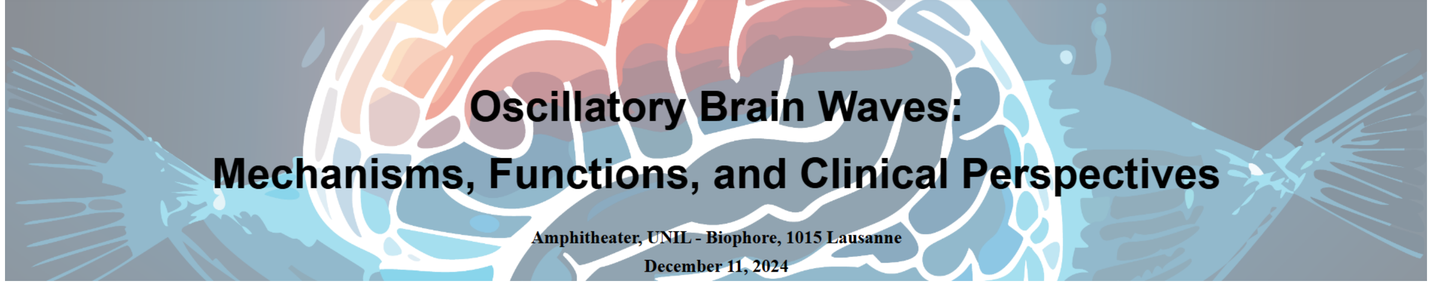


EEG brain networks for epilepsy applications

[Graph Signal Processing]

Dr Isotta Rigoni
@ Epilepsy and EEG unit
11/12/2024

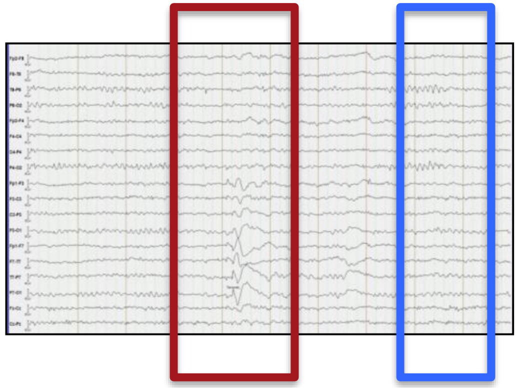
EEG and epilepsy

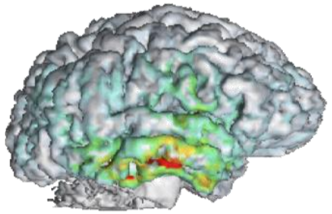
EEG:

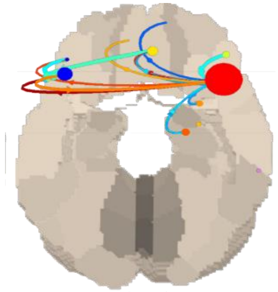
- Directly measures neuronal activity
- Cost-effective, non-invasive, portable
- Low/high-density coverage
- Electrical source imaging (ESI)

Epilepsy:

- Neurological disorder characterized by recurrent unprovoked seizures
- Interictal activity: **spikes** (asymptomatic)
- ESI for spike **localisation** (irritative network), presurgical routine
- Brain network disorder
- EEG → **Biomarkers** for **diagnosis** and **prognosis**

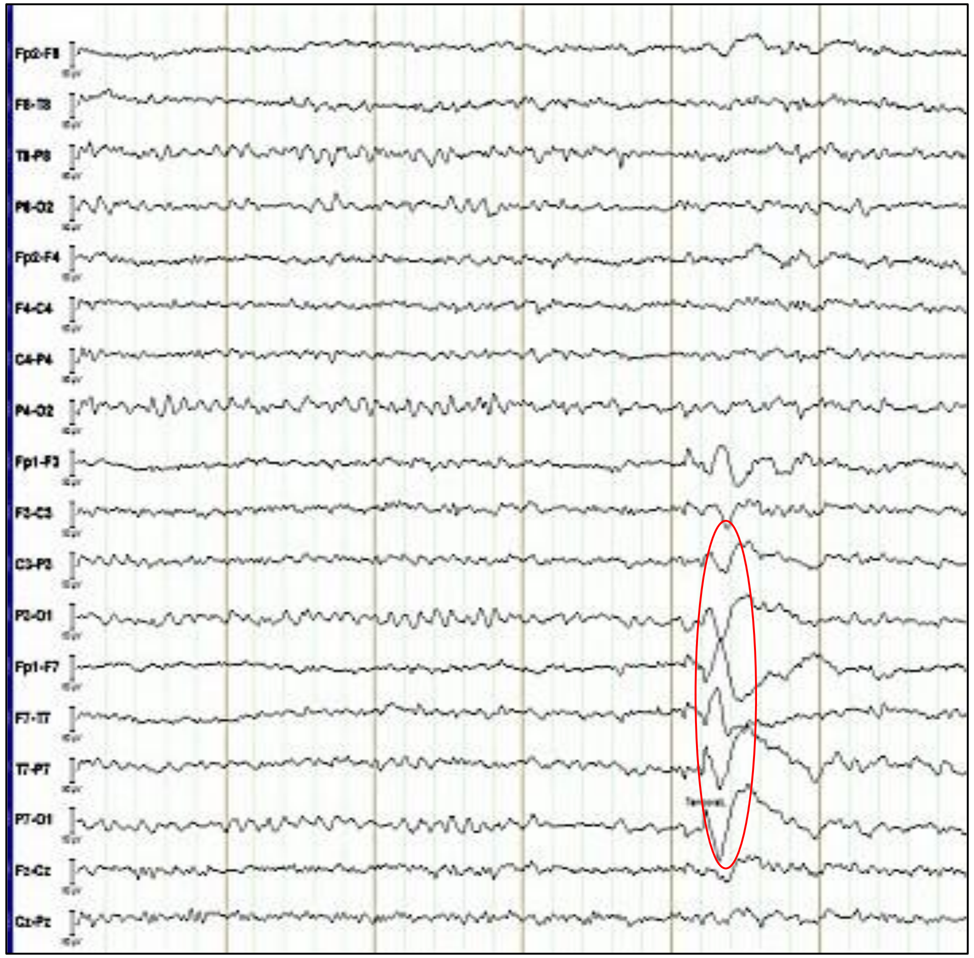




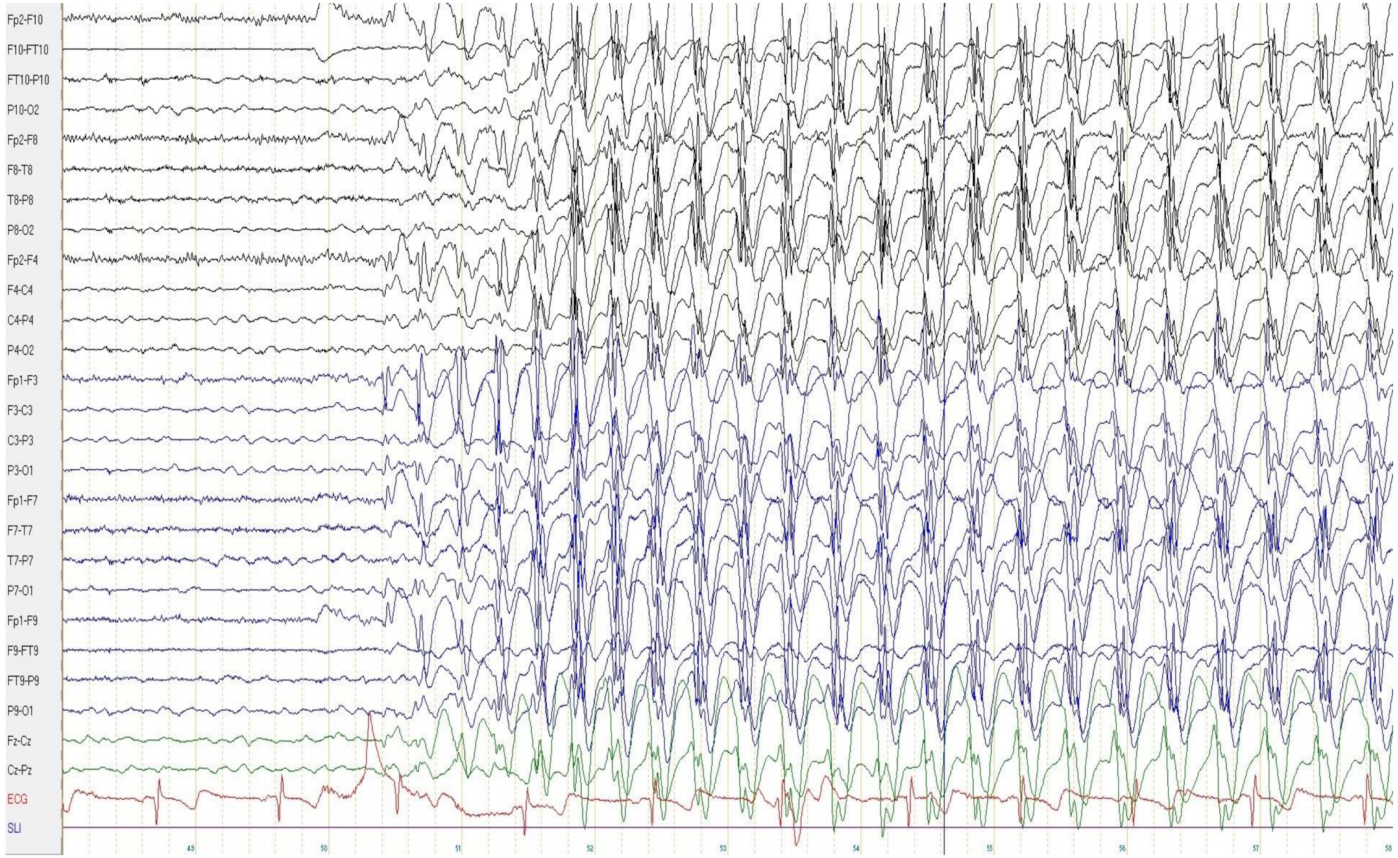


Scalp signal → Sources → Networks

Clinical recordings - examples

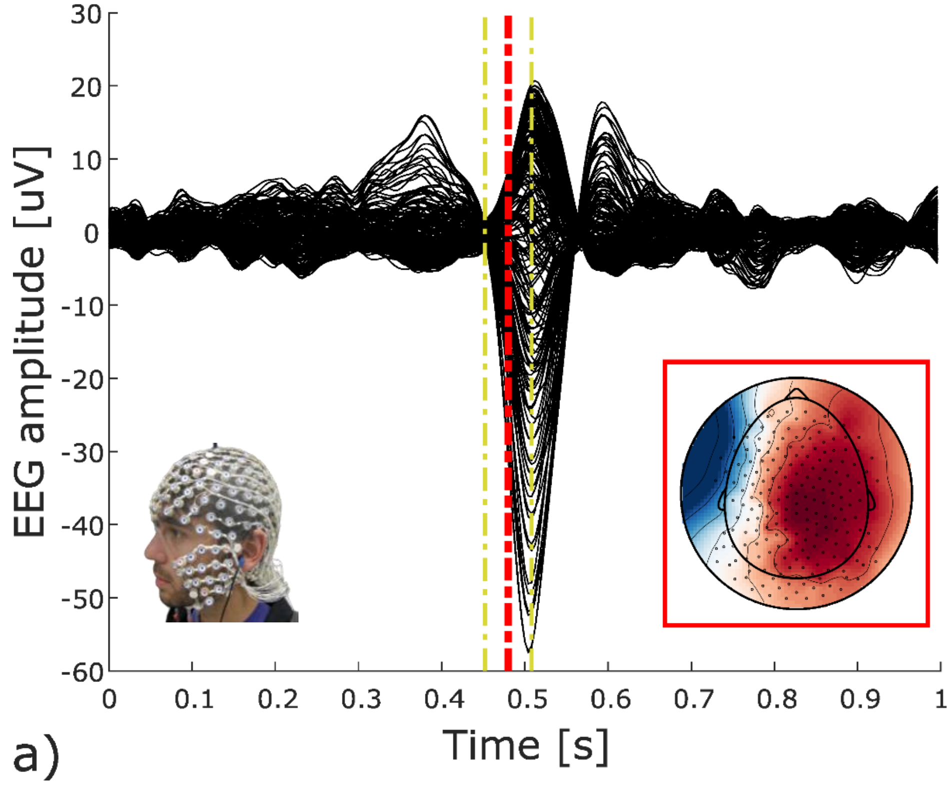


Focal interictal spike

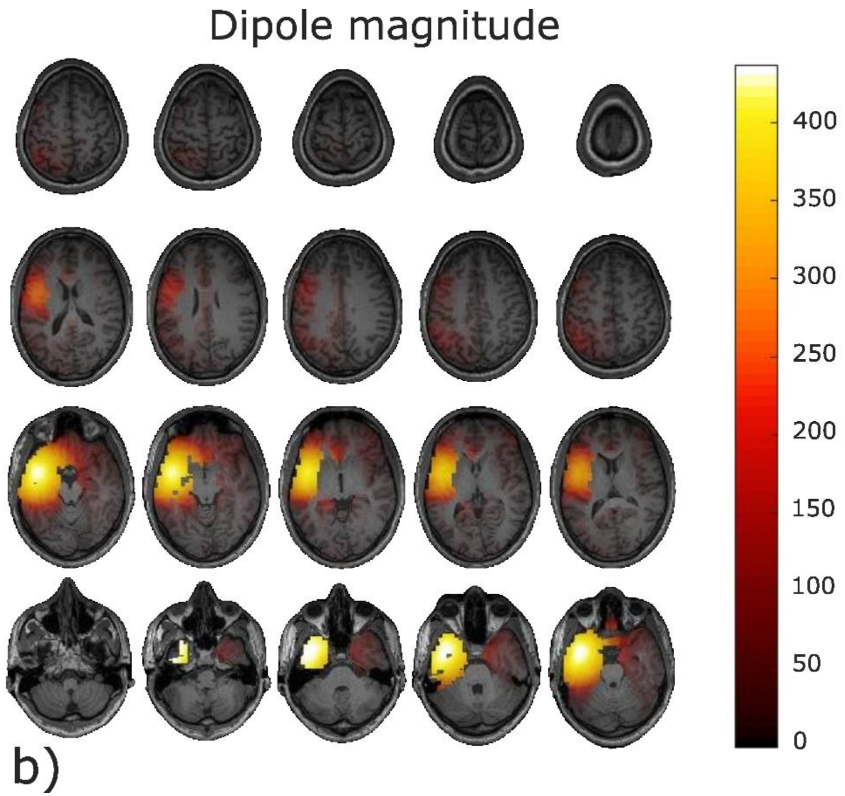


Generalised seizure

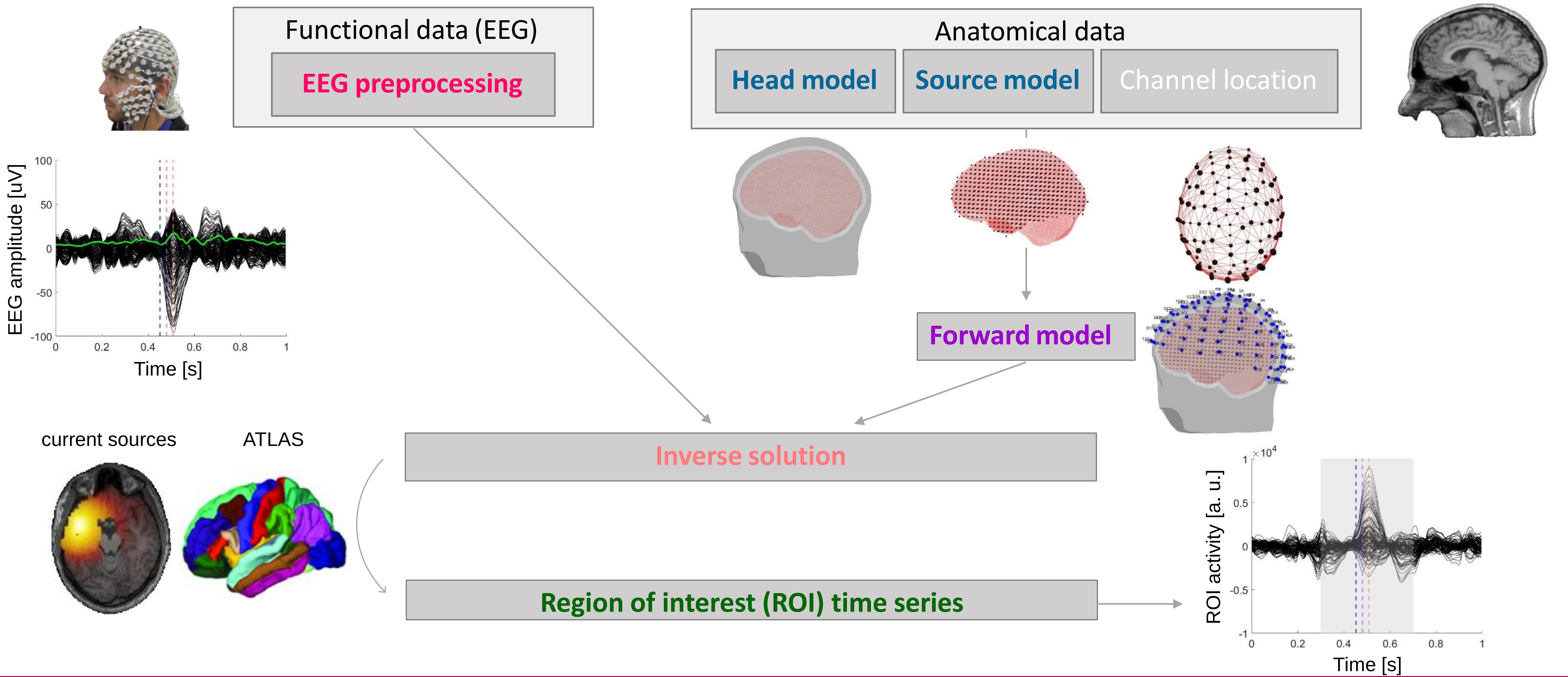
ESI: get signals *in* the brain from EEG



Electrical Source Imaging (ESI)



Electrical Source Imaging



Electrical Source Imaging

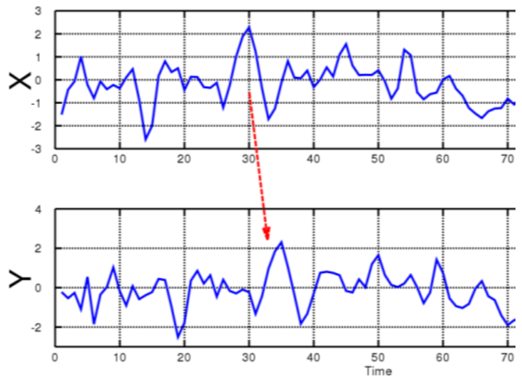
Tutorial: **from scalp to sources**
Presentation + hands on exercises
Open Matlab code (Fieldtrip)

Authors: Isotta Rigoni & Nicolas Roehri

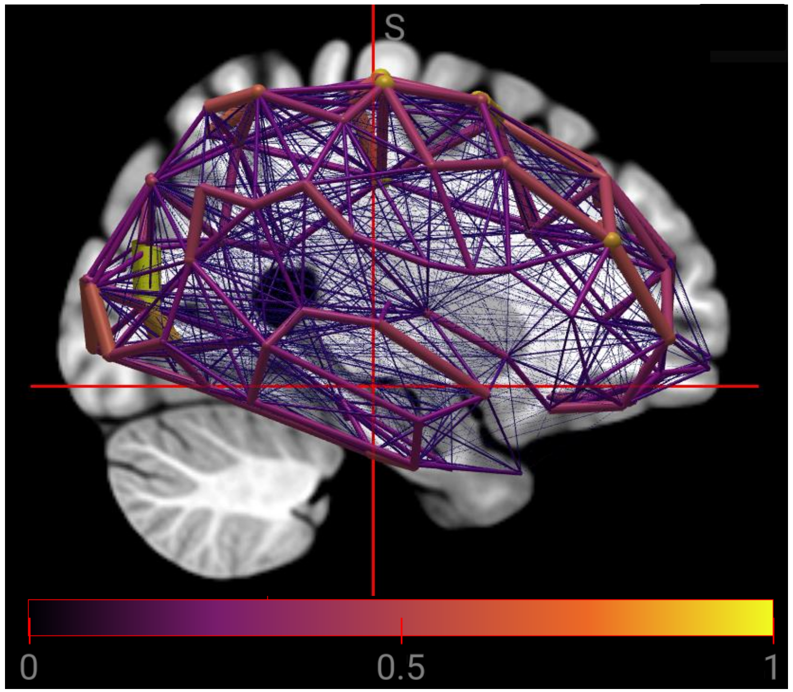
Brain Dynamics on the Connectome
Summer School 2021

Connectivity in the brain

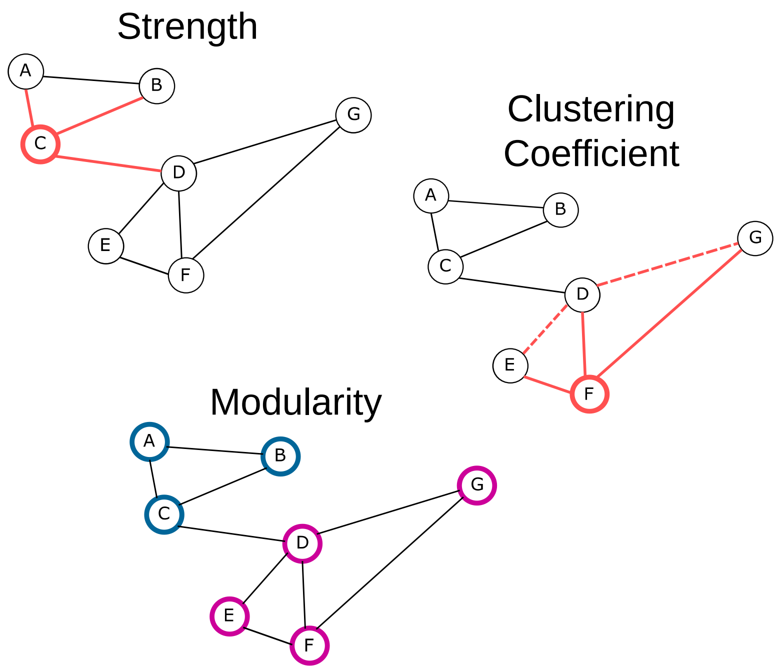
Connectivity metrics
- Amplitude-based
- Phase-based
- Granger causality



Brain network



Graph analyses
- Integration (GE)
- Segregation (CC)
- Whole-brain and nodal measures

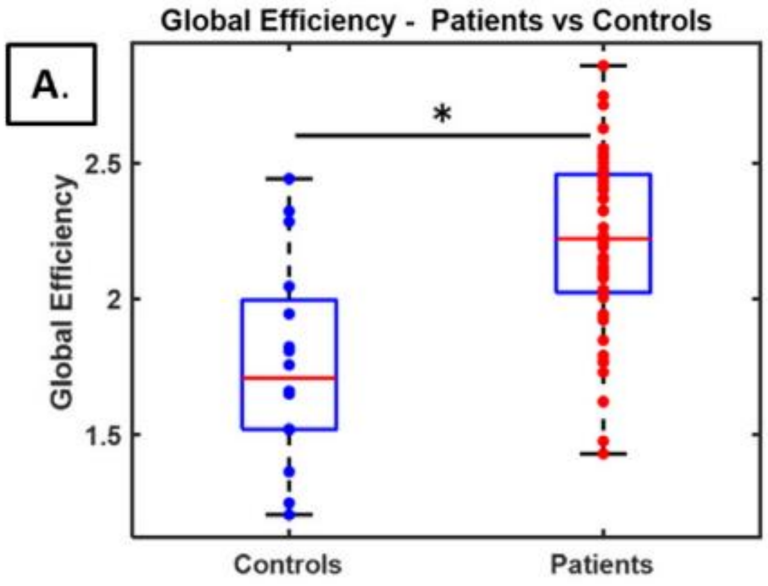


Is EEG connectivity useful for epilepsy?

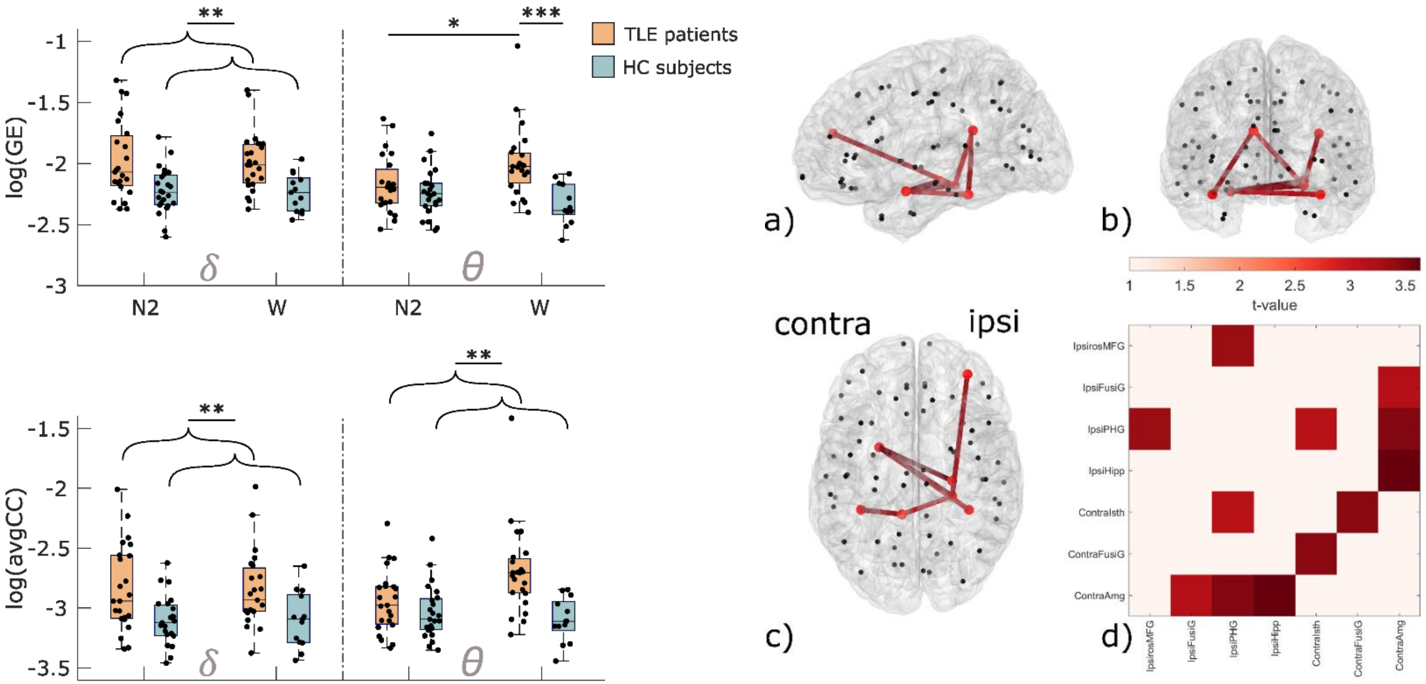
Epilepsy – diagnostic value of connectivity

Investigate connectivity of spike-free interictal activity with HD-EEG in TLE patients

→global efficiency of the network is higher in patients than in controls at the low frequency bands (delta and theta); easier detection during wake



Carboni et al. 2020



Rigoni et al. 2024

Epilepsy – prognostic value of connectivity

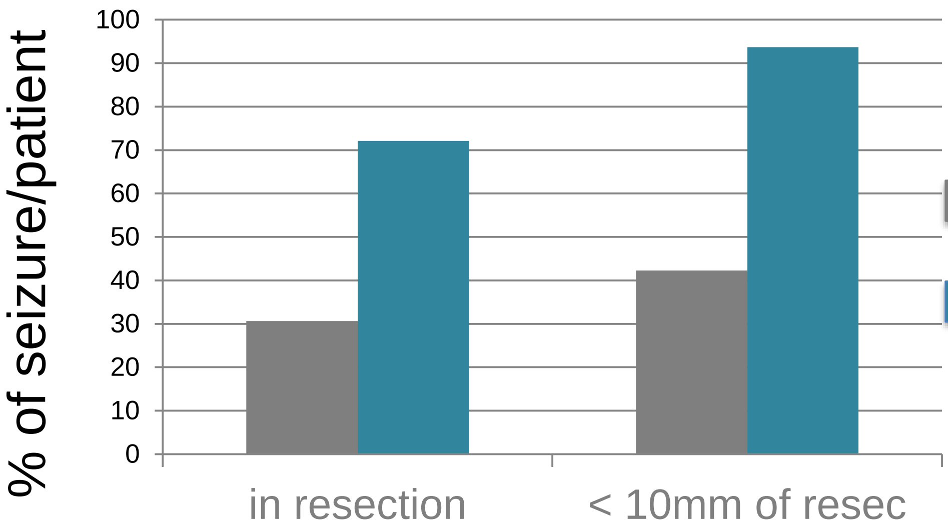
Investigate connectivity added value for localization of seizure onset zone (seizure-free patients)

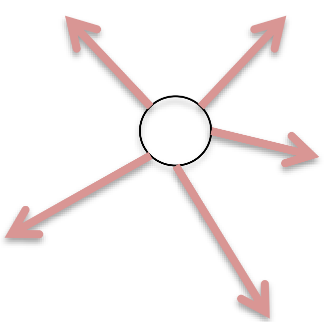
→Summed outflow metric provided a significant added value to ESI alone

Investigate connectivity of spikes for surgical outcome prediction

→Significant difference in network propagation between good-outcome vs bad-outcome

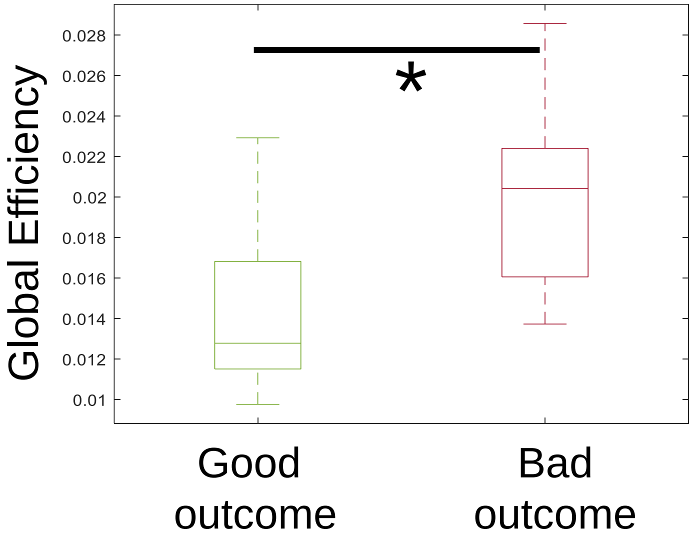
Seizures

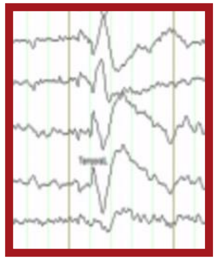




Staljanssens et al. 2017

Global Efficiency



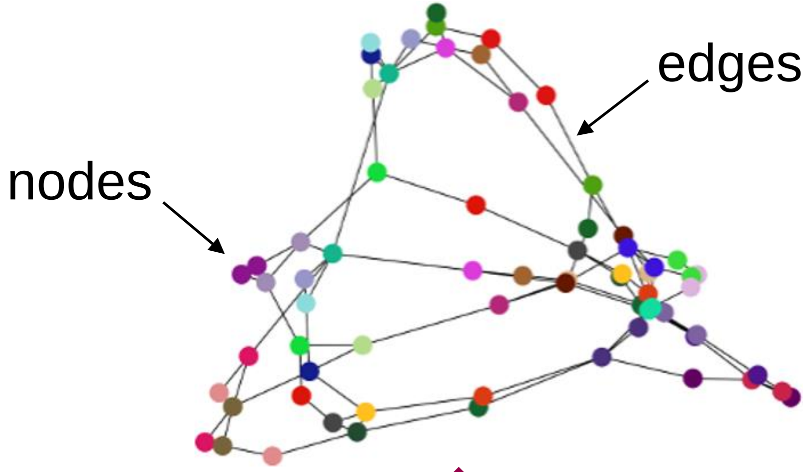


Carboni et al. 2019

Graph signal processing

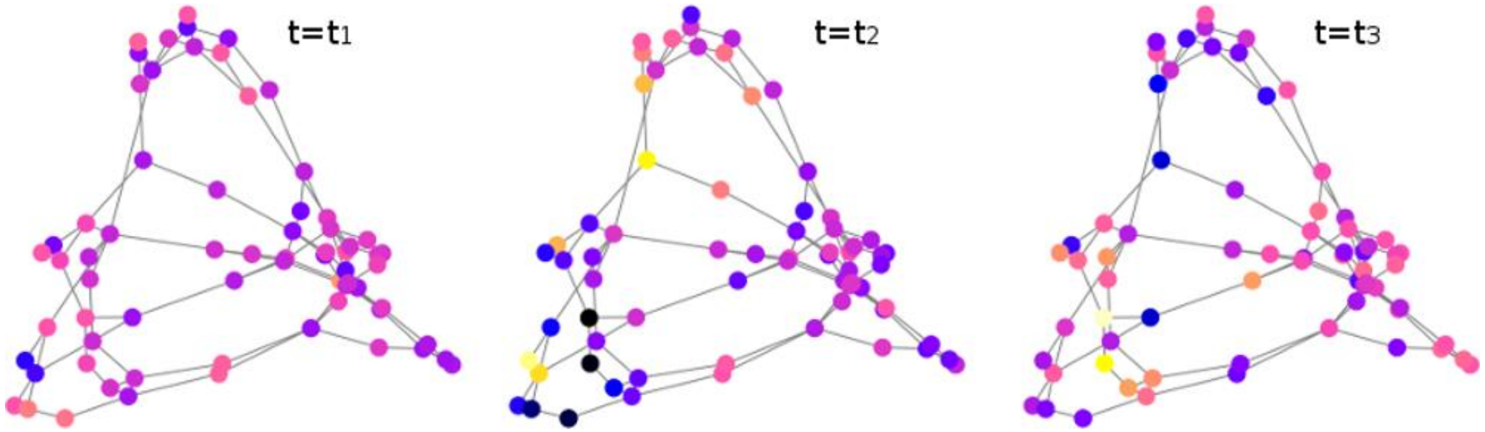
Graph *vs* graph signal

Graph



does NOT change
over time

Graph signal



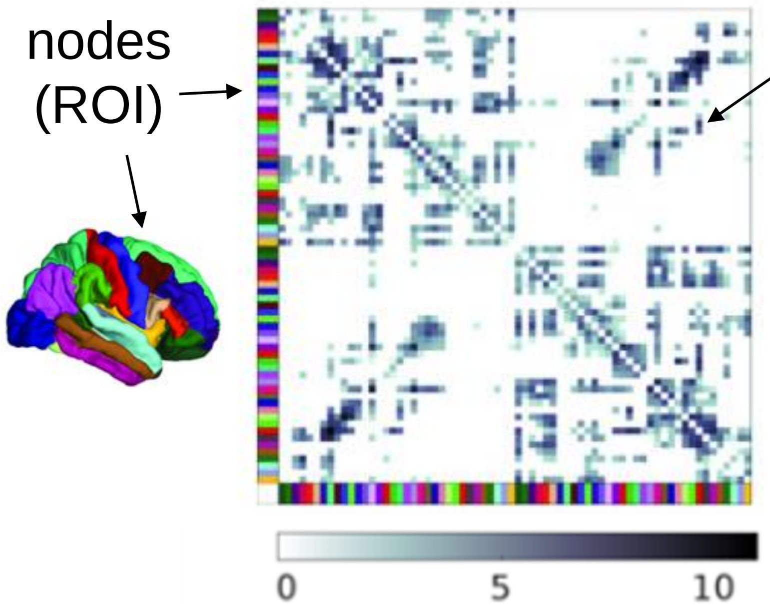
the activity of each node
changes over time

Figures adapted from Glomb 2020

Graph *vs* graph signal – brain data

Graph:

Structural connectome



Graph signal:

Functional brain signal

- BOLD
- Reconstructed EEG

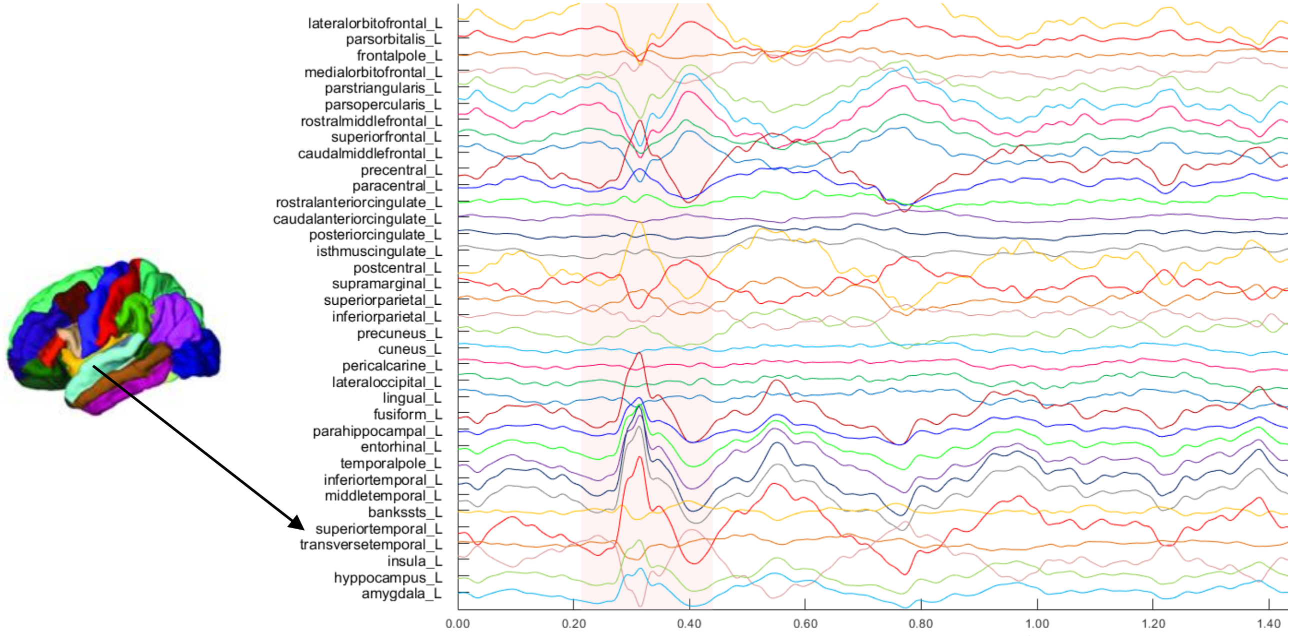
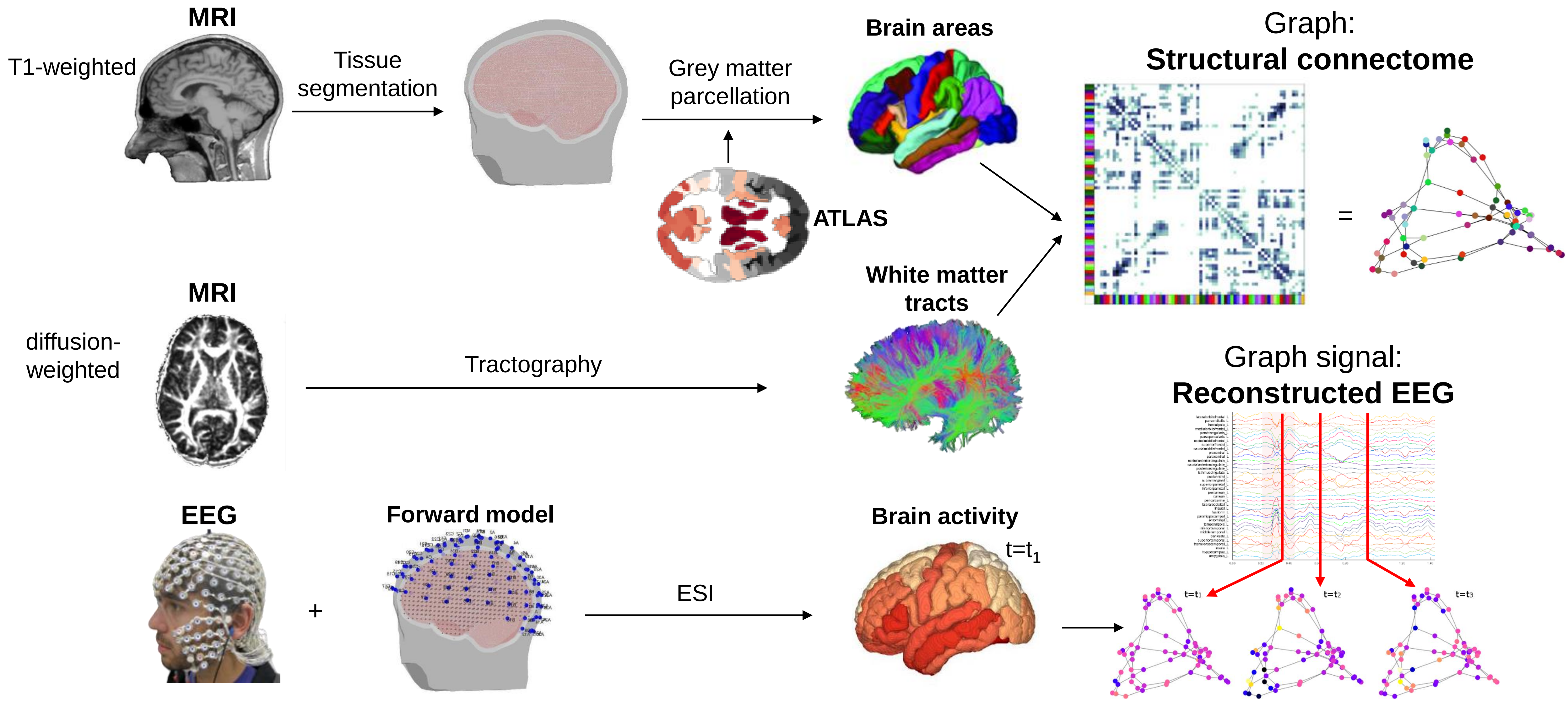


Figure adapted from Glomb 2020

Graph *vs* graph signal – brain data in practice



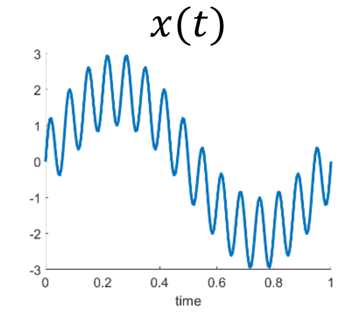
Fourier transform

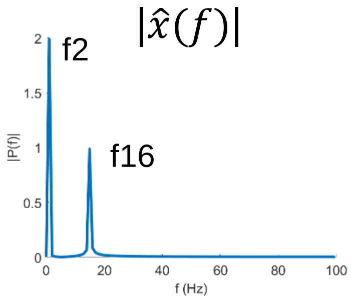
In time domain

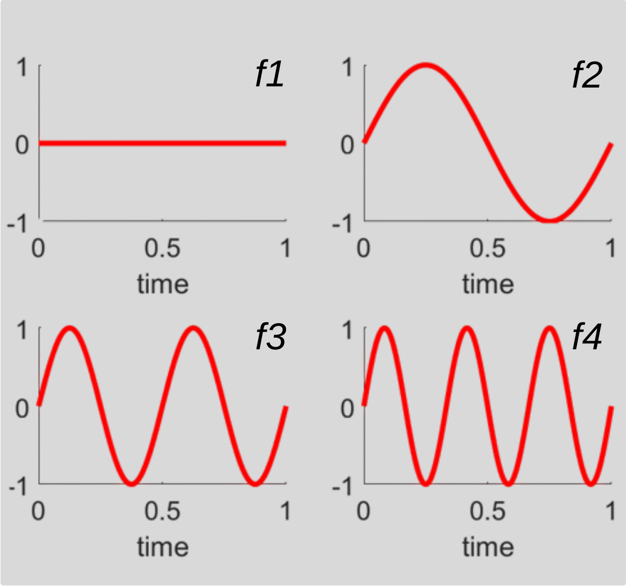
- One dimensional signal defined *over time*
- The *time graph* can be decomposed into sine and cosine waves (Fourier modes)
- The signal can be reconstructed as a linear combination of these modes

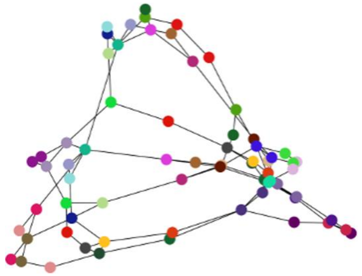
In graph domain:

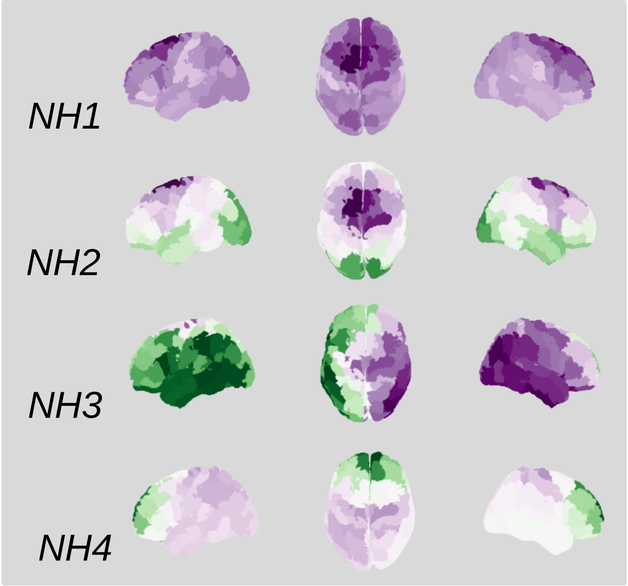
- Graph signal (reconstructed EEG) is defined *over a graph*
- The *(structural) graph* can be decomposed into Fourier modes *-network harmonics (NH)-*
- The graph signal can be reconstructed as a linear combination of these harmonics











Fourier transform – time domain

$$\hat{x}(f) = \int_{-\infty}^{\infty} x(t) * e^{-2\pi i f t}\, dt$$

$$x(t) = \int_{-\infty}^{\infty} \hat{x}(f) * e^{2\pi i f t}\, df$$

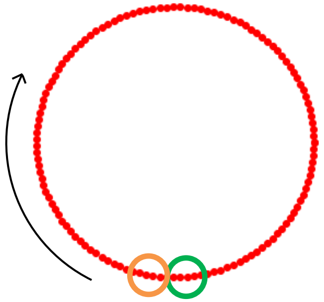
Where do these Fourier modes (f1,f2 etc.) come from?

→ They are the eigenvectors of the graph Laplacian of the time graph

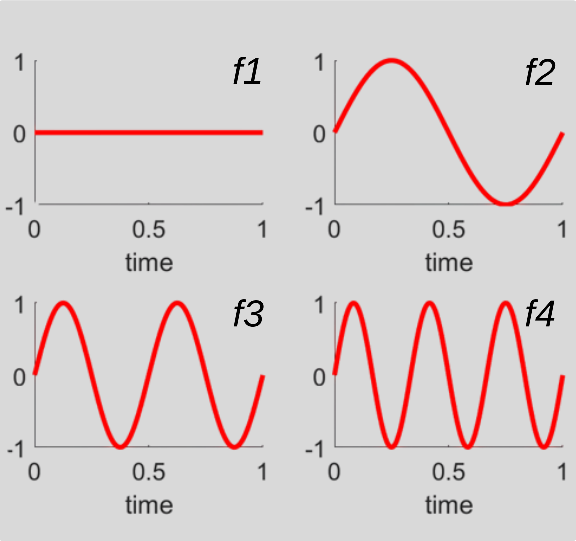
What is the time graph?

- Stationary time is modelled as a 1-d ring graph
- First and last point of signal are connected

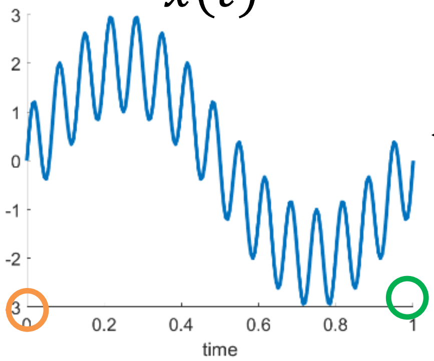
time graph



graph Laplacian →



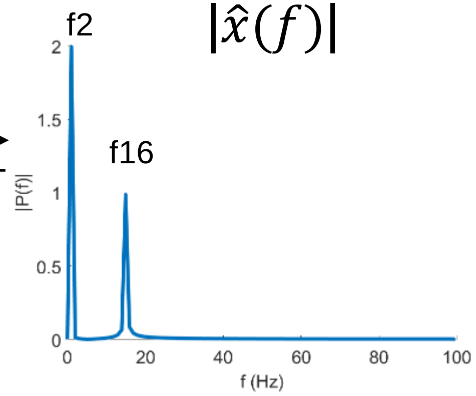
$x(t)$



FT →

← iFT

$|\hat{x}(f)|$



We can write the time-series as a linear weighted combination of these Fourier modes and understand the frequency content of the signal

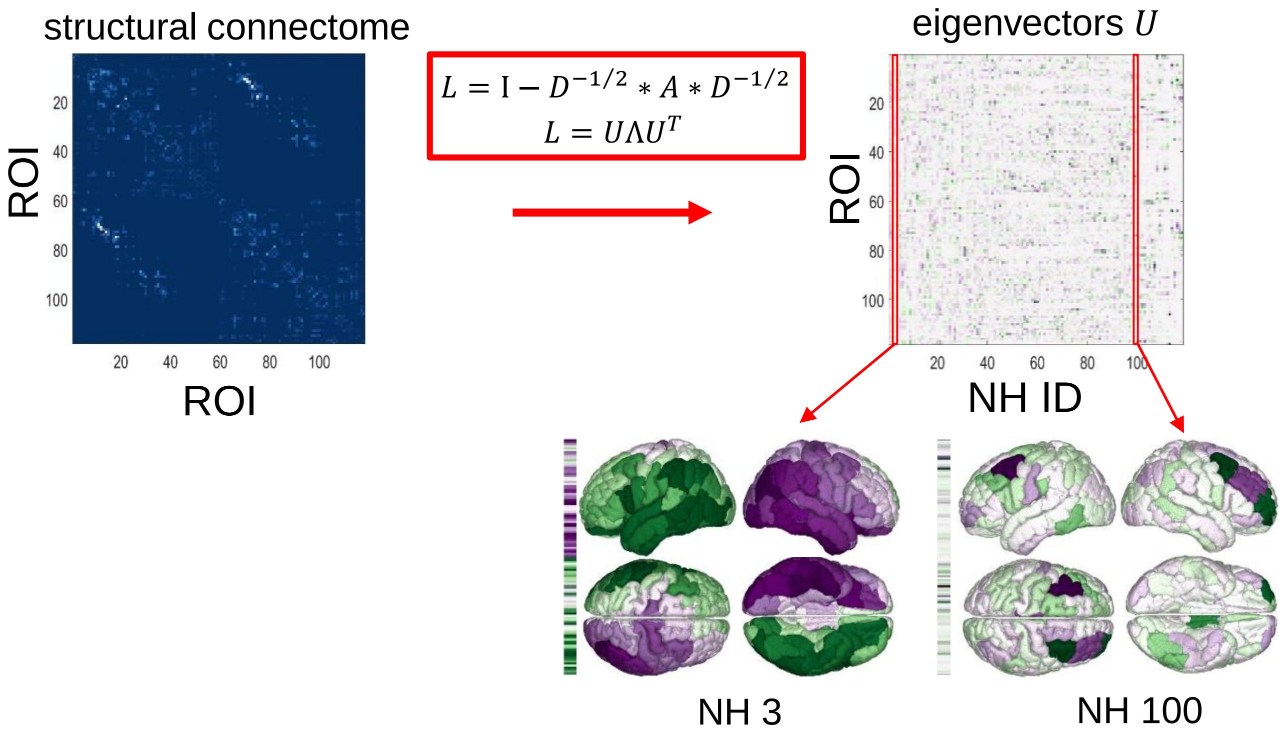
→ These are *time frequencies*

And in the graph domain?

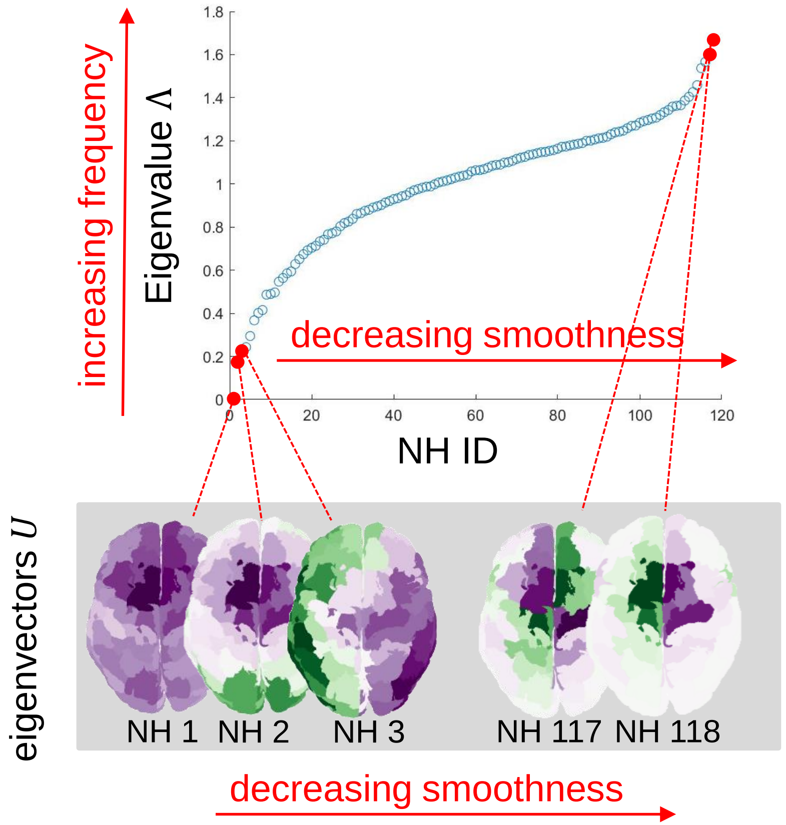
Fourier transform – graph domain

Graph Fourier transform (GFT):

- The EEG-signal lives on the structural connectome
- Calculate the graph Laplacian of the structural connectome
- Eigendecompose the graph Laplacian and extract the Fourier modes or "*network harmonics*" (NH)



$$L = \mathrm{I} - D^{-1/2} * A * D^{-1/2}$$
$$L = U \Lambda U^T$$



→ These are *spatial frequencies*

Fourier transform – graph domain

Graph Fourier transform the reconstructed EEG:

- Multiply the *network harmonics* by the signal in the ROI space $x_R(t)$
- $x_R(t)$ can be recovered by the inverse operation (inverse GFT)

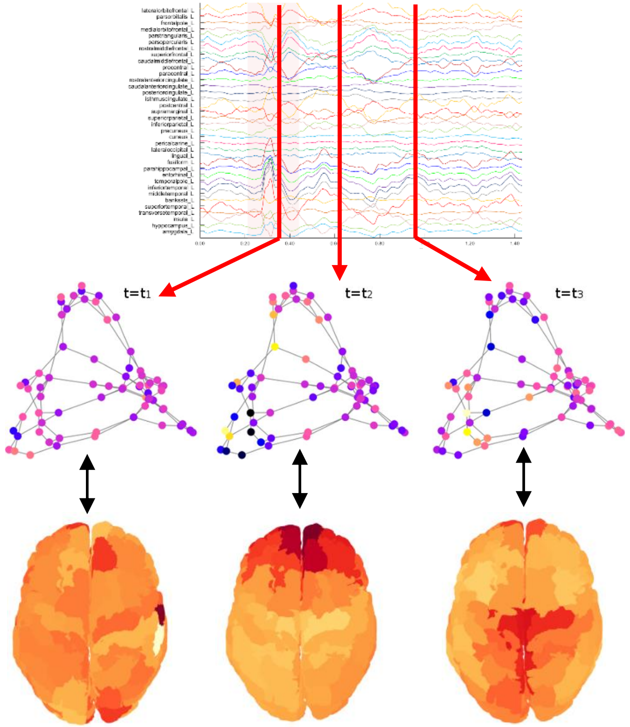
connectome spectrum of the signal $x_R(t)$

$$\hat{x}_\lambda(t) = U^T * x_R(t) \quad \leftarrow \text{GFT}$$

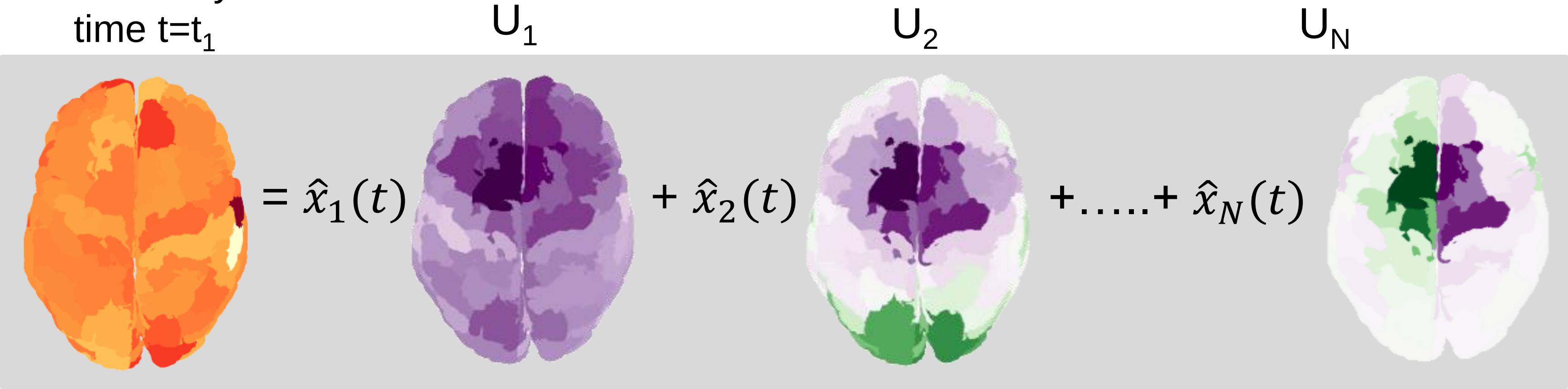
$$x_R(t) = U * \hat{x}_\lambda(t) \quad \leftarrow \text{Inverse GFT}$$

Graph signal:

Reconstructed EEG



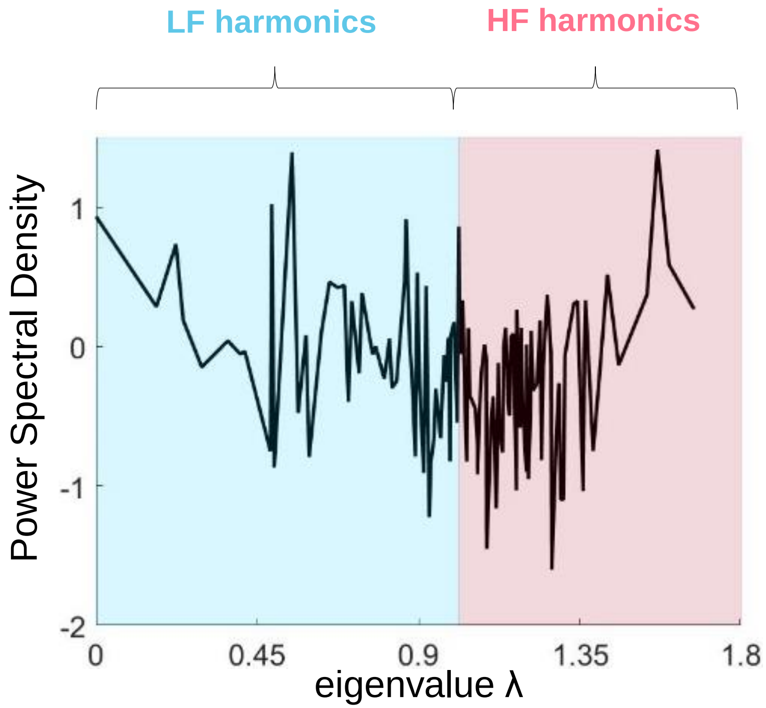
Brain activity at time $t=t_1$

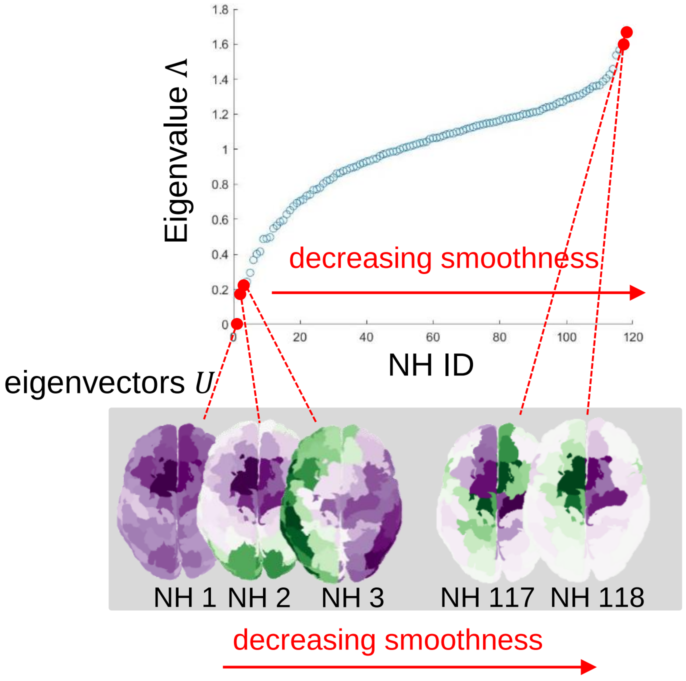


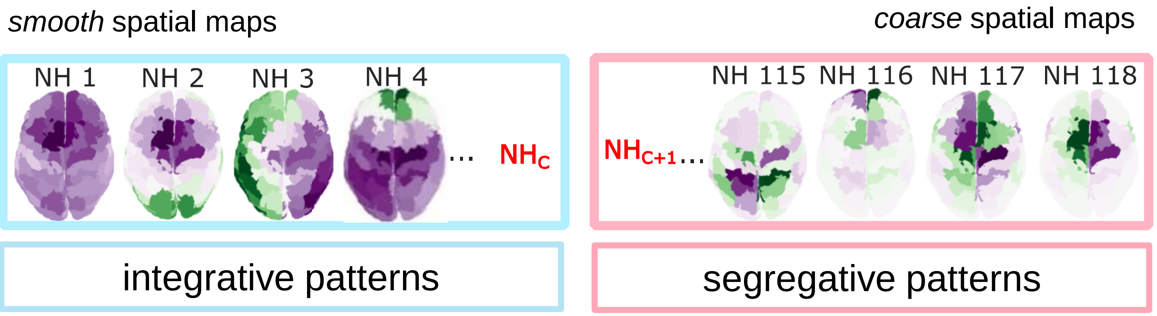
Functional activity decomposition

Graph filtering – spectrum dichotomization

- In classic EEG analyses there are frequency bands of interest
- In the graph domain we have *spatial frequencies* (not time frequencies)
- We split the connectome spectrum in two parts of equal cumulative power:
  - → **low-frequency harmonics**
  - → **high-frequency harmonics**



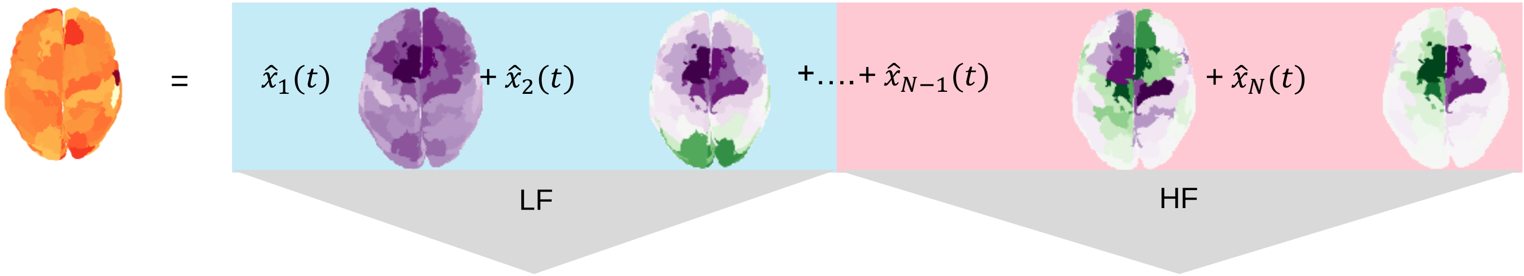




Graph filtering and SDI

- Filter EEG reconstructed signal using one subset of frequencies:
  - → **low-frequency harmonics:** $x_R(t) = U_{LF} * \hat{x}_\lambda\ (t)$
  - → **high-frequency harmonics:** $x_R(t) = U_{HF} * \hat{x}_\lambda\ (t)$
- Get structural decoupling index (SDI) as ratio of the two signals

Brain activity at time *t*



COUPLED/INTEGRATED PORTION OF SIGNAL (x_C)

DECOUPLED/SEGREGATED PORTION OF SIGNAL (x_D)

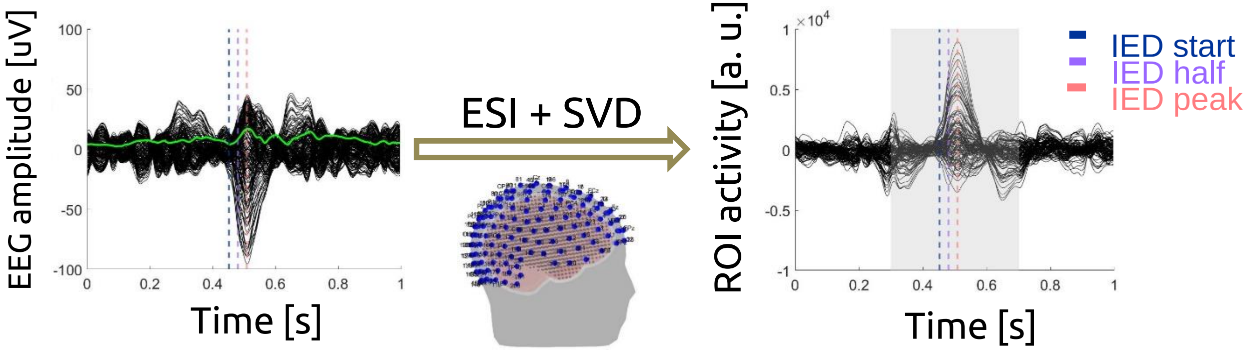
$$\text{STRUCTURAL-DECOUPLING INDEX} = \frac{\text{DECOUPLING}}{\text{COUPLING}}$$

Can GSP predict the surgical outcome?

Study 1: GSP on interictal spikes

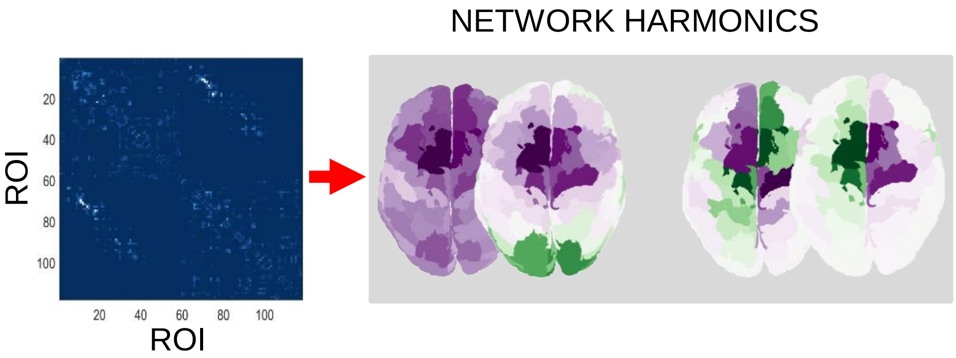
The functional data

- 9 RTLE and 8 LTLE patients
- HD EEG and structural MRI
- IEDs marked and extracted
- Activity of each ROI was reconstructed via ESI



The structural data

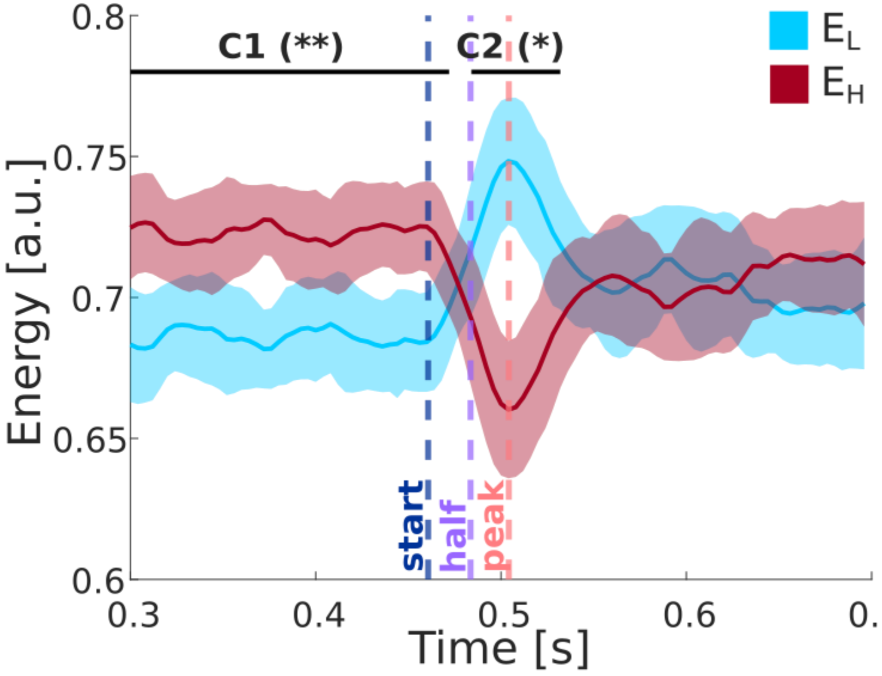
- Consensus structural connectome (SC) from 70 healthy subjects
- Extract network harmonics (NH) as eigenvectors of the SC Laplacian and divide them in low/high frequency harmonics



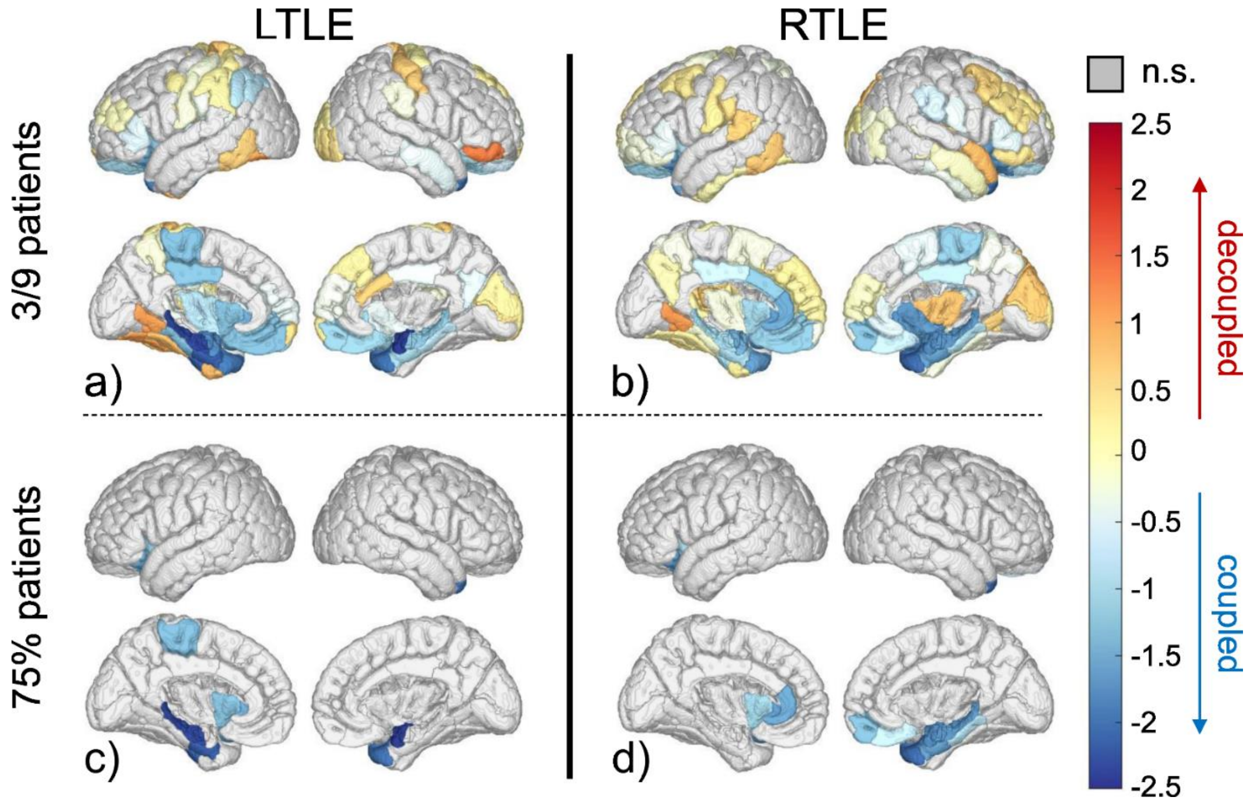
Rigoni et al. 2023

Study 1: GSP on interictal spikes

- **C1**: most energy of the EEG signal is in the HF harmonics (coarse spatial maps) → segregation
- **C2**: predominance of LF harmonics (smooth spatial maps) → integration



- Activity in ipsilateral mesial temporal ROI is more coupled to the structure in 75% of patients than the best performing surrogate along the whole IED duration

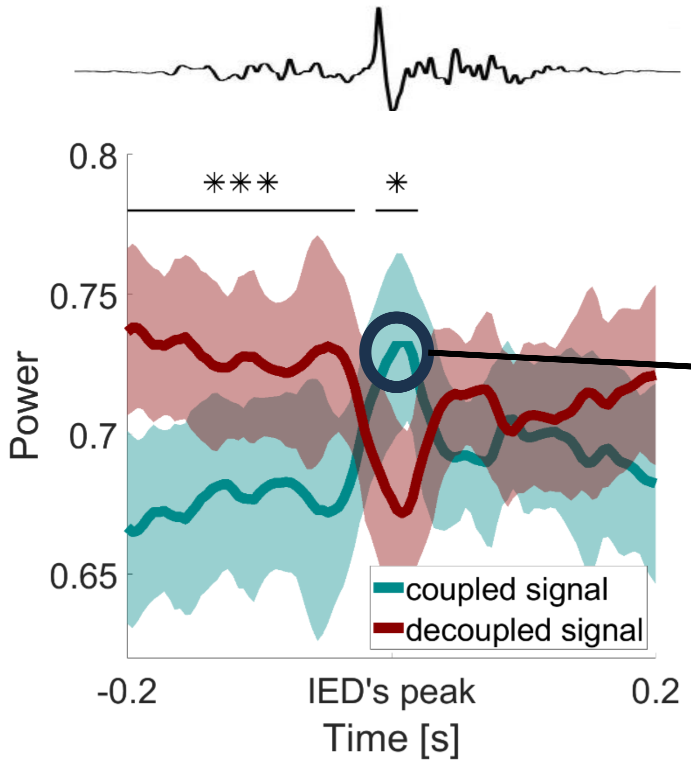


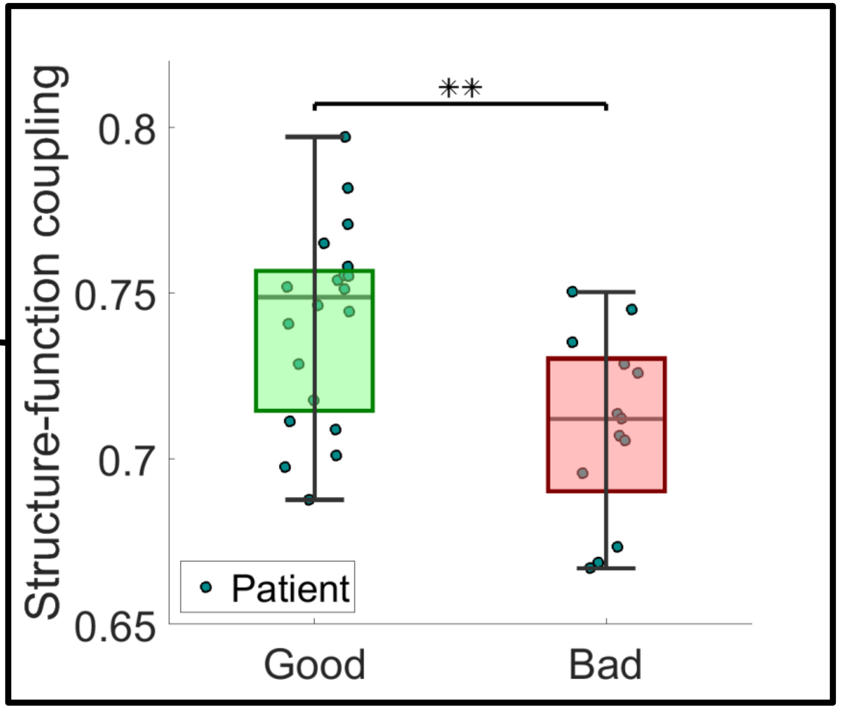
Rigoni et al. 2023

Study 2: GSP on interictal spikes

- 33 patients with temporal lobe epilepsy, operated, with surgical outcome at 1 year
- Replication of previous results on SDI (coupling/decoupling during IED)
- Coupling during the IED could serve as biomarker for surgical outcome

Louise de Wouters d'Oplinter



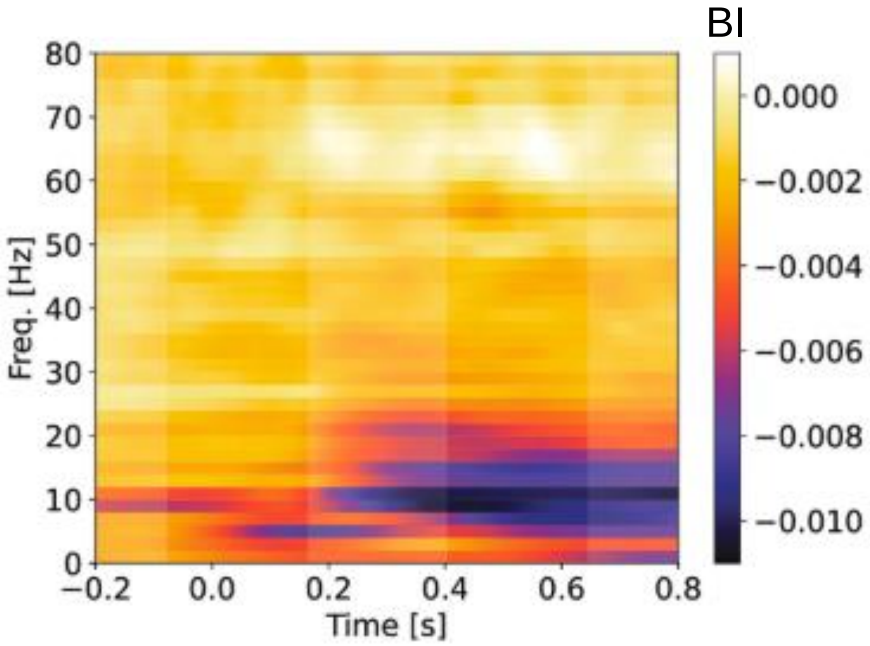


GSP: spatial- and time- frequencies

- Joint time-vertex connectome spectral analysis

→ different information processing mechanisms (int/seg) are carried out at different frequency bands

- Broadcasting index (BI) similar to SDI
- **BI>0** : **HF harmonics (segregation)**
- **BI<0** : **LF harmonics (integration)**

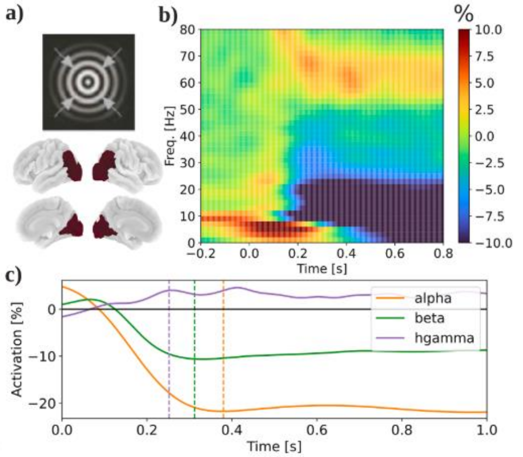


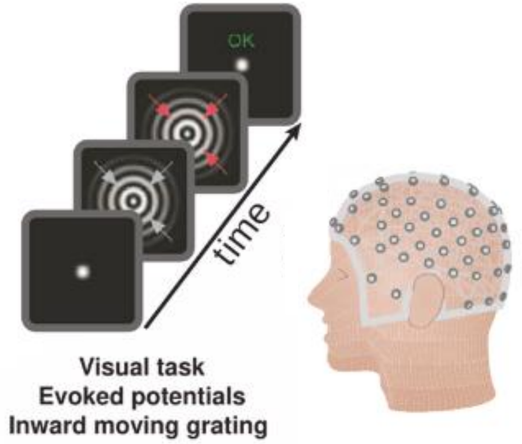
segregative patterns

More localised activity (BI>0) in high gamma

Dominance of smooth NH in alpha/theta

integrative patterns





- **localized electrical activity** (i.e., segregation) is observed **at high temporal frequencies** (high and low gamma) over restricted high spatial graph frequencies

- **spatially distributed activity** (i.e. integration) specifically occurs **at low temporal frequencies** (alpha and theta) and low graph spatial frequencies

Rué-Queralt and Mancini et al. 2023

GSP: references

M. G. Preti and D. Van De Ville, “Decoupling of brain function from structure reveals regional behavioral specialization in humans,” *Nat. Commun.*, vol. 10, no. 1, pp. 1–7, 2019, doi: 10.1038/s41467-019-12765-7.

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J. Rué-Queralt *et al.*, “The connectome spectrum as a canonical basis for a sparse representation of fast brain activity,” *Neuroimage*, vol. 244, no. September, p. 118611, 2021, doi: 10.1016/j.neuroimage.2021.118611.

I. Rigoni *et al.*, “Structure-function coupling increases during interictal spikes in temporal lobe epilepsy: A graph signal processing study,” *Clin. Neurophysiol.*, vol. 153, pp. 1–10, 2023, doi: 10.1016/j.clinph.2023.05.012.

R. Blanco, M. G. Preti, C. Koba, D. Van De Ville, and A. Crimi, “Comparing structure–function relationships in brain networks using EEG and fNIRS,” *Sci. Rep.*, vol. 14, no. 1, pp. 1–18, 2024, doi: 10.1038/s41598-024-79817-x.

J. Rué-Queralt *et al.*, “The coupling between the spatial and temporal scales of neural processes revealed by a joint time-vertex connectome spectral analysis,” *Neuroimage*, vol. 280, no. March, 2023, doi: 10.1016/j.neuroimage.2023.120337.

Thank you!