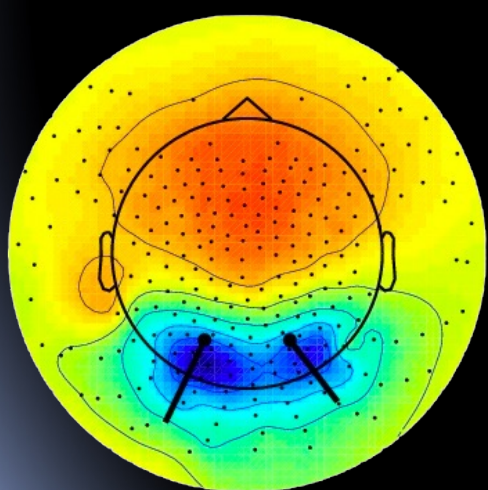
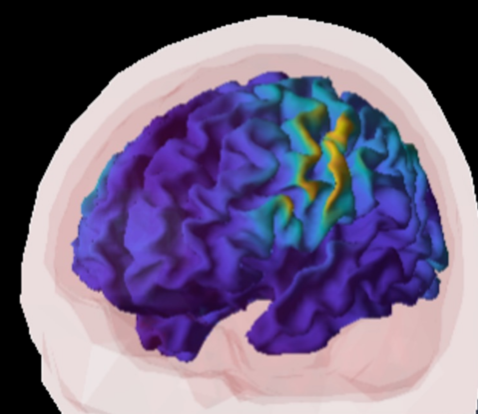
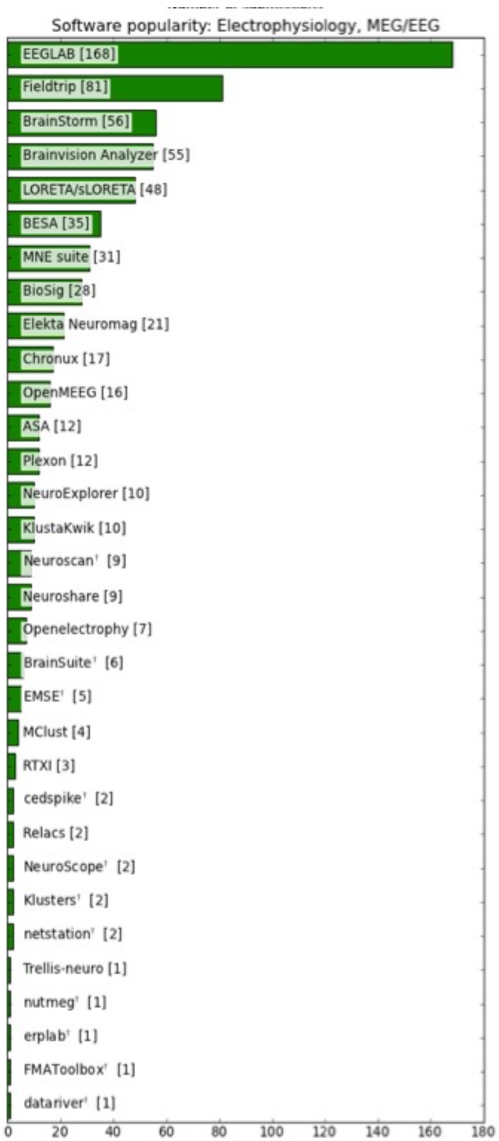
Network Dynamics in EEG

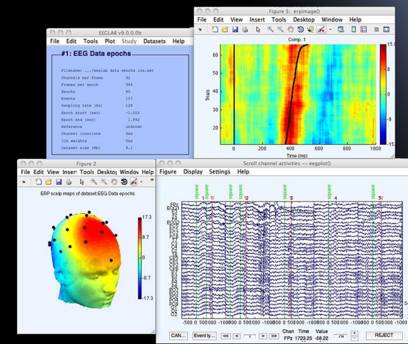


Arnaud Delorme



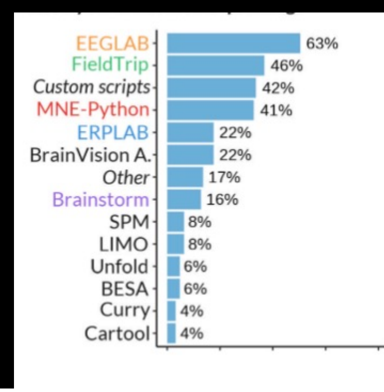


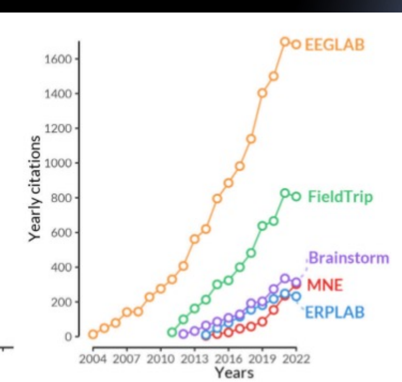
EEGLAB



http://eeglab.org

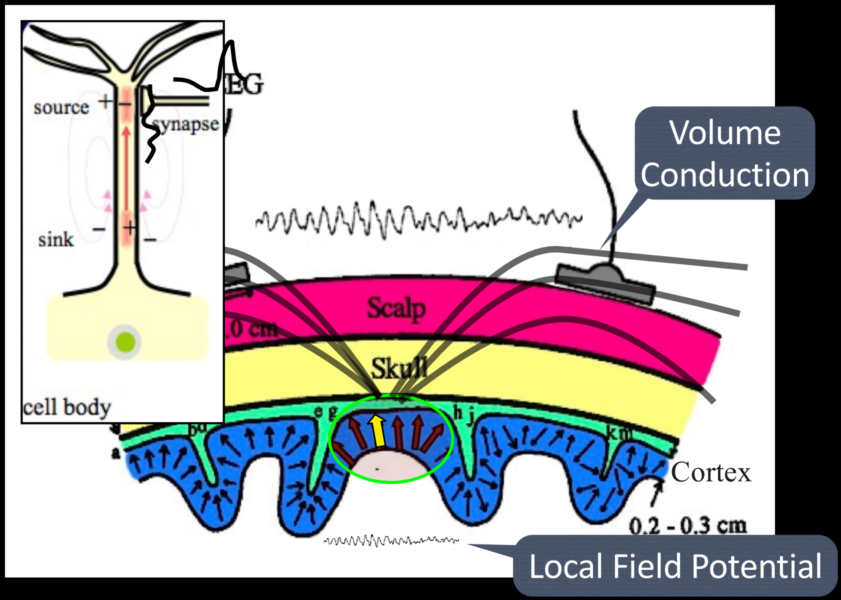
- Collection of over 350 functions (70,000 lines of code)
- About 1M download over the past 23 years
- About 6,500 users on the discussion list and 19,000 on the diffusion list
- 150 plugins





Biophysics of EEG

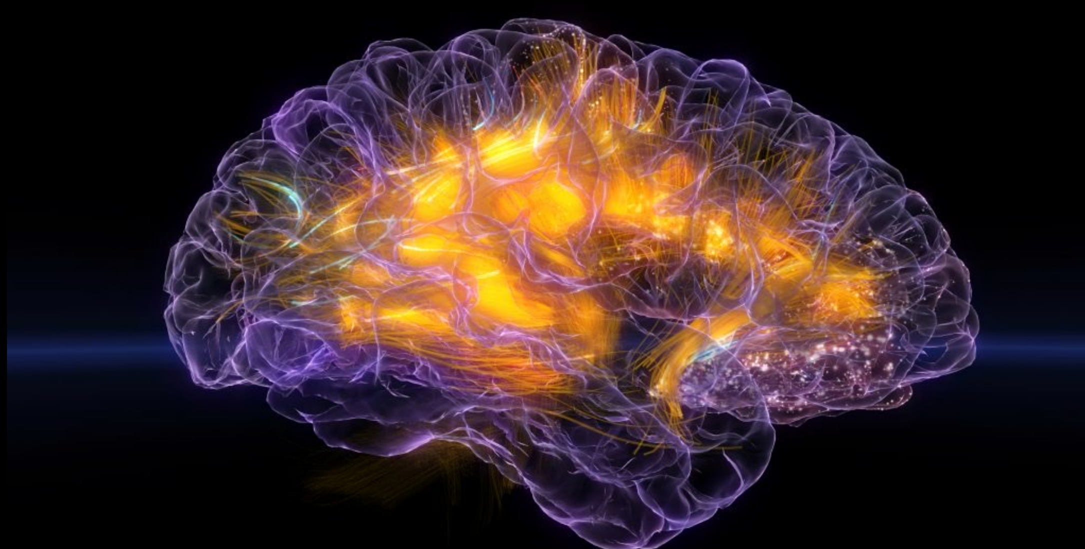
Hans Berger
(1873-1971)



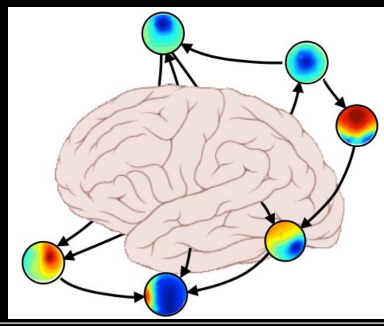
Synchronicity of cell excitation determines amplitude and rhythm of the EEG signal

Connectivity analysis

Aspet, 2025



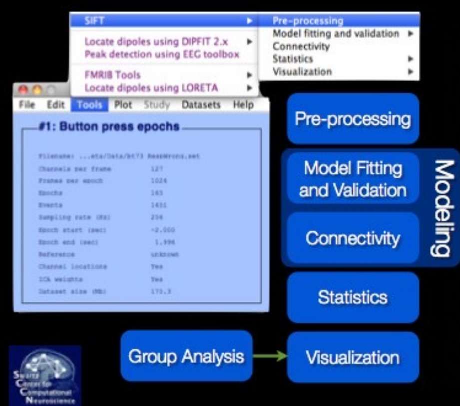
Tim Mullen

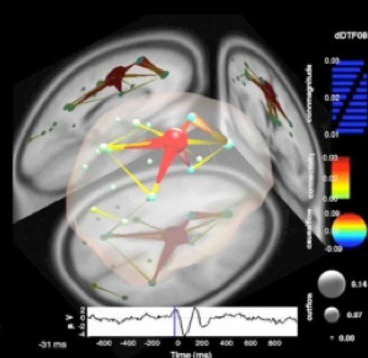


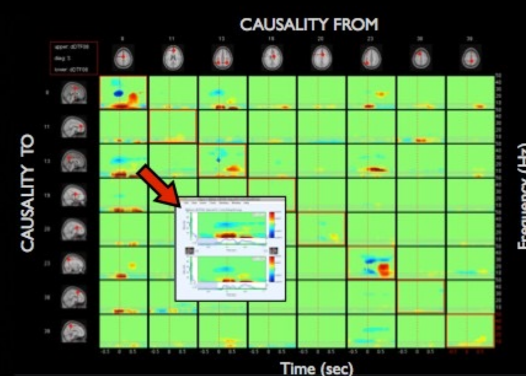
SIFT

Source Information Flow Toolbox

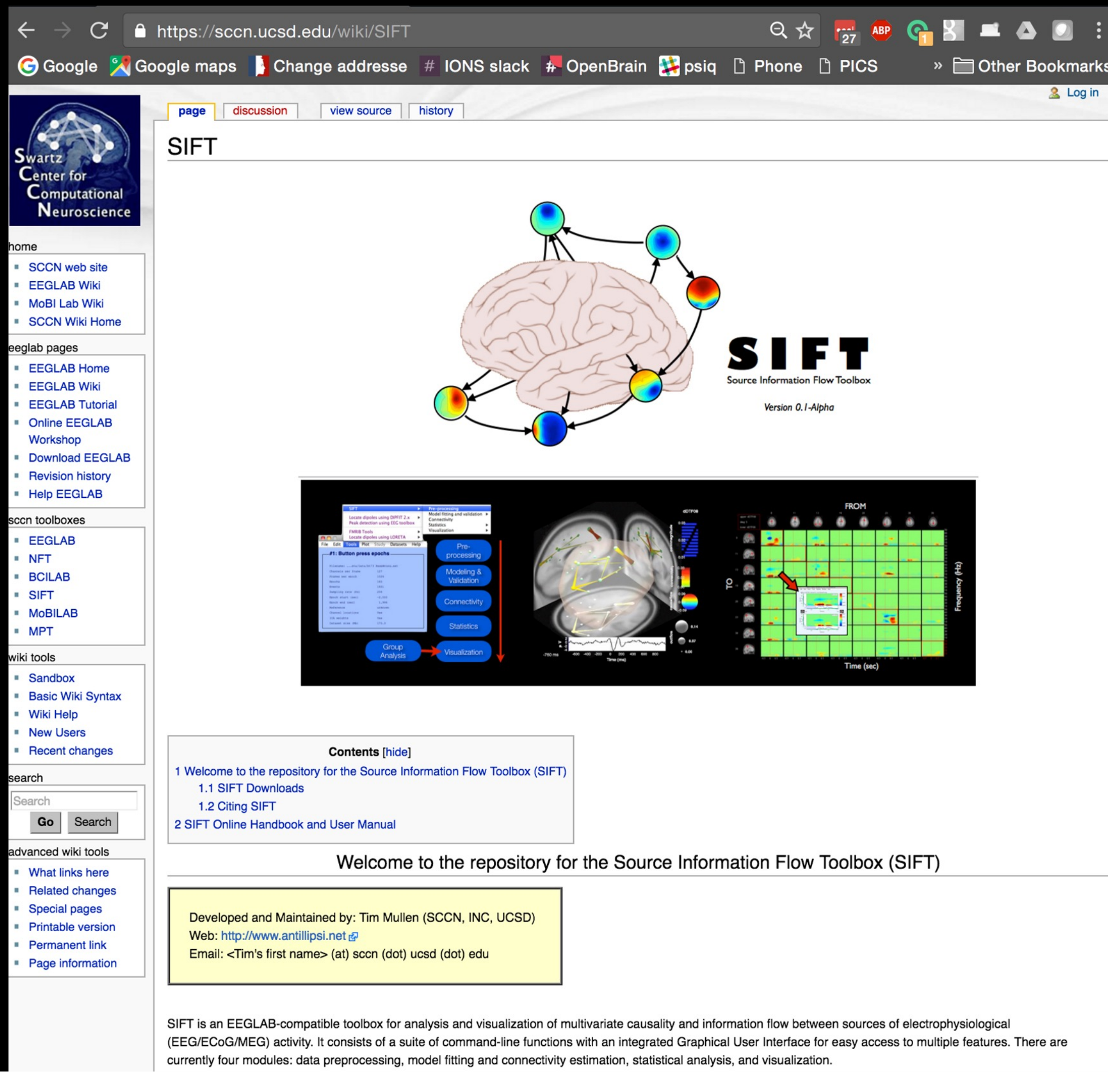
http://sccn.ucsd.edu/wiki/SIFT
Mullen, et al, *Journal of Neuroscience Methods* (in prep, 2012)
Mullen, et al, *Society for Neuroscience*, 2010
Delorme, Mullen, Kothe et al, *Computational Intelligence and Neuroscience*, vol 12, 2011







- A toolbox for (source-space) electrophysiological information flow and causality analysis (single- or multi-subject) integrated into EEGLAB
- Emphasis on vector autoregression and time-frequency domain approaches
- Standard and novel interactive visualization methods for exploratory analysis of connectivity across time, frequency, and spatial location


https://sccn.ucsd.edu/wiki/SIFT

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Swartz Center for Computational Neuroscience

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- EEGLAB Wiki
- MoBI Lab Wiki
- SCCN Wiki Home

eeglab pages
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- EEGLAB Wiki
- EEGLAB Tutorial
- Online EEGLAB Workshop
- Download EEGLAB
- Revision history
- Help EEGLAB

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- EEGLAB
- NFT
- BCILAB
- SIFT
- MoBILAB
- MPT

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- Basic Wiki Syntax
- Wiki Help
- New Users
- Recent changes

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- What links here
- Related changes
- Special pages
- Printable version
- Permanent link
- Page information

SIFT

SIFT
Source Information Flow Toolbox
Version 0.1-Alpha

Pre-processing
Modeling & Validation
Connectivity
Statistics
Group Analysis
Visualization
FROM
TO
Time (sec)
Frequency (Hz)

Contents [hide]

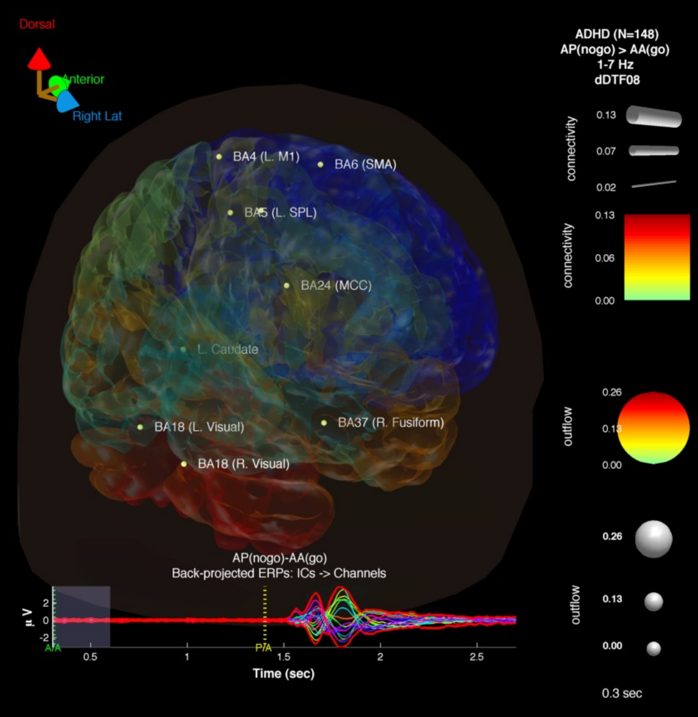
Welcome to the repository for the Source Information Flow Toolbox (SIFT)

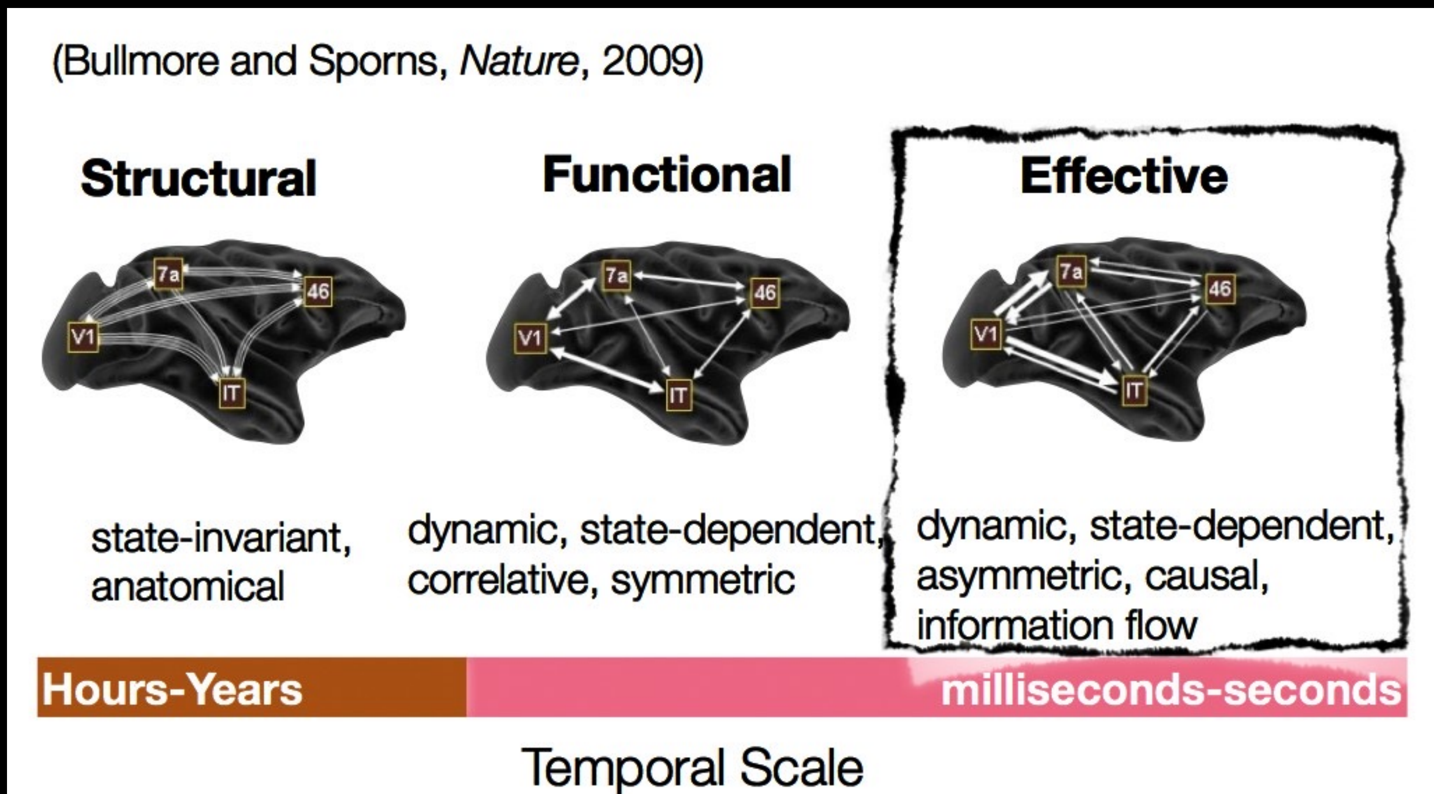
Developed and Maintained by: Tim Mullen (SCCN, INC, UCSD)
Web: http://www.antillipsi.net
Email: <Tim's first name> (at) sccn (dot) ucsd (dot) edu

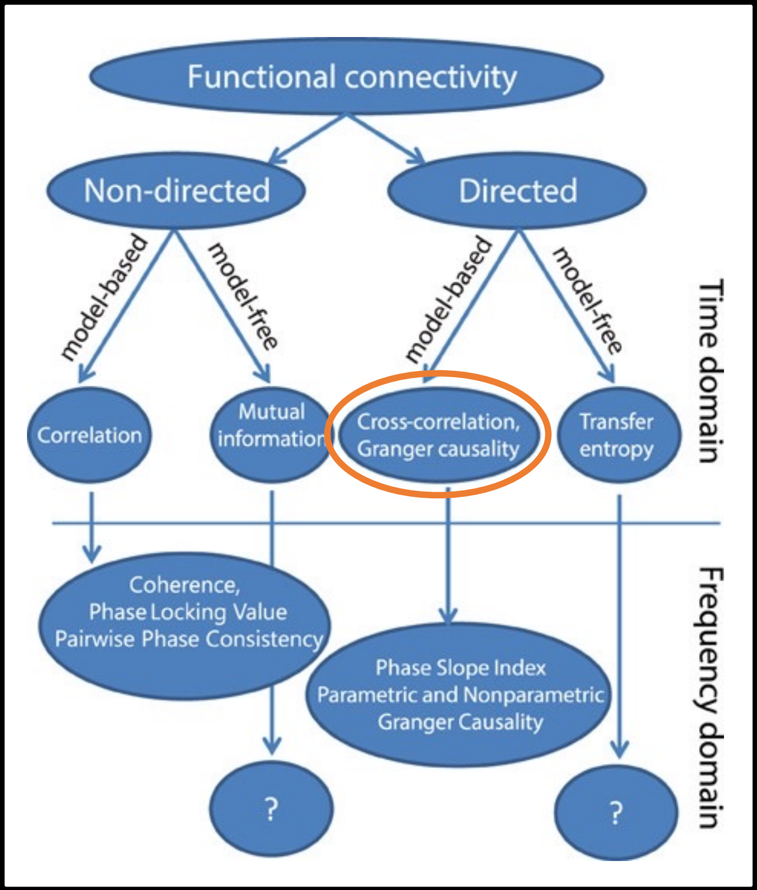
SIFT is an EEGLAB-compatible toolbox for analysis and visualization of multivariate causality and information flow between sources of electrophysiological (EEG/ECoG/MEG) activity. It consists of a suite of command-line functions with an integrated Graphical User Interface for easy access to multiple features. There are currently four modules: data preprocessing, model fitting and connectivity estimation, statistical analysis, and visualization.

The Dynamic Brain

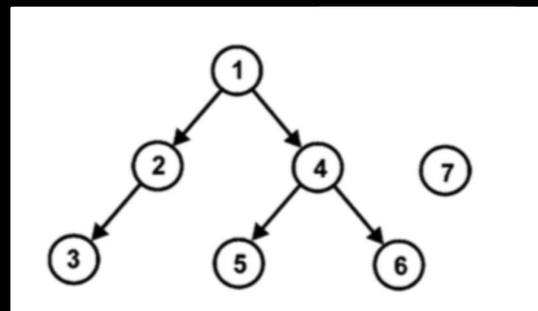
- A key goal: To model temporal changes in neural dynamics and information flow that index and predict task-relevant changes in cognitive state and behavior
- Open Challenges:
  - Non-invasive measures (source inference)
  - Robustness and Validity (constraints   statistics)
  - Scalability (multivariate)
  - Temporal Specificity / Non stationarity / Single-trial (dynamics)
  - Multi-subject Inference
  - Usability and Data Visualization (software)




(Bullmore and Sporns, *Nature*, 2009)
Structural
Functional
Effective
7a
46
V1
IT
state-invariant, anatomical
dynamic, state-dependent, correlative, symmetric
dynamic, state-dependent, asymmetric, causal, information flow
Hours-Years
milliseconds-seconds
Temporal Scale



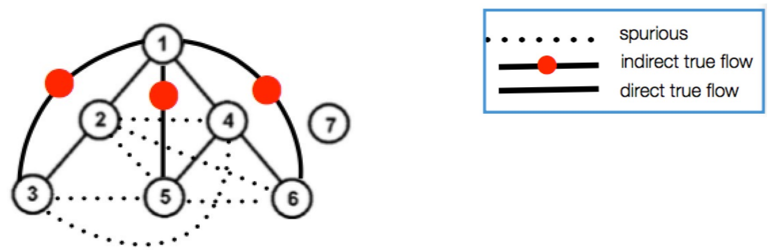
Bastos AM, Schoffelen J-M: **A Tutorial Review of Functional Connectivity Analysis Methods and Their Interpretational Pitfalls**. *Front Sys Neurosci* 2016, **9**:413.



Coherency

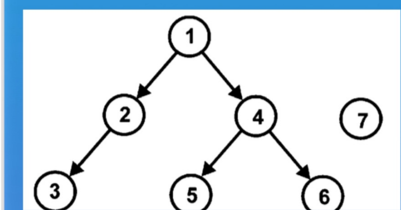
$$C_{ij}(f) = \frac{S_{ij}(f)}{\sqrt{S_{ii}(f)S_{jj}(f)}}$$

(Bendat and Piersol, 1986)

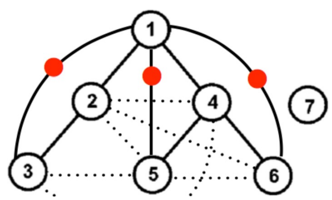


Bivariate measures such as coherence (but also original GC), find spurious connections between nodes if they share a common input.

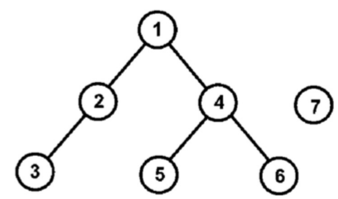
Ground Truth



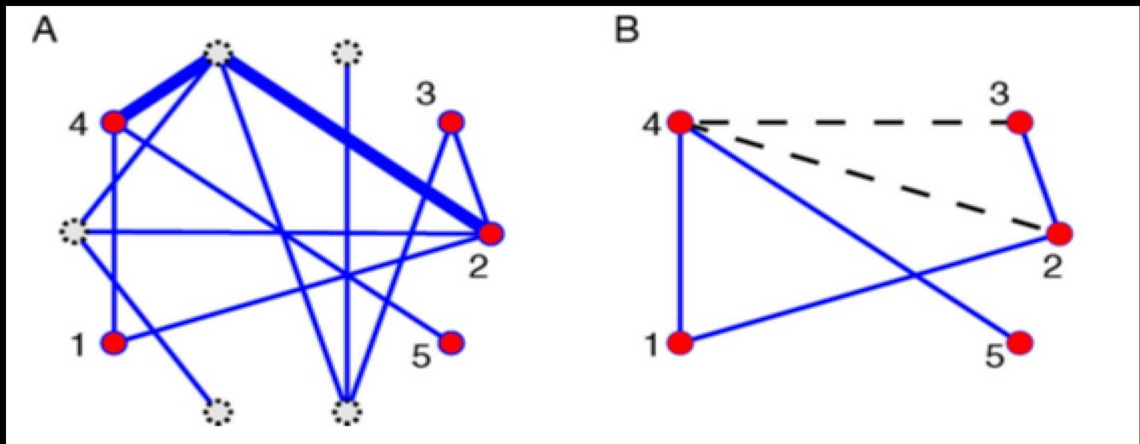
Coherence



Partial coherence



A deeper problem – unobserved nodes



With EEG, it's unavoidable that there will be contributing network nodes (e.g. thalamus) that we cannot observe.

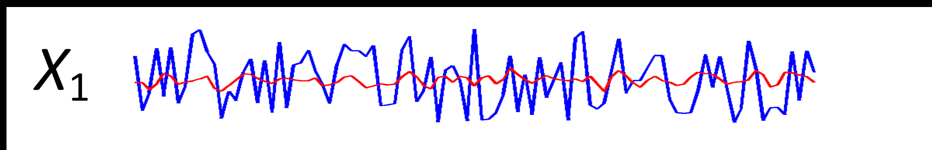
We also can't be sure ICA will identify all important sources…

Granger-causality

- A measure of *statistical* causality based on prediction.
- Widely used in time-series econometrics.
- Nobel Prize in economics, 2003.

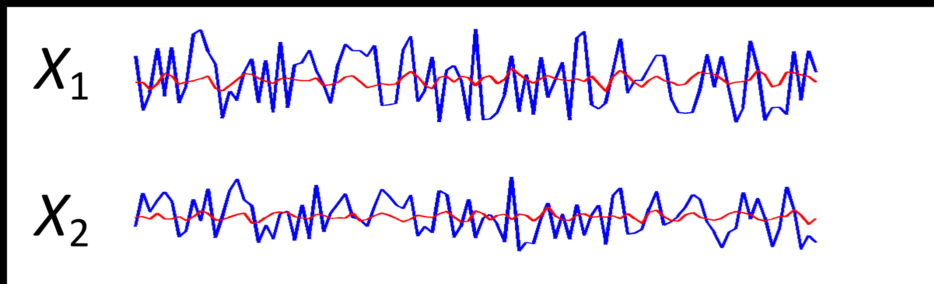
If a signal A causes a signal B, then knowledge of the past of both A and B should improve the predictability of B, as compared to knowledge of B alone.

AR Models (prediction of future of a signal by its past)

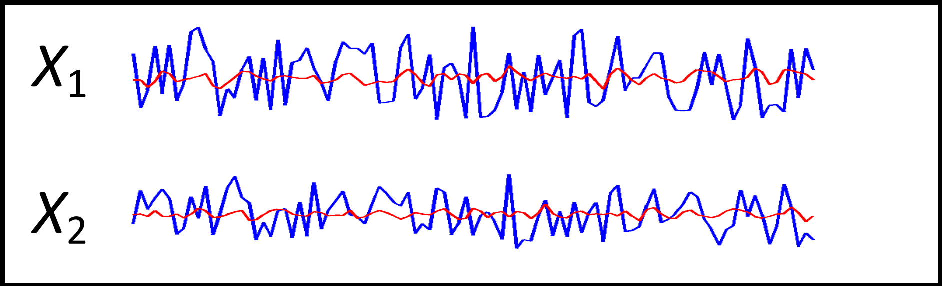


$$X_1(t) = -0.5X_1(t-1) + 0.3X_1(t-2) + 0.1X_1(t-3) \ldots$$

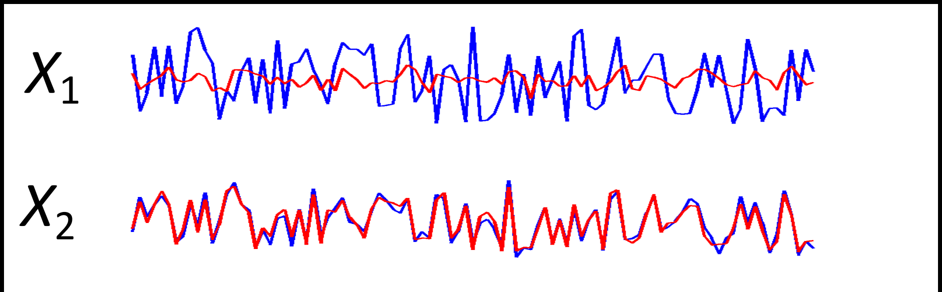
AR Models (prediction of future of a signal by its past)



AR Models (prediction of future of a signal by its past)

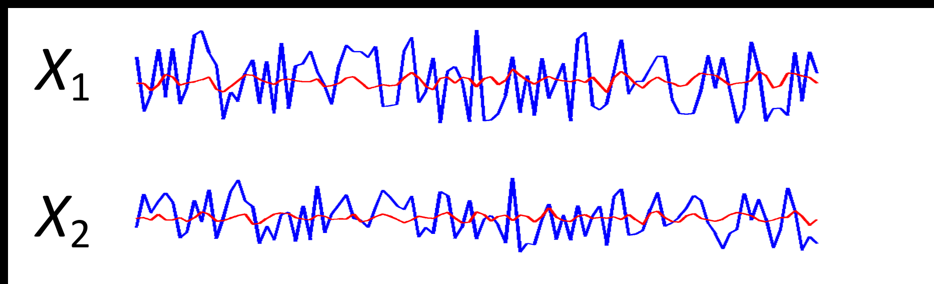


VAR Models (prediction of future of a signal by its past + the other signal's past)

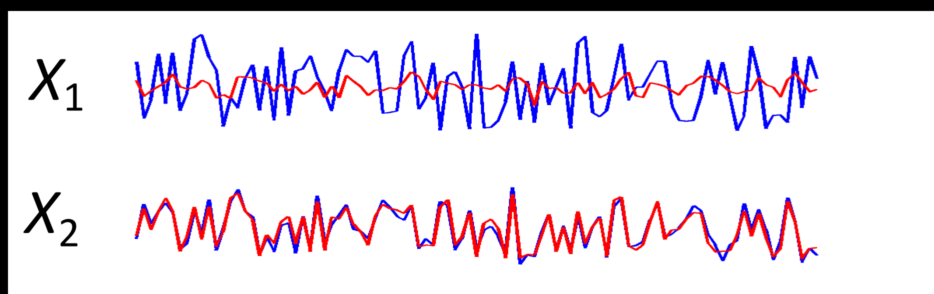


Incorporating information about X_1 improves the prediction of X_2! We say "X_1 granger causes X_2"

AR Models (prediction of future of a signal by its past)



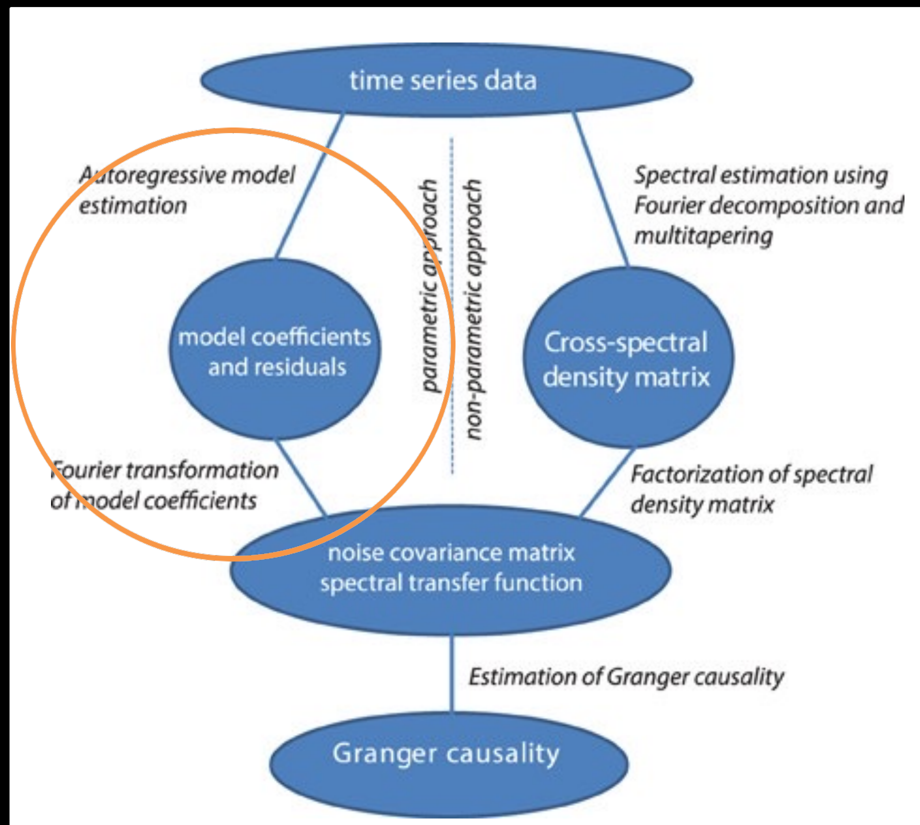
VAR Models (prediction of future of a signal by its past + the other signal's past)



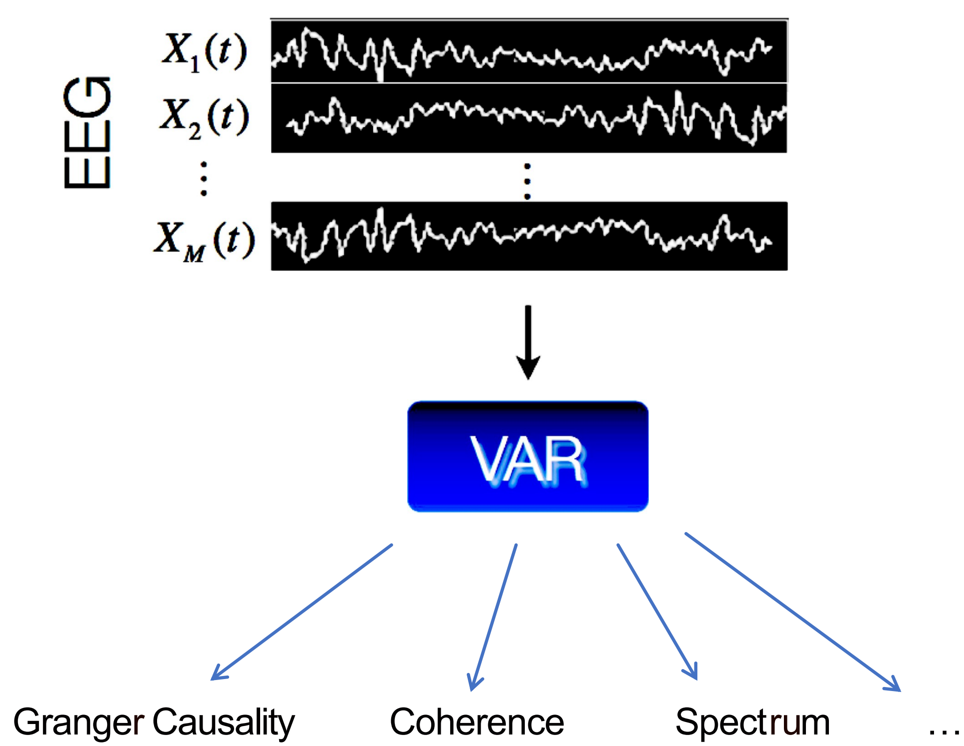
$X_1(t) = -0.5X_1(t-1) + 0.3X_2(t-1) + \ldots$

$X_2(t) = -5X_1(t-1) - 0.1X_2(t-1) + \ldots$

Incorporating information about X_1 improves the prediction of X_2! We say "X_1 granger causes X_2"

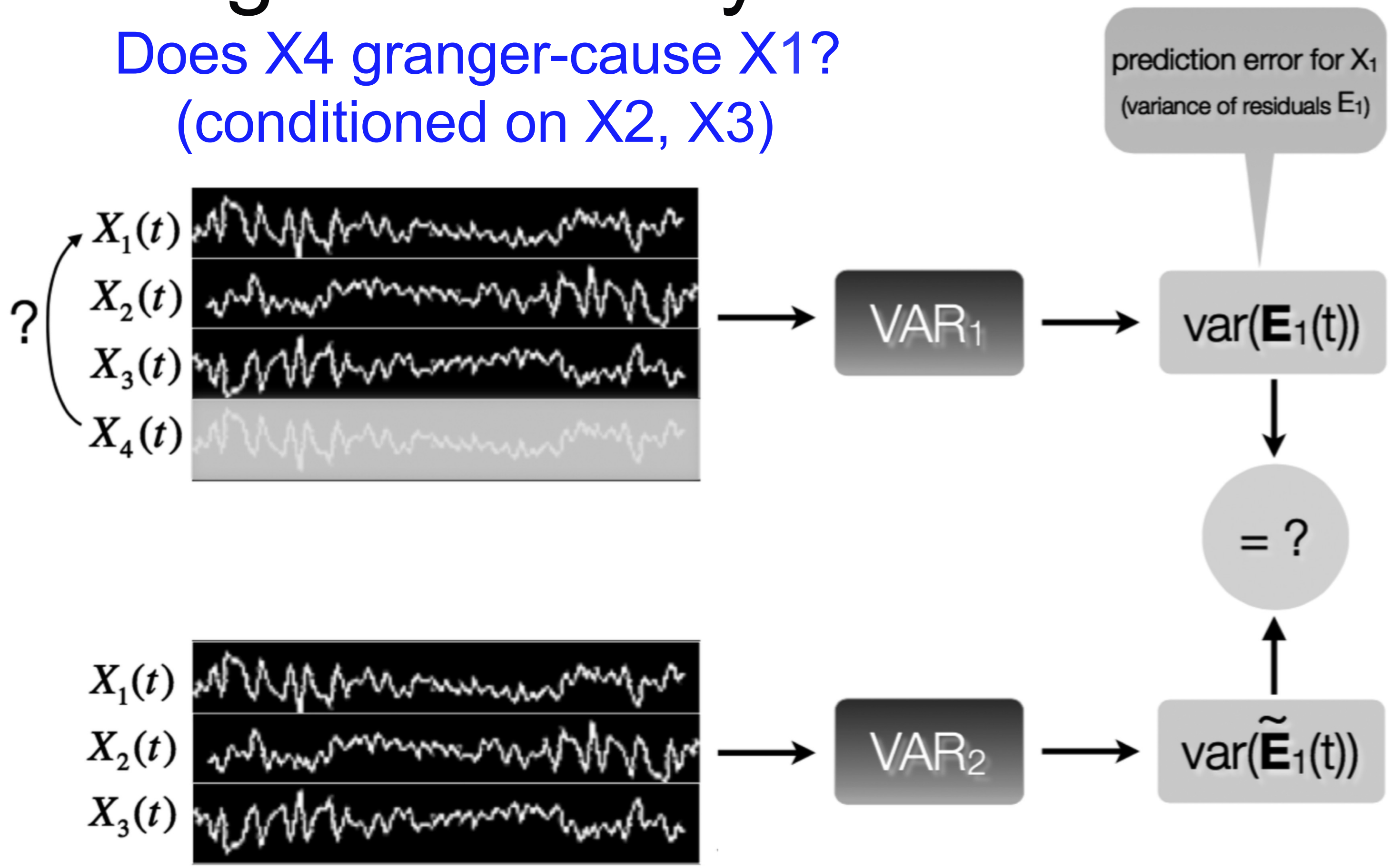

time series data
Autoregressive model estimation
parametric approach
non-parametric approach
Spectral estimation using Fourier decomposition and multitapering
model coefficients and residuals
Cross-spectral density matrix
Fourier transformation of model coefficients
Factorization of spectral density matrix
noise covariance matrix spectral transfer function
Estimation of Granger causality
Granger causality

Vector Autoregressive (VAR / MAR / MVAR) Modeling



Granger Causality

Does X4 granger-cause X1?
(conditioned on X2, X3)



Granger-causality quiz

$$X_1(t) = -0.5X_1(t-1) + \boxed{0X_2(t-1)} + E_1(t)$$
$$X_2(t) = \boxed{0.7X_1(t-1)} + 0.2X_2(t-1) + E_2(t)$$

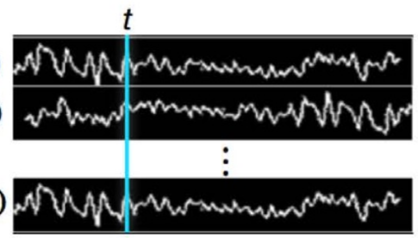
Which causal structure does this model correspond to?

a) $1 \longrightarrow 2$ b) $1 \longleftarrow 2$ c) $1 \longleftrightarrow 2$

The Linear Vector Auto-regressive (VAR) Model

Ordinary Least-Squares

$$X(t) = \begin{matrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{matrix}$$



VAR[p] model

model order

random noise process

$$\mathbf{X}(t) = \sum_{k=1}^{p} \mathbf{A}^{(k)}(t)\mathbf{X}(t-k) + \mathbf{E}(t)$$

M-channel data vector at current time t

M x M matrix of (possibly time-varying) model coefficients indicating variable dependencies at lag k

multichannel data k samples in the past

$$\mathbf{A}^{(k)}(t) = \begin{pmatrix} a_{11}^{(k)}(t) & \cdots & a_{1M}^{(k)}(t) \\ \vdots & \ddots & \vdots \\ a_{M1}^{(k)}(t) & \cdots & a_{MM}^{(k)}(t) \end{pmatrix} \qquad \mathbf{E}(t) = N(0,\mathbf{V})$$

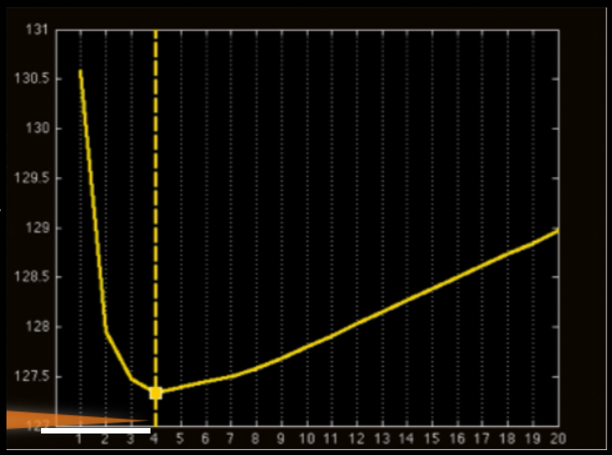
Selecting a VAR Model Order

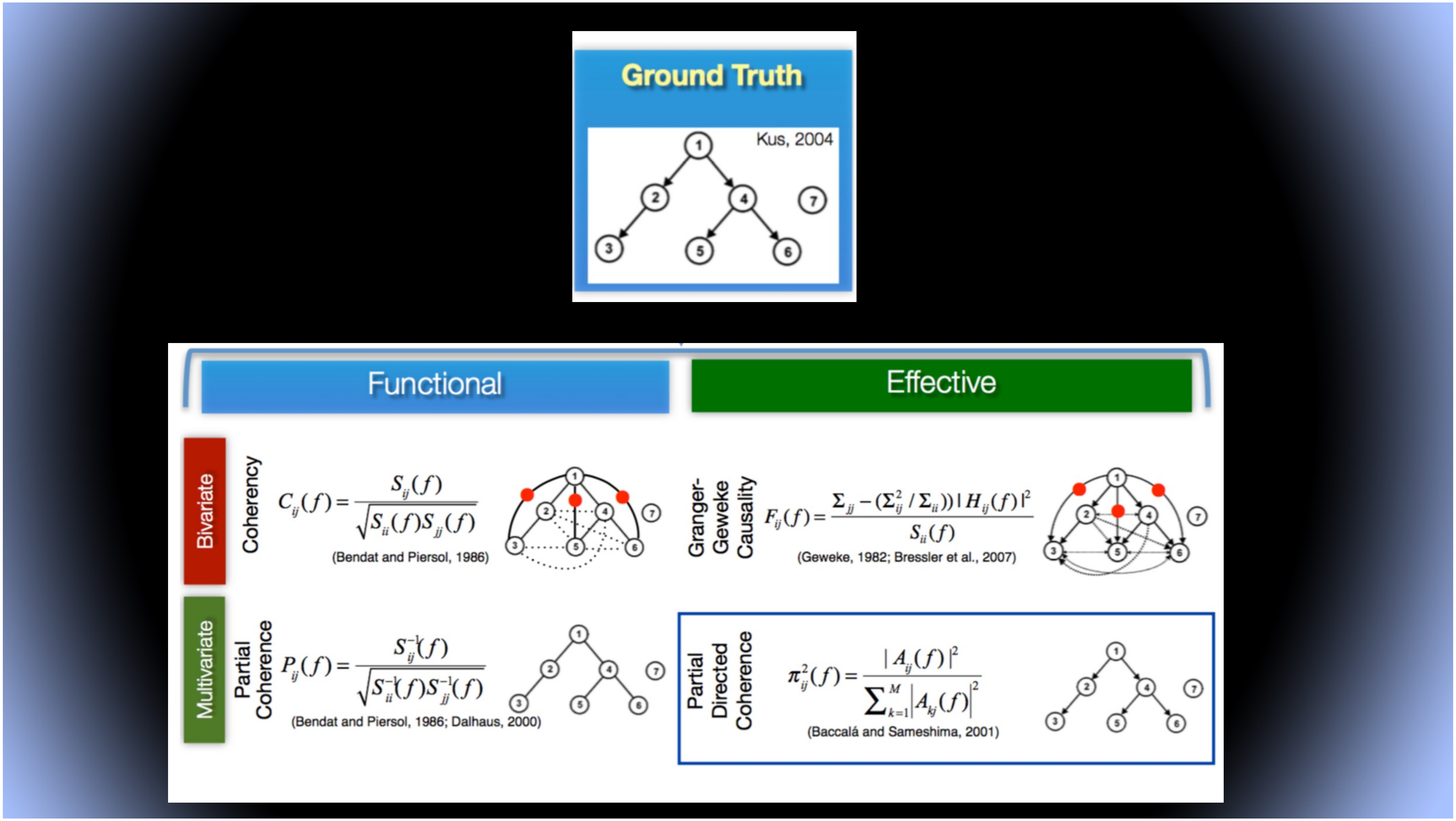
- Model order is typically determined by minimizing information criteria such as Akaike Information Criterion (AIC) for varying model order (p):

AIC(p) = 2log(det(V)) + M2p/N ← **Penalizes high model orders (parsimony)**

entropy rate (amount of prediction error)

- Optimal model order depends on sampling rate (higher sampling rate often requires higher model orders)

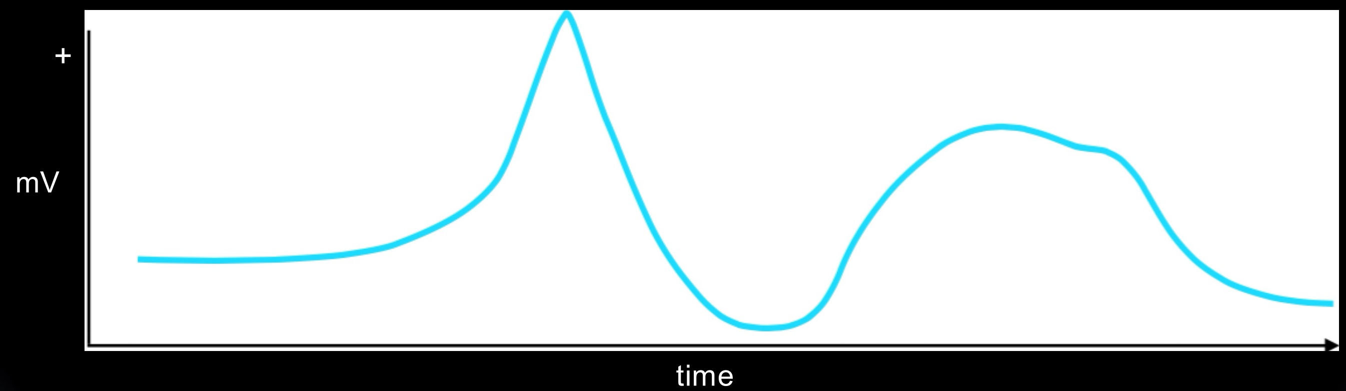




Ground Truth
Kus, 2004
Functional
Effective
Bivariate
Coherency
$C_{ij}(f) = \frac{S_{ij}(f)}{\sqrt{S_{ii}(f)S_{jj}(f)}}$
(Bendat and Piersol, 1986)
Granger-Geweke Causality
$F_{ij}(f) = \frac{\Sigma_{jj} - (\Sigma_{ij}^2 / \Sigma_{ii}) \mid H_{ij}(f) \mid^2}{S_{ii}(f)}$
(Geweke, 1982; Bressler et al., 2007)
Multivariate
Partial Coherence
$P_{ij}(f) = \frac{S_{ij}^{-1}(f)}{\sqrt{S_{ii}^{-1}(f)S_{jj}^{-1}(f)}}$
(Bendat and Piersol, 1986; Dalhaus, 2000)
Partial Directed Coherence
$\pi_{ij}^2(f) = \frac{\mid A_{ij}(f) \mid^2}{\sum_{k=1}^{M} \left| A_{kj}(f) \right|^2}$
(Baccalá and Sameshima, 2001)

Adapting to Non-Stationarity

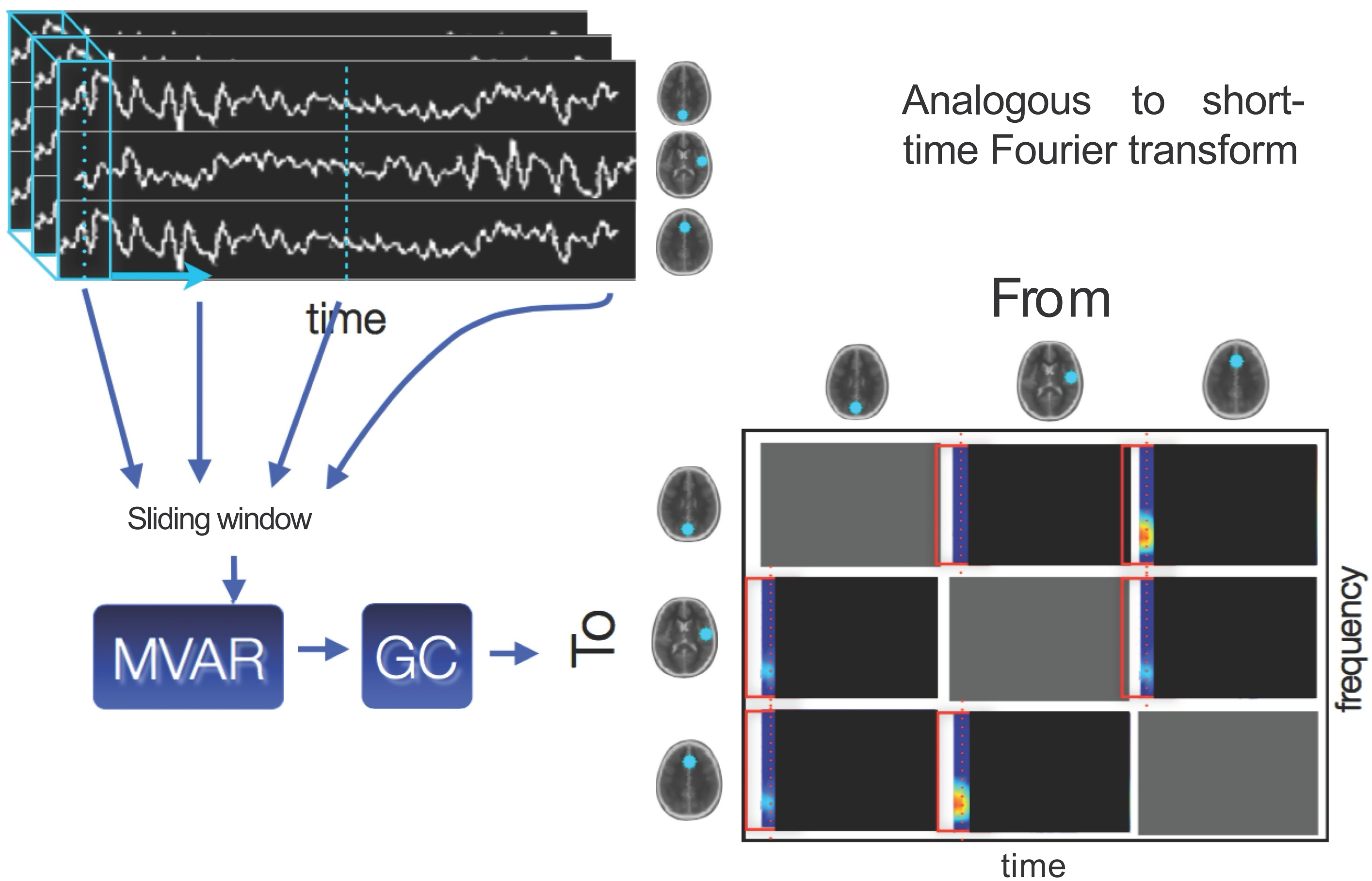
- The brain is **a dynamic system** and measured brain activity and coupling can change rapidly with time (non-stationarity)
  - event-related perturbations (ERSP, ERP, etc)
  - structural changes due to learning/feedback
- How can we adapt to non-stationarity?



Segmentation-based VAR

(Jansen et al., 1981;Florian and Pfurtscheller, 1995; Ding et al,2000)

Analogous to short-time Fourier transform



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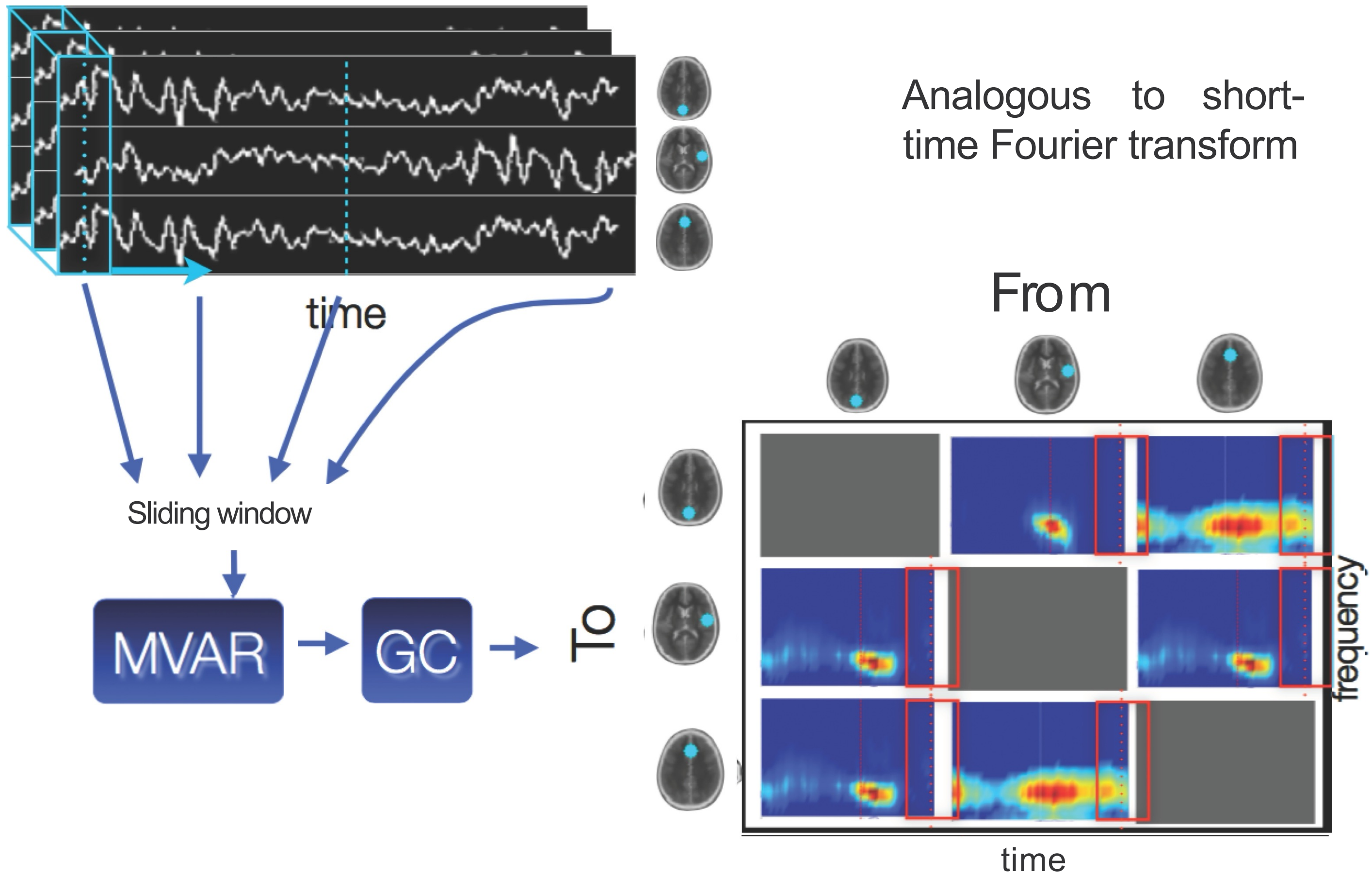
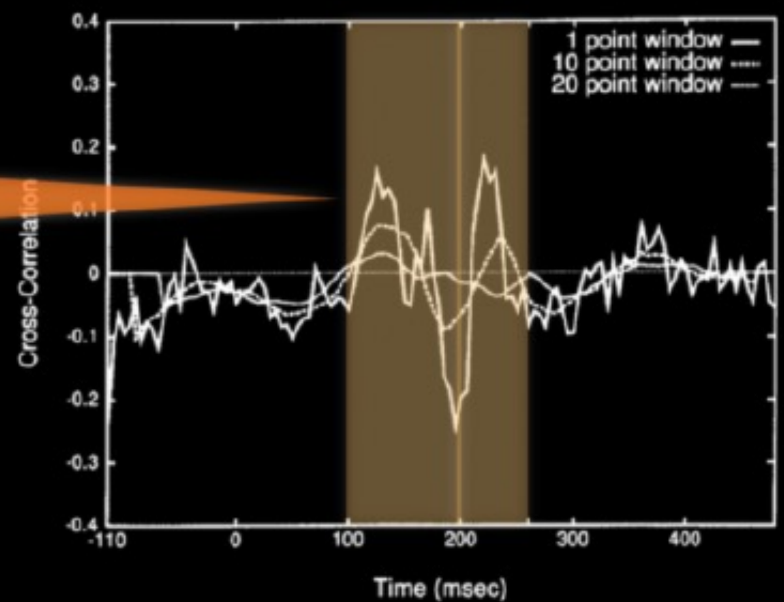


Important Choices

- Model Order
  - Determines complexity of spectrum you can model
  - Larger orders need more data
- Window Length
  - Window must be long enough to contain sufficient data for your chosen model order
  - Must be long enough to encompass the time-scale of interactions
  - Yet not too long as to smear temporal dynamics or include non-stationary data
  - *If trials are present, can optimize AR model over trials*

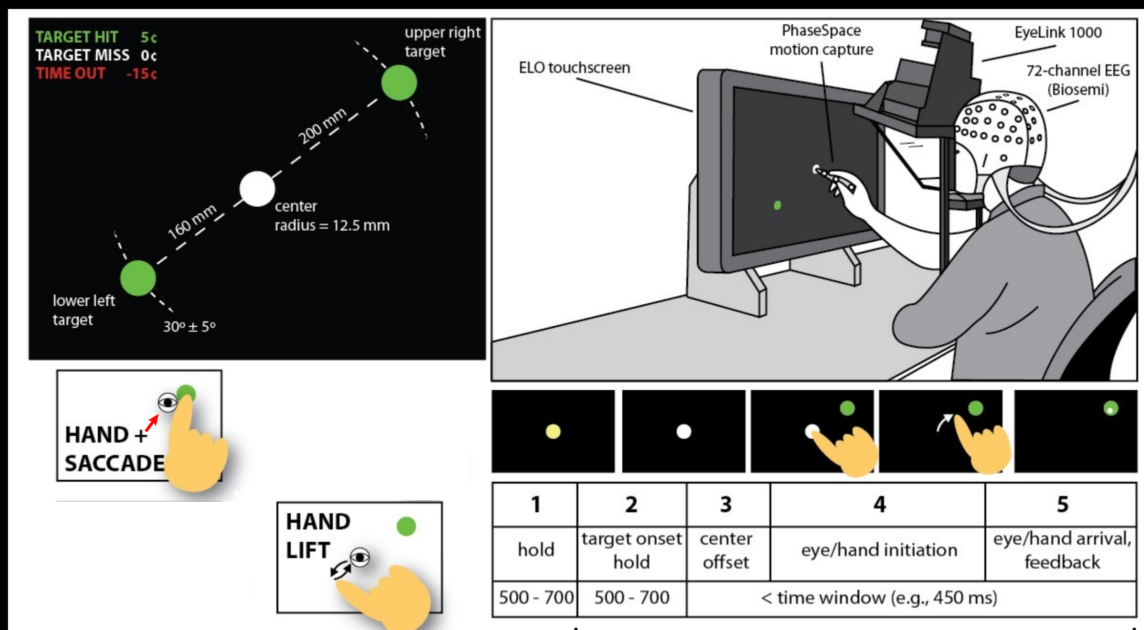
Consideration: Local Stationarity

Too-large, windows may not be locally-stationary

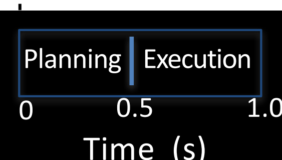


How does brain plan visually guided movements?

- Pointing Task (Park, et al. 2014, *IEEE Trans Neural Syst Rehabil Eng)*



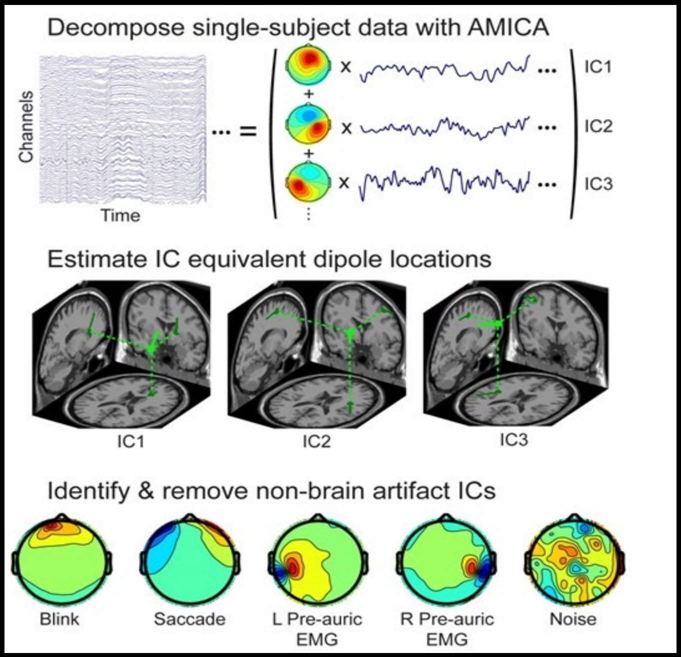
N=10 (right-handed, mean age=21) 70 channel EEG (Biosemi) 512 Hz; 128Hz for connectivity



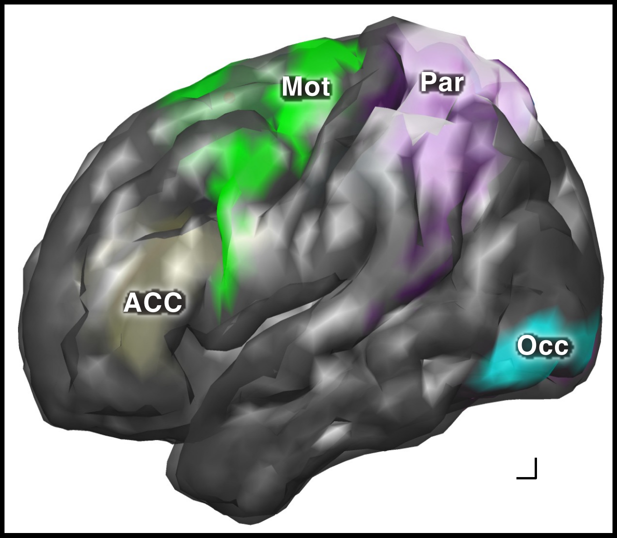
John R. Iversen, Alejandro Ojeda, Tim Mullen, Markus Plank, Joseph Snider, Gert Cauwenberghs, Howard Poizner (2014) EMBC

ICA source space analysis

Independent Component Analysis

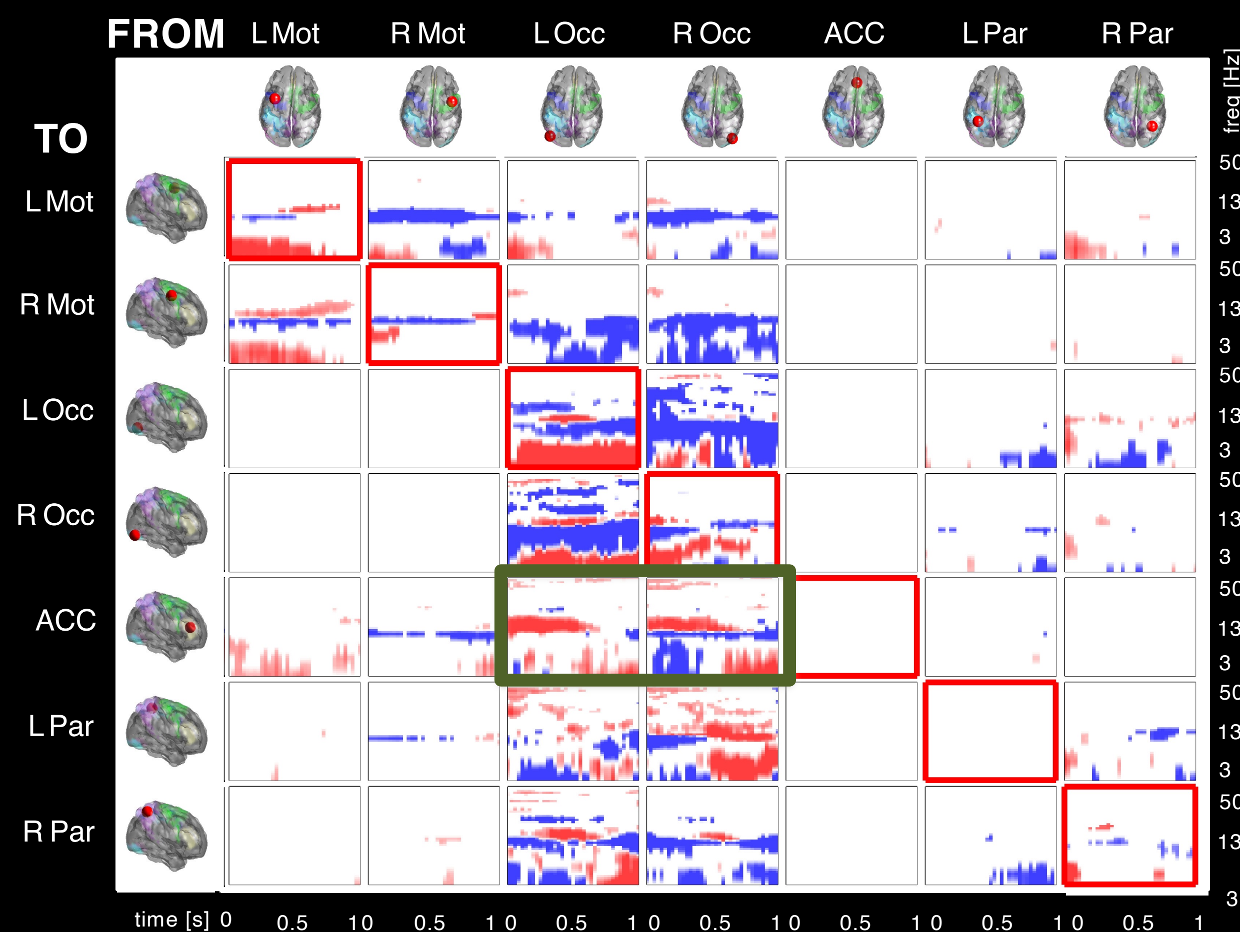


Cortical Regions of Interest



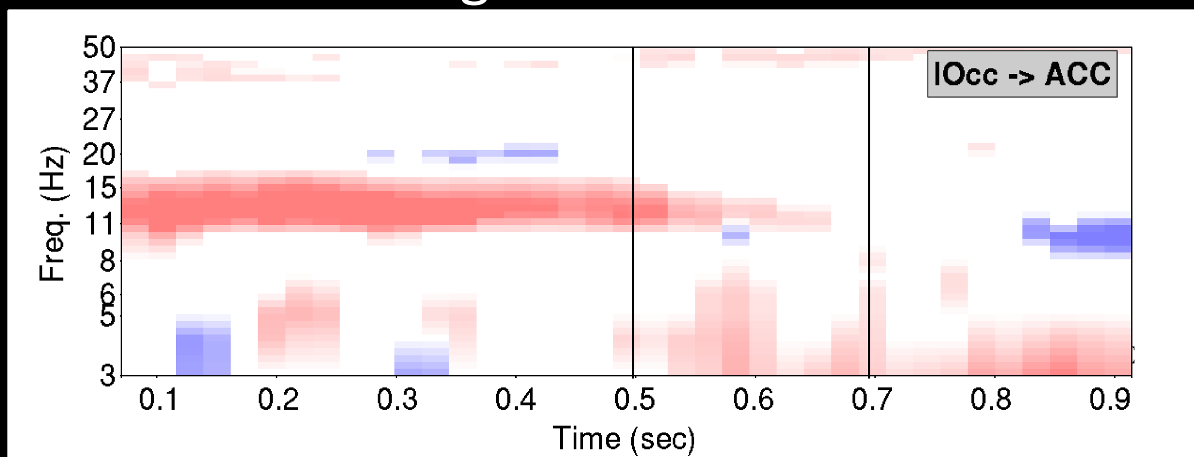
Group SIFT: Project ICs onto cortical surface using LORETA; extract ROI time series. Advantage: Same ROIs for all subjects enables statistical comparison. (*Use BCILAB srcpot*)

Changed causal flow during reaching

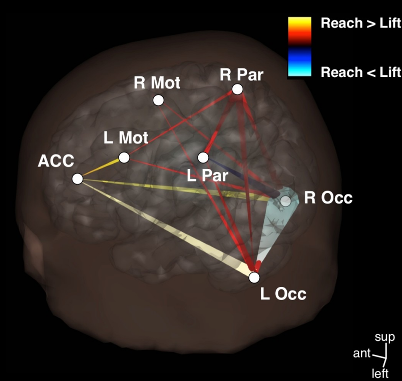


Occipital -> ACC

Planning Execution

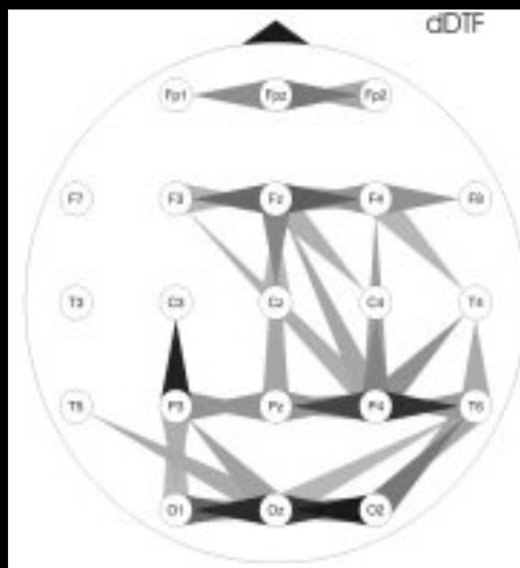


Result discussion

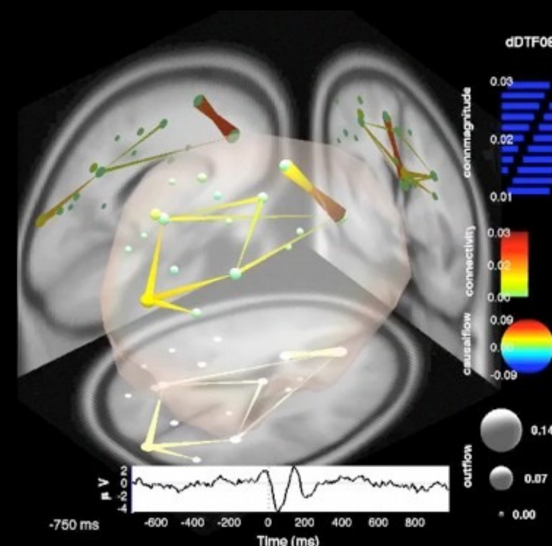


- SIFT is a capable toolkit for causal dynamical analysis at source level
- Parietal network expected for visually guided action (e.g. Heider, et al., 2010)
- ACC more strongly driven by Occipital   Motor. Locus for translation of intention into action (Paus, 2001; Srinivasan, et al. 2013). ACC drives SMA (not shown).
- Causal network results depend on the number of nodes
  - E.g. Occipital " ACC could be mediated by region not included in model
  - There will always be a tradeoff between network size and amount of data needed to fit the model.
  - Regularization

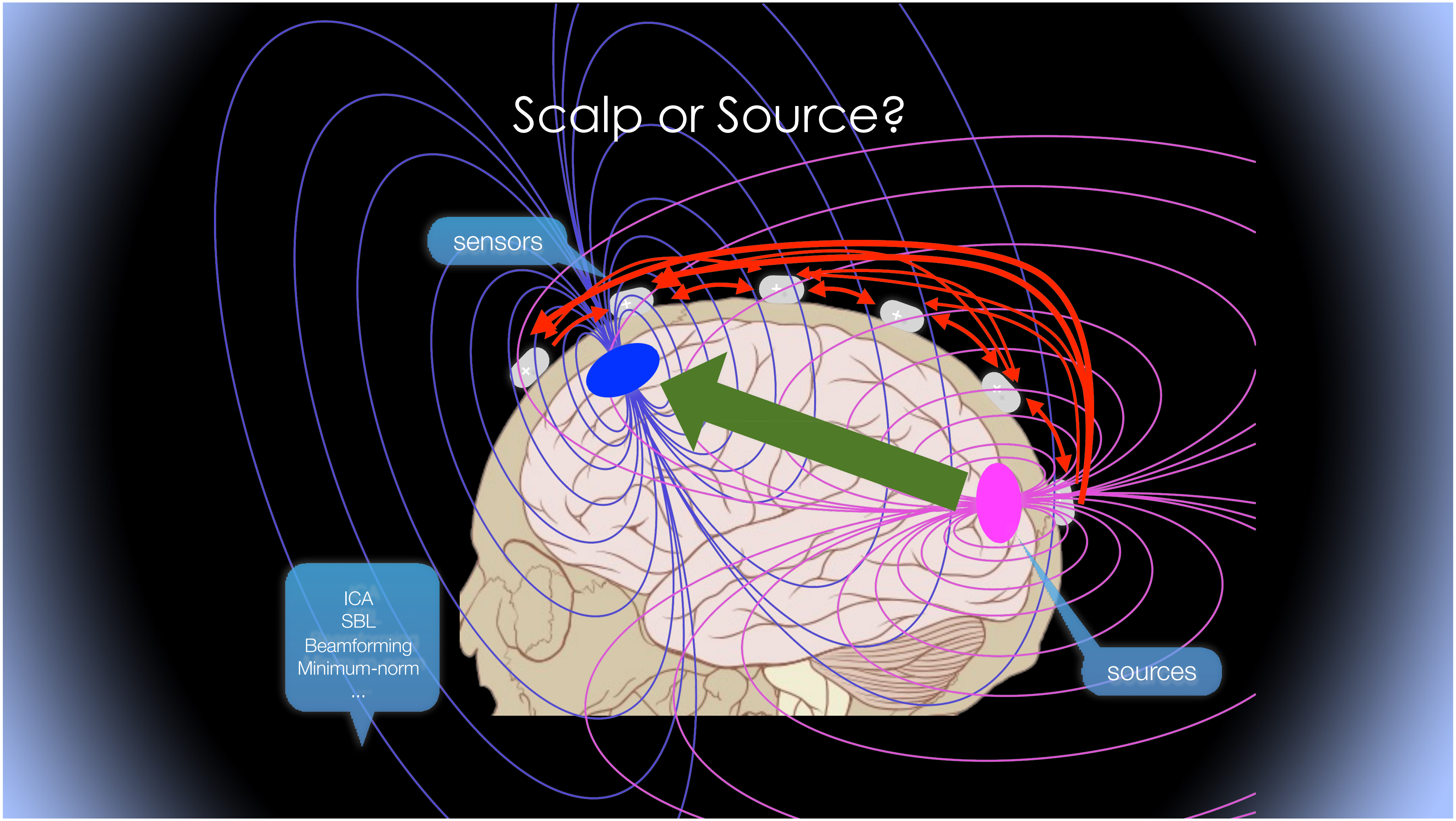
Scalp or Source?

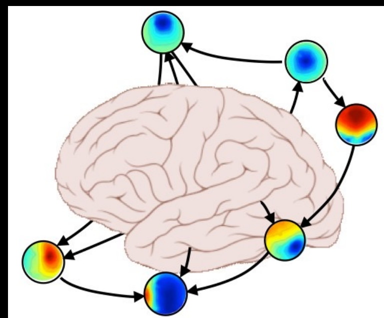


or



Scalp or Source?

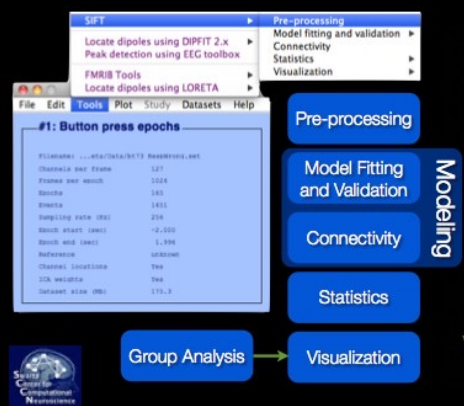


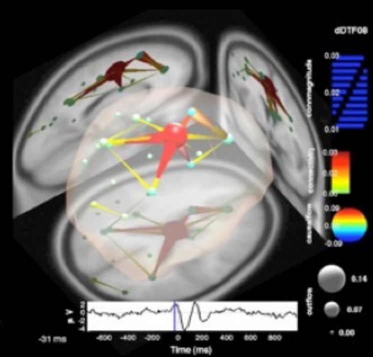


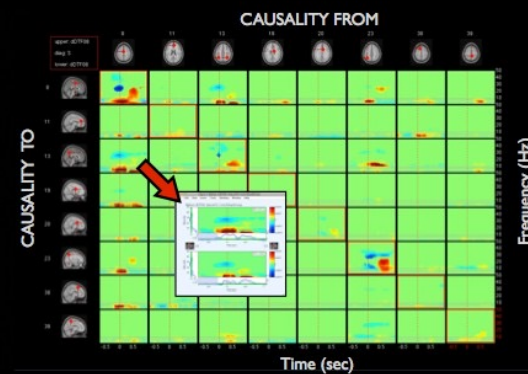
SIFT

Source Information Flow Toolbox

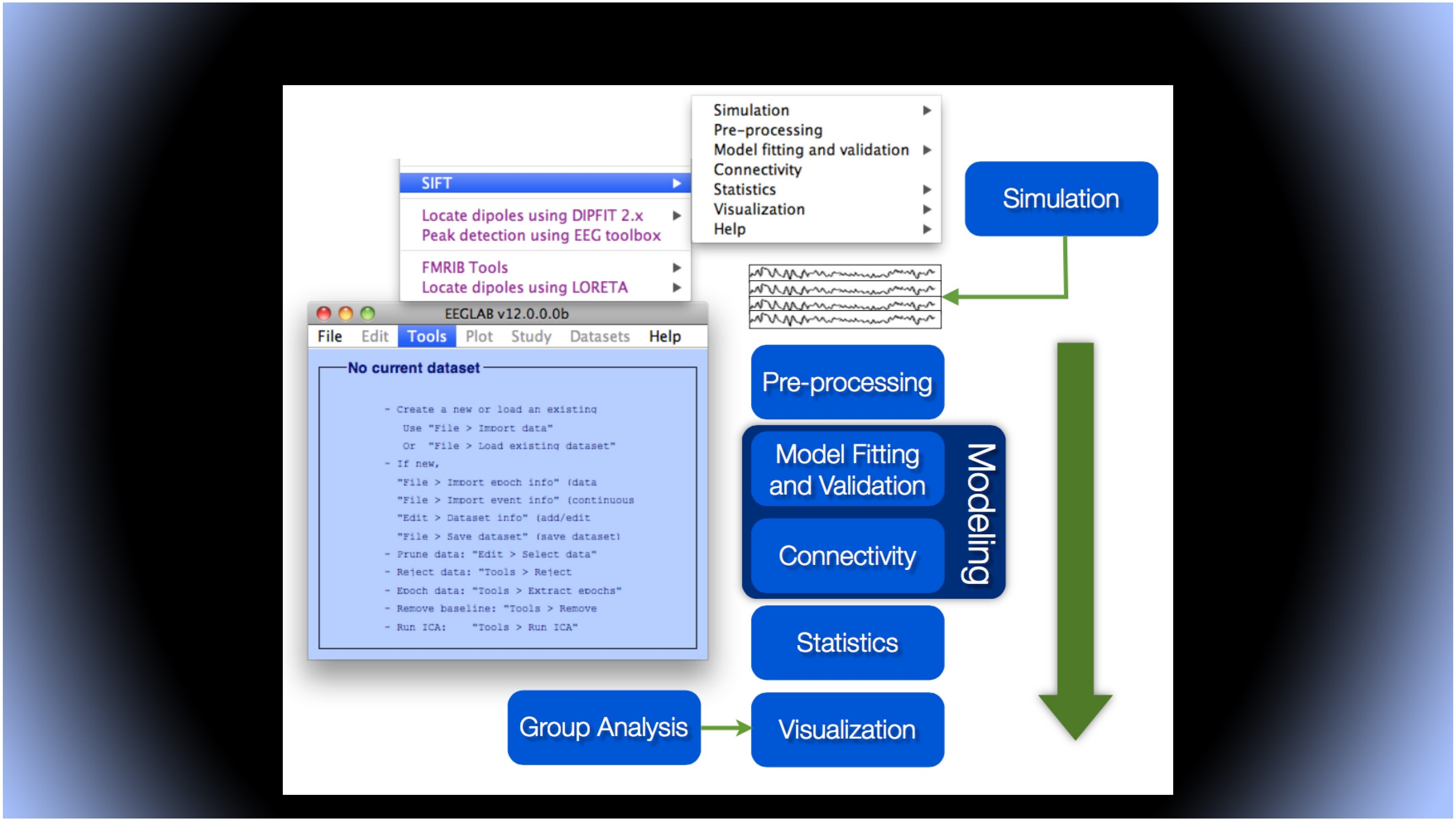
http://sccn.ucsd.edu/wiki/SIFT
Mullen, et al, *Journal of Neuroscience Methods* (in prep, 2012)
Mullen, et al, *Society for Neuroscience*, 2010
Delorme, Mullen, Kothe et al, *Computational Intelligence and Neuroscience*, vol 12, 2011

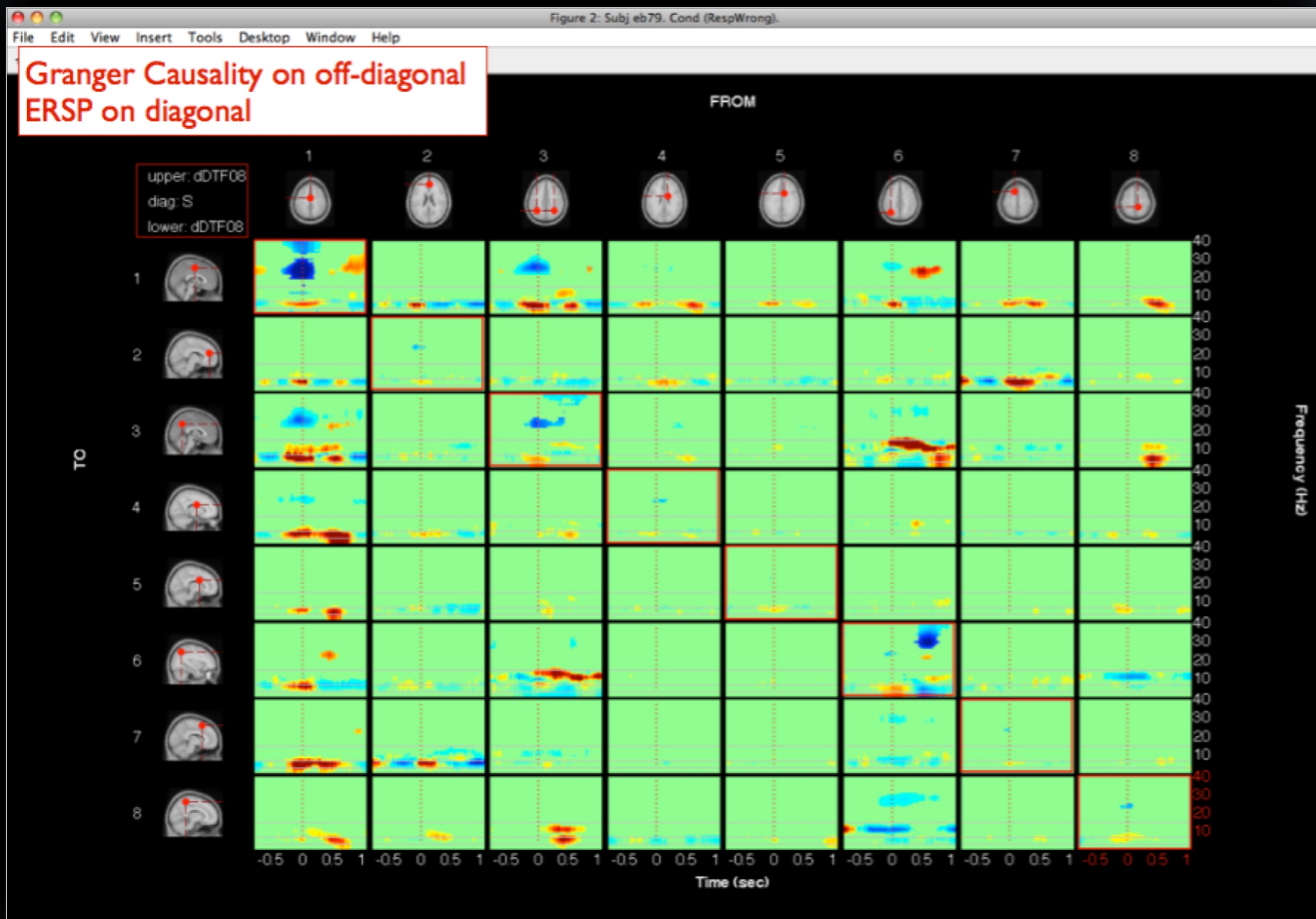




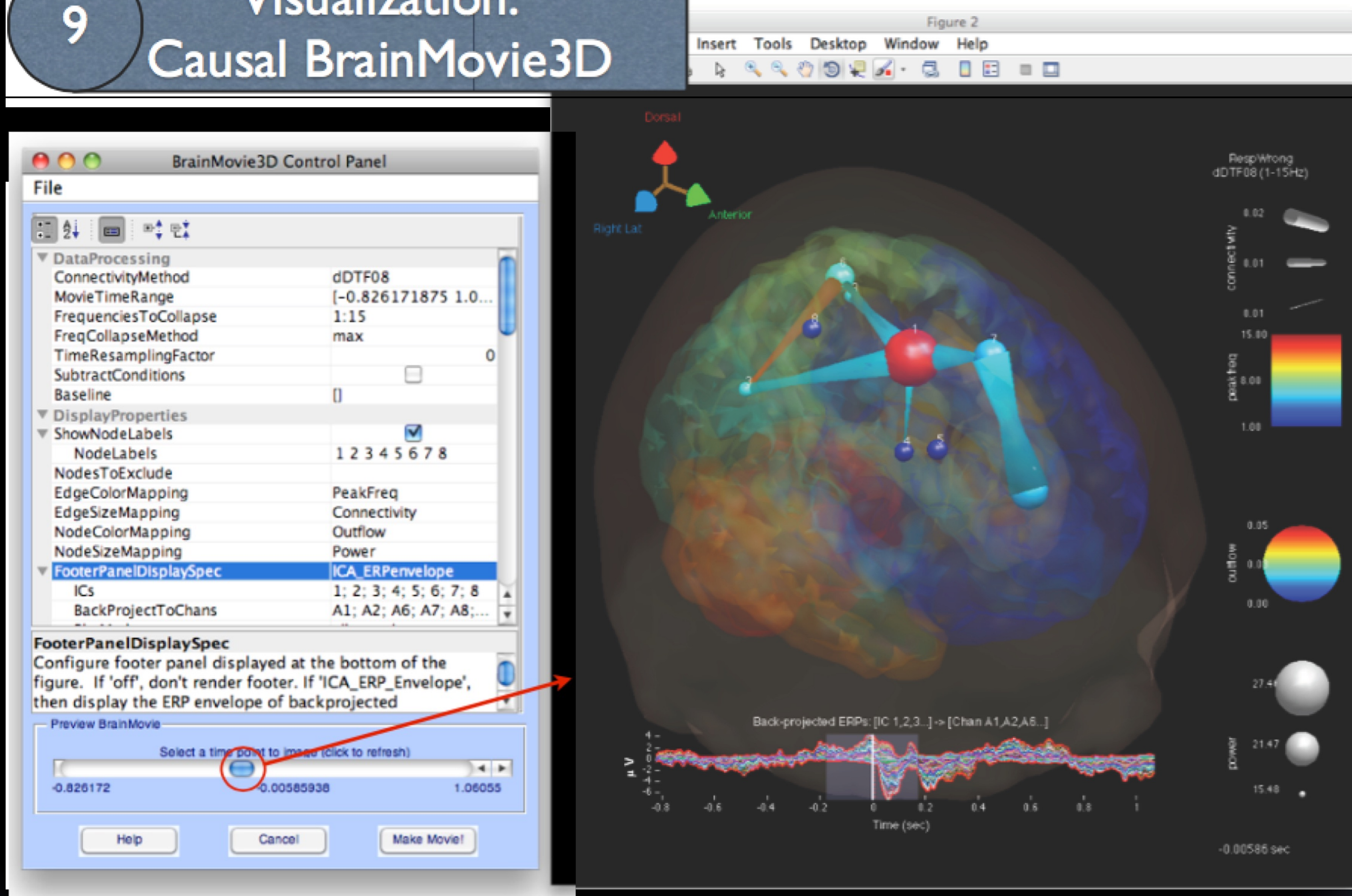


- A toolbox for (source-space) electrophysiological information flow and causality analysis (single- or multi-subject) integrated into the EEGLAB software environment.
- Emphasis on vector autoregression and time-frequency domain approaches
- Standard and novel interactive visualization methods for exploratory analysis of connectivity across time, frequency, and spatial location


Simulation
Pre-processing
Model fitting and validation
Connectivity
Statistics
Visualization
Help
SIFT
Locate dipoles using DIPFIT 2.x
Peak detection using EEG toolbox
FMRIB Tools
Locate dipoles using LORETA
EEGLAB v12.0.0.0b
File Edit Tools Plot Study Datasets Help
No current dataset
- Create a new or load an existing
Use "File > Import data"
Or "File > Load existing dataset"
- If new,
"File > Import epoch info" (data
"File > Import event info" (continuous
"Edit > Dataset info" (add/edit
"File > Save dataset" (save dataset)
- Prune data: "Edit > Select data"
- Reject data: "Tools > Reject
- Epoch data: "Tools > Extract epochs"
- Remove baseline: "Tools > Remove
- Run ICA: "Tools > Run ICA"
Simulation
Pre-processing
Model Fitting and Validation
Connectivity
Modeling
Statistics
Group Analysis
Visualization


Granger Causality on off-diagonal
ERSP on diagonal
Figure 2: Subj eb79. Cond (RespWrong).
File Edit View Insert Tools Desktop Window Help
FROM
TO
upper: dDTF08
diag: S
lower: dDTF08
1 2 3 4 5 6 7 8
40 30 20 10
-0.5 0 0.5 1
Time (sec)
Frequency (Hz)

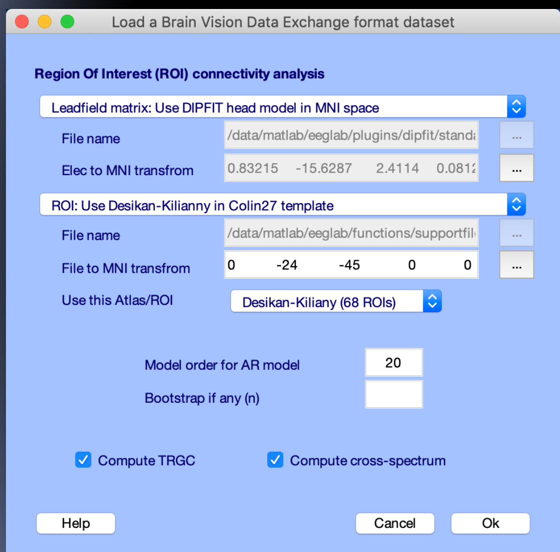
9 Visualization: Causal BrainMovie3D



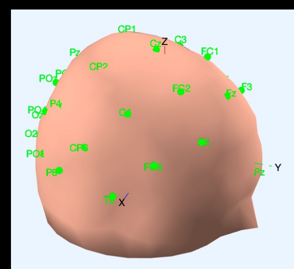
Time-Frequency Analysis of
EEG Time series

More Connectivity analysis

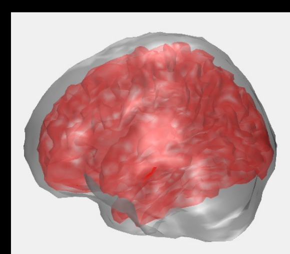
EEGLAB ROI connectivity plugin



Align electrodes with scalp model

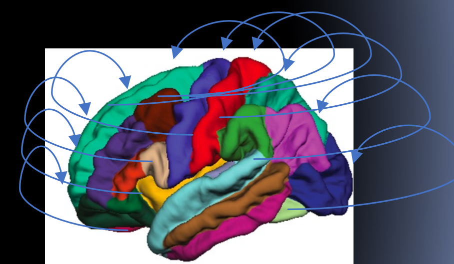


Align atlas with cortex model



Distributed source modeling

Group voxels in regions and compute connectivity



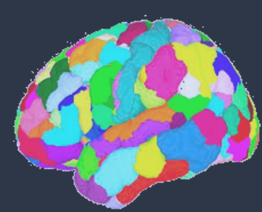
Measures TRGC, GC, TRPDC, PDC, TRDTF, DTF and CS

Haufe, S., Nikulin, V. V., Miller, K. R., & Nolte, G. (2013). A critical assessment of connectivity measures for EEG data: a simulation study. Neuroimage, 64, 120-133.

Connectivity analysis using EEG

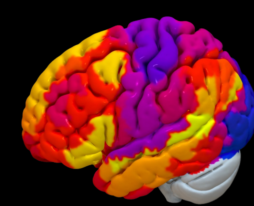
Volumetric atlases

AFNI MNI



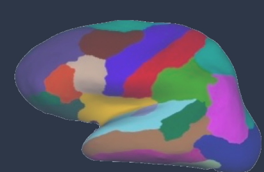
Brainnetome

Schaefer 2018

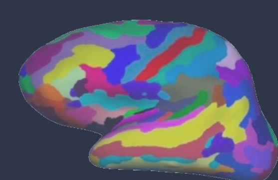


Surface atlases

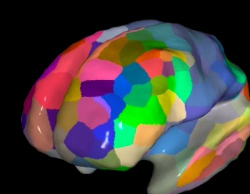
Desikan Kiliany



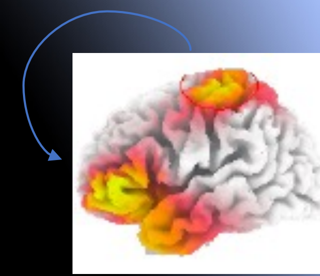
Destrieux



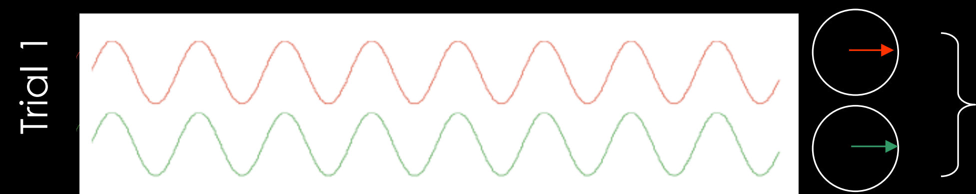
PrAGMATiC



Cross-coherence amplitude and phase

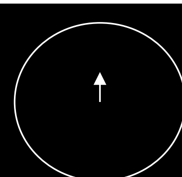


2 areas, comparison on the same trials

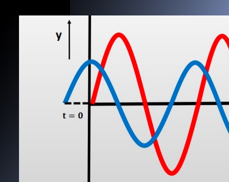


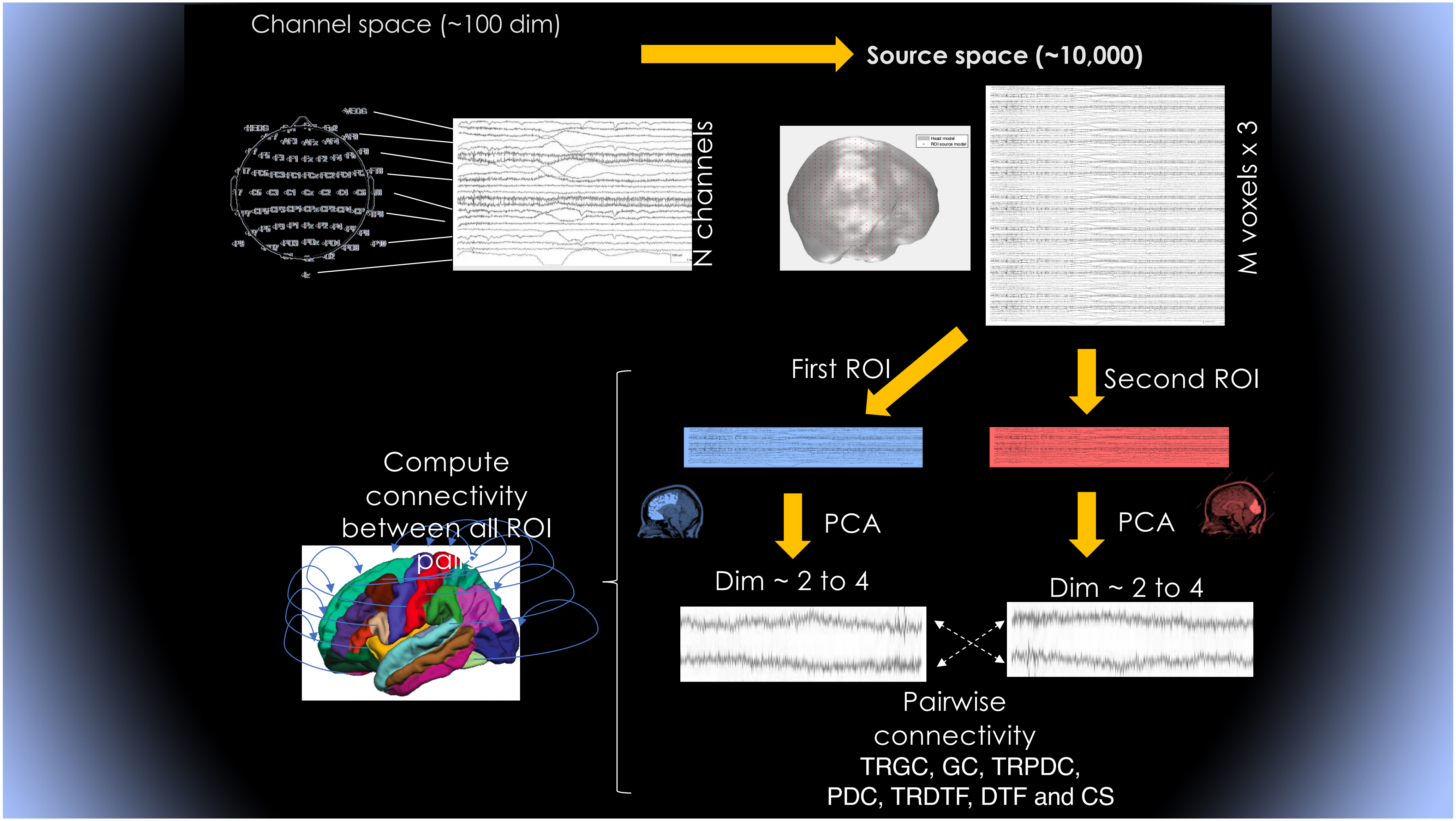
Coherence amplitude 1
Phase coherence 0

COHERENCE = mean(phase vector)



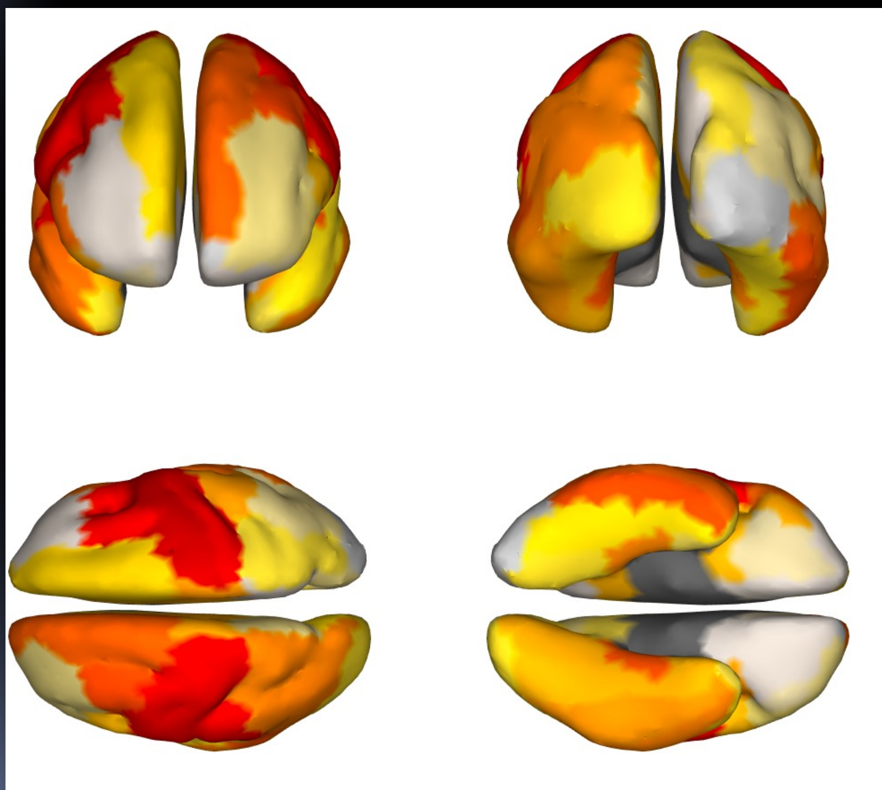
Norm 0.33
Phase 90 degree



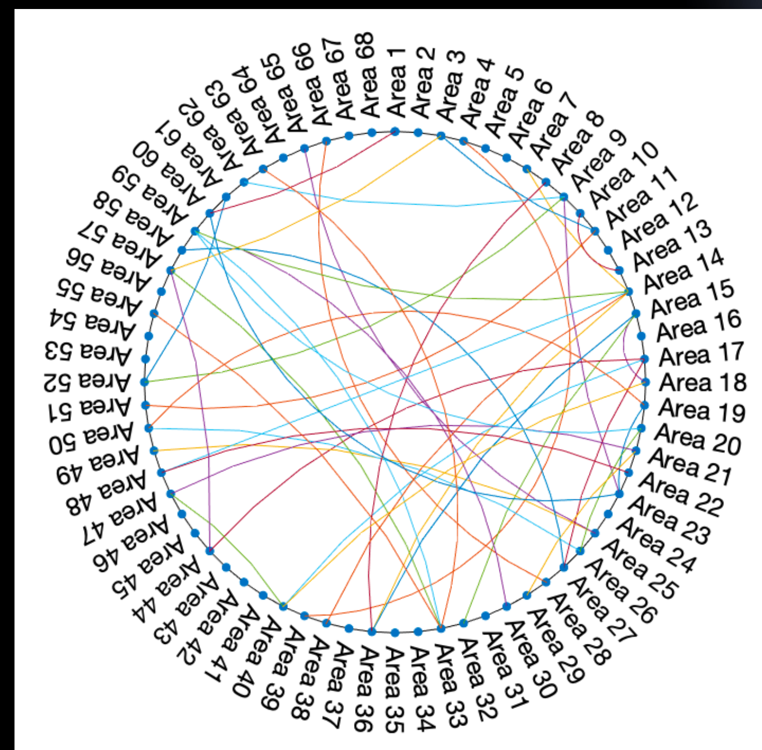


Channel space (~100 dim)
Source space (~10,000)
N channels
M voxels x 3
First ROI
Second ROI
Compute connectivity between all ROI pairs
PCA
PCA
Dim ~ 2 to 4
Dim ~ 2 to 4
Pairwise connectivity
TRGC, GC, TRPDC, PDC, TRDTF, DTF and CS

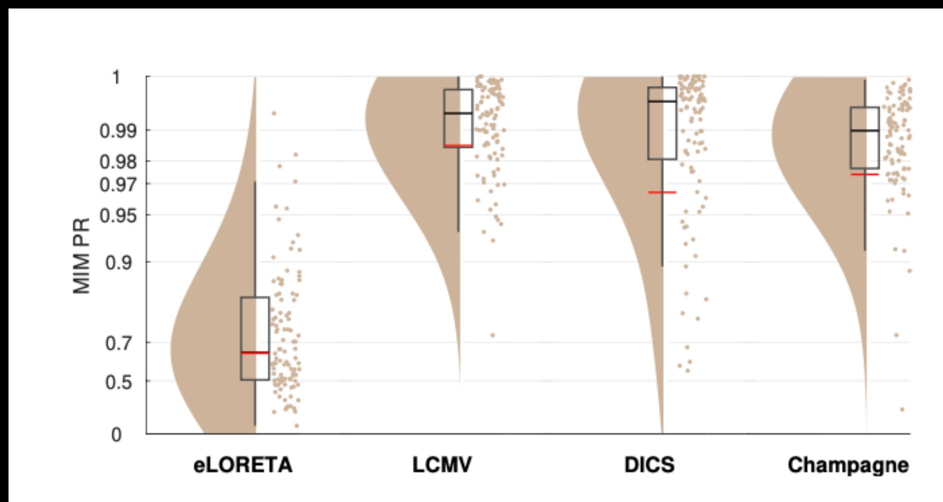
Red regions are highly interacting



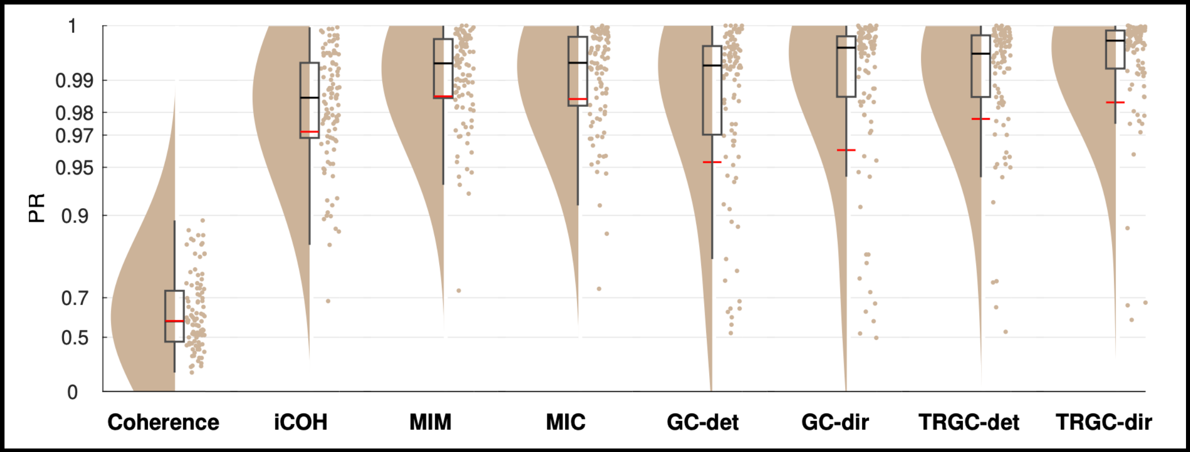
Connectivity matrix between 68 ROIs



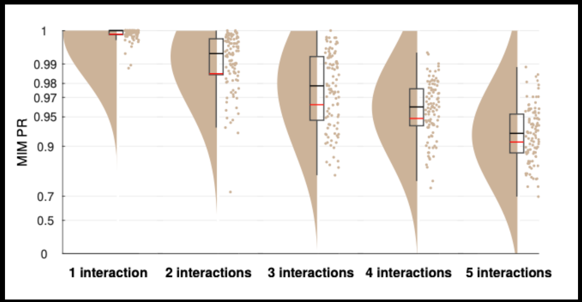
Inverse method



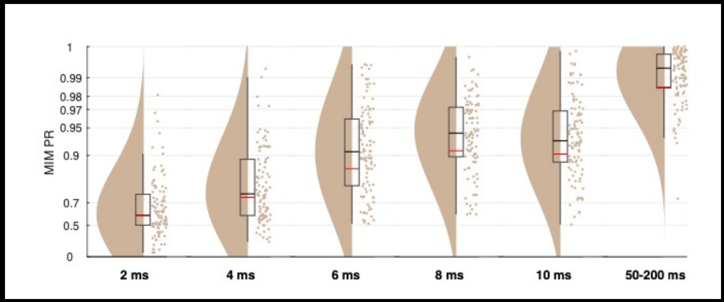
Connectivity method



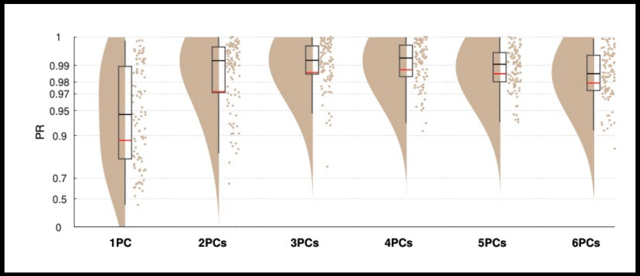
Number of interactions



Delay between sources



Number of PCA comp.



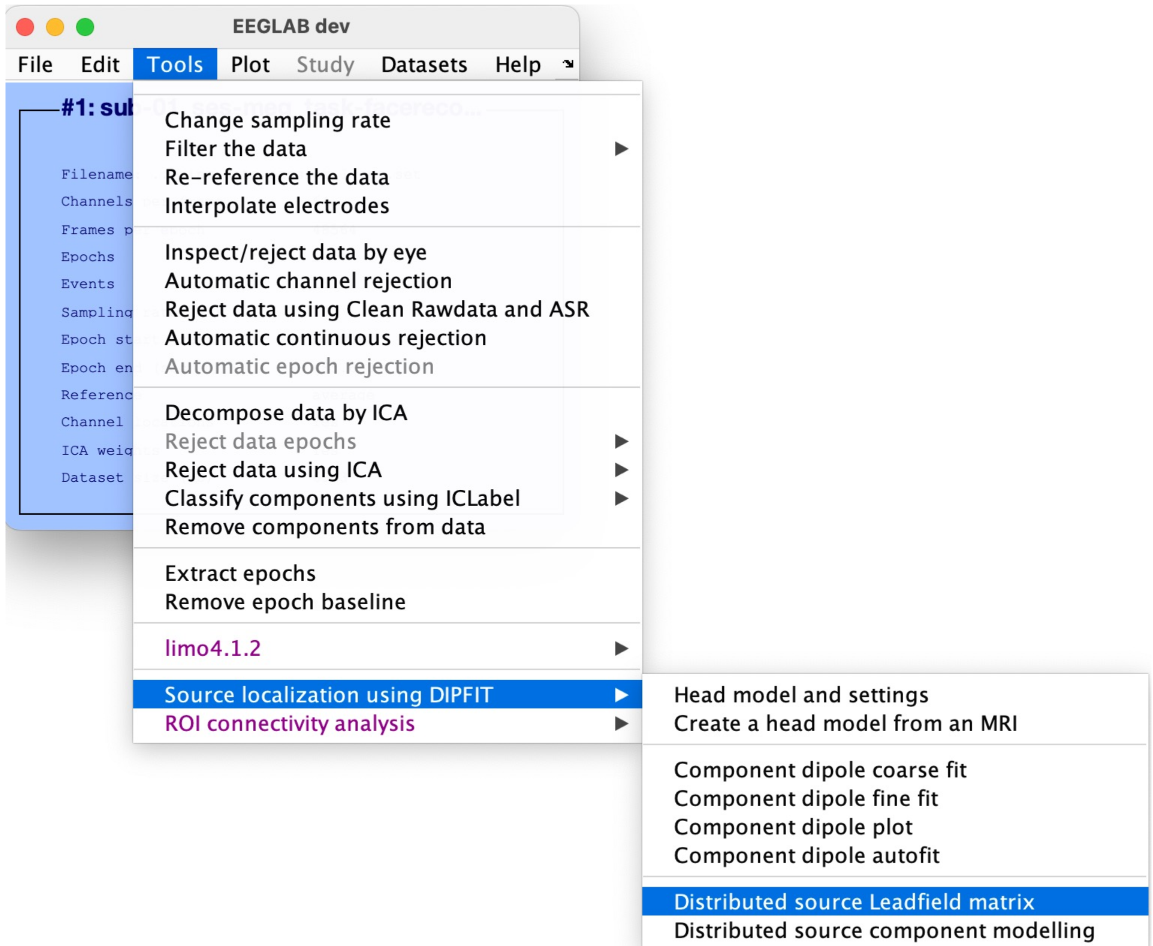
Data intake

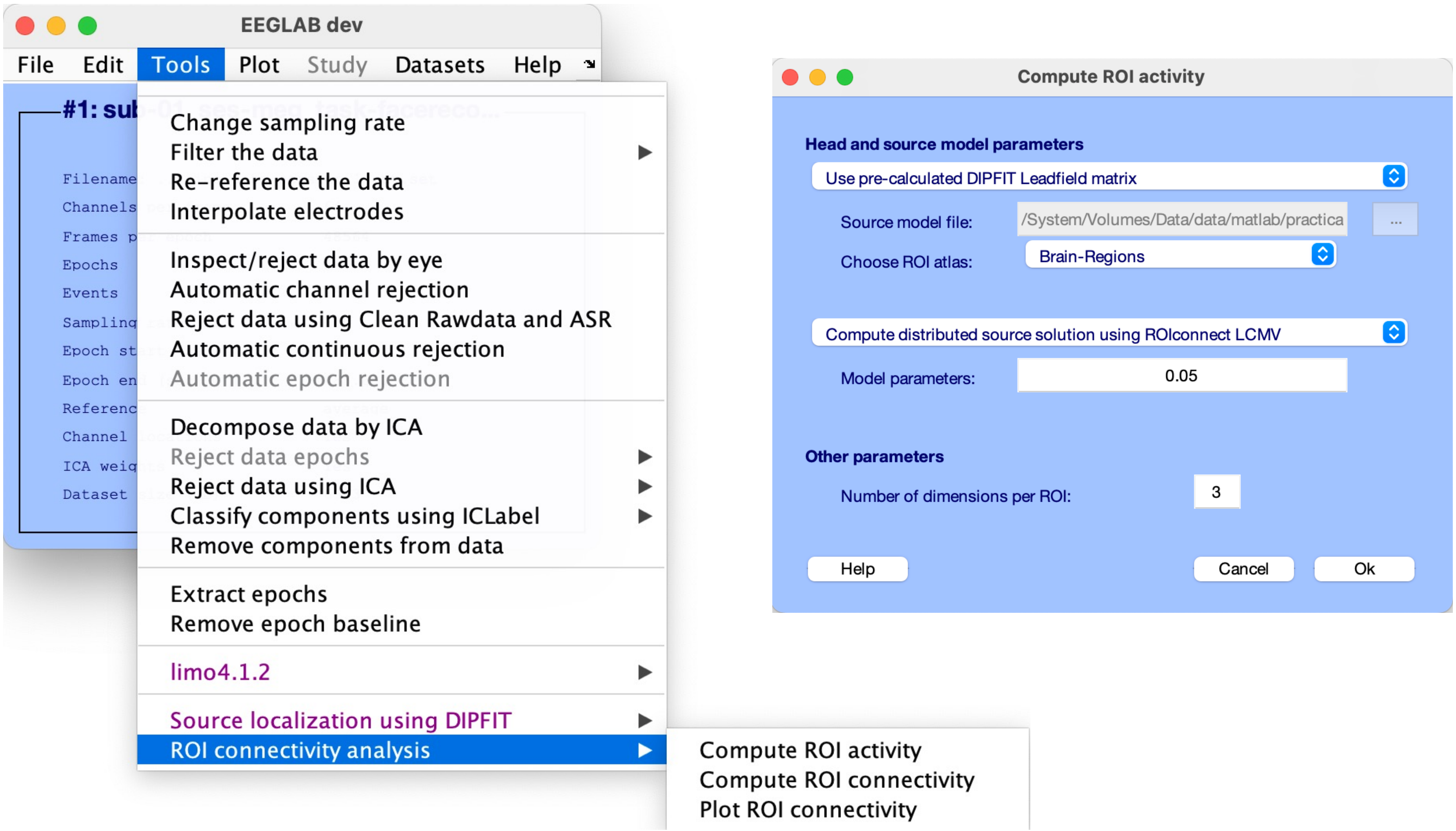
- Stationary continuous data
- About 100 Hz
- 2 second data chunks (or epochs)
- Same length of data for each condition
- No dynamics – static image

Exercise

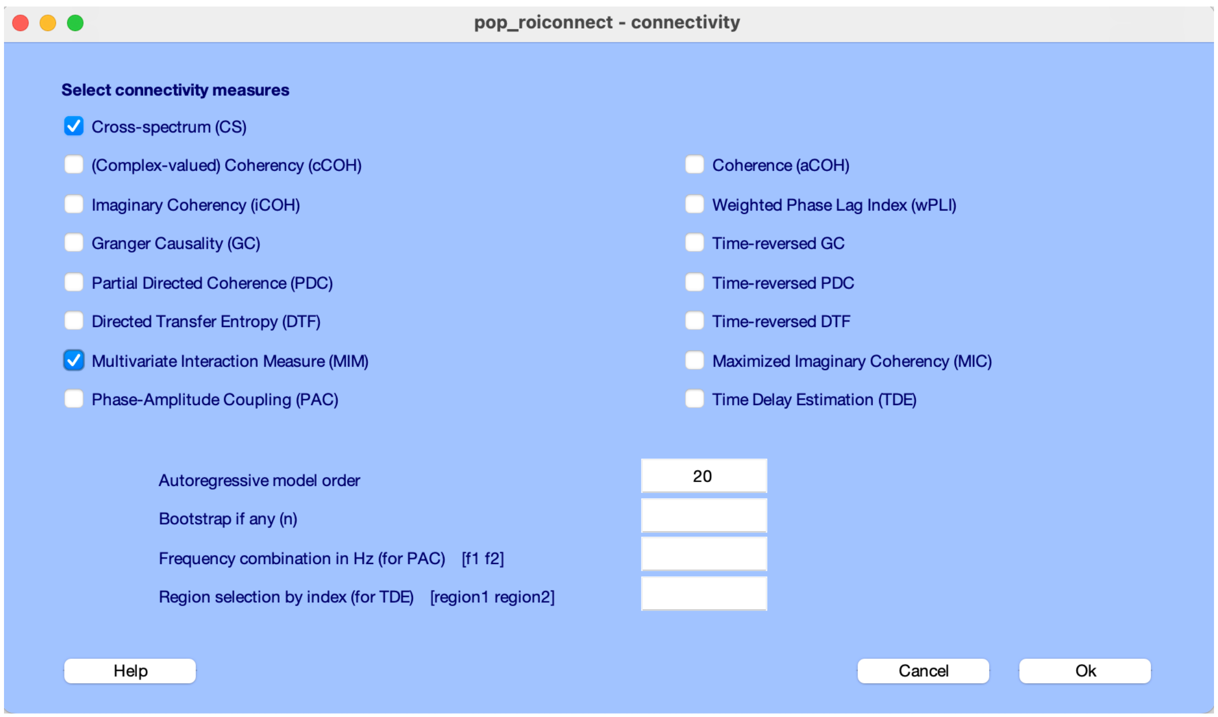
Load .set file using menu item *File > Load existing dataset*

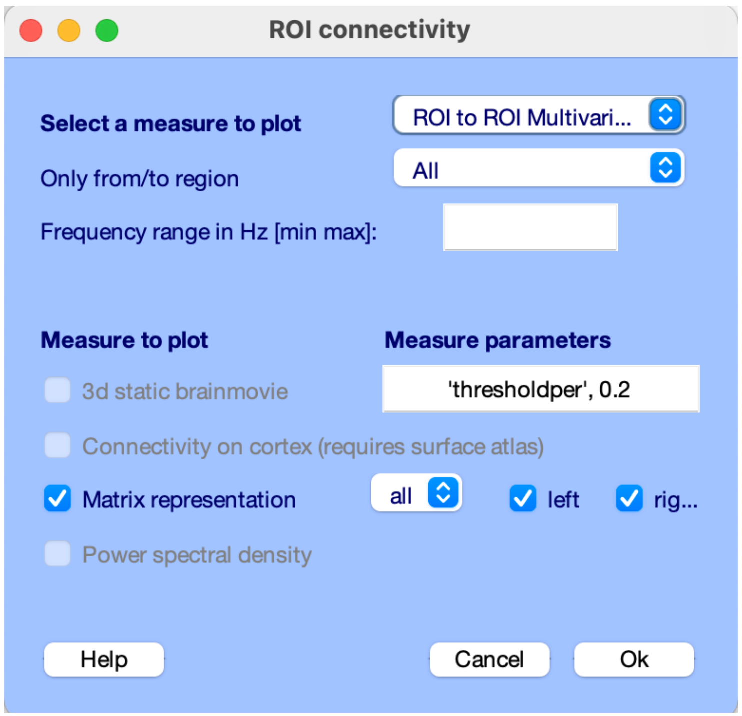
‘ds000117_pruned/derivatives/meg_derivatives/sub-01/ses-meg/meg/wh_S01_run_01_preprocessing_data_session_1_out.set’

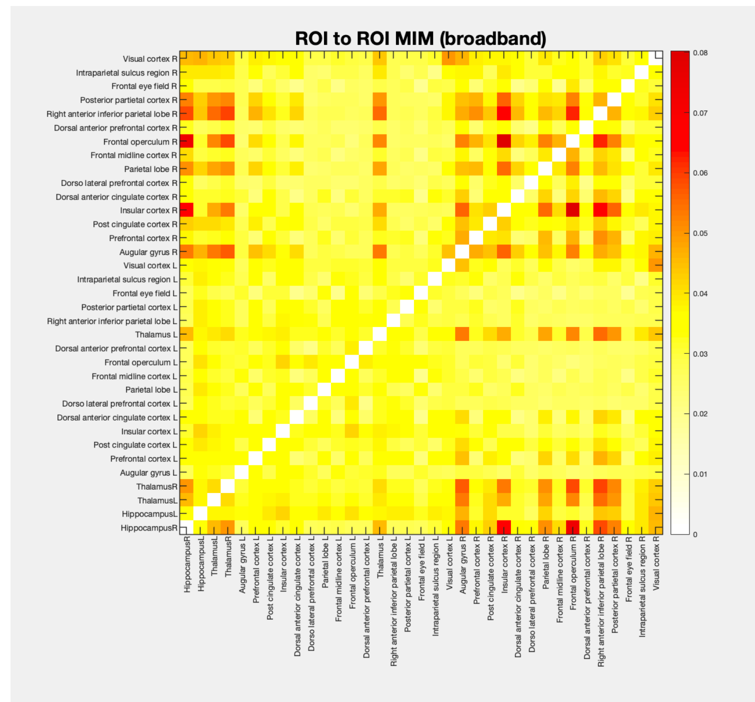

EEGLAB dev
File
Edit
Tools
Plot
Study
Datasets
Help
Change sampling rate
Filter the data
Re-reference the data
Interpolate electrodes
Inspect/reject data by eye
Automatic channel rejection
Reject data using Clean Rawdata and ASR
Automatic continuous rejection
Automatic epoch rejection
Decompose data by ICA
Reject data epochs
Reject data using ICA
Classify components using ICLabel
Remove components from data
Extract epochs
Remove epoch baseline
limo4.1.2
Source localization using DIPFIT
ROI connectivity analysis
Head model and settings
Create a head model from an MRI
Component dipole coarse fit
Component dipole fine fit
Component dipole plot
Component dipole autofit
Distributed source Leadfield matrix
Distributed source component modelling
Epochs
Events
Channel
Dataset



EEGLAB dev
File
Edit
Tools
Plot
Study
Datasets
Help
Change sampling rate
Filter the data
Re-reference the data
Interpolate electrodes
Inspect/reject data by eye
Automatic channel rejection
Reject data using Clean Rawdata and ASR
Automatic continuous rejection
Automatic epoch rejection
Decompose data by ICA
Reject data epochs
Reject data using ICA
Classify components using ICLabel
Remove components from data
Extract epochs
Remove epoch baseline
limo4.1.2
Source localization using DIPFIT
ROI connectivity analysis
Compute ROI activity
Compute ROI connectivity
Plot ROI connectivity
Compute ROI activity
Head and source model parameters
Use pre-calculated DIPFIT Leadfield matrix
Source model file:
/System/Volumes/Data/data/matlab/practica
...
Choose ROI atlas:
Brain-Regions
Compute distributed source solution using ROIconnect LCMV
Model parameters:
0.05
Other parameters
Number of dimensions per ROI:
3
Help
Cancel
Ok


pop_roiconnect - connectivity
Select connectivity measures
Cross-spectrum (CS)
(Complex-valued) Coherency (cCOH)
Coherence (aCOH)
Imaginary Coherency (iCOH)
Weighted Phase Lag Index (wPLI)
Granger Causality (GC)
Time-reversed GC
Partial Directed Coherence (PDC)
Time-reversed PDC
Directed Transfer Entropy (DTF)
Time-reversed DTF
Multivariate Interaction Measure (MIM)
Maximized Imaginary Coherency (MIC)
Phase-Amplitude Coupling (PAC)
Time Delay Estimation (TDE)
Autoregressive model order
20
Bootstrap if any (n)
Frequency combination in Hz (for PAC) [f1 f2]
Region selection by index (for TDE) [region1 region2]
Help
Cancel
Ok


ROI connectivity
Select a measure to plot
ROI to ROI Multivari...
Only from/to region
All
Frequency range in Hz [min max]:
Measure to plot
Measure parameters
3d static brainmovie
'thresholdper', 0.2
Connectivity on cortex (requires surface atlas)
Matrix representation
all
left
rig...
Power spectral density
Help
Cancel
Ok


ROI to ROI MIM (broadband)
Visual cortex R
Intraparietal sulcus region R
Frontal eye field R
Posterior partietal cortex R
Right anterior inferior parietal lobe R
Dorsal anterior prefrontal cortex R
Frontal operculum R
Frontal midline cortex R
Parietal lobe R
Dorso lateral prefrontal cortex R
Dorsal anterior cingulate cortex R
Insular cortex R
Post cingulate cortex R
Prefrontal cortex R
Augular gyrus R
Visual cortex L
Intraparietal sulcus region L
Frontal eye field L
Posterior partietal cortex L
Right anterior inferior parietal lobe L
Thalamus L
Dorsal anterior prefrontal cortex L
Frontal operculum L
Frontal midline cortex L
Parietal lobe L
Dorso lateral prefrontal cortex L
Dorsal anterior cingulate cortex L
Insular cortex L
Post cingulate cortex L
Prefrontal cortex L
Augular gyrus L
ThalamusR
ThalamusL
HippocampusL
HippocampusR
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Exercise

- Compute leadfield
- Compute ROI activity
- Compute ROI connectivity
- Plot ROI connectivity

The end/La fin