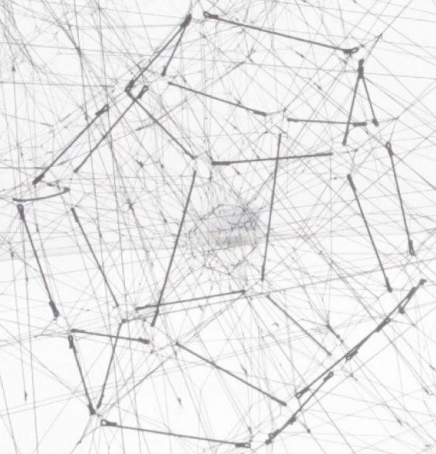
Optimized multilayer network model for interacting brains



Onerva Korhonen

Tampere Health Data Science webinar

27.10.2025

Tampere University

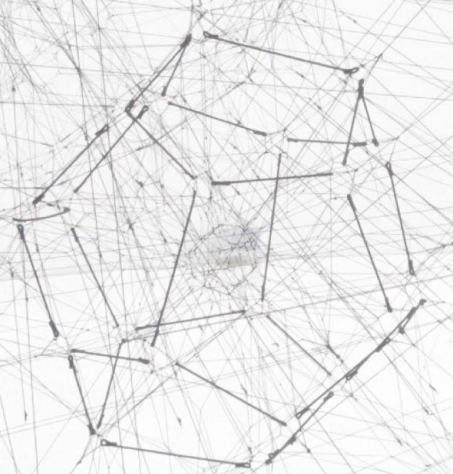
Slides: https://github.com/onerva-korhonen/presentations/blob/master/hds_271025.pdf

Background: Tomás Saraceno: Algo-R(h)i(y)thm (Photo: Milja Heikkinen)

Networks: what and why?

Network: a model for connections and interactions

- Internet, public transport, social networks



Tomás Saraceno: Algo-R(h)i(y)thm
(Photo: Milja Heikkinen)

Networks: what and why?

Network: a model for connections and interactions

- Internet, public transport, social networks

Nodes: network's basic elements

- Web pages, stops, people

Tomás Saraceno: Algo-R(h)i(y)thm
(Photo: Milja Heikkinen)

Networks: what and why?

Network: a model for connections and interactions

- Internet, public transport, social networks

Nodes: network's basic elements

- Web pages, stops, people

Links: connections between nodes

- Web links, transport lines, social relationships

Tomás Saraceno: Algo-R(h)i(y)thm
(Photo: Milja Heikkinen)

Network neuroscience

(Bassett & Muldoon 2016, Bassett & Sporns 2017)

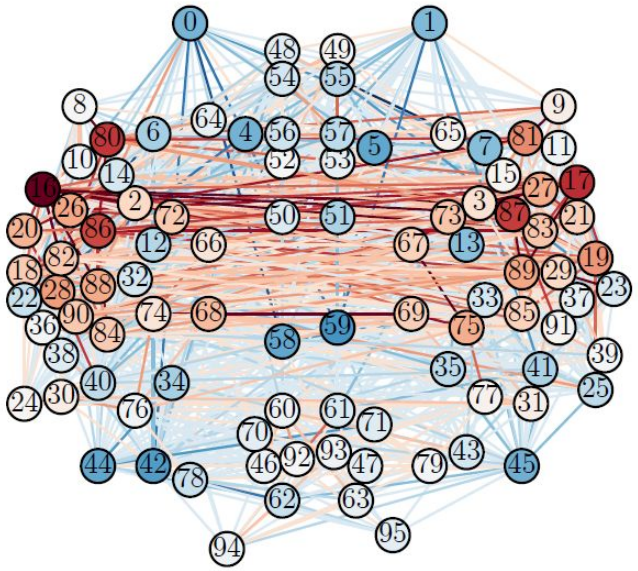
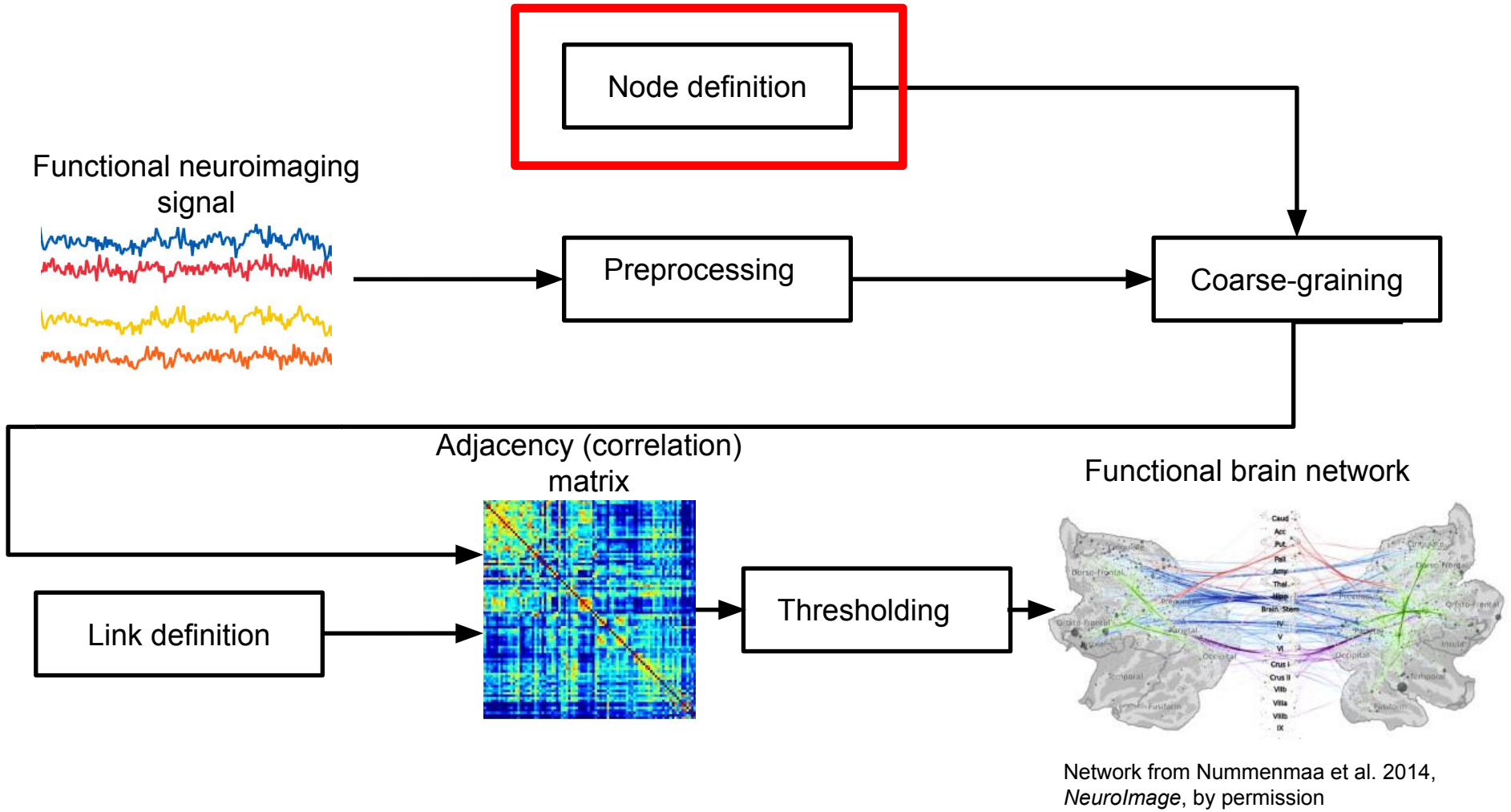


Fig: Alakörkkö *et al.* 2017, *European Journal of Neuroscience*

- Network neuroscience = applying network tools on the brain
- Two aims:
  1. Understand the healthy brain
  2. Find causes of diseases
- Broad scales:
  - Molecule – neuron – brain area – human
  - Milliseconds – years
- Different brain networks:
  - Structural: anatomic connections
  - ***Functional:*** temporal similarity
  - Effective: causality

Functional brain networks: how-to?



Network from Nummenmaa et al. 2014, *NeuroImage*, by permission

for a review, Korhonen et al. 2021

The problem of node definition

No natural candidates above the scale of neurons

=> huge variation in node definition

- Number of nodes: from < 100 to 10^5

Node definition affects network properties (e.g. Wang et al. 2009)

Common strategies (for a review, Korhonen et al. 2021, section 3.2):

- voxels/vertices
- random clumps of voxels/vertices
- Regions of Interest (**ROIs**): collections of voxels/vertices

Measurement points vs ROIs

Measurement points:

- fMRI voxels, MEG/EEG source points
- native imaging resolution
- noisy signals?
- ~10.000 nodes
- large computational load

More on this:

- Korhonen et al. 2017
- Ryyppö et al. 2018

ROIs:

- collections of measurement points
- defined by anatomy, function, connectivity, …
- ***homogeneous*** (= all measurement points are similar?)
- ROI time series to represent measurement point dynamics:

$$X_I = \frac{1}{N_I} \sum_{i \in I} x_i$$

Violent?

How homogeneous are ROIs?

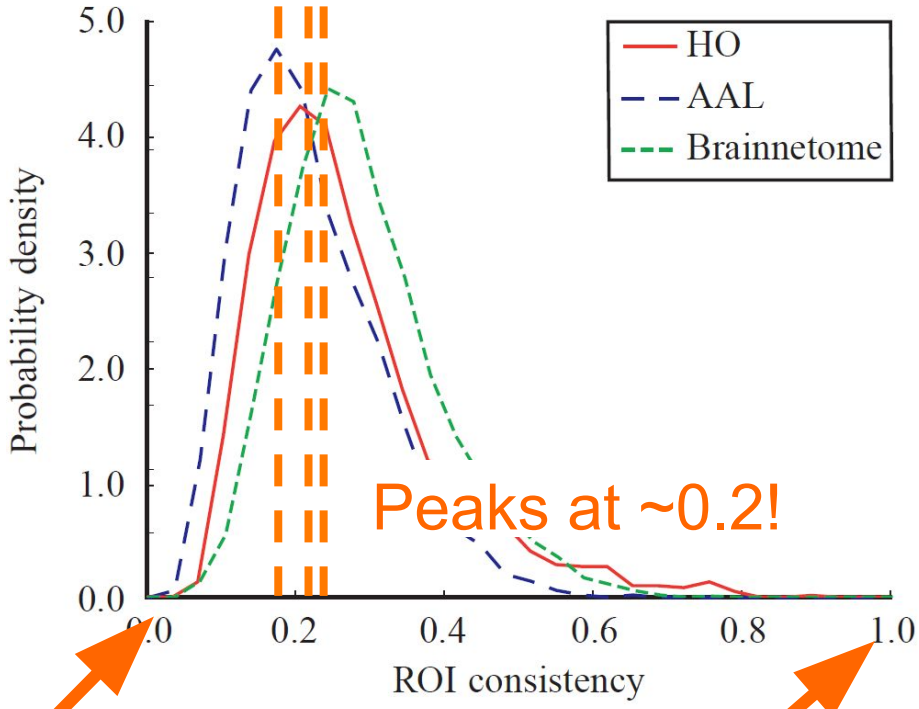
- ***Spatial consistency***

= measure of functional homogeneity:

$$\varphi_{spat}(I) = \frac{1}{N_I(N_I - 1)} \sum_{i,i' \in I} C(x_i, x_{i'})$$

- Straightforward to calculate
- Easy to interpret

Korhonen et al., 2017. *Network Neuroscience*



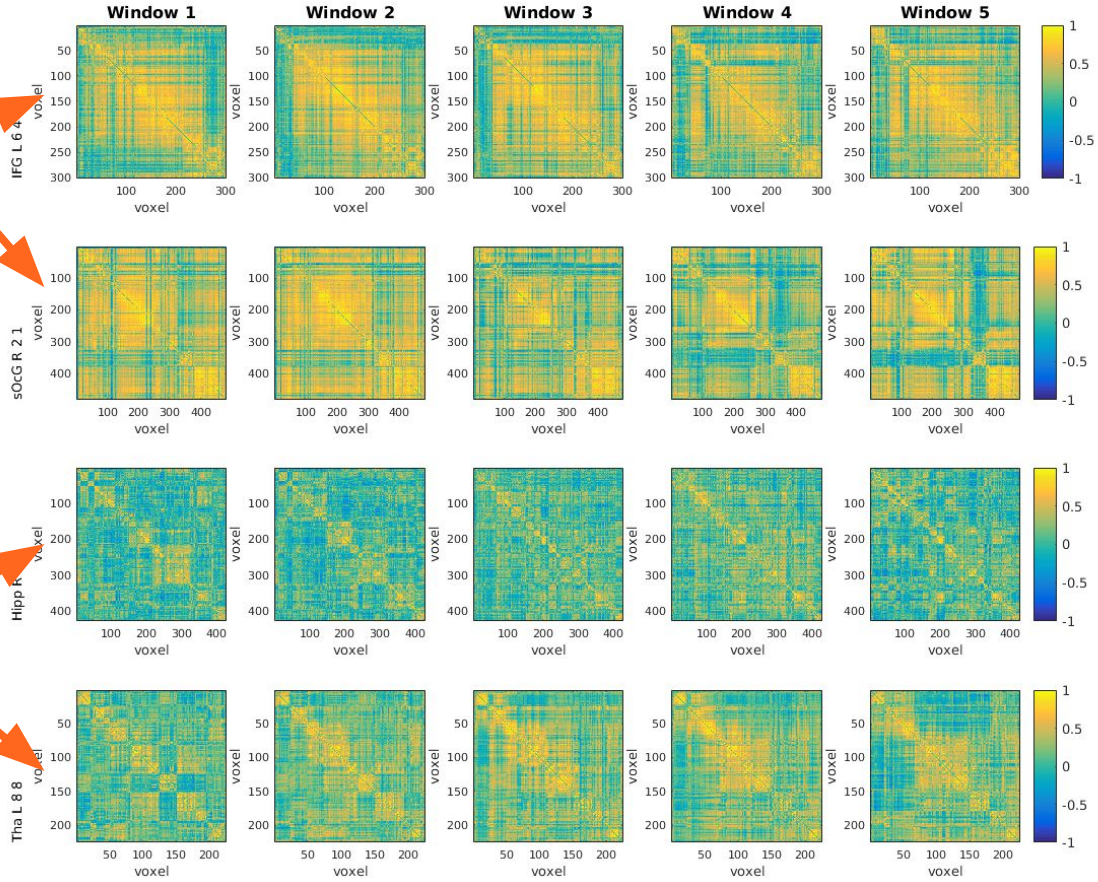
Lack of homogeneity

Perfect homogeneity

ROIs have rich internal connectivity structure

High spatial consistency

Low spatial consistency

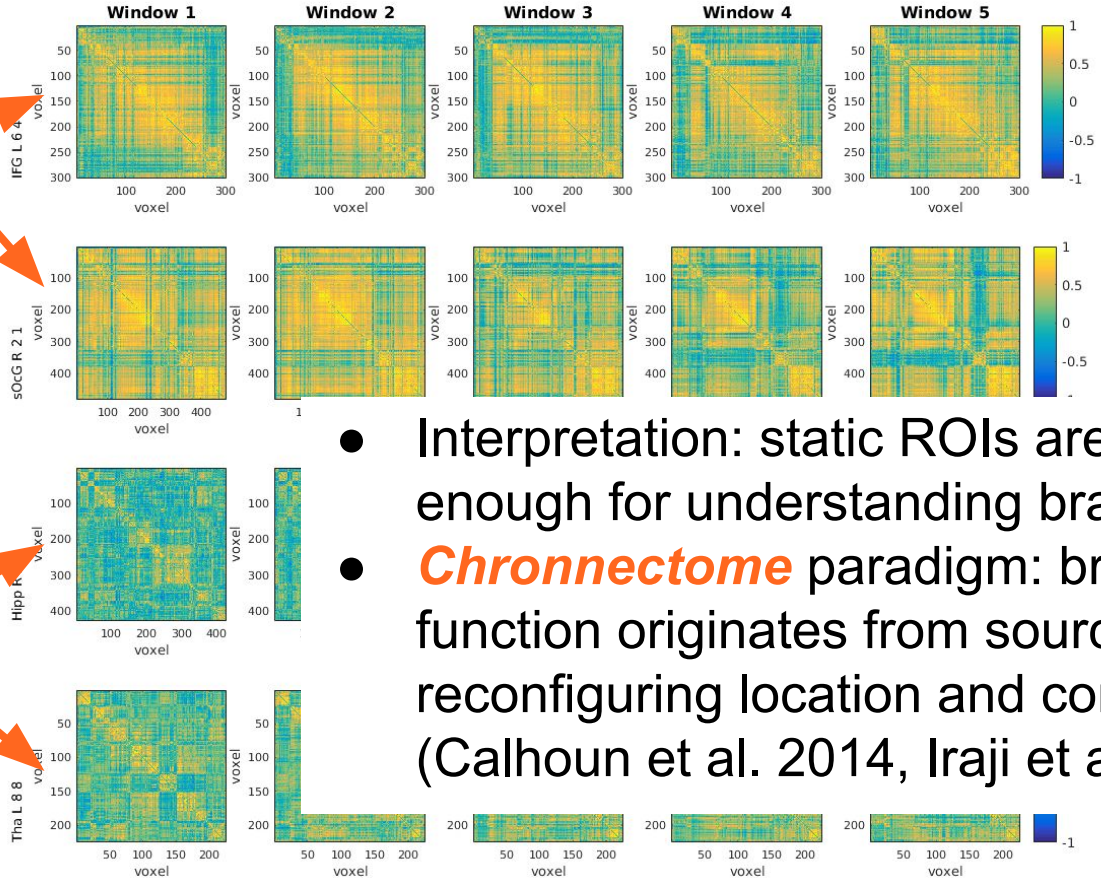


Ryyppö et al., 2018. *Network Neuroscience*

ROIs have rich internal connectivity structure

High spatial consistency

Low spatial consistency



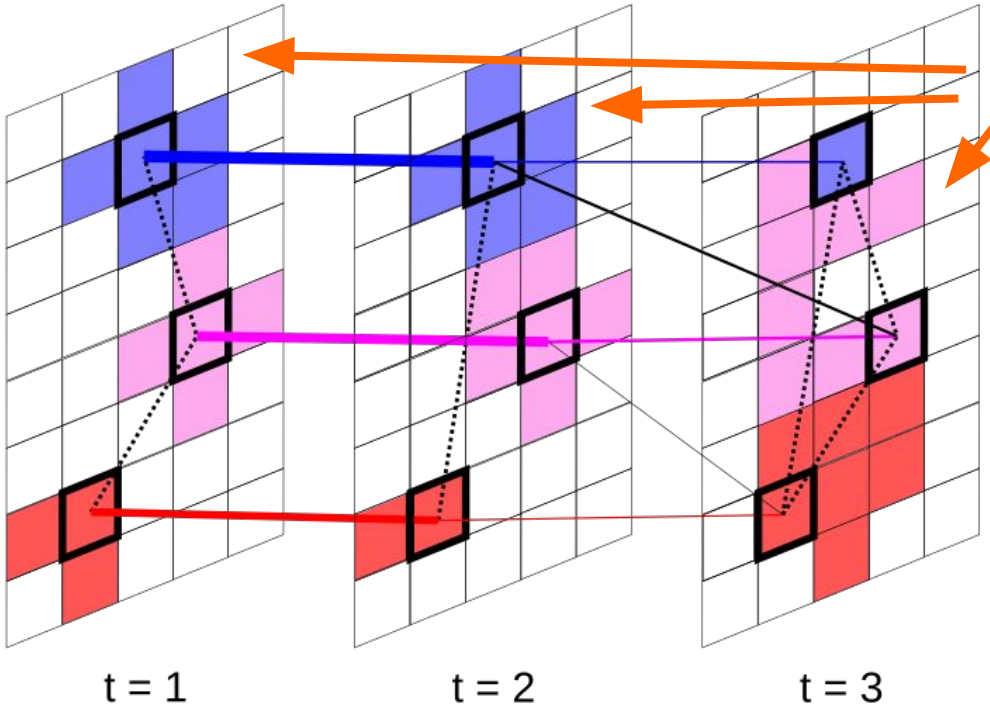
- Interpretation: static ROIs are not enough for understanding brain function
- ***Chronnectome*** paradigm: brain function originates from sources with reconfiguring location and connectivity (Calhoun et al. 2014, Iraji et al. 2019)

Ryyppö et al., 2018. *Network Neuroscience*

Node-reconfiguring multilayer network model

(Nurmi et al. 2025)

Based on ***multilayer networks*** (= different connections in the same network), for review: Kivelä et al. 2014



1. Layers = time windows

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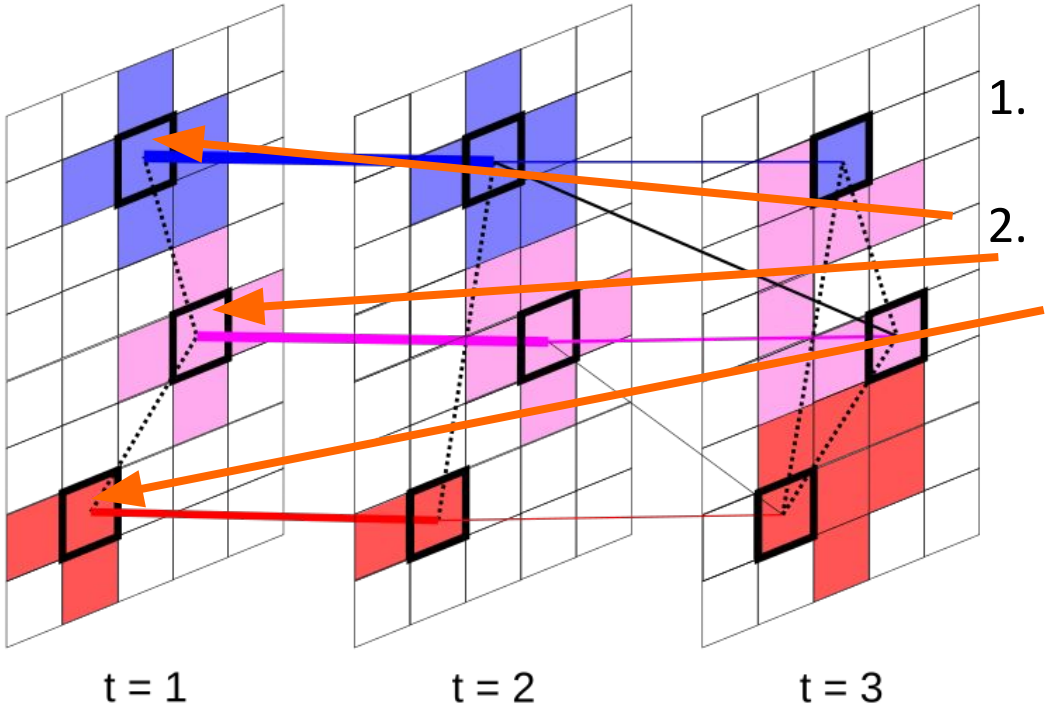

1. Layers = time windows
2. ROIs optimized inside layers for maximal homogeneity (voxel-level clustering)

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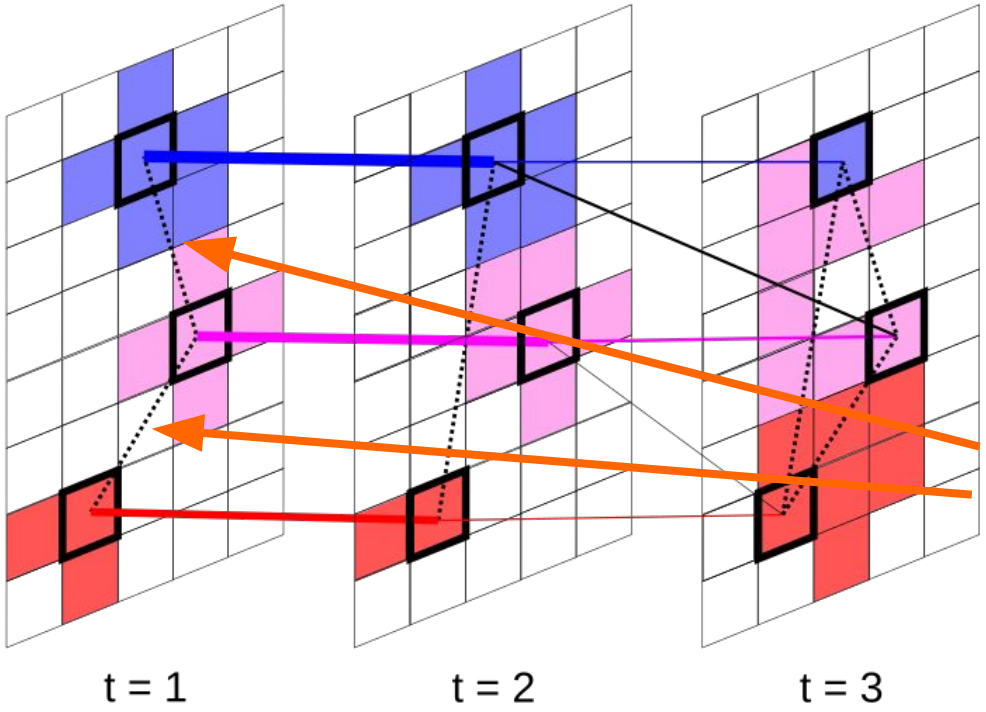

1. Layers = time windows
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3. Intralayer links = Pearson correlation

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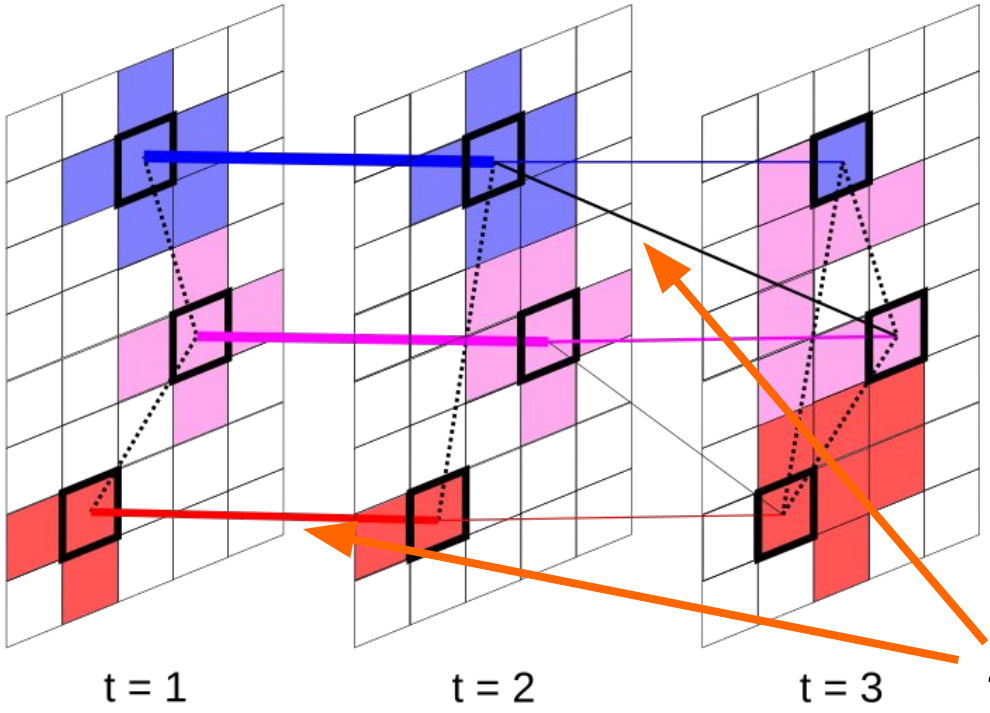
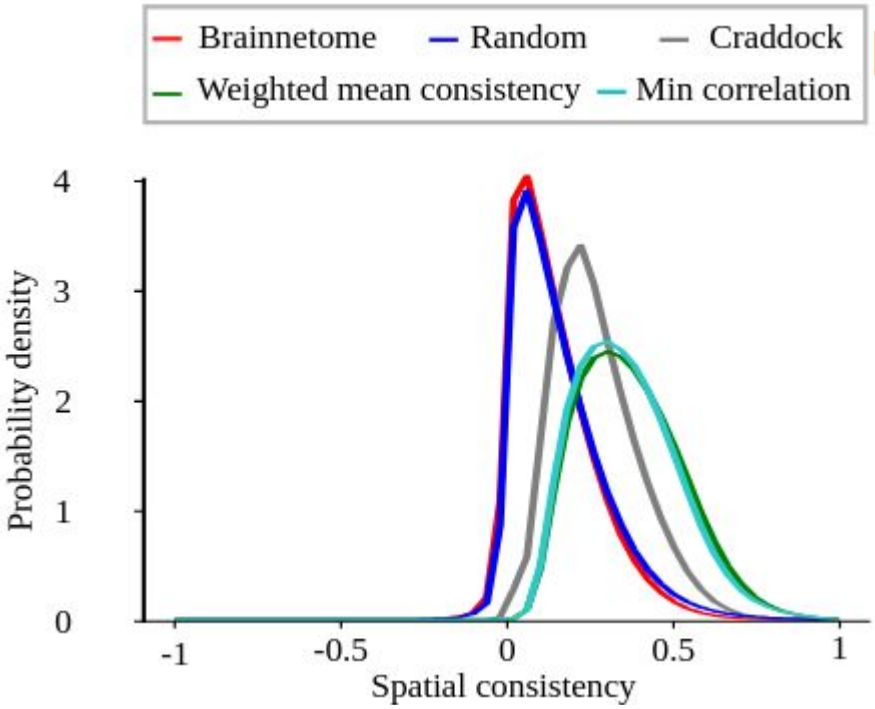


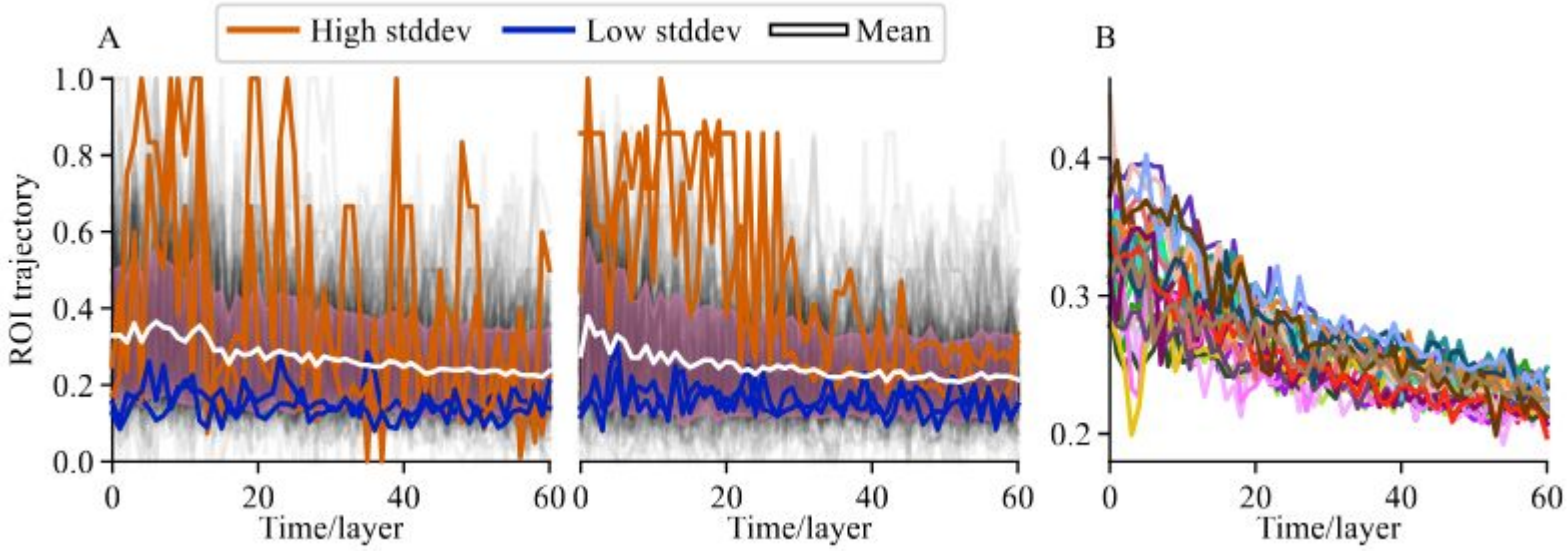
1. Layers = time windows
2. ROIs optimized inside layers for maximal homogeneity (voxel-level clustering)
3. Intralayer links = Pearson correlation
4. Interlayer links = spatial overlap

Node-reconfiguring multilayer network model

(Nurmi et al. 2025)



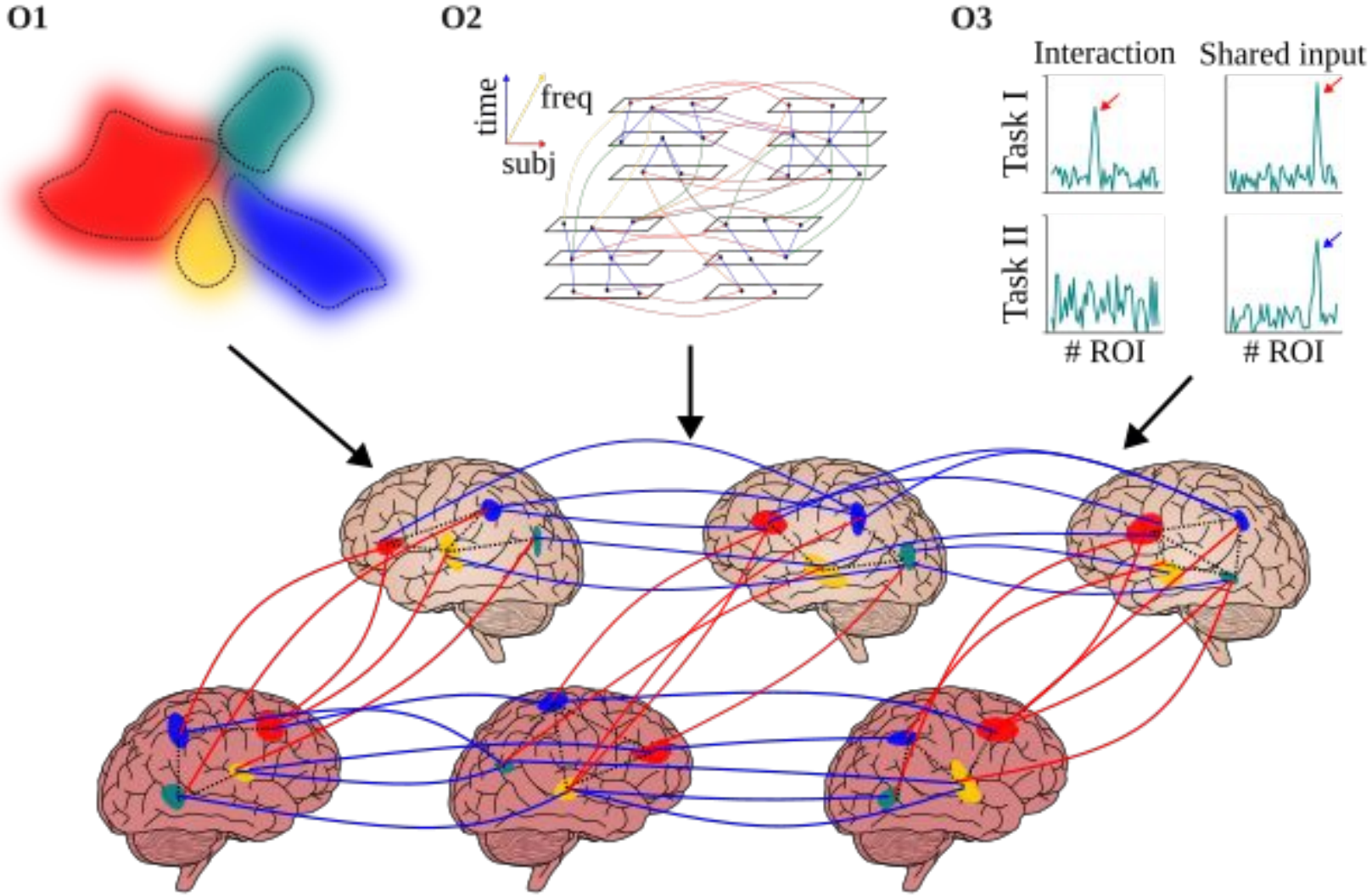
- Notably increases functional homogeneity of ROIs (measured as spatial consistency)
- Enables tracking changes in ROI boundaries (trajectory defined as Jaccard index between ROI members in consecutive windows)



Future work I: Optimized multilayer network model for interacting brains

- During social interaction, functional connectivity both within the brains of single subjects and as ***hyperconnectivity*** between interacting brains (Hari & Kujala 2009)
- ***Hyperscanning***: simultaneous functional neuroimaging of several (interacting) subjects (Czeszumski et al. 2020)
- Approaches based on magnetoencephalography (MEG) and electroencephalography (EEG) are particularly promising (Czeszumski et al. 2020)
- Problem: high complexity of data requires specially tailored tools

Future work I: Optimized multilayer network model for interacting brains



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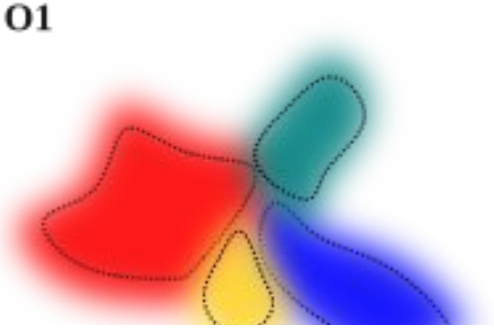
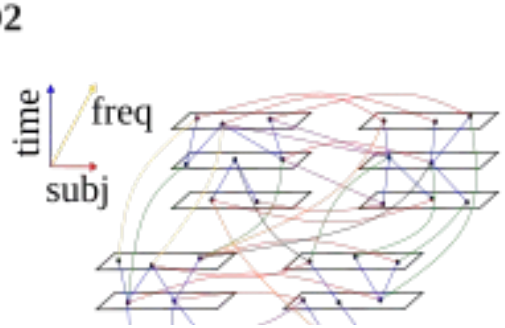
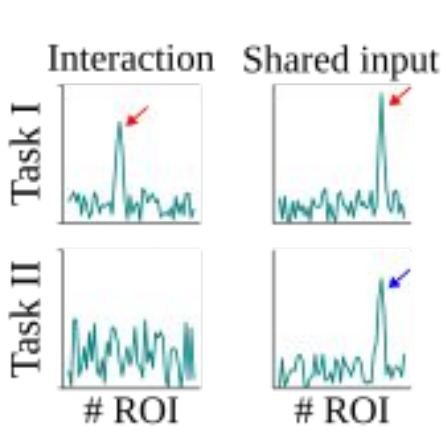
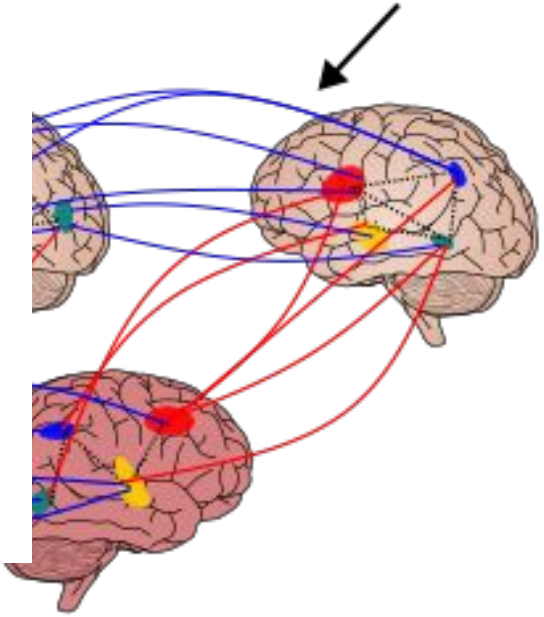




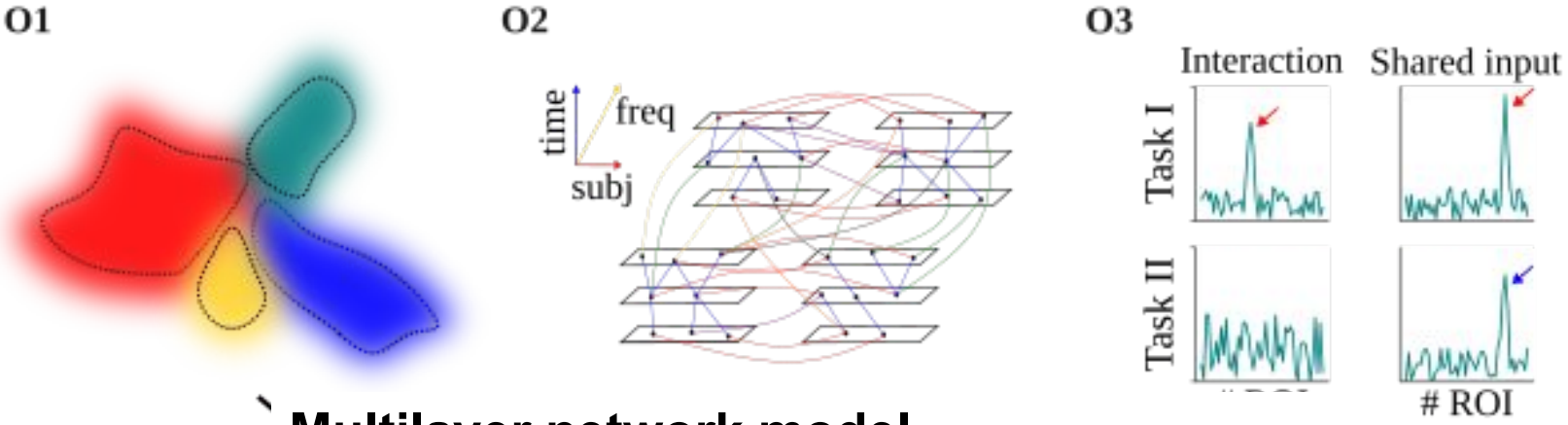


Node optimization

1. measurement-point level multiplex network (layers = time windows, nodes = measurement points, intralayer links = temporal similarity, interlayer links = identity)
2. clustering with Stochastic Block Models
3. model selection based on Minimum Description Length
4. Filtering to reduce signal leakage

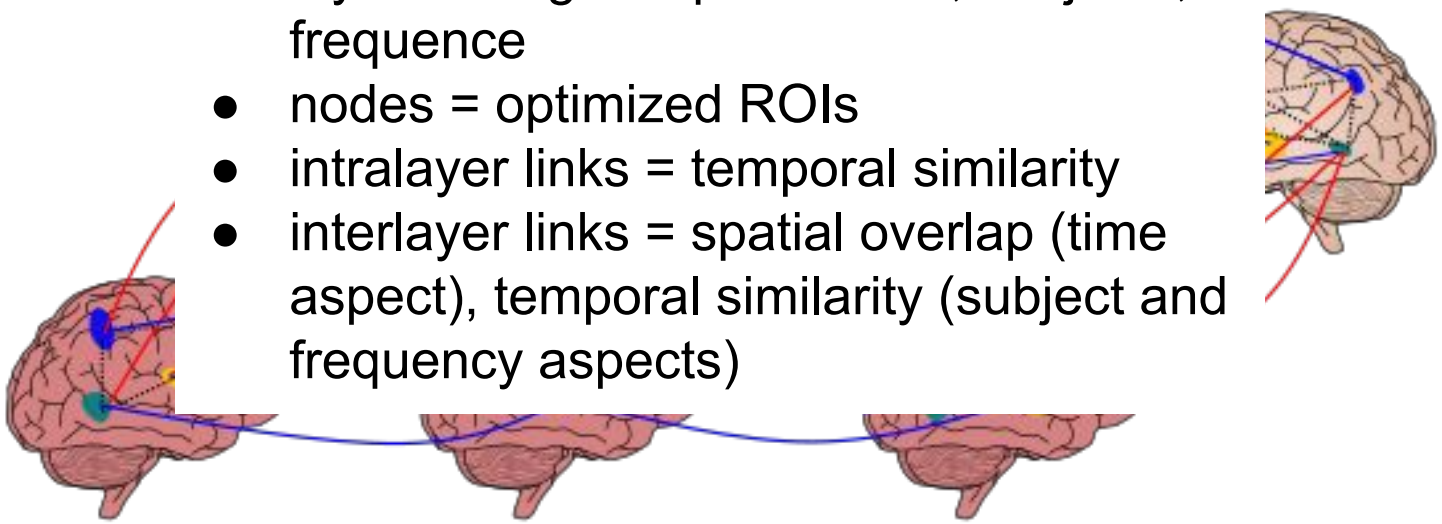


Future work I: Optimized multilayer network model for interacting brains



Multilayer network model

- layers along 3 aspects: time, subjects, frequence
- nodes = optimized ROIs
- intralayer links = temporal similarity
- interlayer links = spatial overlap (time aspect), temporal similarity (subject and frequency aspects)



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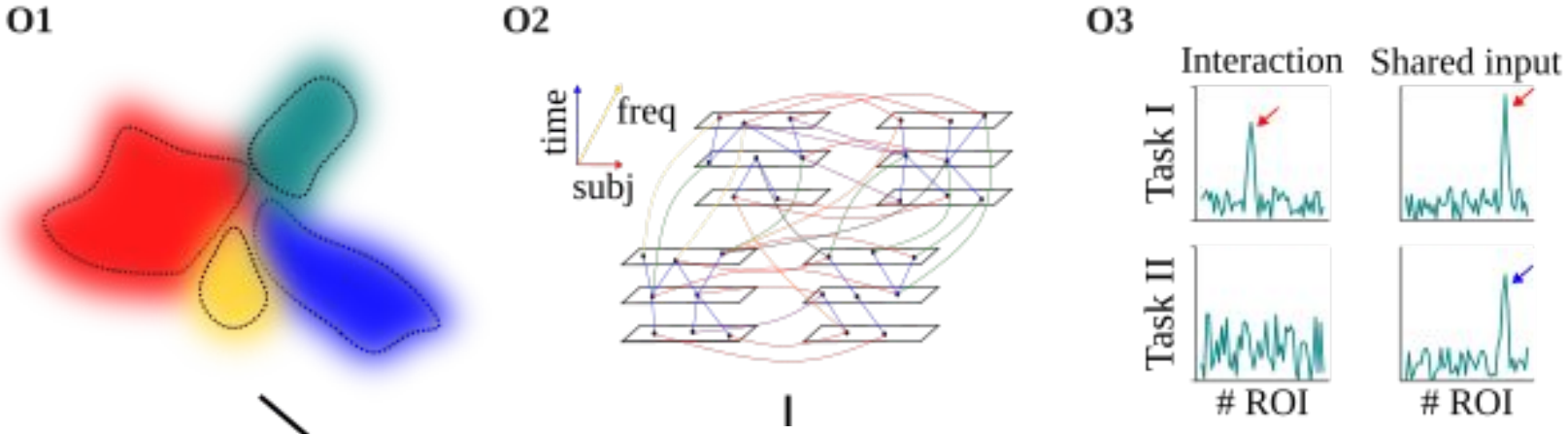
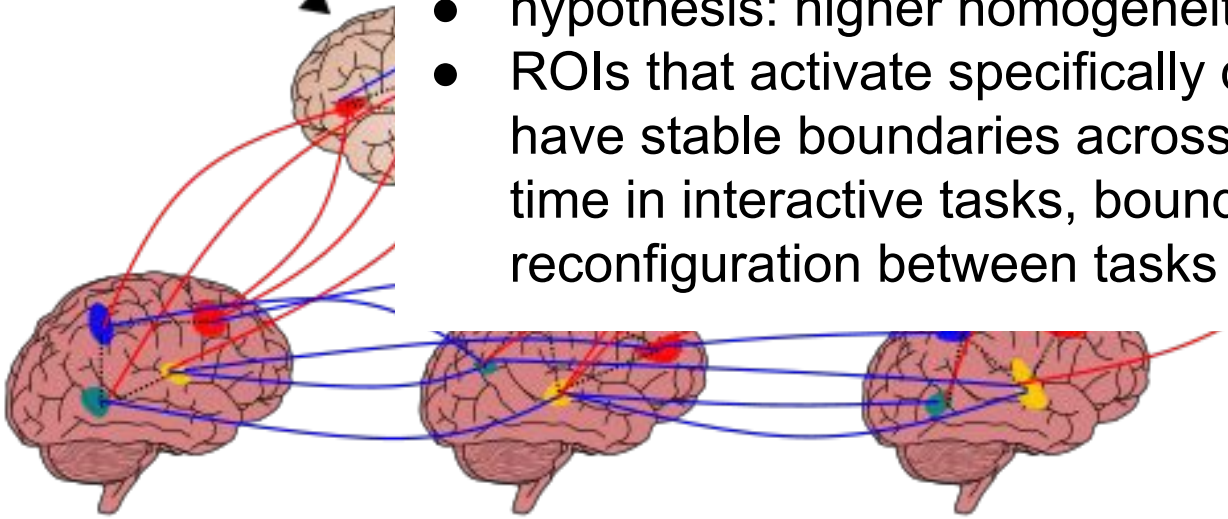


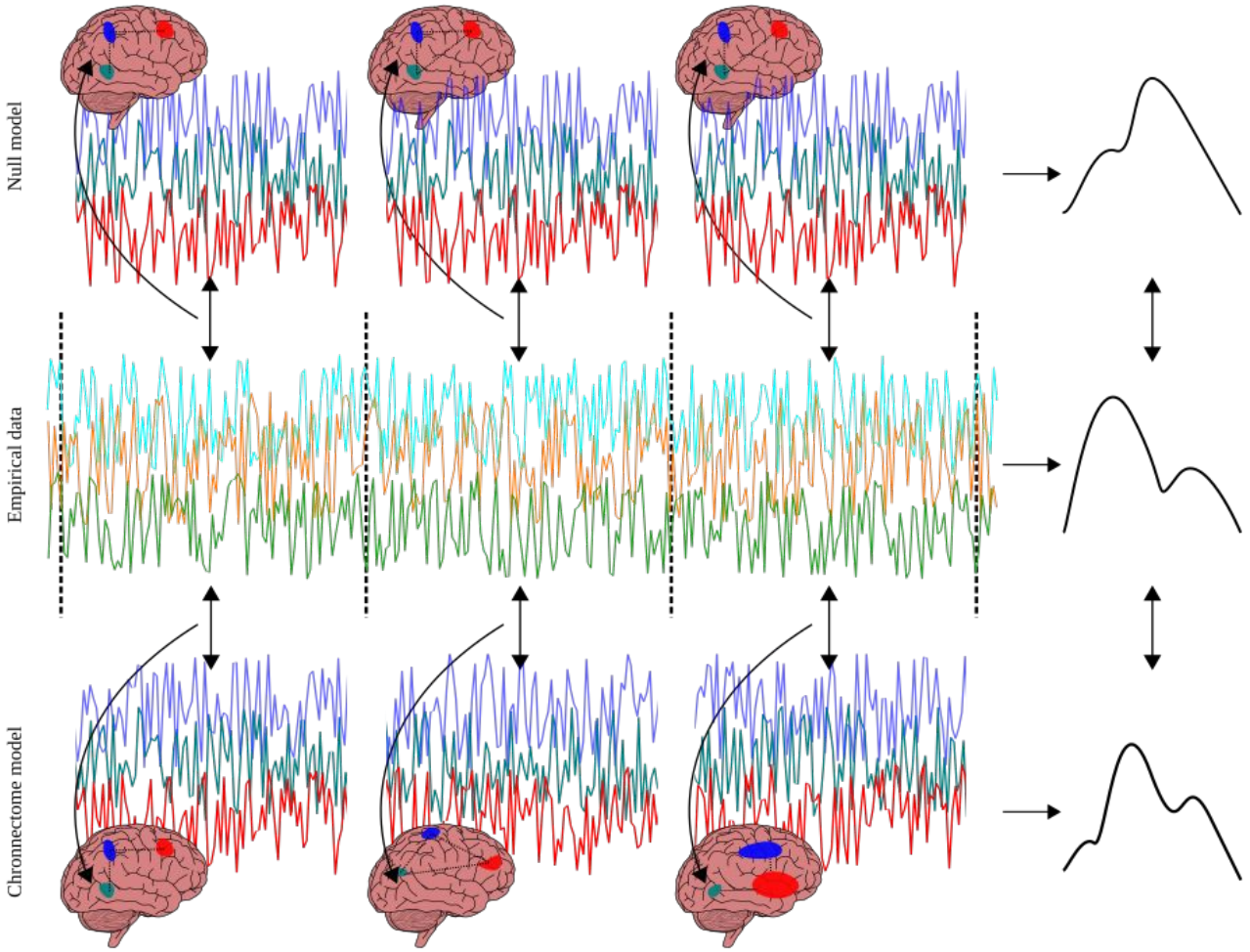
Detection of interaction-specific connectivity

- hypothesis: higher homogeneity in active ROIs
- ROIs that activate specifically due to interaction have stable boundaries across subjects and time in interactive tasks, boundary reconfiguration between tasks



Future work II: Testing the chronnectome hypothesis

The chronnectome hypothesis (brain function originates from reconfiguring sources) hasn't been tested against a null model



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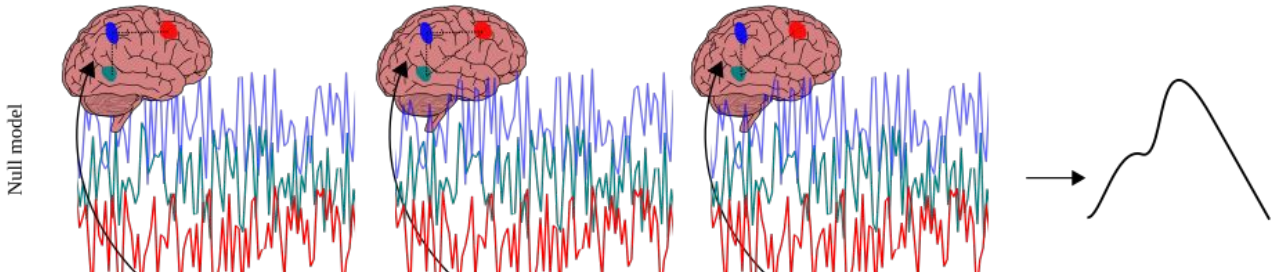
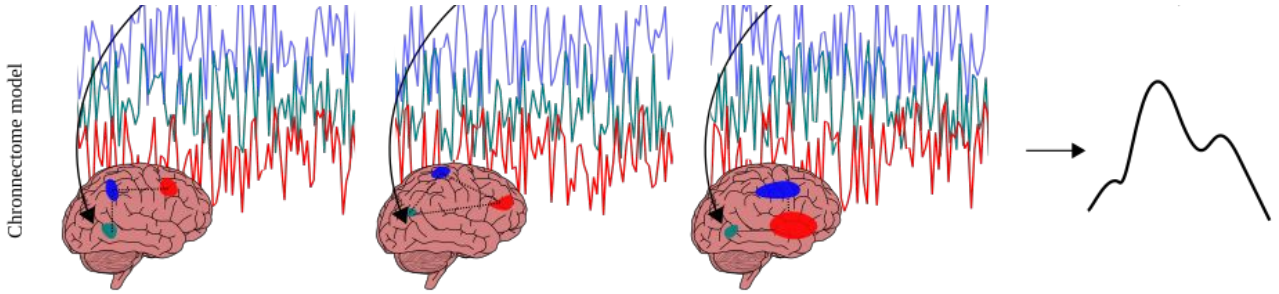
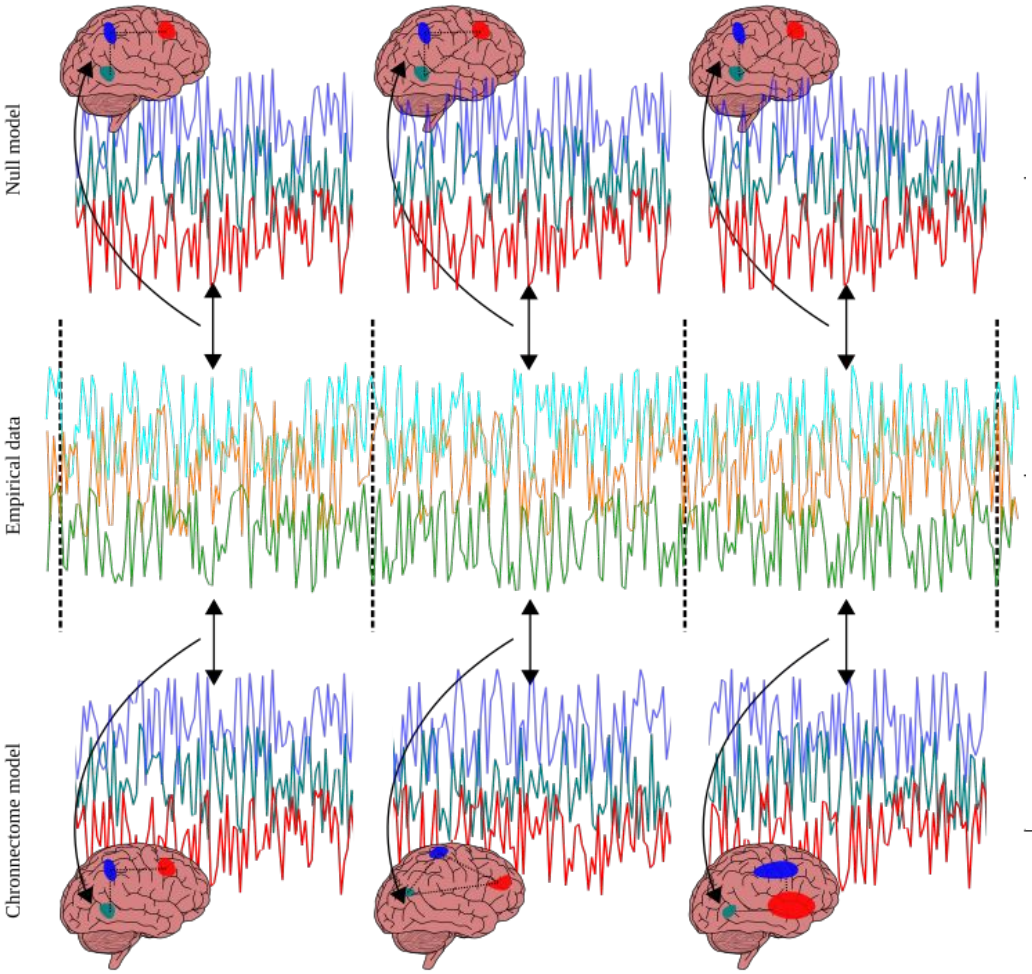


Data simulation

- null model: static ROIs, chronnectome model: reconfiguring ROIs
- time series (Morlet-filtered white noise) for each ROI
- measurement point time series: mixture of ROI time series and independent noise
- time-dependent ROI-level connectivity: correlated ROI time series



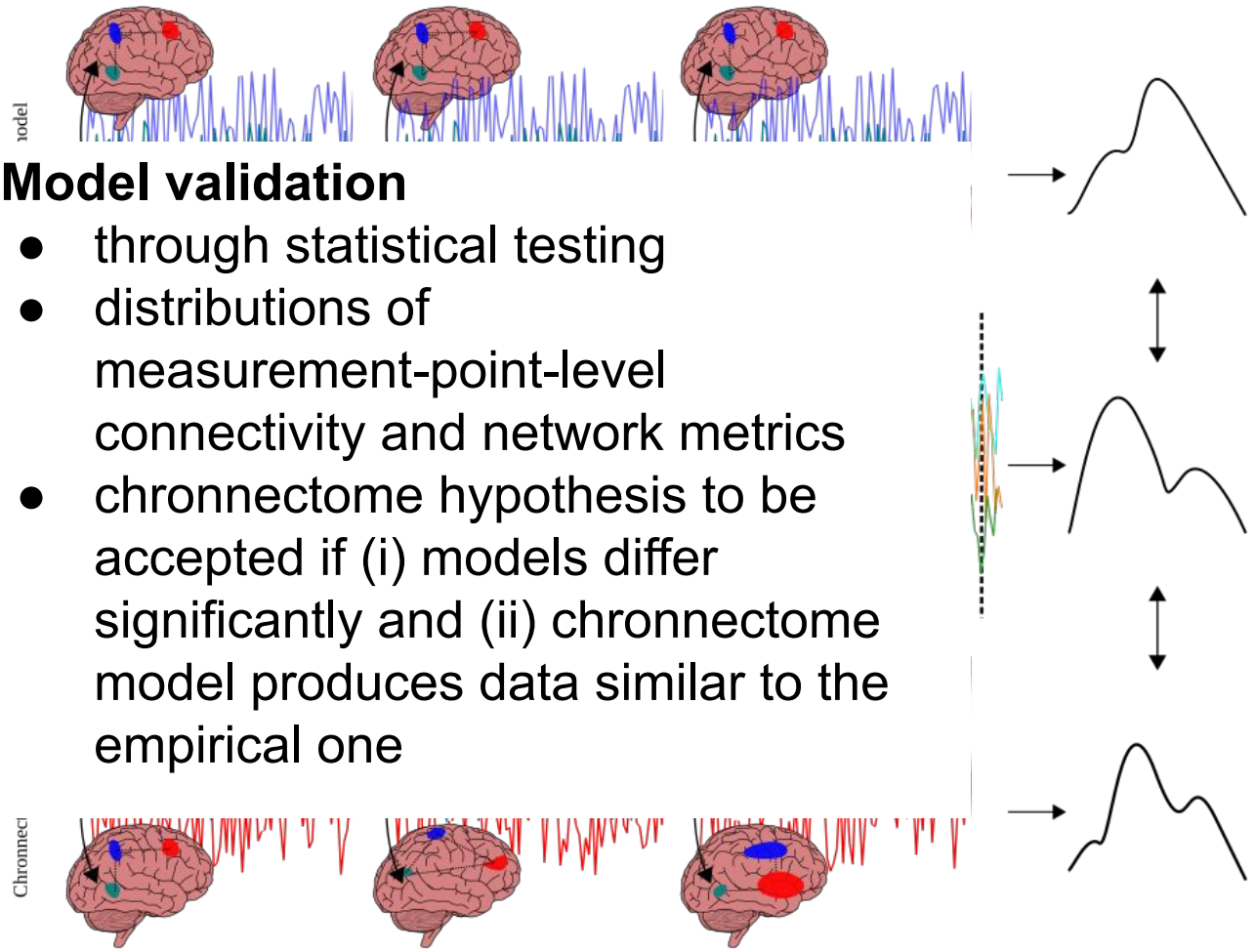
Research line II: Testing the chronnectome hypothesis



Parameter selection

- comparison with empirical data
- how? MDL?
- after model validation, enables inferring ROI boundaries and connectivity

Research line II: Testing the chronnectome hypothesis



Model validation

- through statistical testing
- distributions of measurement-point-level connectivity and network metrics
- chronnectome hypothesis to be accepted if (i) models differ significantly and (ii) chronnectome model produces data similar to the empirical one

Conclusions

- Network neuroscience = studying the brain with network tools
- Constructing functional brain networks is not trivial
  - Node definition?
  - Other factors: preprocessing, space, thresholding, link definition, interpretation of analysis outcomes?
  - **Know your methods (and questions)!**
- Currently used nodes functionally inhomogeneous
  - Internal connectivity structure of ROIs changes in time
  - **Time-dependent nodes needed**
- Possible (chronnectome-oriented) solutions
  - Node-reconfiguring multilayer model (for fMRI)
  - Optimized multilayer network model for interacting brains (for MEG)
  - Framework for testing the chronnectome hypothesis

References

Alakörkkö, T., Saarimäki, H., Glerean, E., Saramäki, J., & Korhonen, O. 2017. Effects of spatial smoothing on functional brain networks. *European Journal of Neuroscience* 46(9).

Bassett, D. S. & Sporns, O. 2017. Network Neuroscience. *Nature Neuroscience* 20(3).

Calhoun, V. D., Miller, R., Pearlson, G., & Adalı, T. 2014. The chronnectome: time-varying connectivity networks as the next frontier in fMRI data discovery. *Neuron* 84(2).

Czeszumski, A. Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., Schreiber, F., Rendon, Z. Z., & König, P. 2020. Hyperscanning: a valid method to study neural inter-brain underpinnings of social interaction. *Frontiers in Human Neuroscience*, 14.

Hari, R. & Kujala, M. V. 2009. Brain basis of human social interaction: from concepts to brain imaging. *Physiological Reviews* 89(2).

Iraji, A., Deramus, T. P., Lewis, N., Yaesoubi, M., Stephen, J. M., Erhardt, E., ... & Calhoun, V. D. 2019. The spatial chronnectome reveals a dynamic interplay between functional segregation and integration. *Human Brain Mapping* 40(10).

Kivelä, M., Arenas, A., Barthelemy, M., Gleeson, J. P., Moreno, Y., & Porter, M. A. 2014. Multilayer networks. *Journal of Complex Networks* 2(3).

Korhonen, O., Saarimäki, H., Glerean, E., Sams, M., & Saramäki, J. 2017. Consistency of Regions of Interest as nodes of fMRI functional brain networks. *Network Neuroscience* 1(3).

Korhonen, O., Zanin, M., Papo, D., 2021. Principles and open questions in functional brain network reconstruction. *Human Brain Mapping* 42(11).

Muldoon, S. F. & Bassett, D. S. 2016. Network and multilayer network approaches to understanding human brain dynamics. *Philosophy of Science* 82(5).

Nummenmaa, L., Saarimäki, H., Glerean, E., Gostopoulos, A., Jääskeläinen, I. P., Hari, R., & Sams, M. 2014. Emotional speech synchronizes brains across listeners and engages large-scale dynamic brain networks. *NeuroImage* 102.

Nurmi, T., De Luca, P., Hakonen, M., Kivelä, M., & Korhonen, O. 2025. Node-reconfiguring multilayer networks of human brain function. *ArXiv preprint*, arXiv-2410.

Ryyppö, E., Glerean, E., Brattico, E., Saramäki, J., & Korhonen, O. 2018. Regions of Interest as nodes of dynamic functional brain networks. *Network Neuroscience* 2(4).

Wang, J., Wang, L., Zang, Y., Yang, H., Tang, H., Gong, Q., … He, Y. 2009. Parcellation-dependent small-world brain functional networks: A resting-state fMRI study. *Human Brain Mapping* 30(5).

Thank you!

Questions, comments?

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Slides:
https://github.com/onerva-korhonen/presentations/blob/master/hds_271025.pdf