Analysis of Brain Networks

Brain Dynamics on the Connectome Summer School 2021

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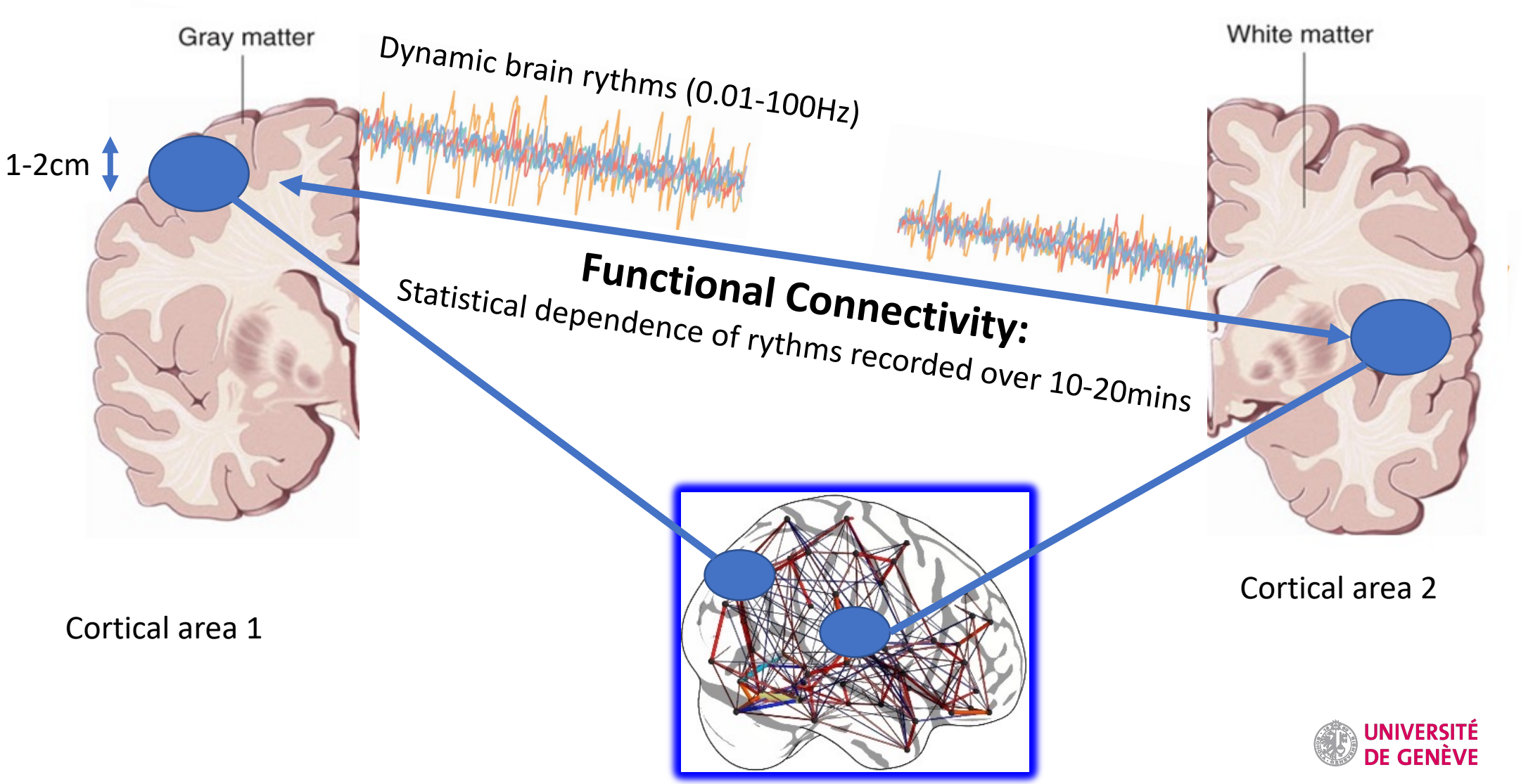
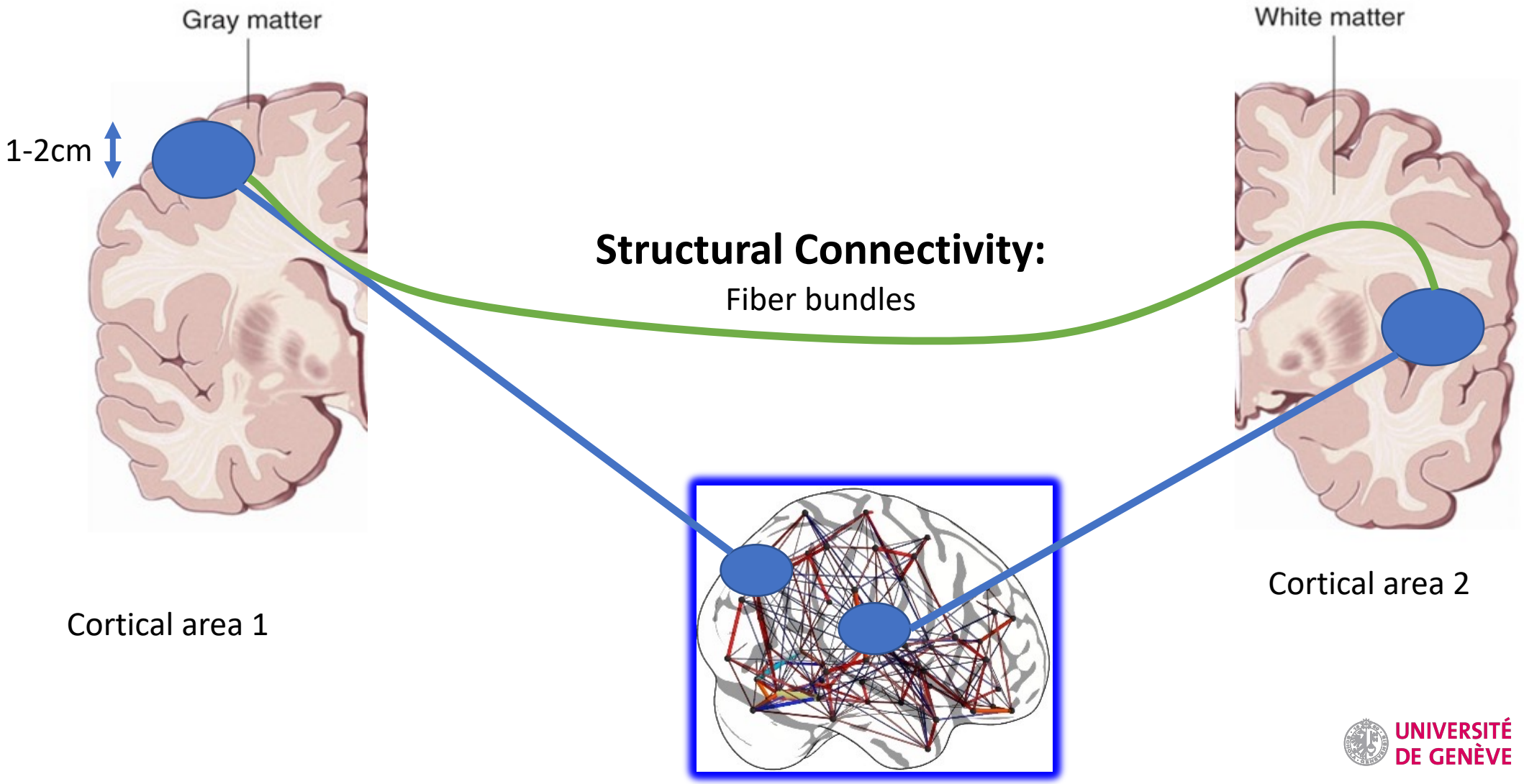
Outline

- EEG and fMRI connectivity
- Graph analysis
- Combination of EEG and fMRI

Accessing how brain regions-communicate in a network at multiple scales



Accessing how brain regions-communicate in a network at multiple scales

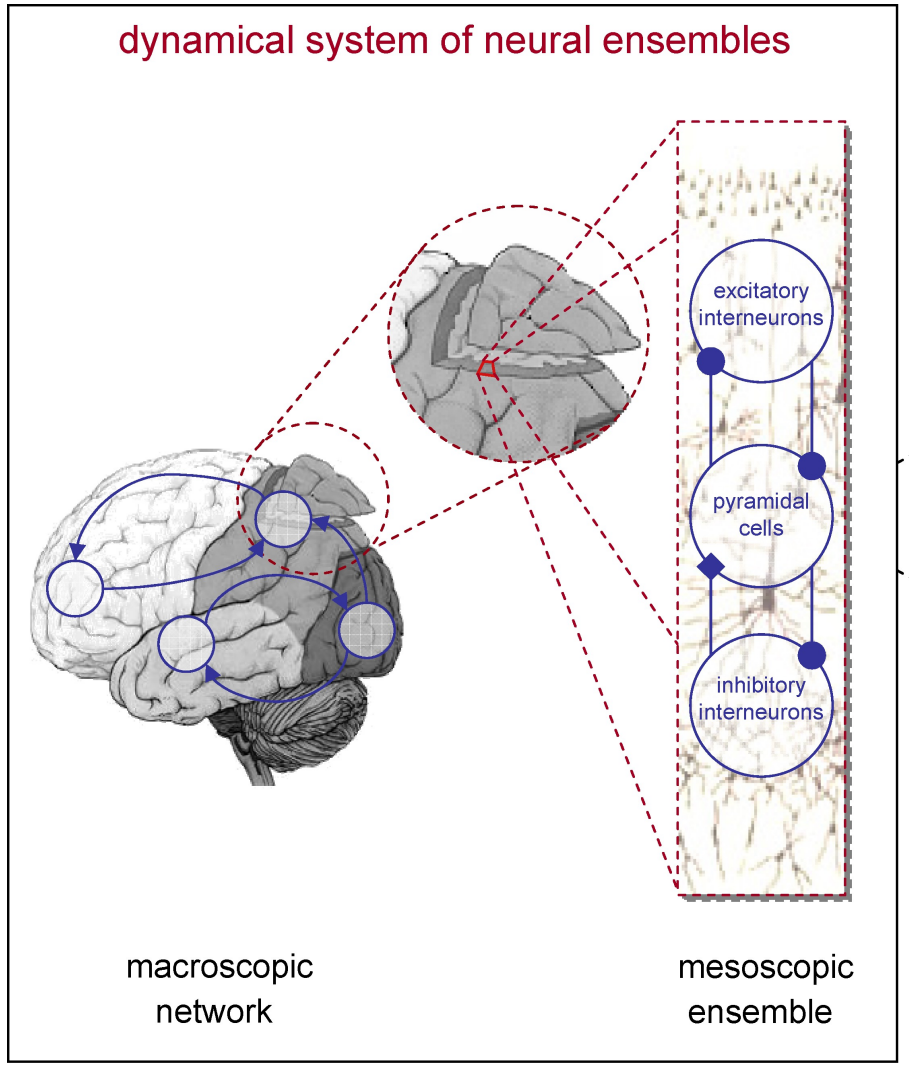


Non-invasive means to measure the human connectome

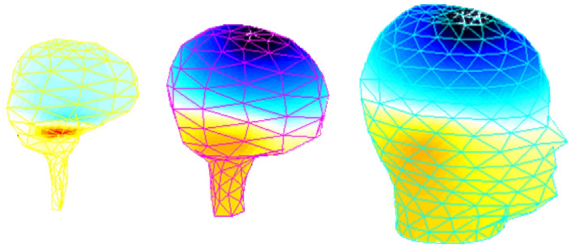
EEG

MRI

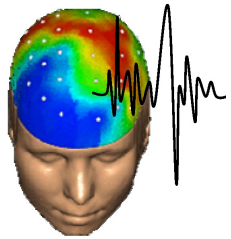
EEG and fMRI signal



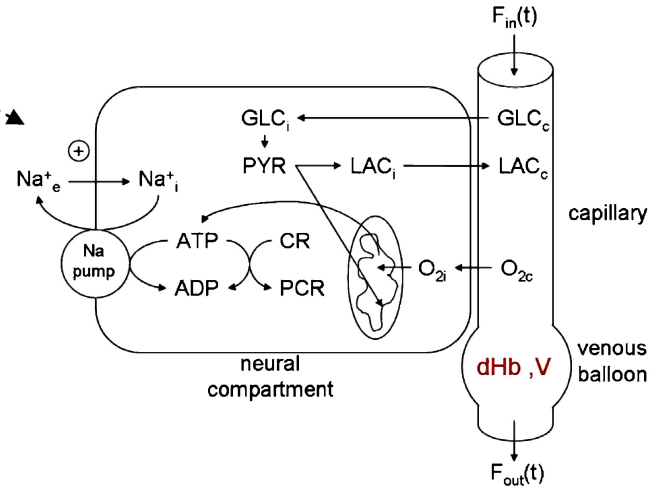
[Rosa 2010, J Integr Neurosci]



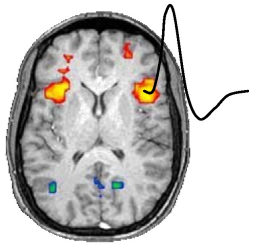
propagation of electrical potential through head tissues (EEG gain model)



EEG

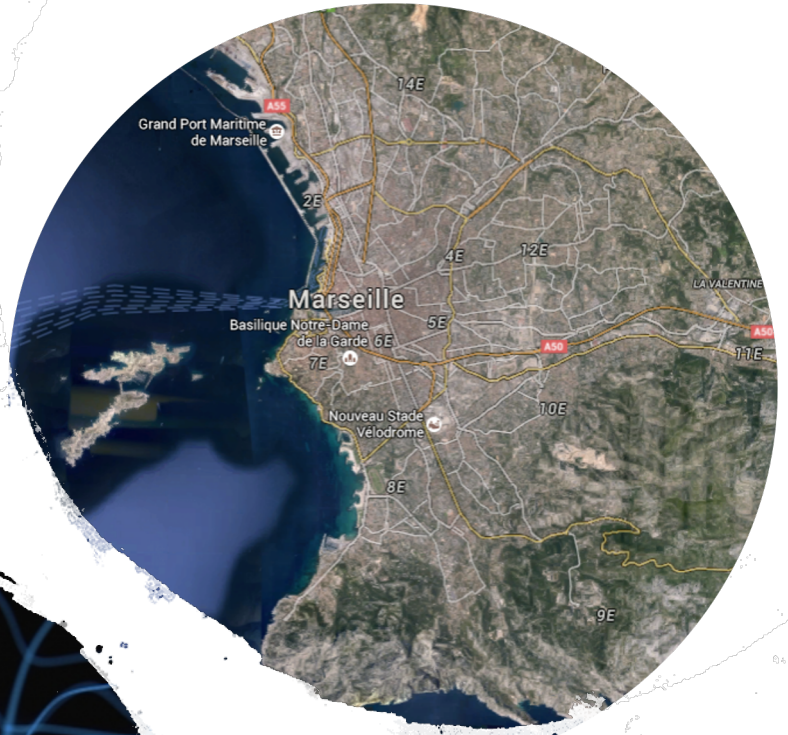


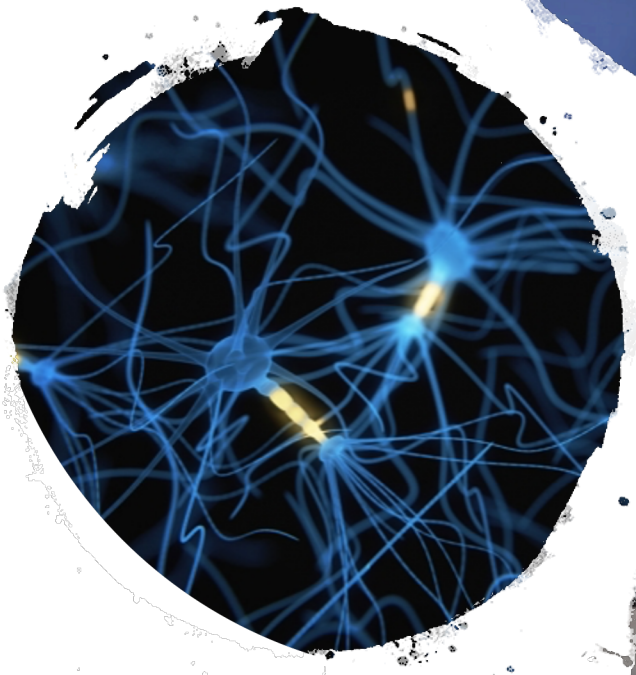
metabolic and hemodynamic cascade (extended fMRI balloon model)



fMRI

Brain Connectivity





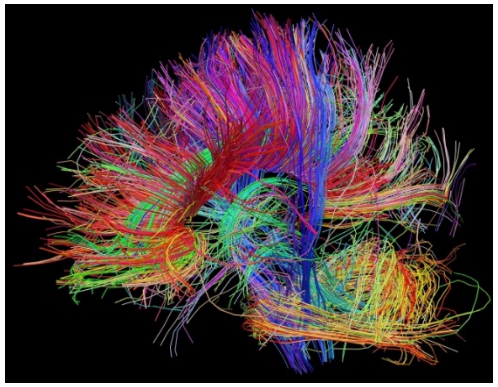
- Brain = City with a lot of connected streets

- Brain activity: Number of cars in one region

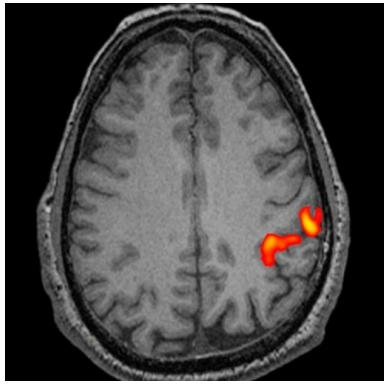
Building Network Graphs

Measures of connectivity

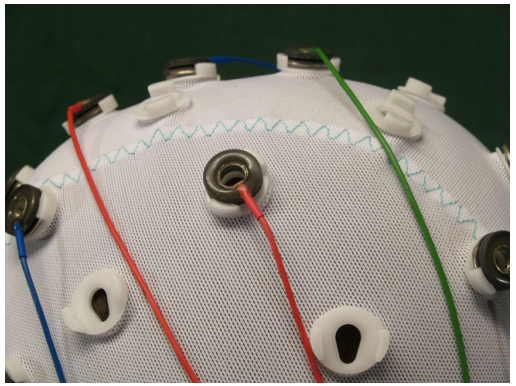
Number of lanes =
dMRI based number
of fiber tracts



Consumption of gas
measured at a gas station =
functional MRI based
BOLD signal



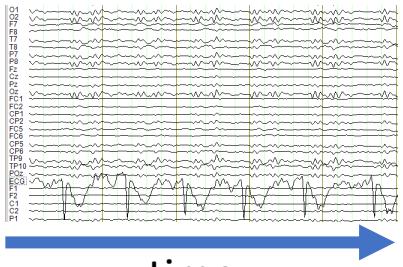
Smog caused by cars =
EEG signal



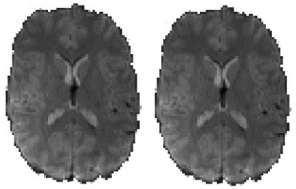
Constructing the multimodal connectome

Connectome Connectivity matrix

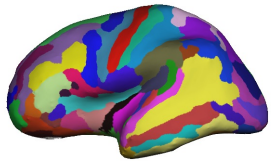
EEG
1ms
>1cm



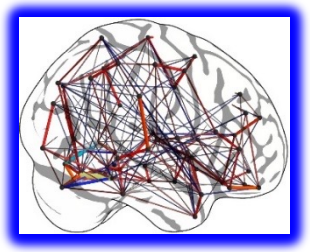
Functional MRI
1-2s
3mm

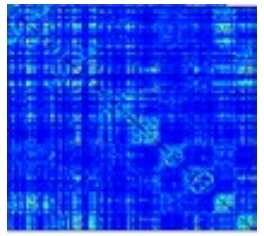


Tractography diffusion MRI
3mm

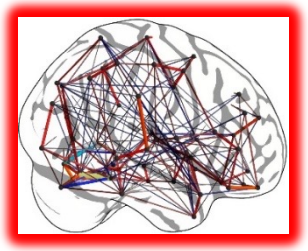


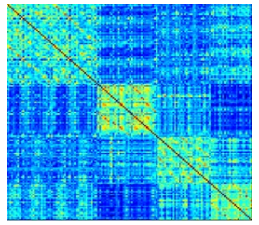
Atlas





EEG neuronal functional connectivity

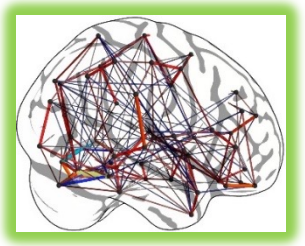


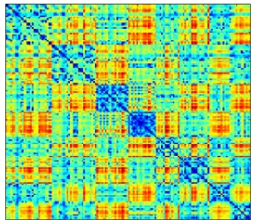


regions

fMRI metabolic functional connectivity

regions





dMRI structural connectivity

Connectome Connectivity matrix

brain dynamics occur on the millisecond timescale → concurrent recordings are needed for the full picture

Trimodal See e.g. [Wirsich 2017, NeuroImage], **structure vs. function later presentations**

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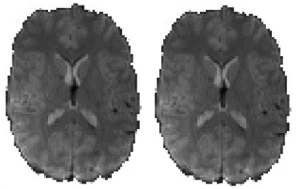
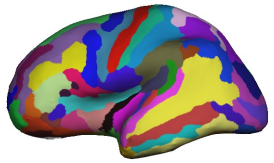
Constructing the multimodal connectome

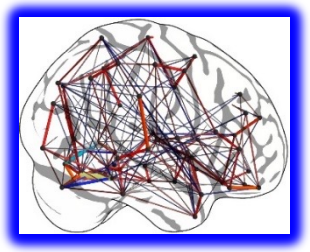
EEG
1ms
>1cm

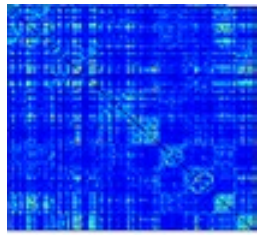
Functional MRI
1-2s
3mm

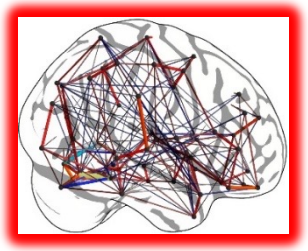


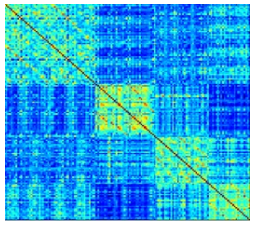


Connectome Connectivity matrix









Design of network analysis:

- What task?
- Which preprocessing steps?
- What atlas to use?
- What kind of connectivity?
- What properties of the graph?

Task Paradigm

resting state vs. task

Source: Wikimedia

Task-based see next presentation: Functional Connectivity (FC) and Dynamical FC

Resting state

- **Connections most commonly derived from <u>resting state</u>**

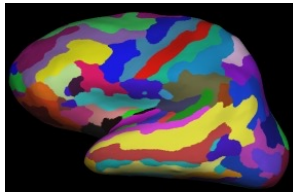
- **Session length most commonly 5-20min**
- Long enough for multiple cycles of infraslow (<0.1Hz) frequencies (fMRI), faster cycle possible with EEG
- Short enough to minimize mental state change
- Shorter term time-varying dynamics (e.g. sliding window)

Preprocessing fMRI

- **Preprocessing: same considerations as any fMRI connectivity study:**
  - Motion correction
  - Slice time correction
  - Physiological nuisance measures (ECG, breathing, etc.)?
  - Compartment signal regression (Gray Matter aka. Global mean, White Matter, Cerebrospinal-Fluid)

  - EEG covered in previous lecture

Anatomical atlases



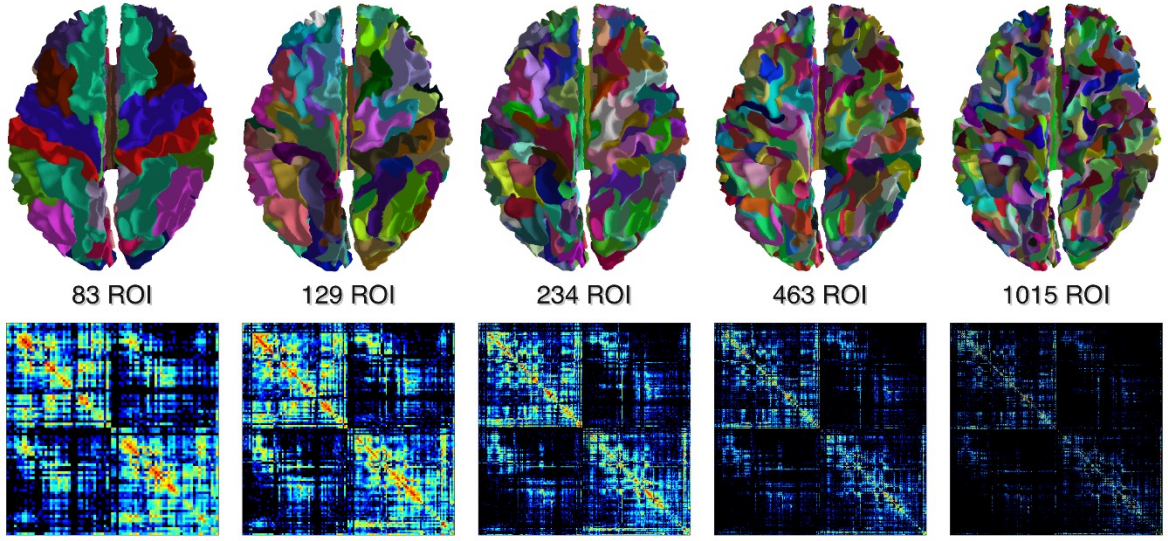
FreeSurfer (Destrieux)

Nodes:

- Internally coherent / homogeneous (connectivity)
- Externally independent

Anatomical atlases

- Talairach & Tournoux
- Automated Anatomical Labeling (AAL) template
- Eickhoff-Zilles (Cytoarchitectonic)
- FreeSurfer (Individual surface-based)
- Lausanne (subdivision of Freesurfer)



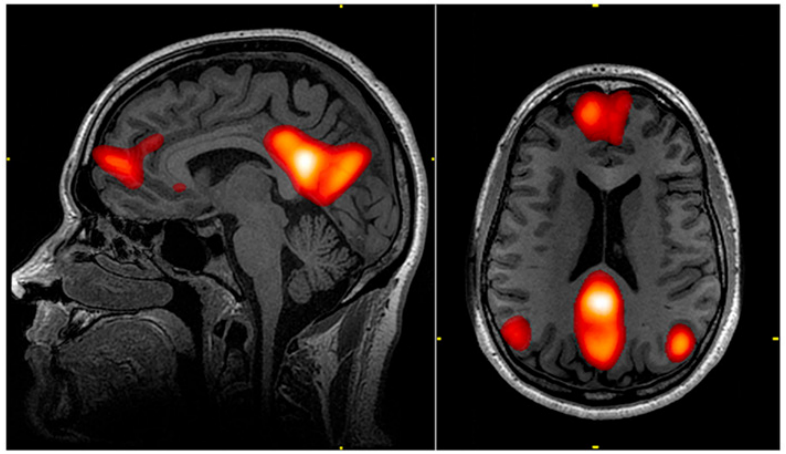
Lausanne Atlas [Daducci 2012, PlosOne]

- ☺ Comparability (across subjects and modalities)
- ☹ Highly variable node size

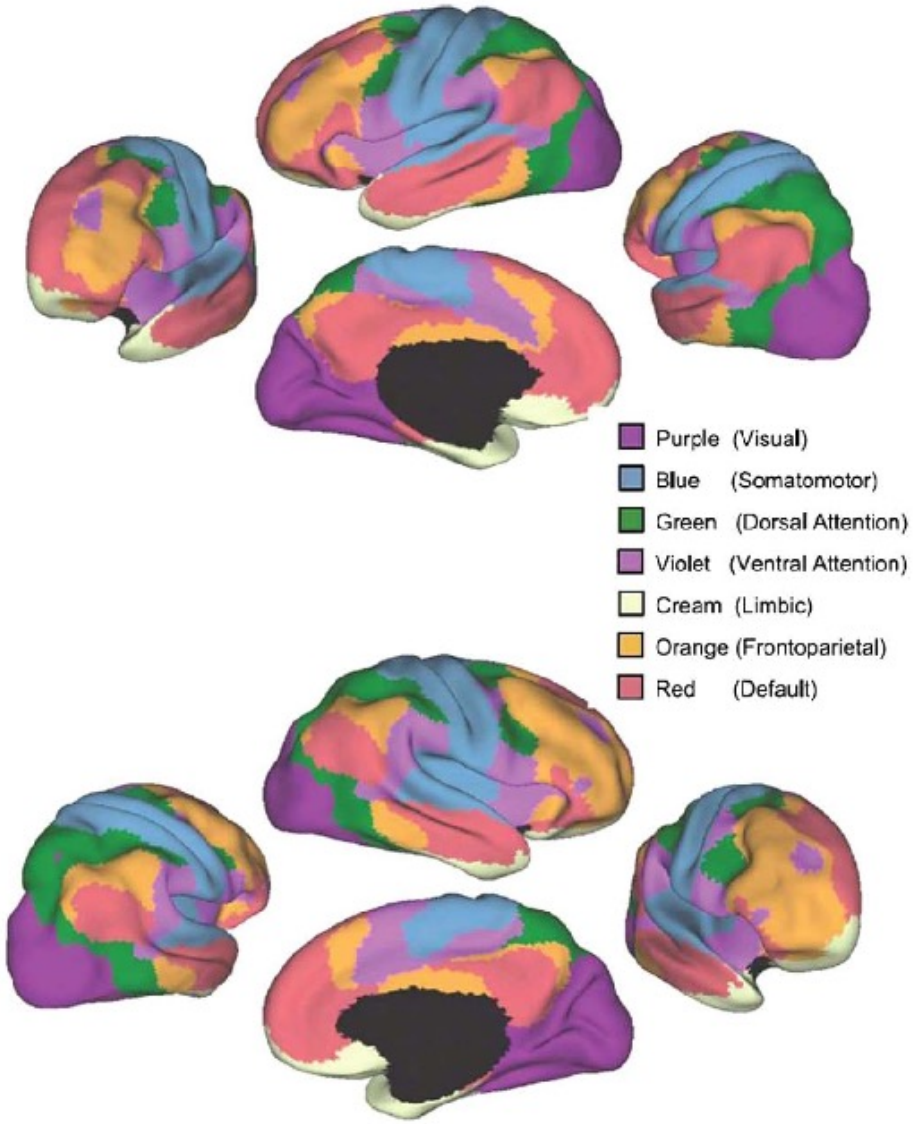
(can be mediated by subdividing such as Lausanne atlas). Not functionally coherent.

Intrinsic connectivity networks (M/EEG and fMRI)

Resting-state = Default mode network activated



[Graner 2013, Front in NeuroSci]

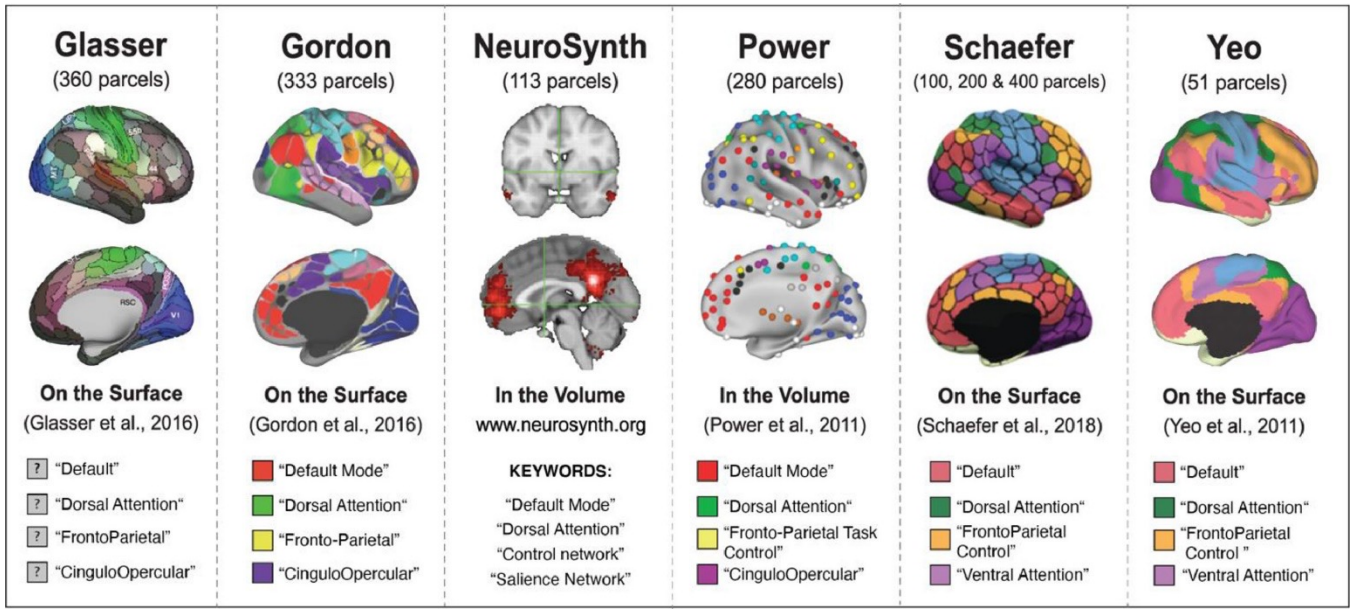


[Yeo 2011, J Neurophysiol]

Functional atlases

- Functional atlases
  - Comparability across subjects.
  - Functionally coherent

  (but suboptimal for individuals)



[Bryce 2021, NeuroImage]

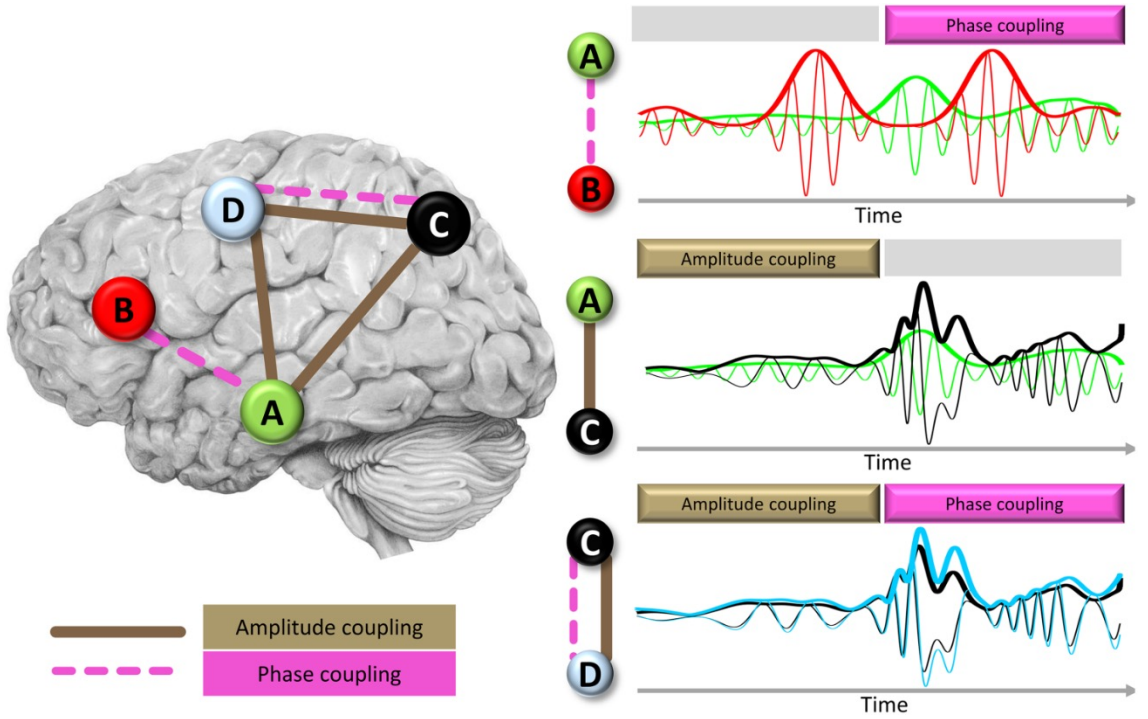
Functional subject-specific parcellations

- ICA (Seed-based)
- Connectivity homogeneity: Craddock
- Functionally coherent
- Time-intensive

List of atlases: https://en.wikibooks.org/wiki/SPM/Atlases

Edges in EEG and fMRI

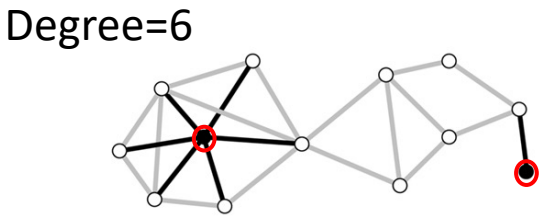
- Based on magnitude of temporal covariation
  - Pearson's cross-correlations (by far most common)
  - Partial correlations
  - Mutual information
  - → symmetric adjacency matrices (undirected graphs)



[Sadaghiani and Wirsich 2020, Network NeuroSci]

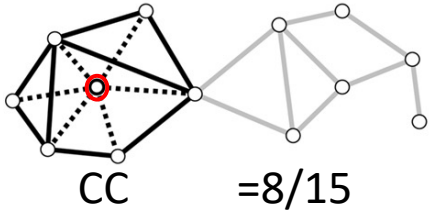
- Directionality problematic in fMRI (but measures of effective connectivity possible)
- EEG: coherence, amplitude correlations, etc. directionality less problematic but source leakage

Nodal Measures



Degree

- Number of edges connected to a node



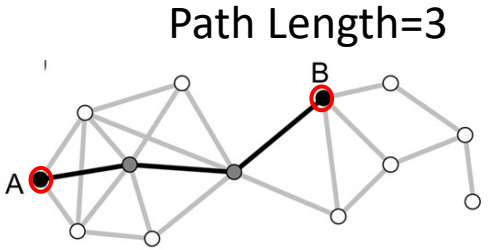
CC =8/15 =0.53

(n(n-1)/2)

Nodal Clustering Coefficient (➔ basis for measure of global segregation)

- Fraction of all possible edges realized among a node's neighbors

  = Fraction of all possible triangles around a node



Shortest Path Length (➔ basis for measure of global integration)

- Number of edges on shortest geodesic path between two nodes

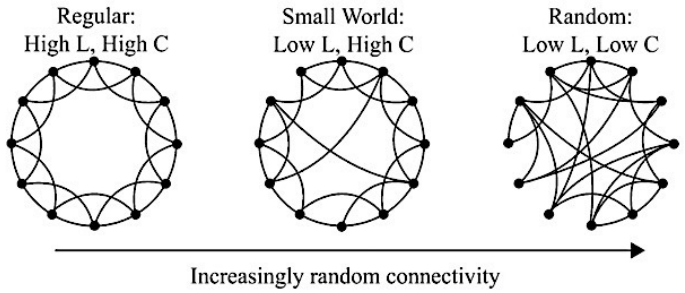
[Sporns 2011, Ann NY Acad Sci]

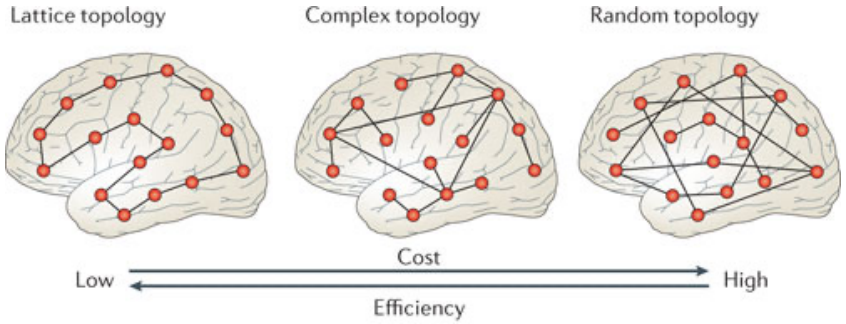
Global Measures

Small-worldness

- Optimal balance between functional segregation and integration:
  - C (high = segregated): Clustering Coefficient$_{real}$ / Clustering Coefficient$_{random}$
  - L (low = integrated): Characteristic Path Length$_{real}$ / Characteristic Path Length$_{random}$

[Watts and Strogatz 1998, Nature]

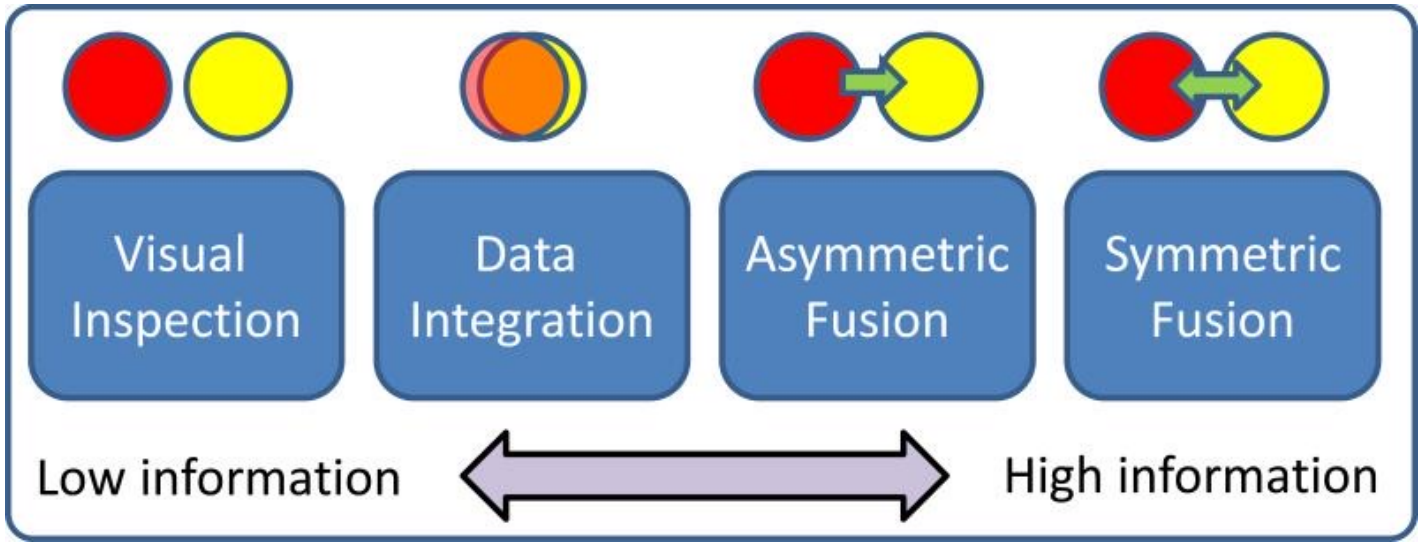




☺Functionally specialized (segregated) modules *AND* intermodular (integrating) edges

- A very easy global parameter is the spatial correlation between sessions subjects or modalities

Fusion and Integration of EEG and fMRI

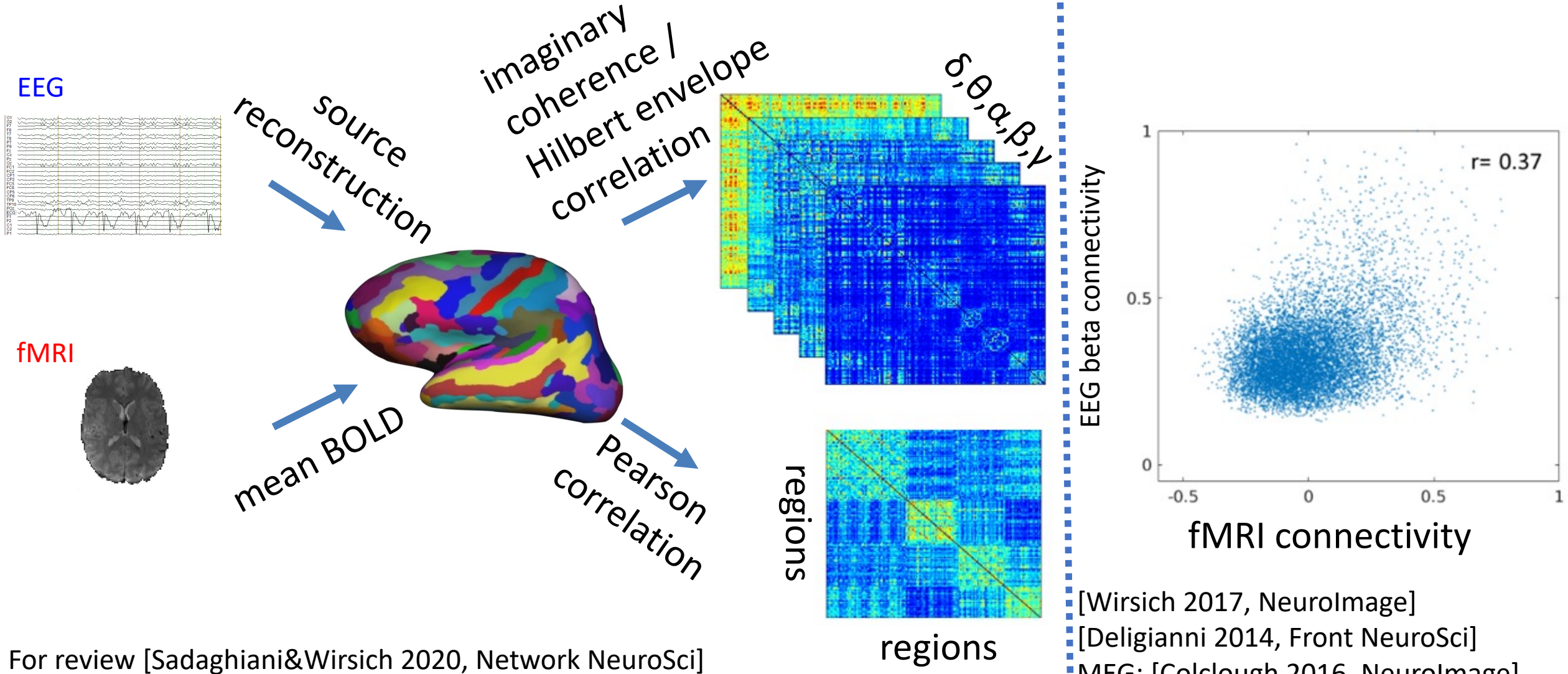


Source: [Calhoun 2016, BPCN Neuro]

Source: xkcd.com

- Low information: Comparison of graph properties (e.g. clustering, small-worldness)
- Fusion: high temporal resolution of EEG and high spatial resolution of fMRI are used: see e.g. [Wirsich 2014, NeuroImage]

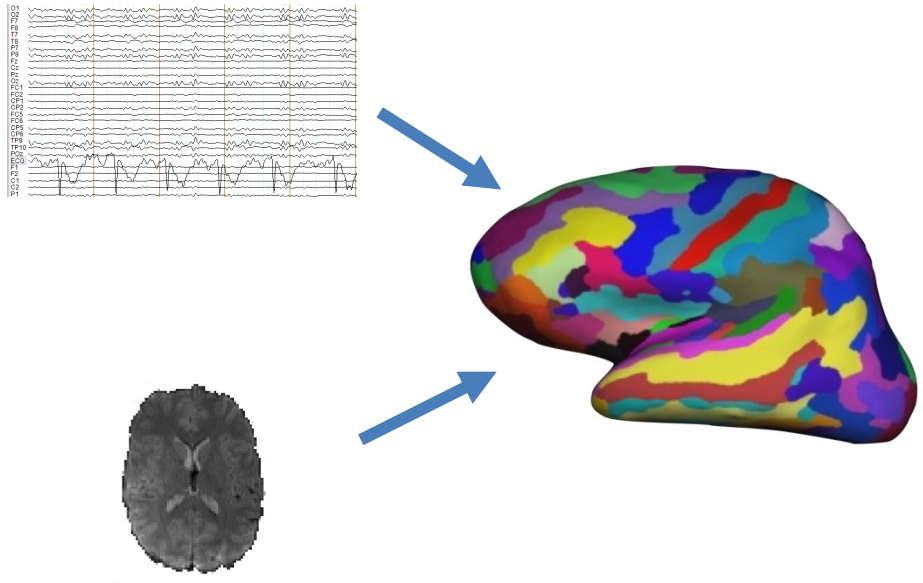
Spatial integration of EEG and fMRI connectomes

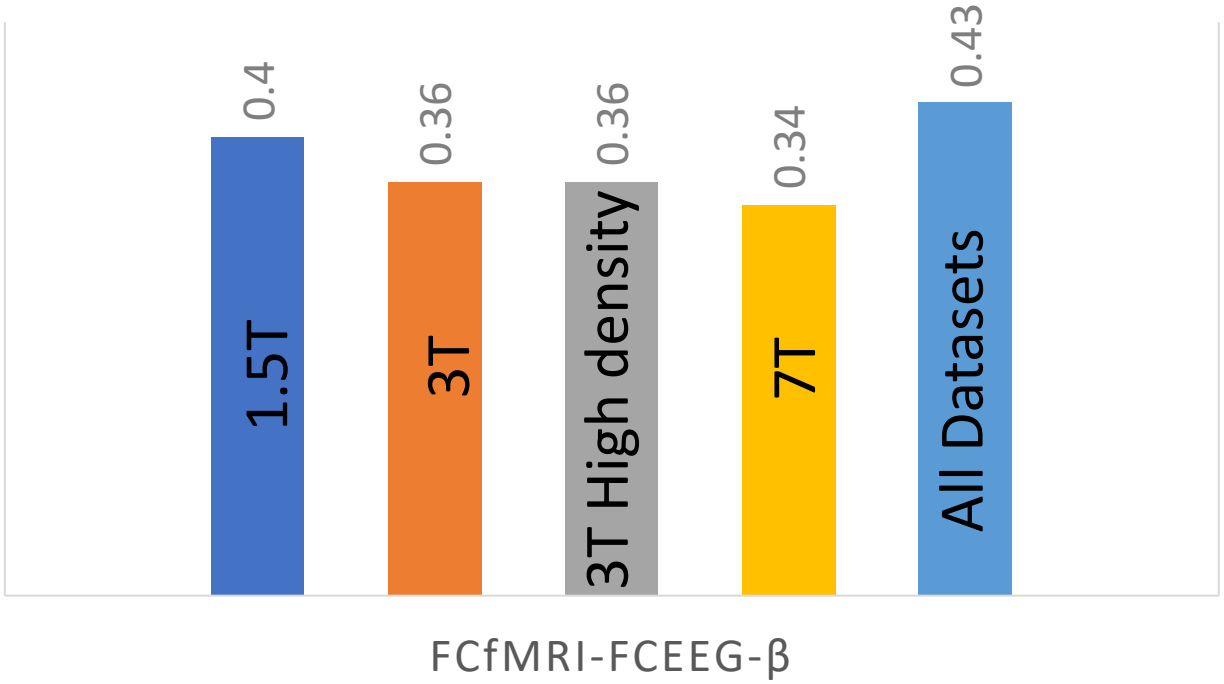


For review [Sadaghiani&Wirsich 2020, Network NeuroSci]

[Wirsich 2017, NeuroImage]
[Deligianni 2014, Front NeuroSci]
MEG: [Colclough 2016, NeuroImage]

Spatial correlation of group average EEG and fMRI connectomes

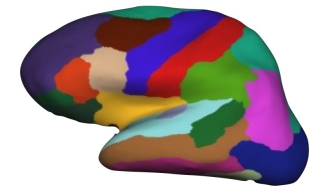




Correlation around r=0.3, gamma performs well only on 1.5T, averaging all datasets results in best results

[Wirsich et al. 2021, NeuroImage]

Increased EEG-fMRI correlation in smaller atlas



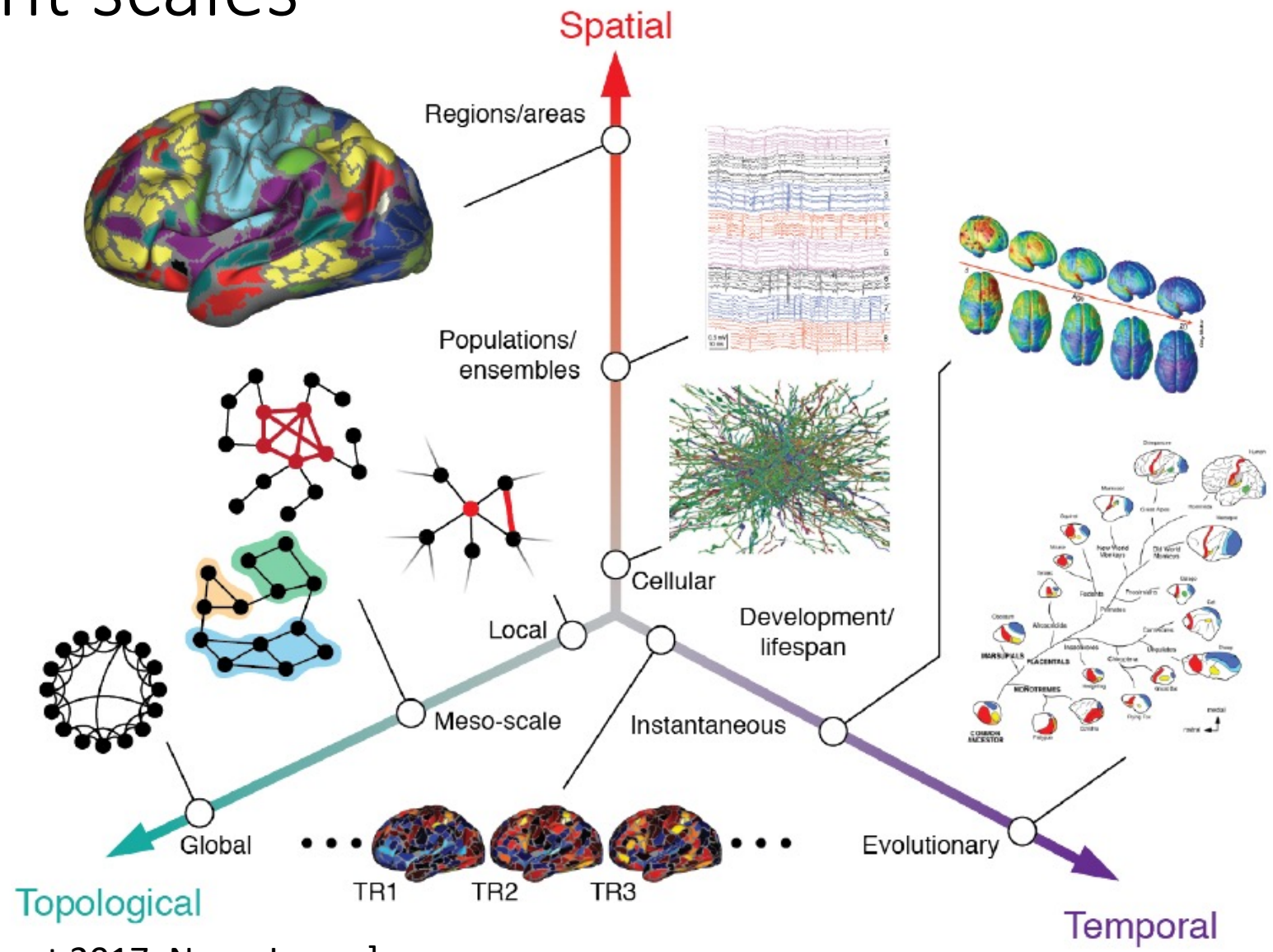
Imaginary coherence Beta	64Ch-1.5T	64Ch-3T	256Ch-3T	64Ch-7T	All combined
Desikan n=68	0.40	0.36	0.36	0.34	0.43
Destrieux n=148	0.29	0.33	0.26	0.31	0.36

- Quality of Destrieux can be boosted by combining more datasets

→ Different setups seem to do better for some connections

[Wirsich et al. 2021, NeuroImage]

Understanding the brain = know how to link different scales



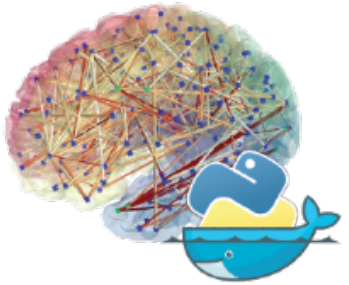
[Betzel and Basset 2017, NeuroImage]

Resources

Preprocessing

Connectomemapper

https://connectome-mapper-3.readthedocs.io/en/latest/



Graph analysis

MATLAB-based: **Brain Connectivity Toolbox (**Rubinov and Sporns, 2010)

- https://sites.google.com/site/bctnet/

  - Python-based: **NetworkX** (Hagberg et al., 2008)
- https://networkx.github.io

Reading

- Rubinov M, Sporns O. Complex network measures of brain connectivity: Uses and interpretations. NeuroImage. 2010 Sep;52(3):1059–69.
- Bullmore ET, Bassett DS. Brain Graphs: Graphical Models of the Human Brain Connectome. Annu Rev Clin Psychol. 2010 Apr;7(1):113–40.
- Sadaghiani S, Wirsich J. Intrinsic connectome organization across temporal scales: New insights from cross-modal approaches. Network Neuroscience 2020 4:1, 1-29
- Daducci et al. The Connectome Mapper: An Open-Source Processing Pipeline to Map Connectomes with MRI. PlosOne 2012