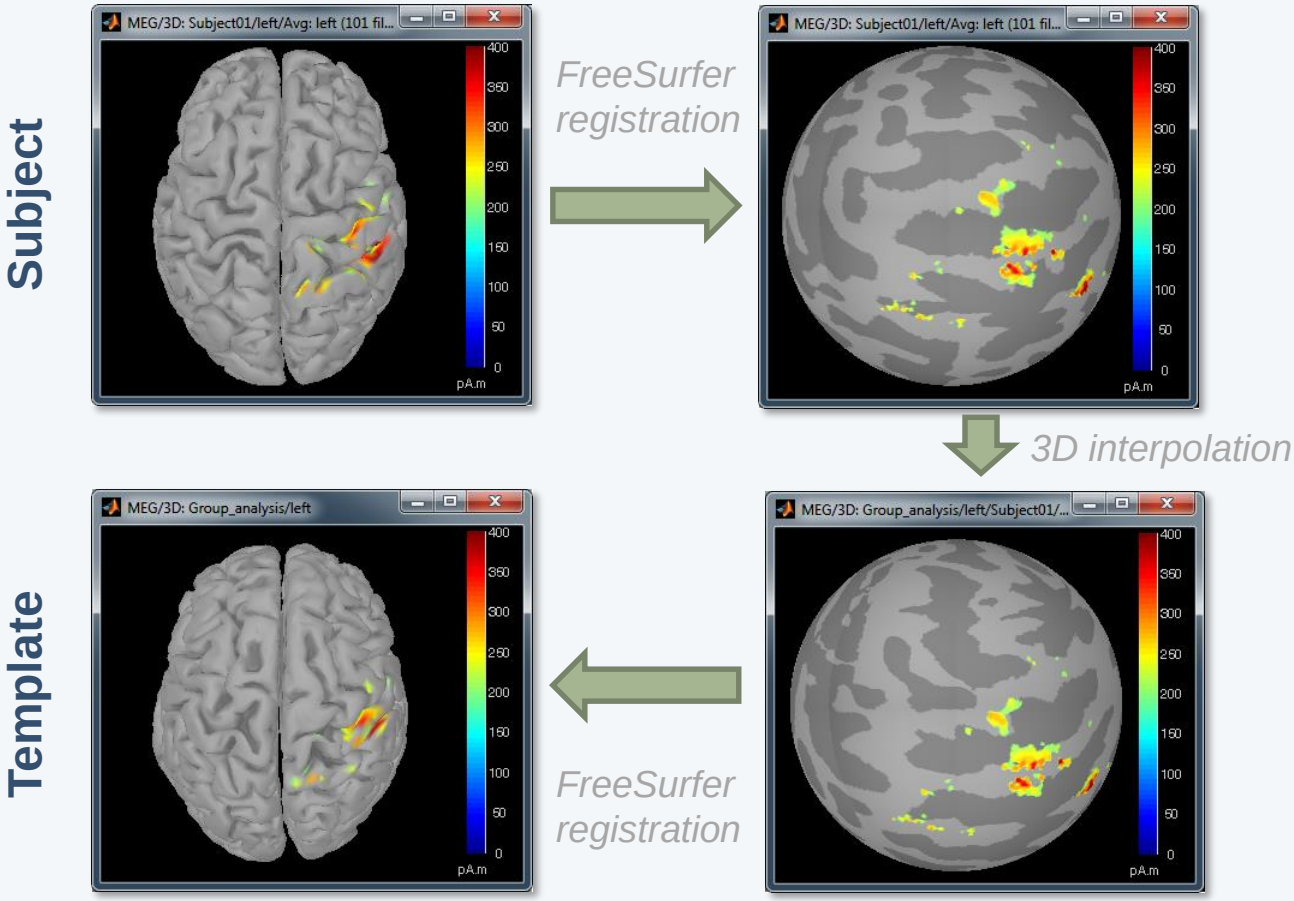
- Registration of individual sources on a template
  (ICBM152, Colin27, DNI, infants…)



Brainstorm

Group analysis

- Using FreeSurfer registration



Brainstorm

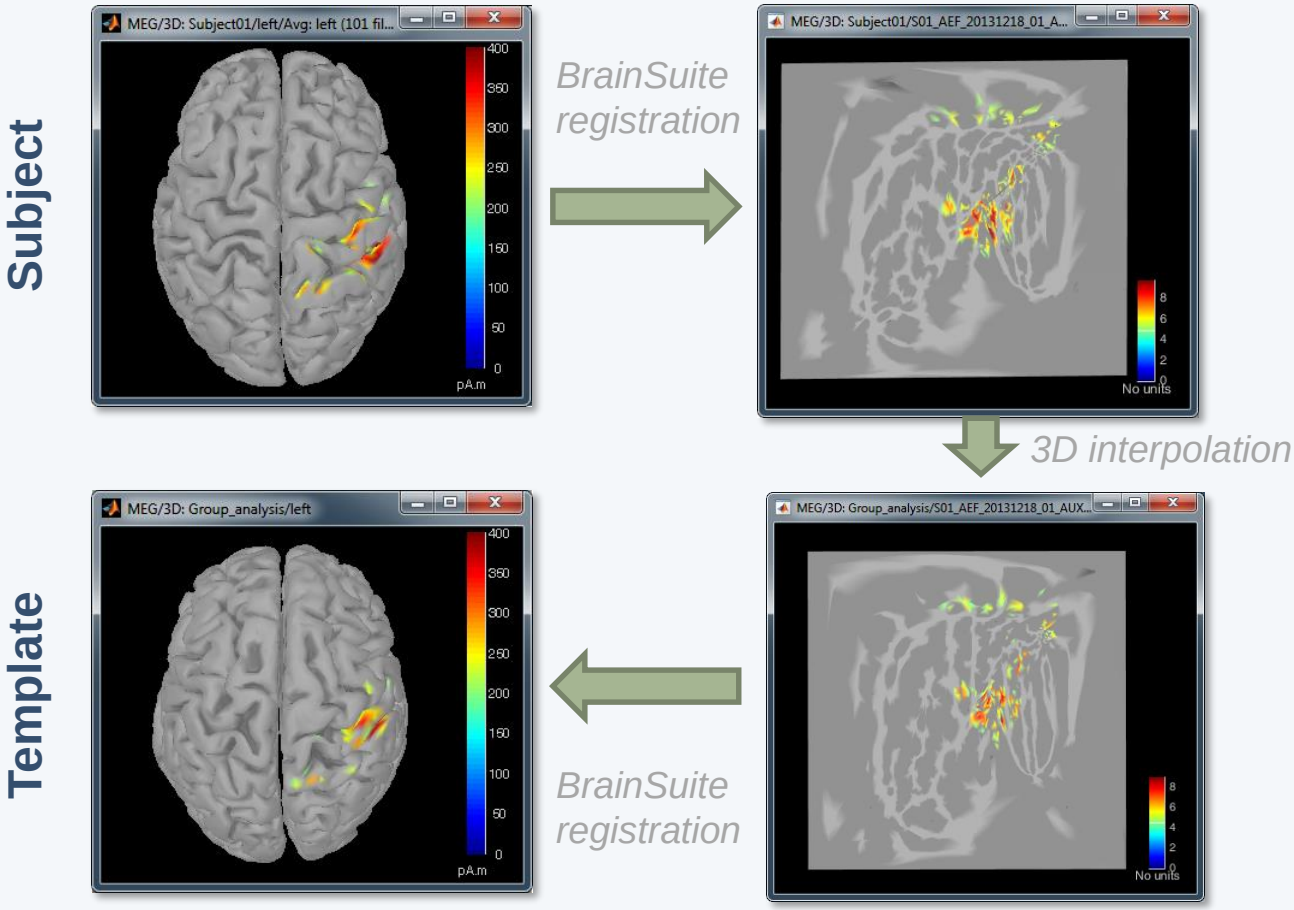
Group analysis

Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

- Using BrainSuite registration



Brainstorm

Group analysis

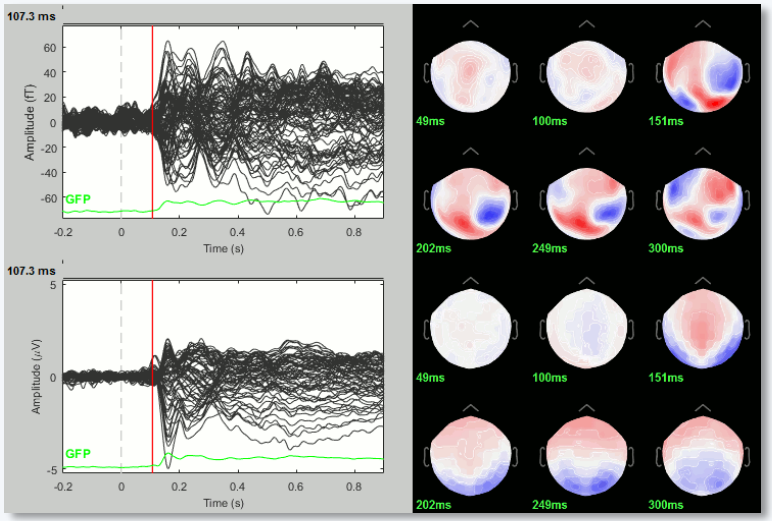
Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

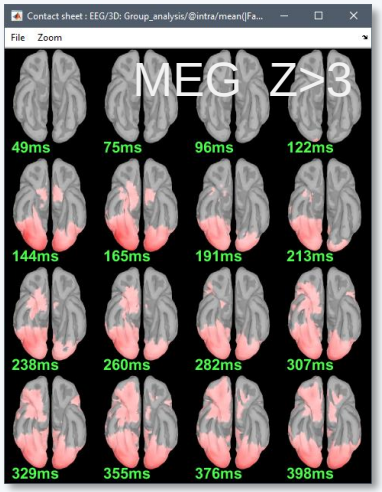
Quality control
Workflow

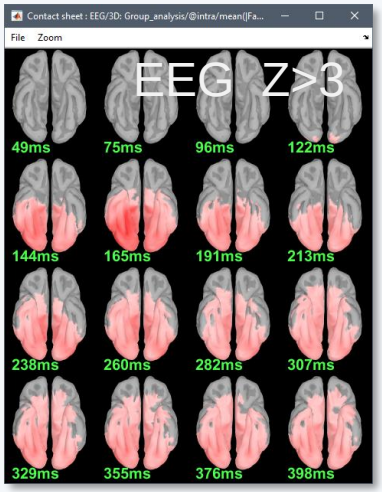
- Faces - Scrambled

MEG

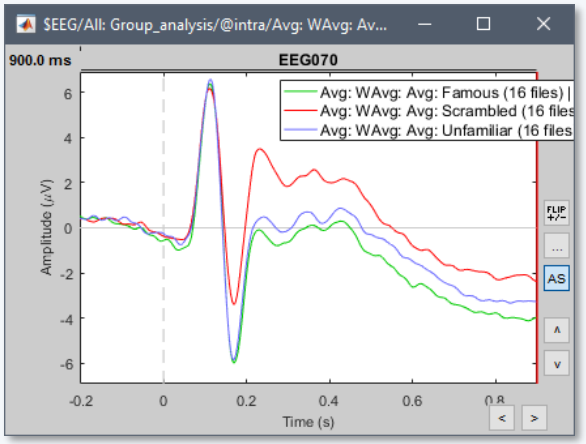


EEG

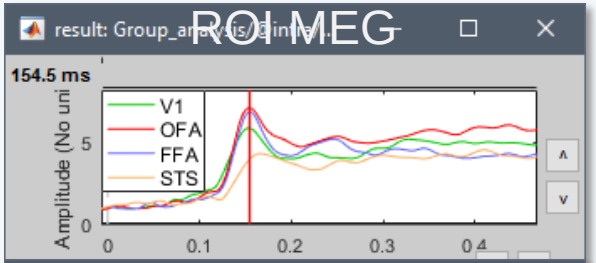




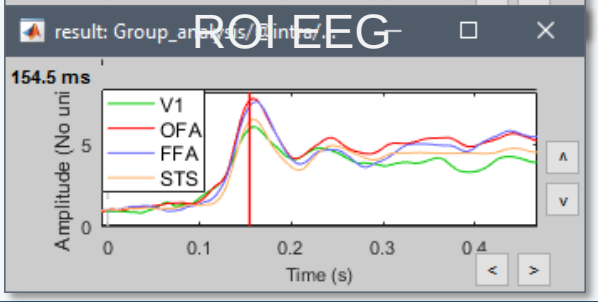
EEG 070



ROI MEG



ROI EEG



Brainstorm

Group analysis

Subject averages
Low-pass
Normalize
Project

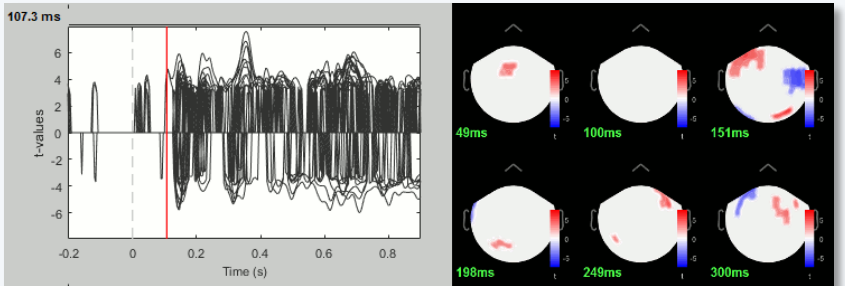
Group averages
Group statistics

Quality control
Workflow

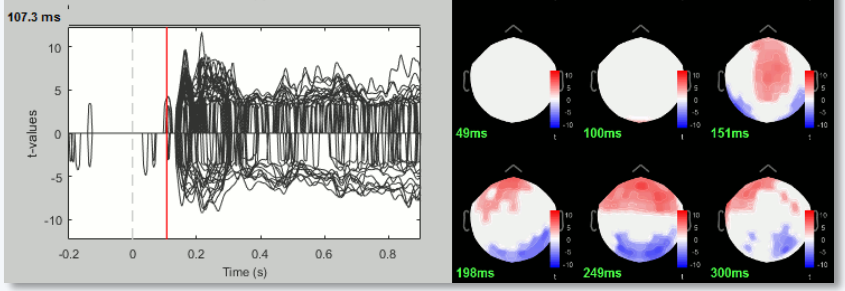
- Faces - Scrambled

Permutation t-test, 1000 rand, p<0.05 FDR-corrected

MEG

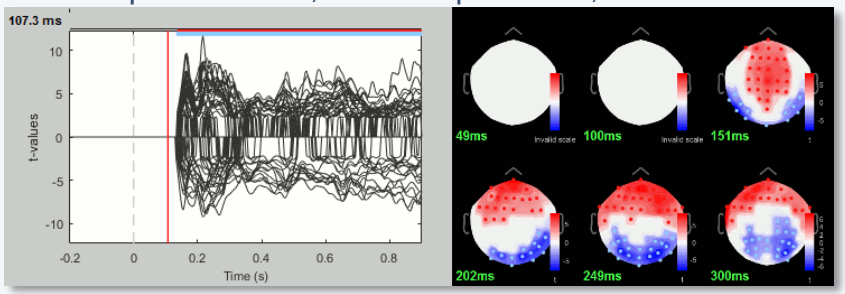


EEG

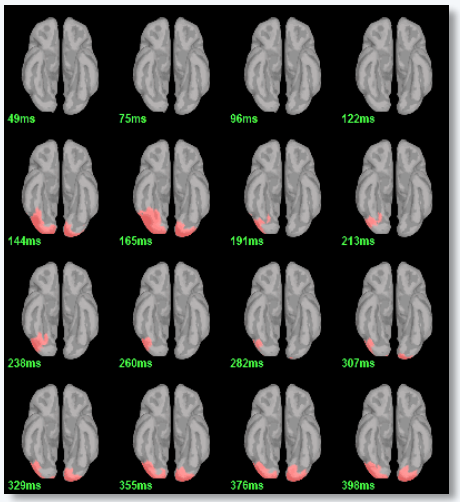


FieldTrip cluster test, cluster alpha=0.05, 1000 rand

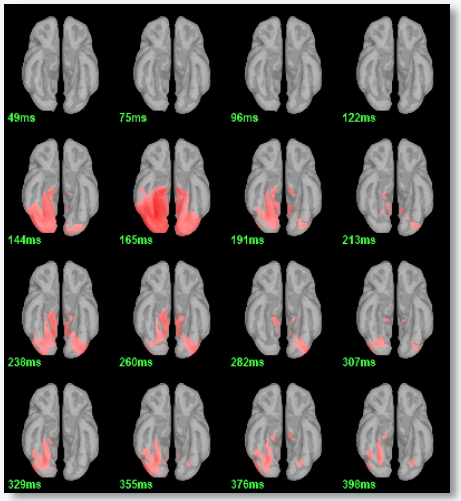
EEG



Parametric Chi2-test
log(|Faces-Scrambled|)=0
p<0.05 FDR-corrected



MEG



EEG

Brainstorm

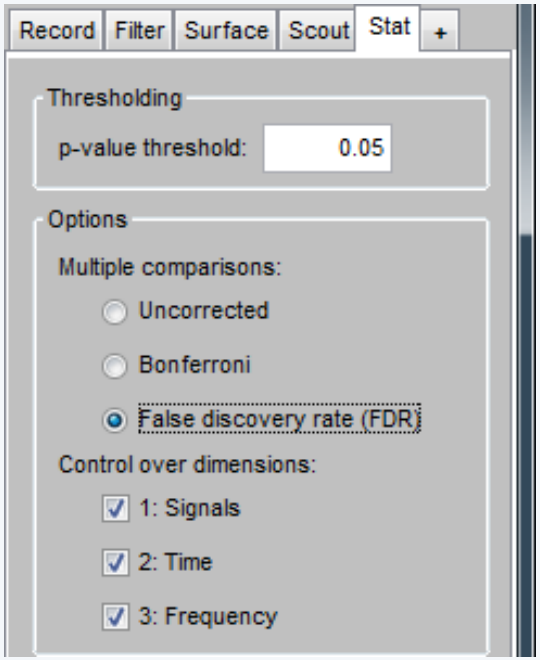
Group analysis

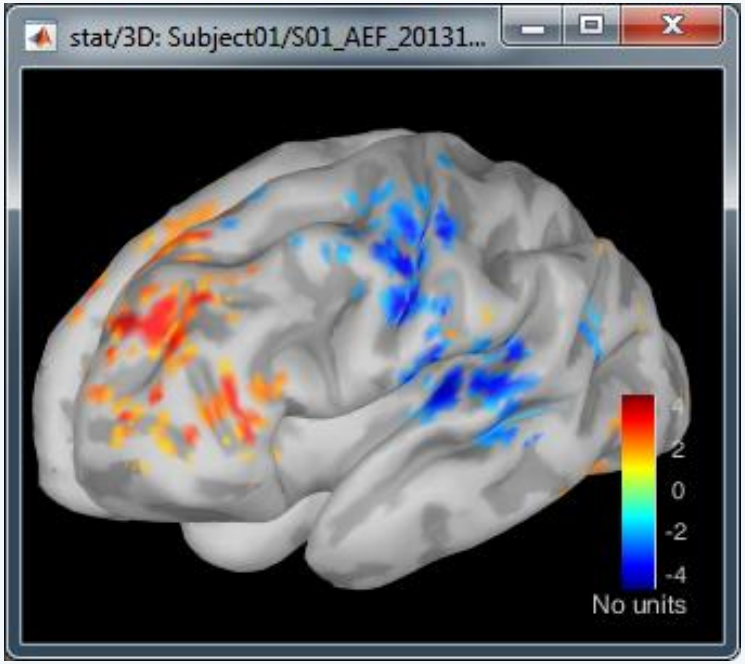
Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

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





Brainstorm

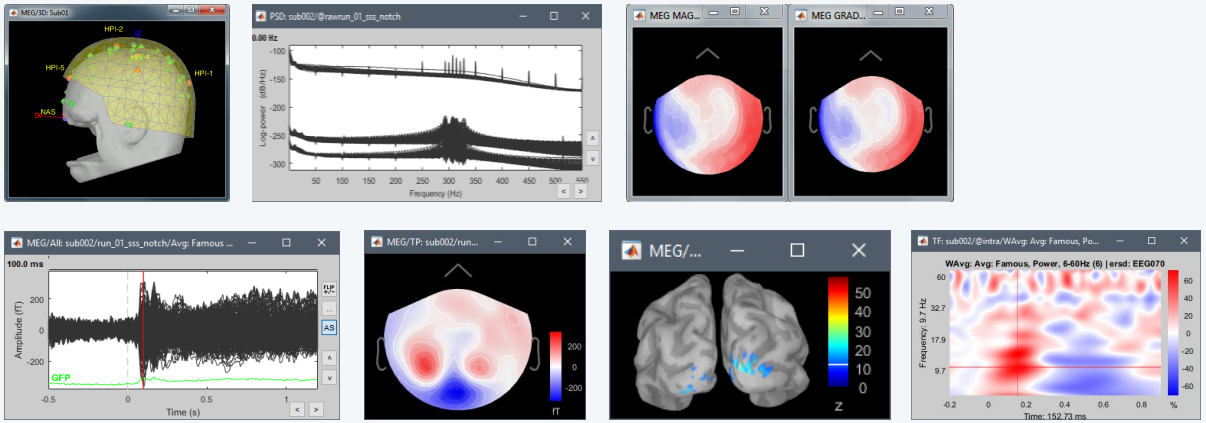
Group analysis

Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

- When scripting the analysis, we recommend you always check visually the following items for each run separately:
  - MRI/sensors registration
  - PSD before and after filters
  - SSP and ICA component topographies
  - ERP/ERF: Sensors time series
  - ERP/ERF: Sensors topo of primary response
  - ERP/ERF: Sources of primary response
  - Any other metric of interest



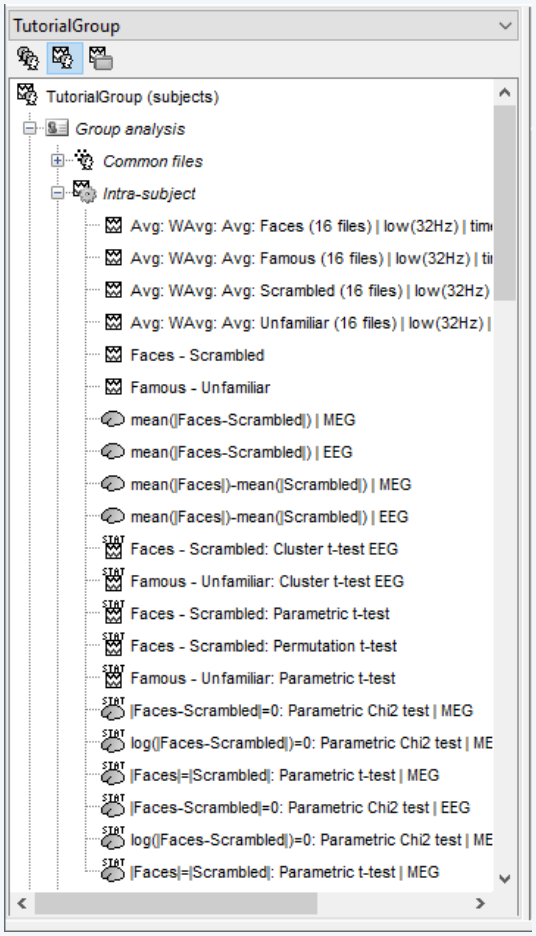
Group analysis

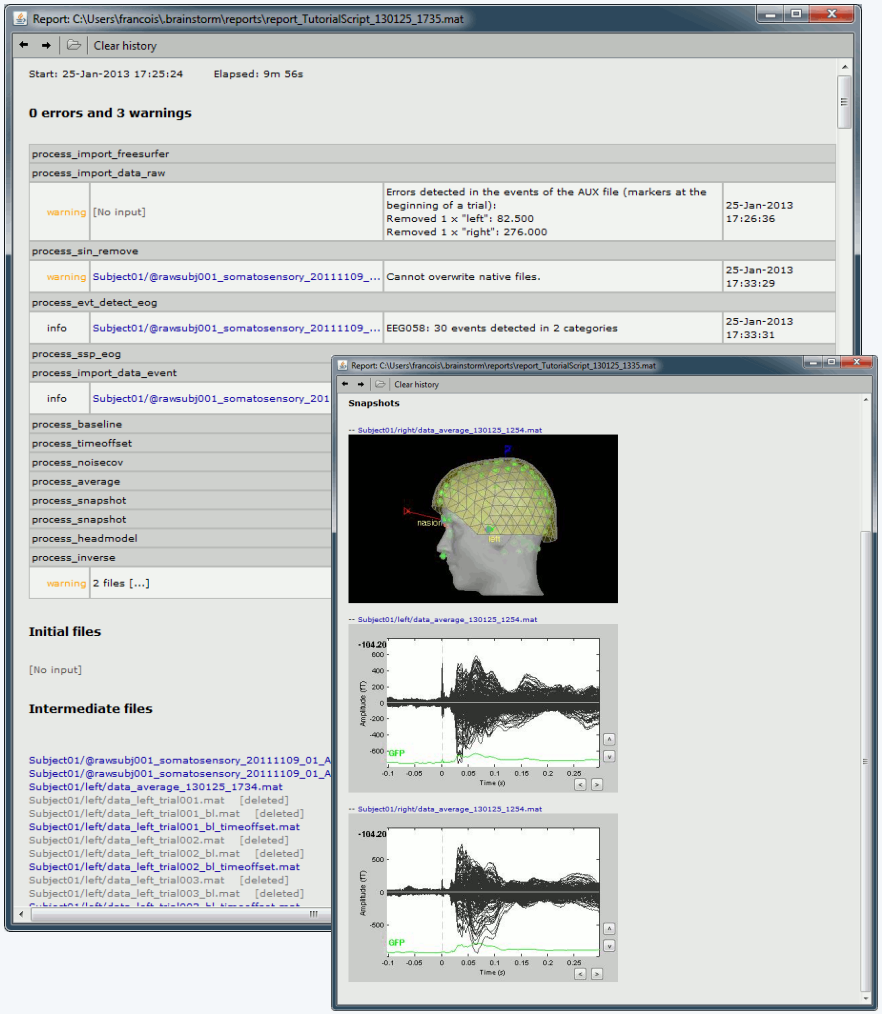
Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

- Execution reports with snapshots saved in HTML





Brainstorm

Group analysis

- Prototype the analysis interactively with one subject.
  Write down all the parameters to reproduce with a script.
- Set the anatomical fiducials for all the subjects.
- **Script #1**: Import the anatomy for all the subjects
- **Script #2**: Pre-processing (loop on subjects)
  - Link the raw files, register with MRI, compute PSD
  - Detect or import event markers
  - Pre-processing: Filtering, detect artifacts, SSP, ICA
- **Manual inspection**:
  - Check the execution reports for script 2
  - Fix the SSP/ICA (re-compute, manual selection)
  - Mark bad channels and bad segments

Group analysis

Subject averages
Low-pass
Normalize
Project

Group averages
Group statistics

Quality control
Workflow

- **Script #3**: Subject-level analysis (loop on subjects)
  - Importing and averaging
  - Source estimation
  - Time-frequency
- **Manual inspection**:
  - Check the execution reports for script #3
  - Define regions of interest
- **Script #4**: Group analysis
  - Subject-level averages
  - Group-level averages
  - Statistics
  - Anything that involves regions of interest

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)
- Examples of recent external contributions:
  - MVPA decoding (Oliva, MIT)
  - Microstate segmentation (Cacioppo, UChicago)
  - Eyetracker/EEG synchronization (Uni Freiburg)

User community

- 16,000 users registered on the website

Find users next to you

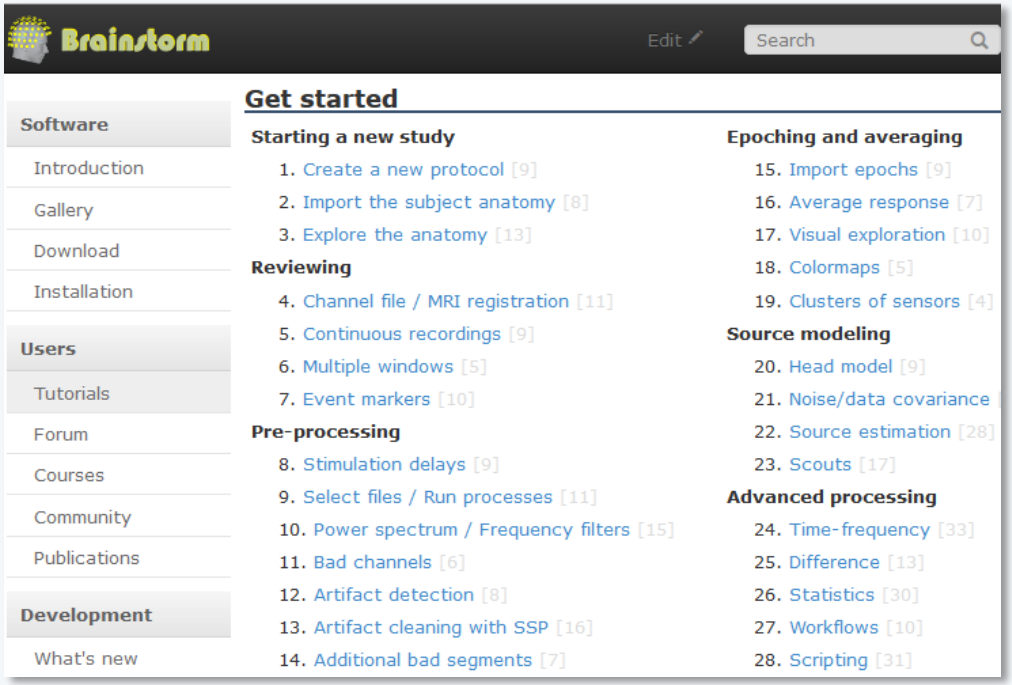
Location: montreal

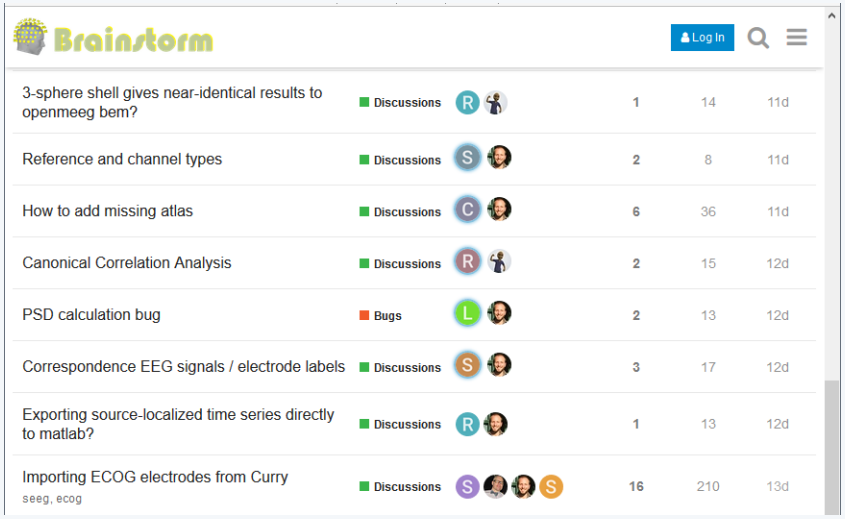
josieannebertrand	UQAM, Montreal	EEG	post-doc	2013
timothynest	Montreal, McGill	MEG, fNIRs	research	2013
Clara Moreau	Montreal	MEG	stagiare	2013

Brainstorm

User support

- Online tutorials: 30-hour self-training program
- Active user forum: 150 posts/month
- Daily updates: 750 downloads/month





Brainstorm

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And...

Matti Hamalainen
Antoine Ducorps
Denis Schwartz
…

MEG @ McGill


Elizabeth Bock
MEG engineer


Guiomar Niso
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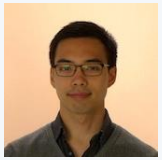
Soheila Samiee
PhD student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USC


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Aix-Marseille Univ


Rey Ramirez
UW

Sample data

Epilepsy recordings: Localization of frontal spikes

- Patient recorded at the Epilepsy Centre of the University Hospital in Freiburg, Germany
- Focal epilepsy with focal sensory, dyscognitive and secondarily generalized seizures since the age of eight years
- Histological analysis revealed a focal cortical dysplasia

- One hour of sleep recordings
- Neurofile NT EEG system, sampled at 256Hz
- 58 epileptic spikes marked by the epileptologists in Freiburg

- MRI processed with FreeSurfer 5.3