Master's Thesis Defense

Simulation of Brain Functional and Structural Connectivity on Empirical and Randomized Complex Networks

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Nachwuchsgruppe, *Nonlinear Dynamics and Control in Neuroscience*

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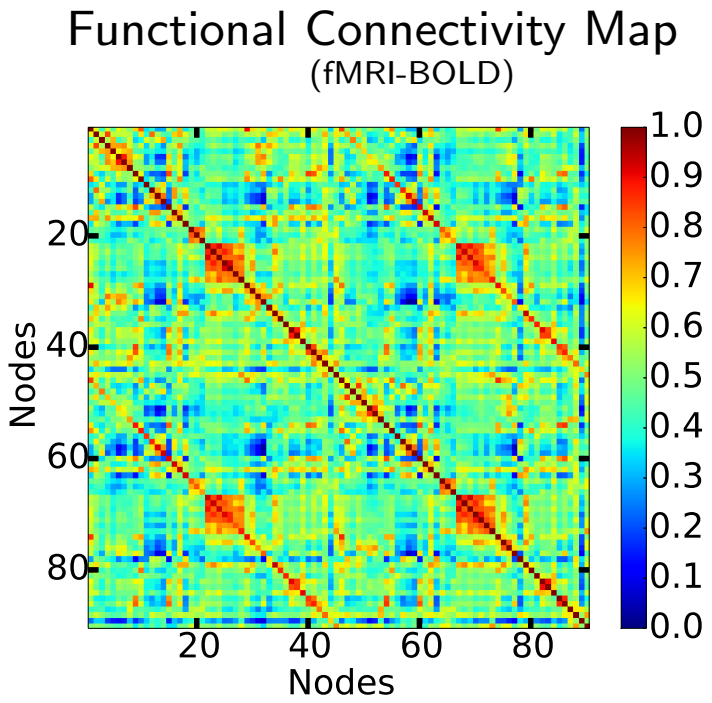
Motivation

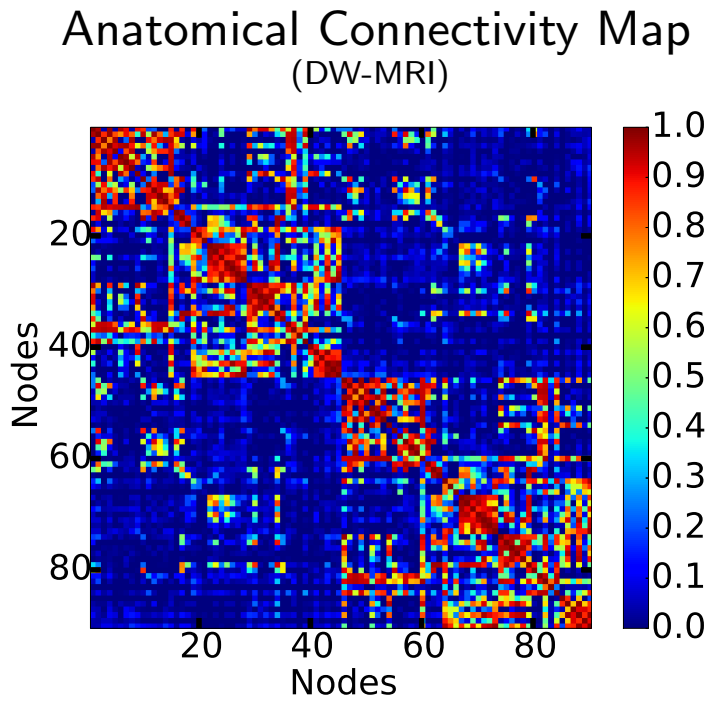
- *i)How does functionally correlated behavior arise from structural connectivity?*
- *ii)What is characteristic for the brain network? Does it differ from random graphs ?*
- resting-state
- Experimental results combined with modeling approaches
- Graph theory / network science, nonlinear dynamics, computational neuroscience

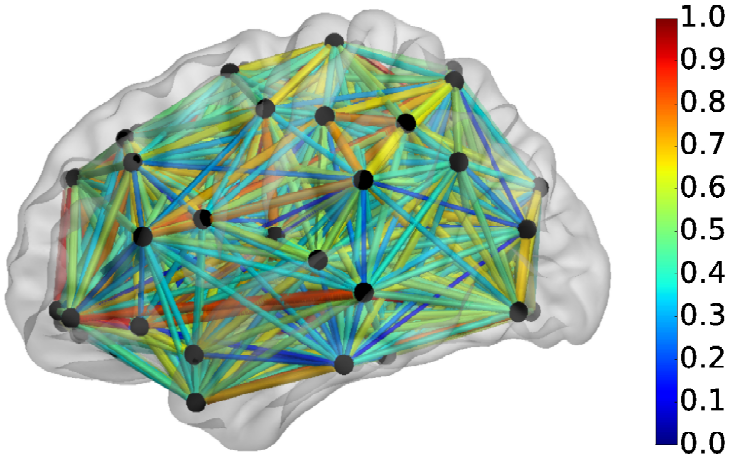
Outline

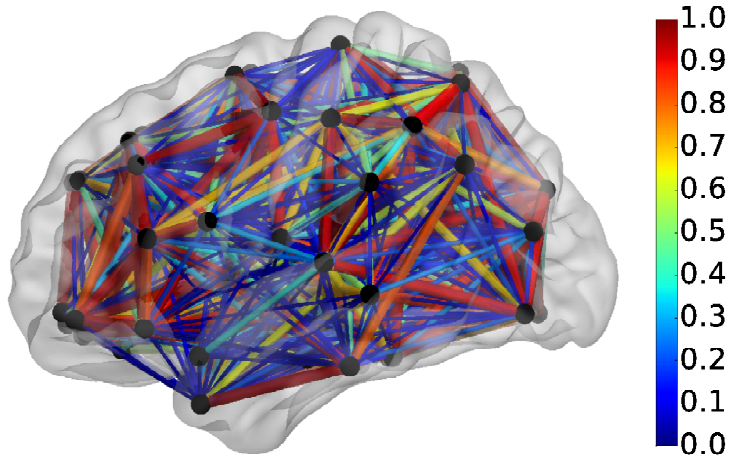
1. Empirical Data
2. The Brain Graph
3. Randomization Methods
4. Network Characterizations
5. Neuronal Activity Model *(FitzHugh-Nagumo Oscillators [1, 2])*
6. BOLD Activity Model *(Balloon-Windkessel Hemodynamic Model [3])*
7. Results
8. Future Directions
9. Discussion

1.Empirical Data

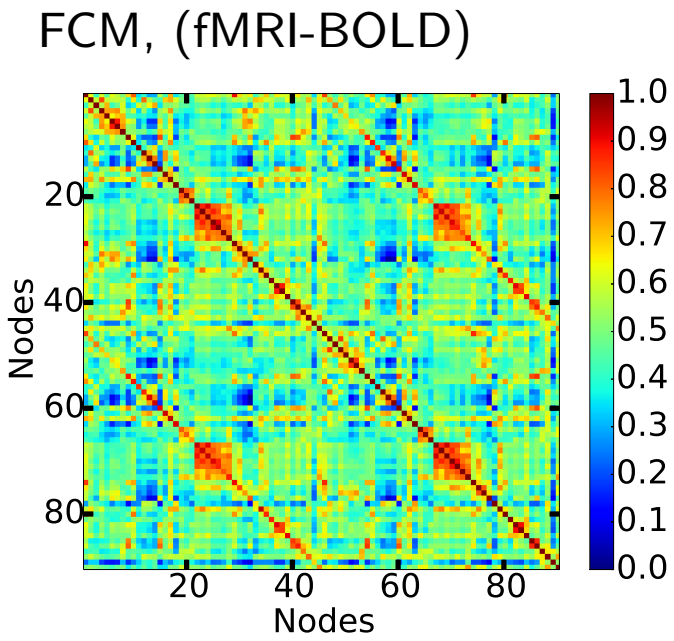


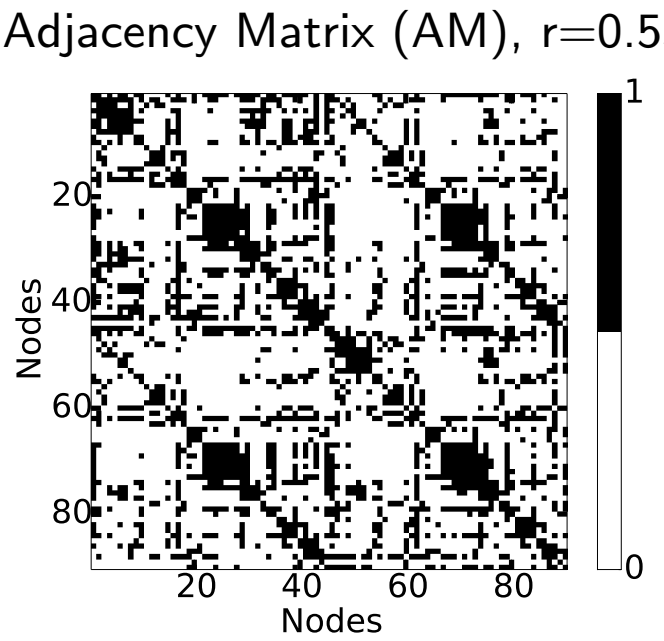


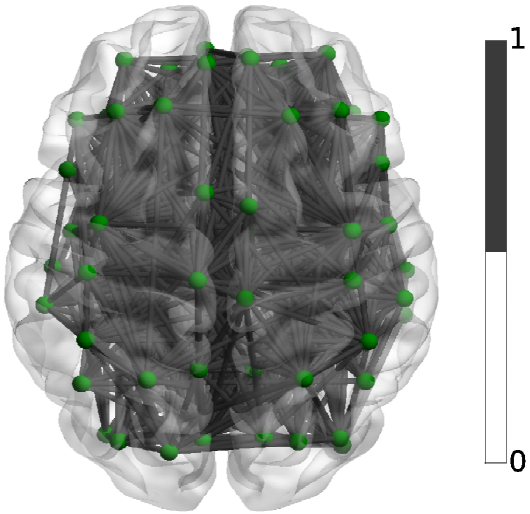




2.The Brain Graph







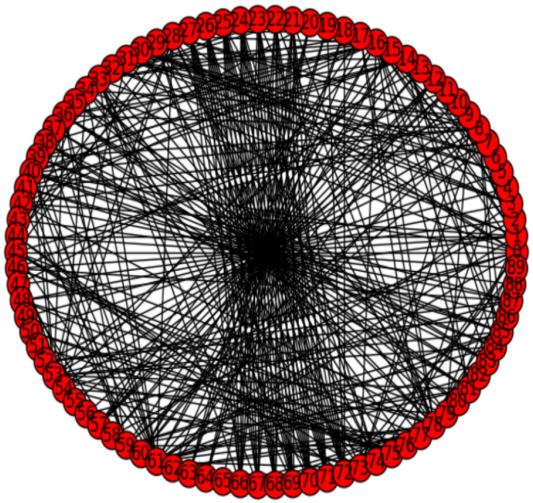
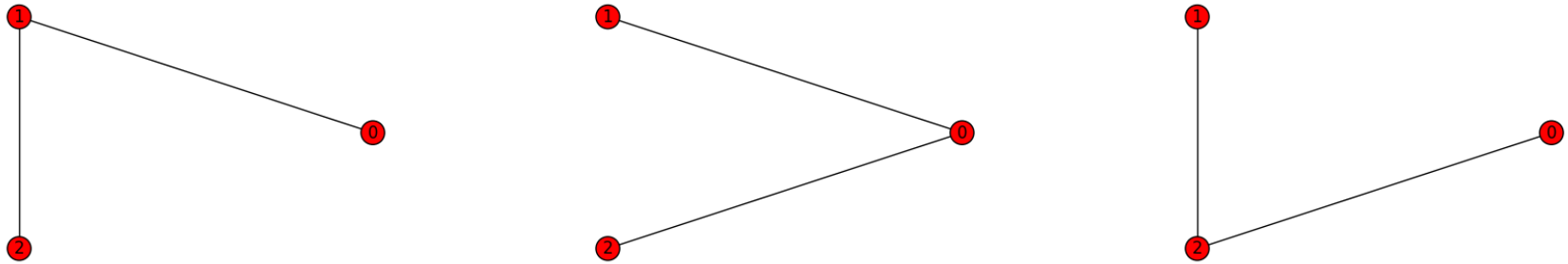


Table : Abbreviations for the brain graph and the randomly constructed graphs

Abbreviation	Description	method
R_{BG}	the brain graph	NetworkX [4]
R_{ER}	Erdős-Rényi, G(N,L)	NetworkX[4]
R_{DES}	double-edge-swap	NetworkX[4]
R_{PDD}	preserved-degree-distribution	BCT [5]
R_{CM}	configuration model	NetworkX[4]
R_{PR}	partial randomization	BCT[5]

3.The Randomization Methods

R_{ER}, Erdős-Rényi-Type Randomization [6], $G(N, L)$
(P : a binomial distribution for number of edges per node)



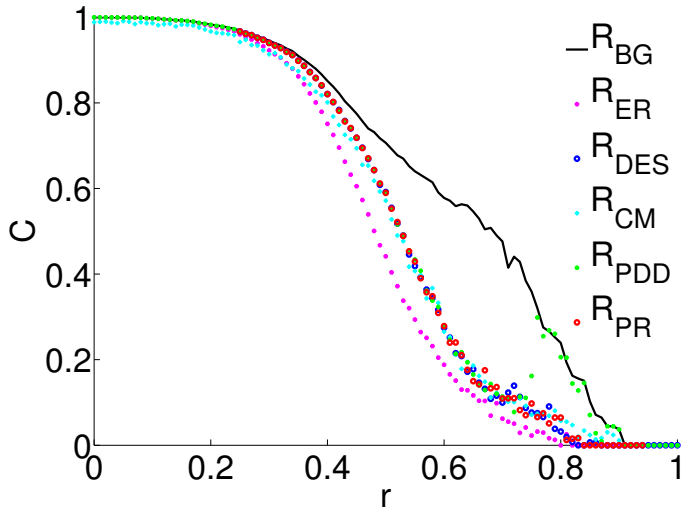
$L = \binom{N}{2} P$

Table : Statistical measures to characterize networks

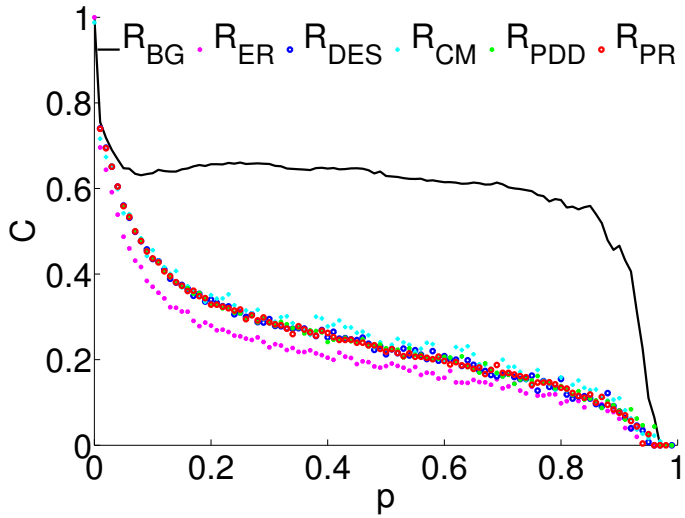
Network Measures
Network Density, κ
Average Clustering Coefficient, C
Transitivity, T
Connected Components
Small-Worldness, S
Global and Local Efficiency, E and E_{loc}
Degree Distribution, $p(k)$

Average Clustering Coefficient, $C = \frac{1}{n}\sum_{i\epsilon N} C_i = \frac{1}{n}\sum_{i\epsilon N} \frac{2t_i}{k_i(k_i-1)}$

FCM related graphs



ACM related graphs

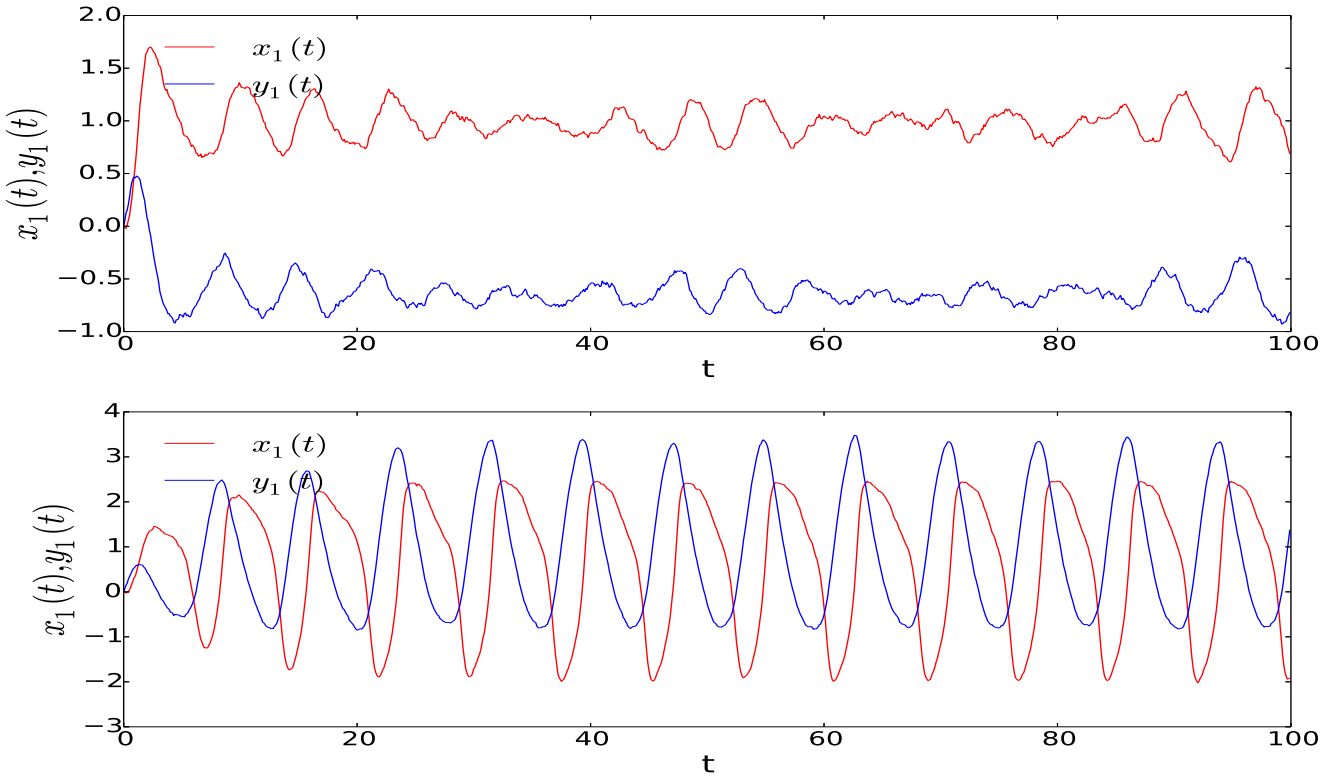


5.Neuronal Activity Model

FitzHugh-Nagumo Oscillations, Network Dynamics [7,8]

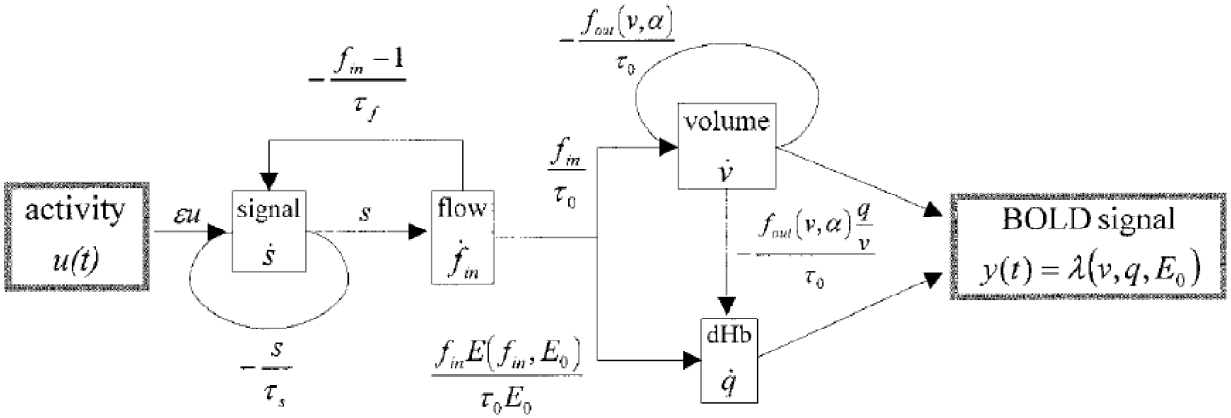
$$\dot{x}_i = \tau\left(y_i + \gamma x_i - \frac{x_i^3}{3}\right) - c\sum_{j=1}^{N} a_{ij}x_j(t - \Delta t_{ij}) + Dn_x \tag{1a}$$

$$\dot{y}_i = -\frac{1}{\tau}(x_i - \alpha + by_i) + Dn_y, \tag{1b}$$



6.BOLD Activity Model

Balloon-Windkessel Hemodynamic Model [3]



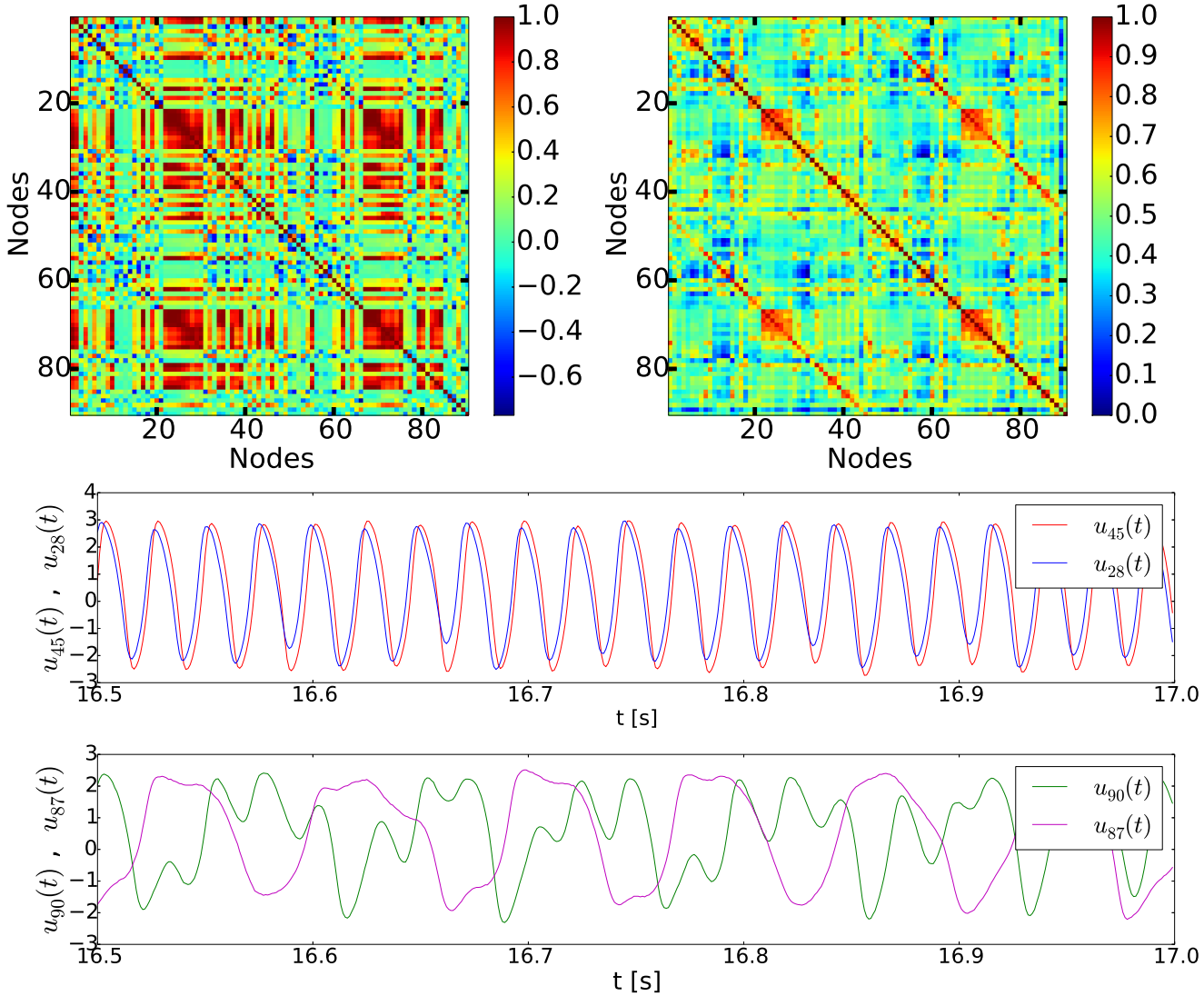
- neuronal activity $\Rightarrow$ regional changes in surrounding
- CBV, CBF, O_2-level, *Hb* and *dHB* level in capillaries
- Friston et. al.: mediating between non-linear time-series and BOLD activity

7.Results

Parameter Analysis

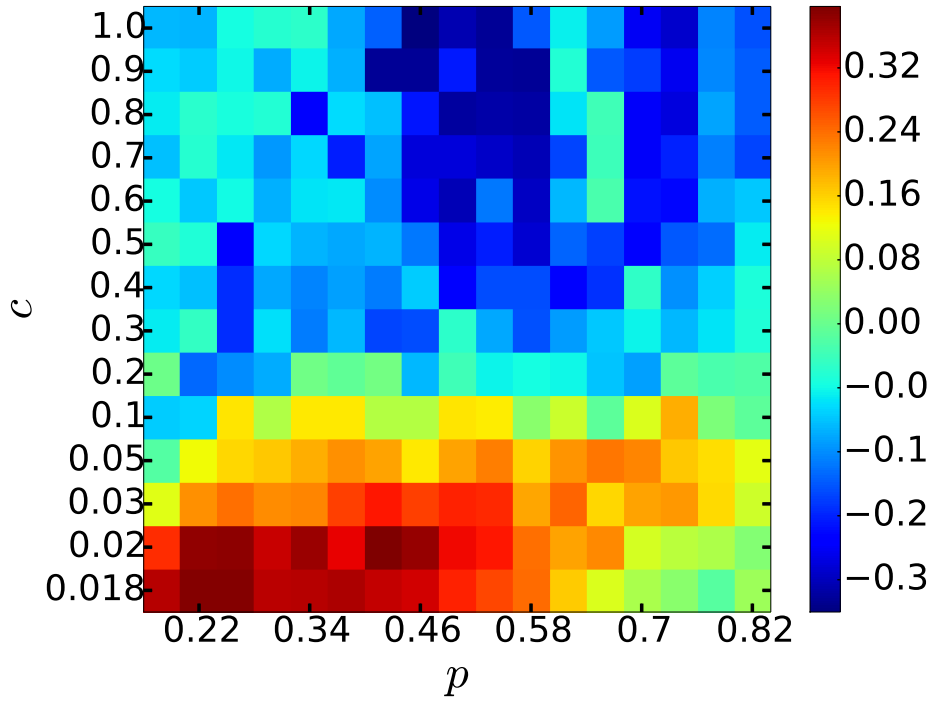
- c, the coupling strength (FHN network model)
- v, the axonal propagation velocity, $\Delta t_{ij} = d_{ij}/v$ (FHN network model)
- r or p, threshold or probability (network topology)

Neuronal Activity Simulations of FCM Related Brain Graphs to fMRI-BOLD Data



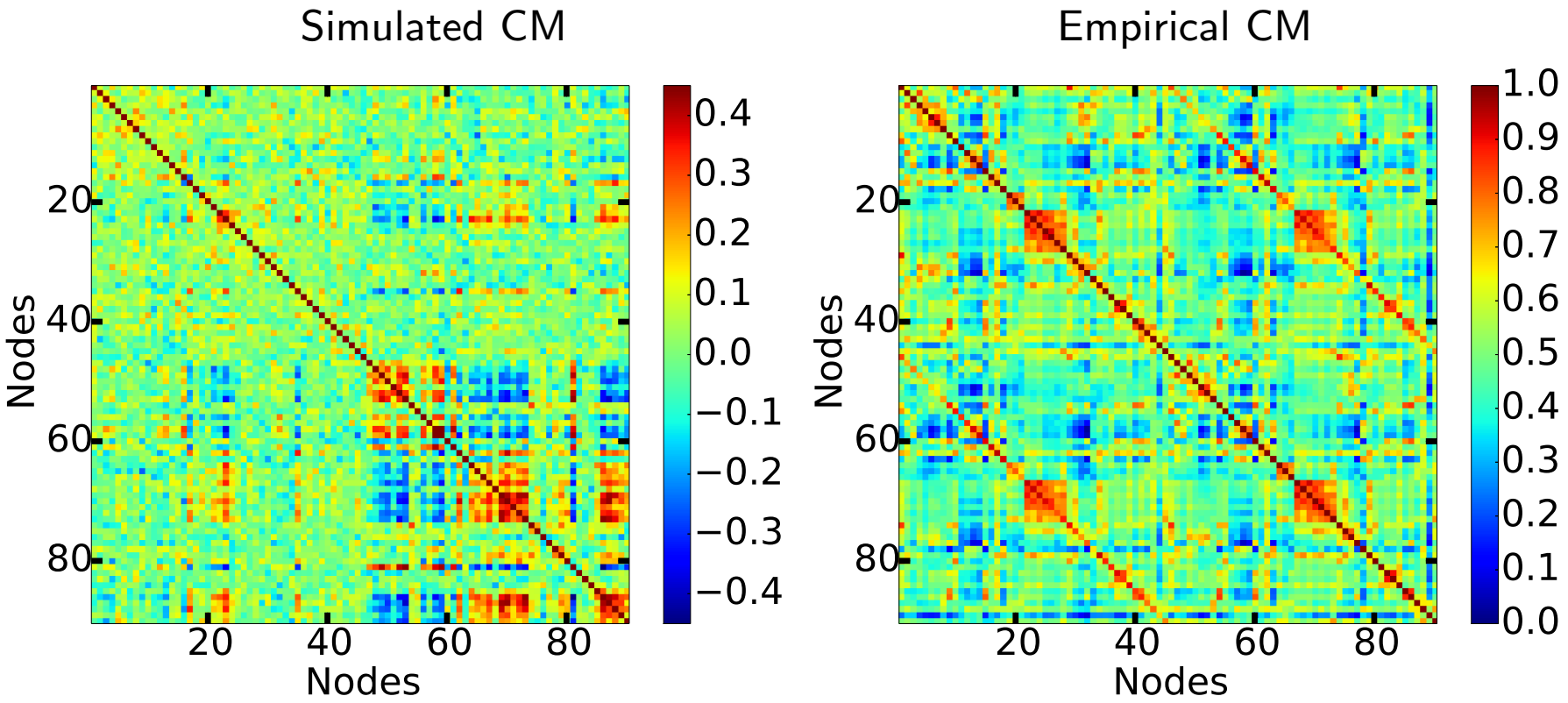
$c = 0.2, \quad v = 7m/s, \quad r = 0.60, \quad \rho_{e,s} = 0.43, \quad \rho_{45,28} = 0.88, \quad \rho_{90,87} = 0.13$

Comparing BOLD Simulations of Anatomical Brain Graphs to fMRI-BOLD Data



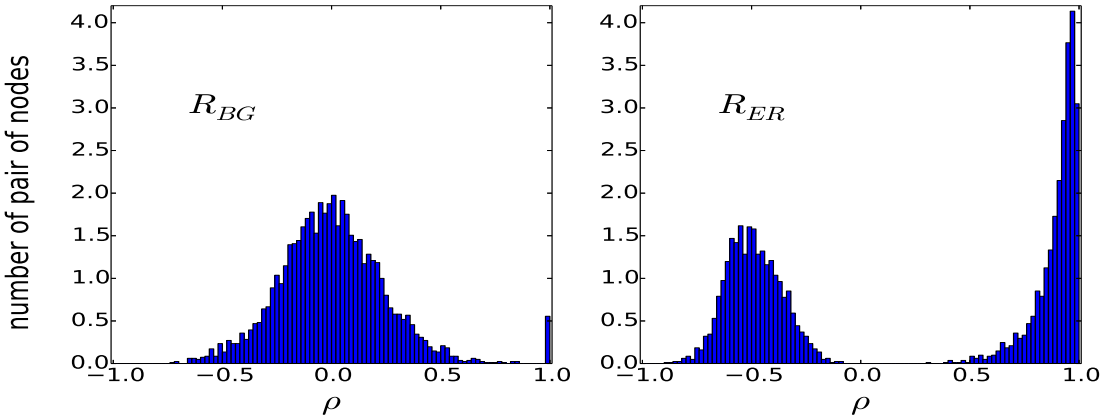
$v = 3m/s$

Comparing BOLD Simulations of Anatomical Brain Graphs to fMRI-BOLD Data

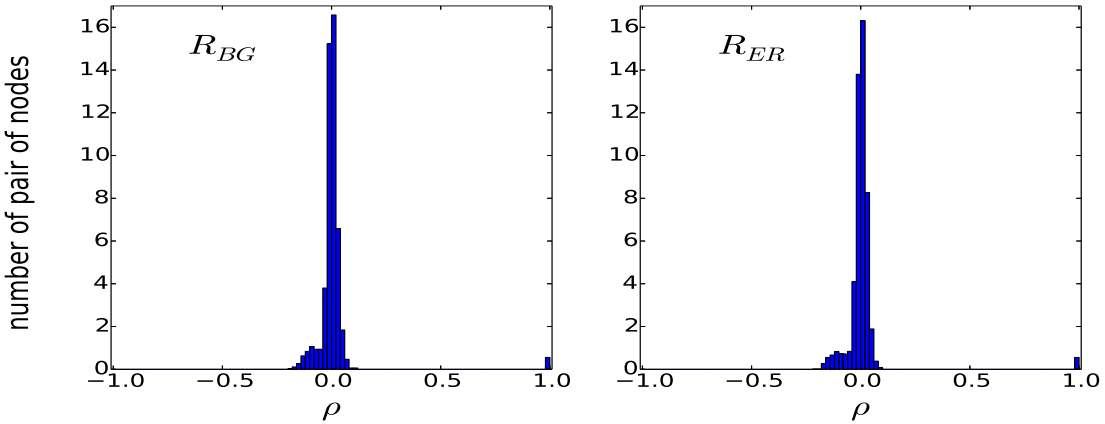


$c = 0.03, \quad v = 3m/s, \quad p = 0.54, \quad \rho_{e,s} = 0.22$

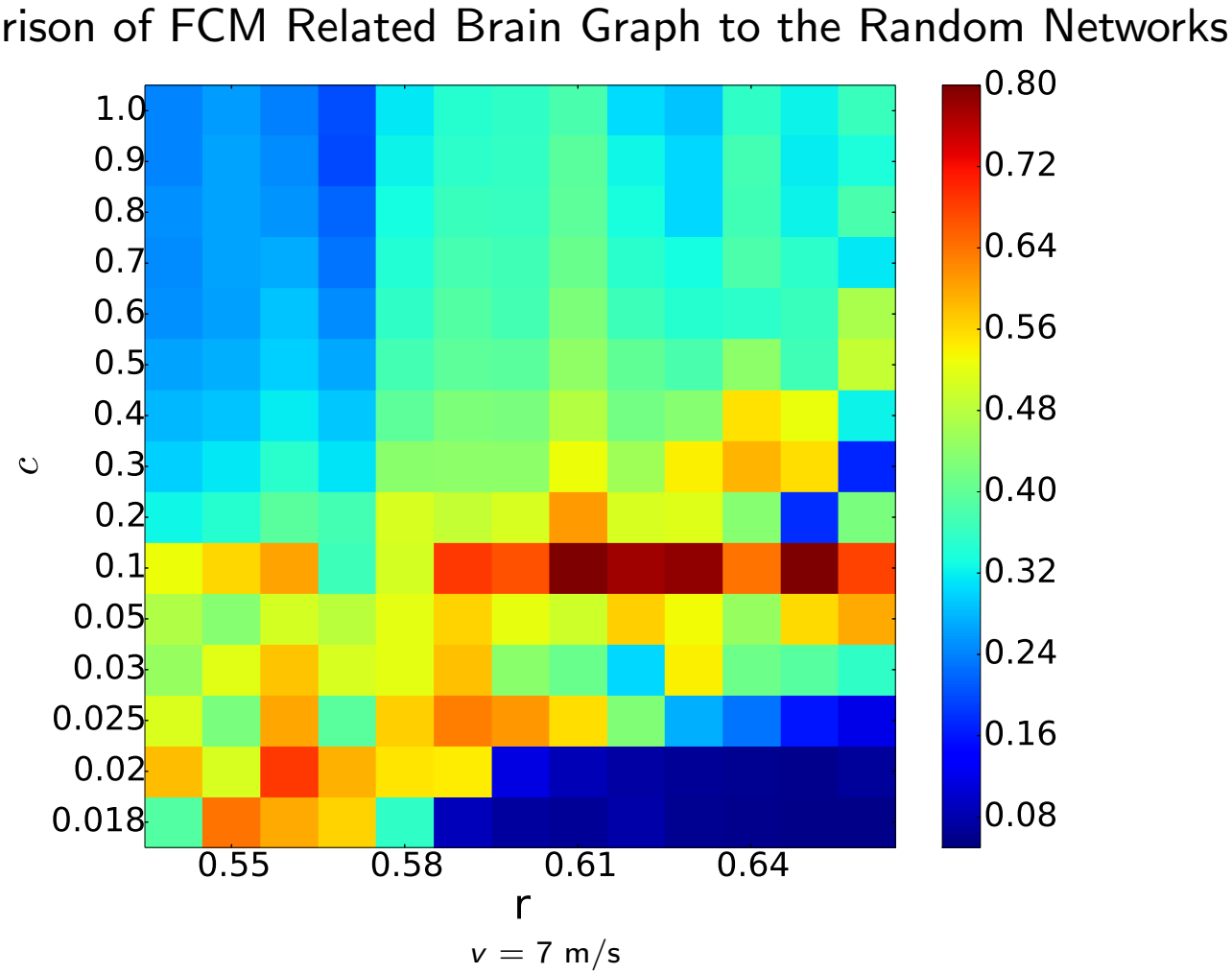
Comparison of FCM Related Brain Graph to the Random Networks



$r = 0.61, \quad c = 0.1, \quad v = 7$ m/s



$r = 0.60, \quad c = 0.018, \quad v = 7$ m/s


Comparison of FCM Related Brain Graph to the Random Networks
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0.03
0.025
0.02
0.018
c
0.55
0.58
0.61
0.64
r
0.80
0.72
0.64
0.56
0.48
0.40
0.32
0.24
0.16
0.08
v = 7 m/s

8.Future Directions

- ... low coupling strengths ?
- ... comparison of temporal BOLD activities of R_{BG} and R_{ER} ?

Thanks

Dr. Philipp Hövel[1]

Dr. Vesna Vuksanović[1]

Prof. Jochen Braun[2]

[1] TU Berlin, Institut für Theoretische Physik, BCCN-Nachwuchsgruppe: Nonlinear Dynamics and Control in Neuroscience
[2] OVGU Magdeburg, Institute of Biology, Faculty of Science, Cognitive Biology Group

References

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2 FitzHugh, R. 1961.Impulses and physiological states in theoretical models of nerve membrane, *Biophys. J.*, 1:445–466

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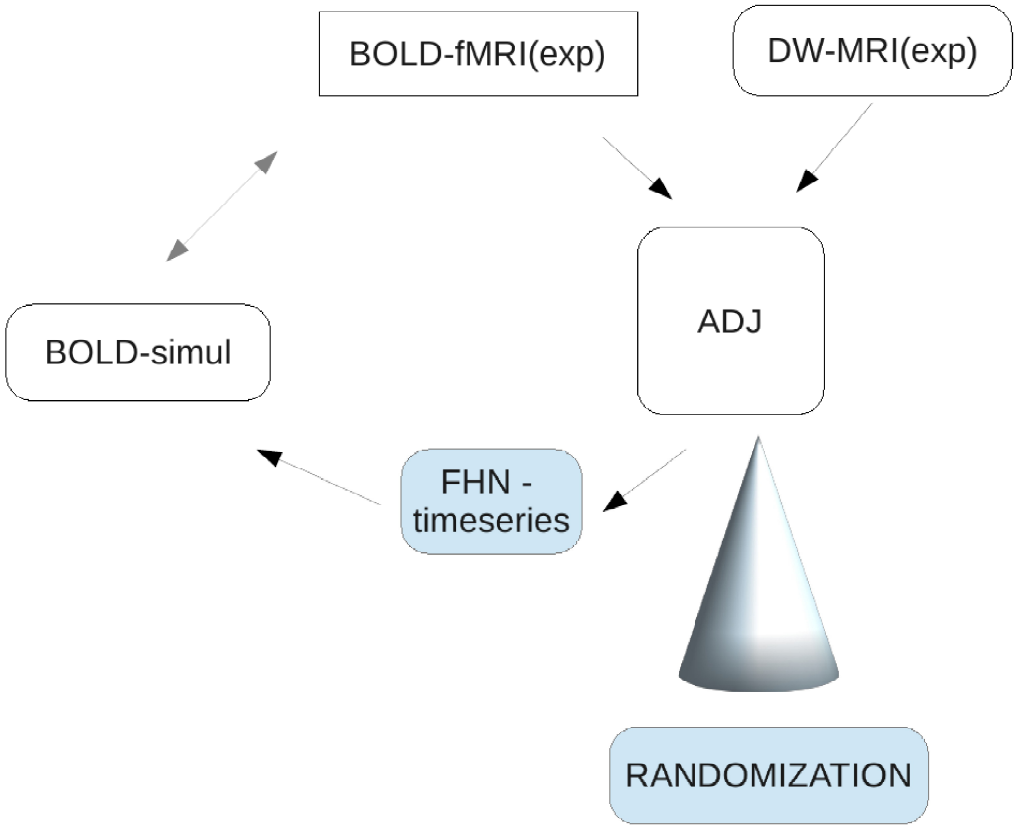
8 Ghosh, A. and Rho, Y. and McIntosh, A. R. and Kötter, R. and Jirsa, V. K. 2008. Cortical network dynamics with time delays reveals functional connectivity in the resting brain, 2:115–120

9.Discussion

Appendix

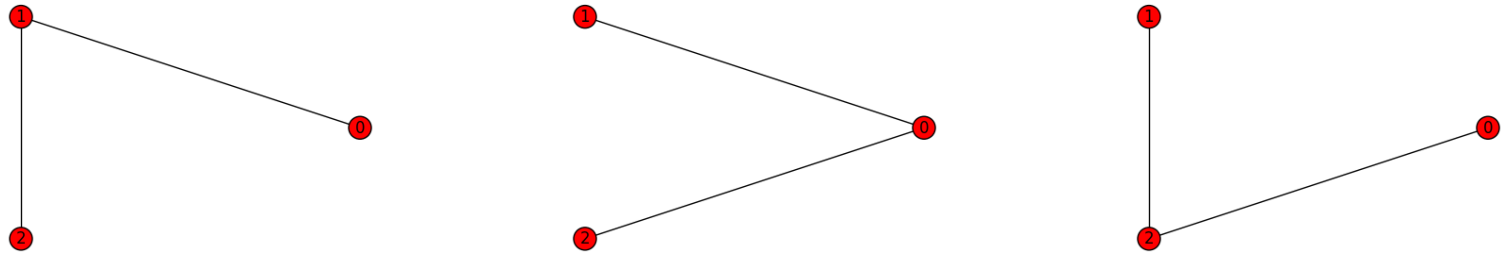
Research Proposals on the Schema... *i)How does functionally correlated behavior among cortical and subcortical brain regions emerge from the structural connectivity?*

ii)Does the topological properties as well as temporal dynamics of the brain graph differ from that of random graphs?

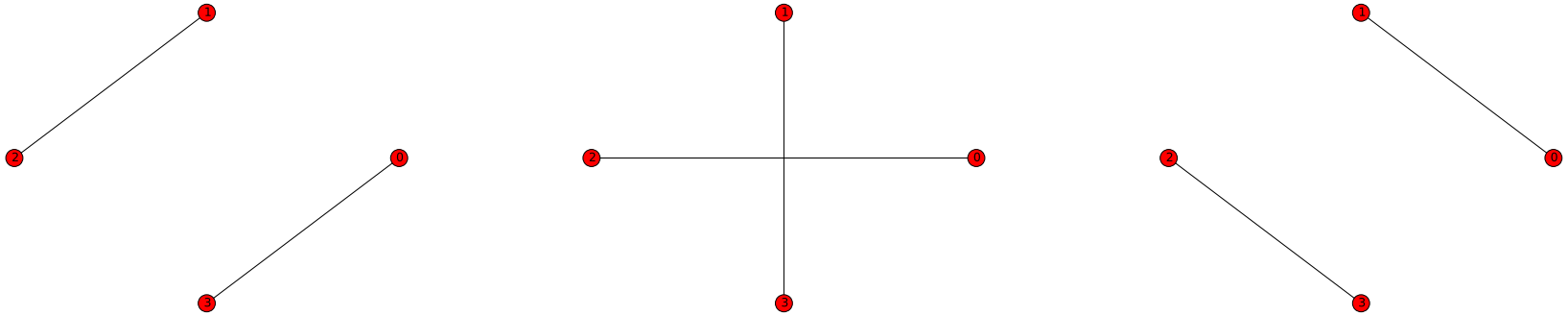


Randomization Methods...

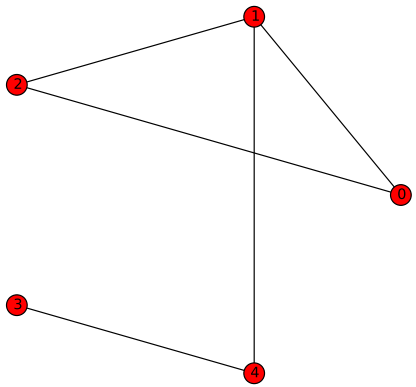
Erdős-Rényi-Type Randomization, $G(N, L)$

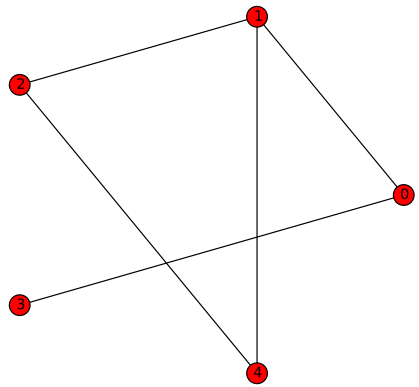


Double-Edge-Swap Type Randomization, k_i



Randomization Methods... Preserved-Degree-Distribution Type Randomization,



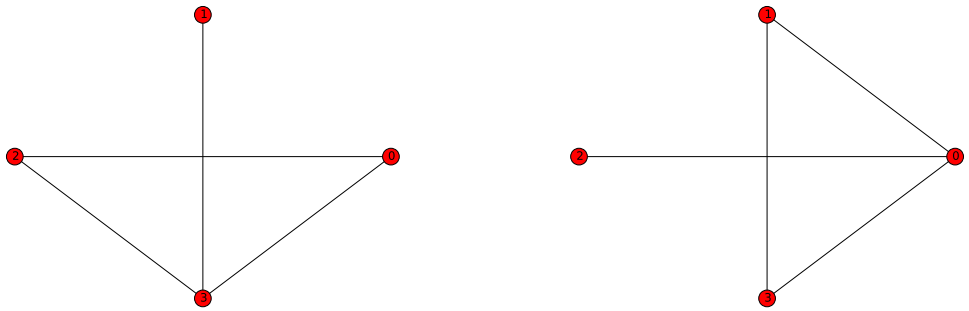


$p(k)$

$$p(k=1)=\frac{1}{5},\ p(k=2)=\frac{3}{5},\ \text{and}\ p(k=3)=\frac{1}{5}$$

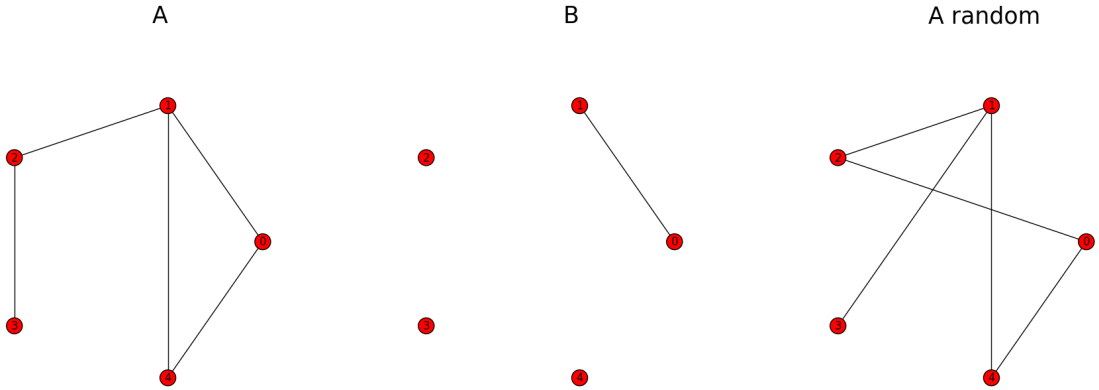
Randomization Methods...

Configuration Model Randomization



(left): $k_0 = 2$, $k_1 = 1$, $k_2 = 2$, $k_3 = 3$ (right): $k_0 = 3$, $k_1 = 2$, $k_2 = 1$, $k_3 = 2$. The degree sequence in non-increasing order in both graphs: $\{3, 2, 2, 1\}$

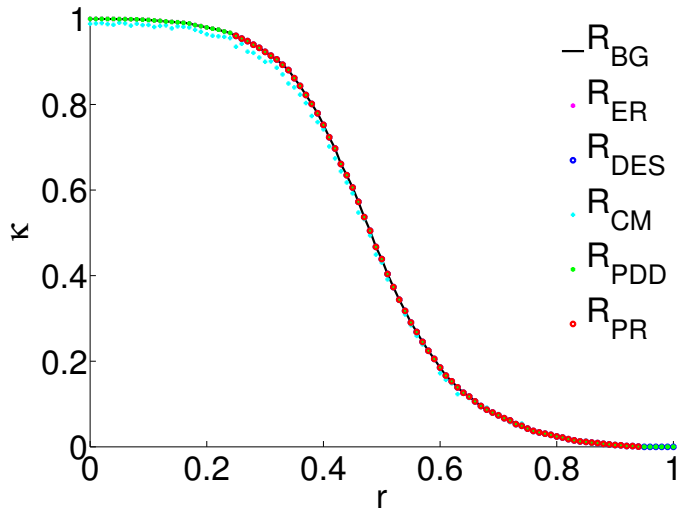
Partial Randomization



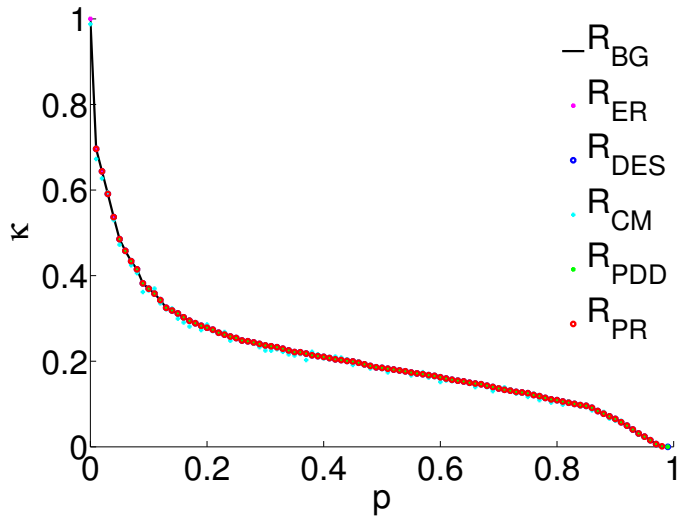
Network Characterizations...

Network Density, $\kappa = \frac{2L}{N(N-1)}$

FCM related graphs



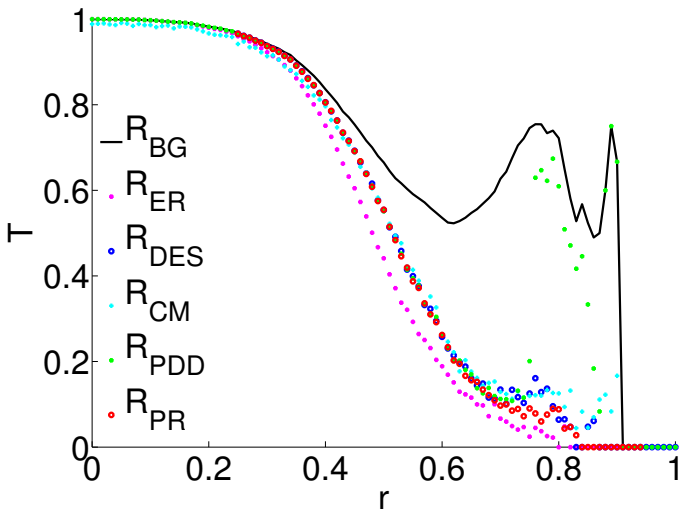
ACM related graphs



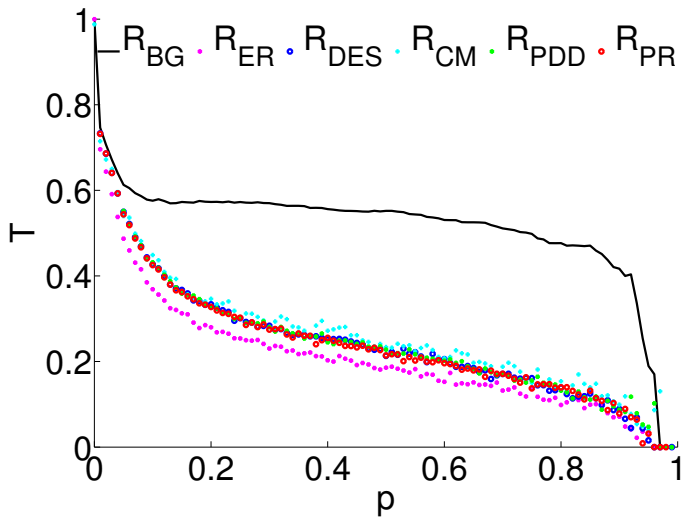
Network Characterizations...

$$\text{Transitivity, } T = \frac{2\sum_{i\epsilon N} t_i}{\sum_{i\epsilon N} k_i(k_i-1)}$$

FCM related graphs



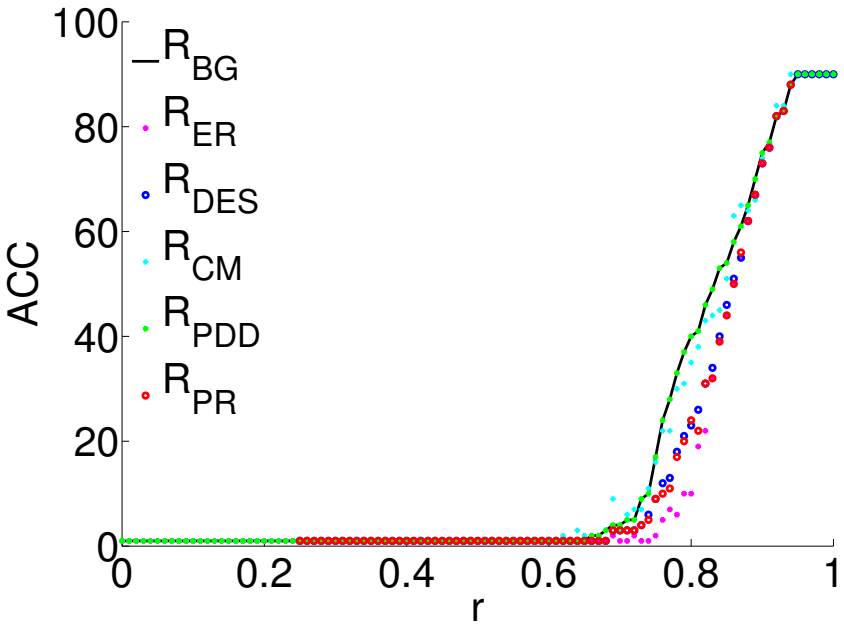
ACM related graphs



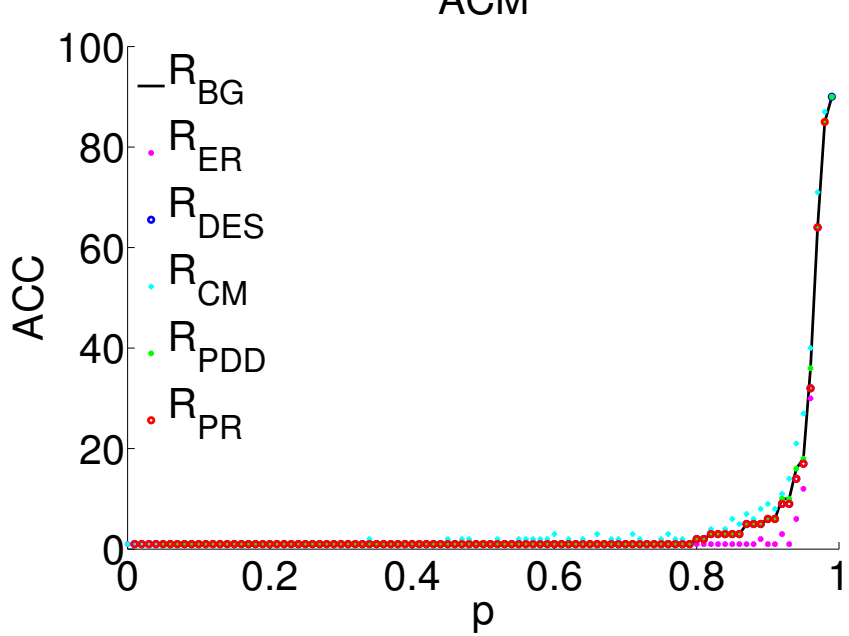
Network Characterizations...

Average number of connected components

FCM related graphs



ACM related graphs

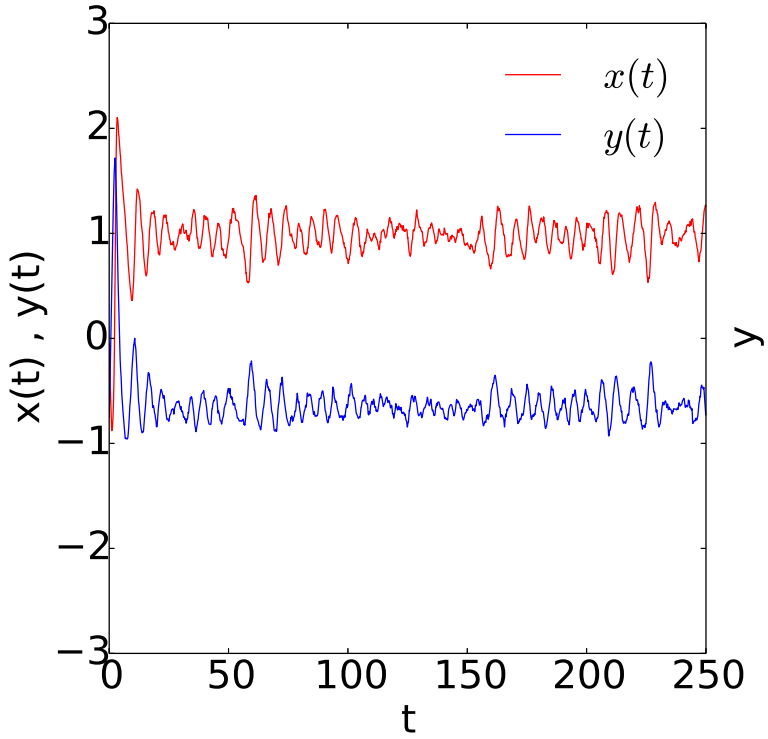


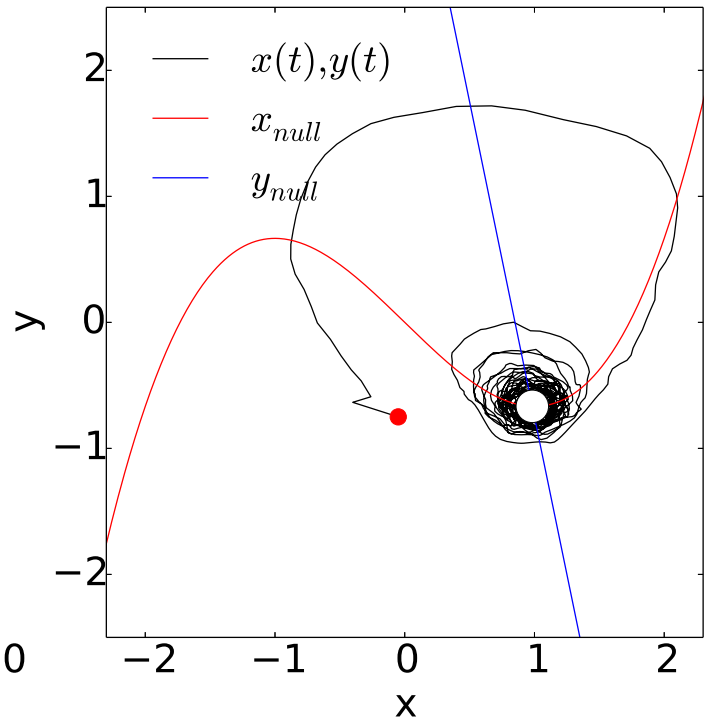
Appendix

FitzHugh-Nagumo Oscillations, Local Dynamics with Gaussian White Noise Source (noise induced oscillations, system in excitable regime)

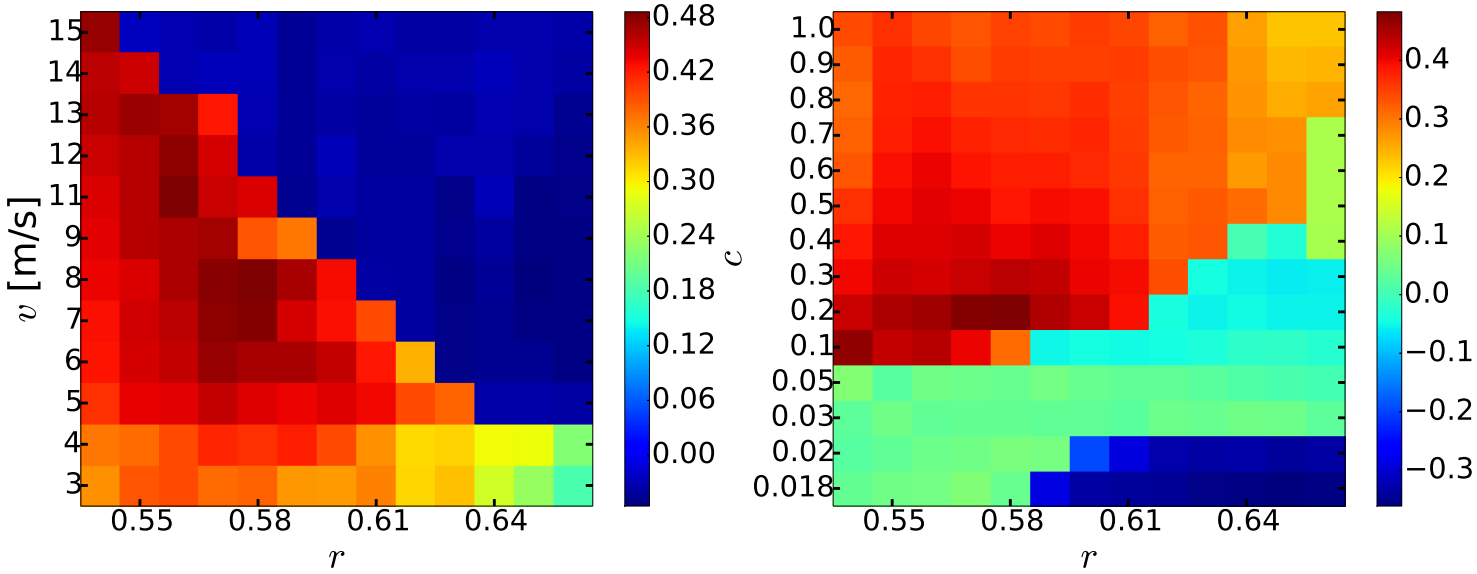
$$\dot{x} = \tau \left(y + \gamma x - \frac{x^3}{3} \right) + Dn_x \tag{2a}$$

$$\dot{y} = -\frac{1}{\tau}(x - \alpha + by) + Dn_y, \tag{2b}$$



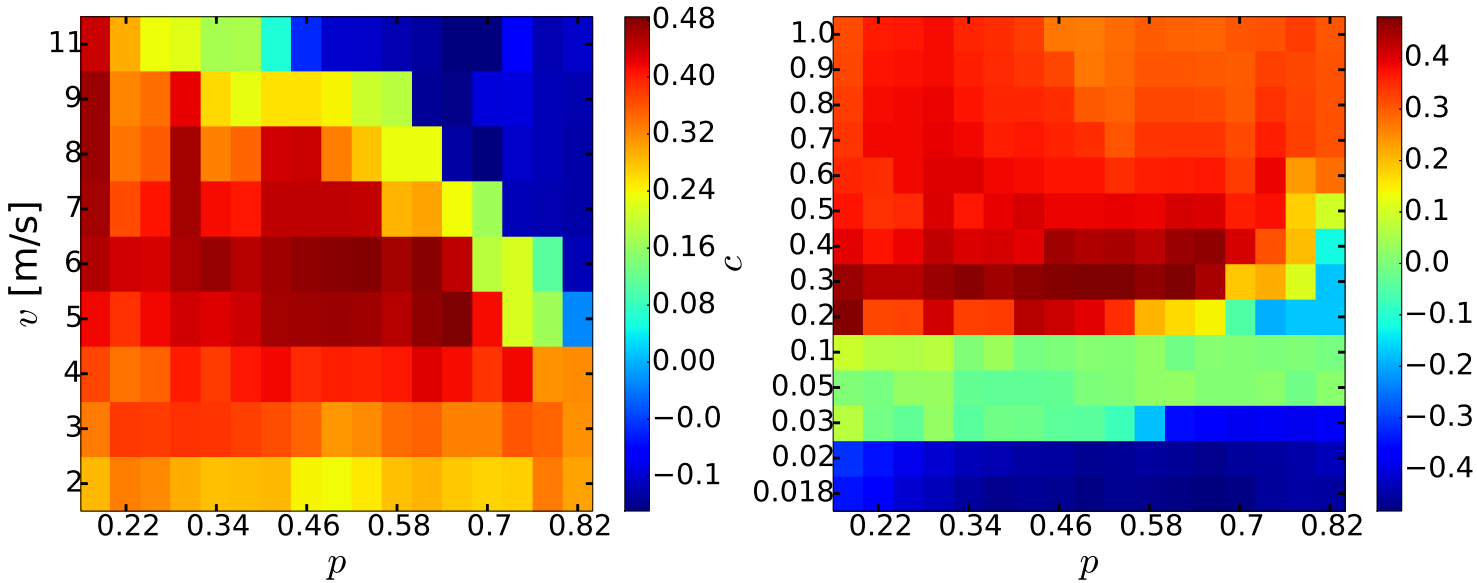


Results... Neuronal Activity Simulations of FCM Related Brain Graphs to fMRI-BOLD Data



Results...

Neuronal Activity Simulations of ACM Related Brain Graphs to DW-MRI Data



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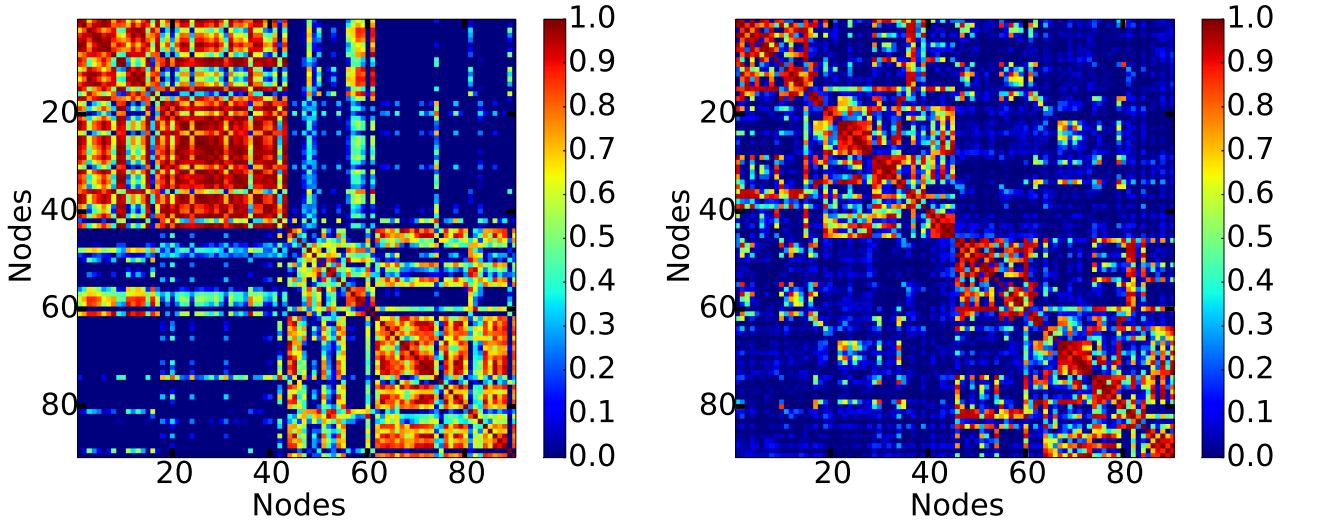
Results...

Neuronal Activity Simulations of ACM Related Brain Graphs to DW-MRI Data



$\rho_{43,31} = 0.86,$ $\rho_{90,83} = 0.15$

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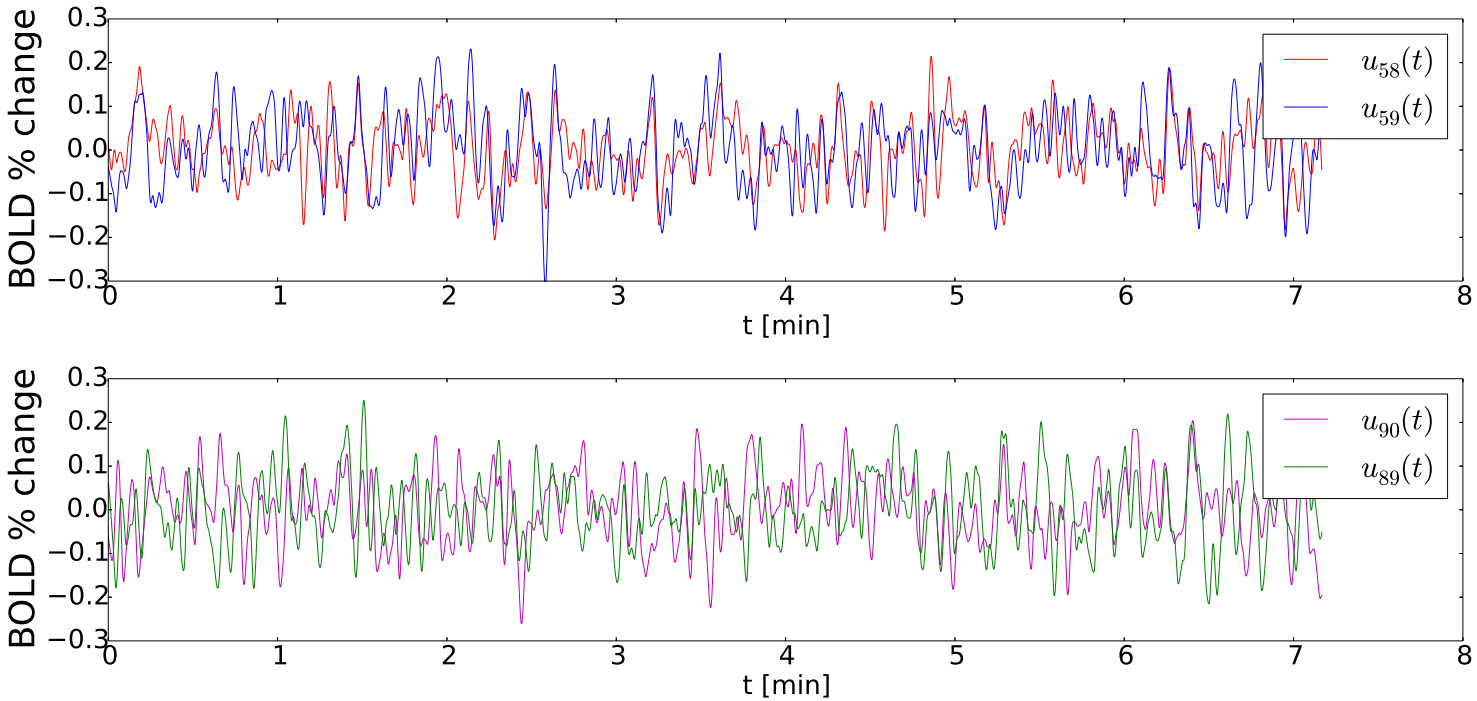
Results...

Comparing BOLD Simulations of Anatomical Brain Graphs to fMRI-BOLD Data



$\rho_{58,59} = 0.48$ $\rho_{90,89} = 0.11$

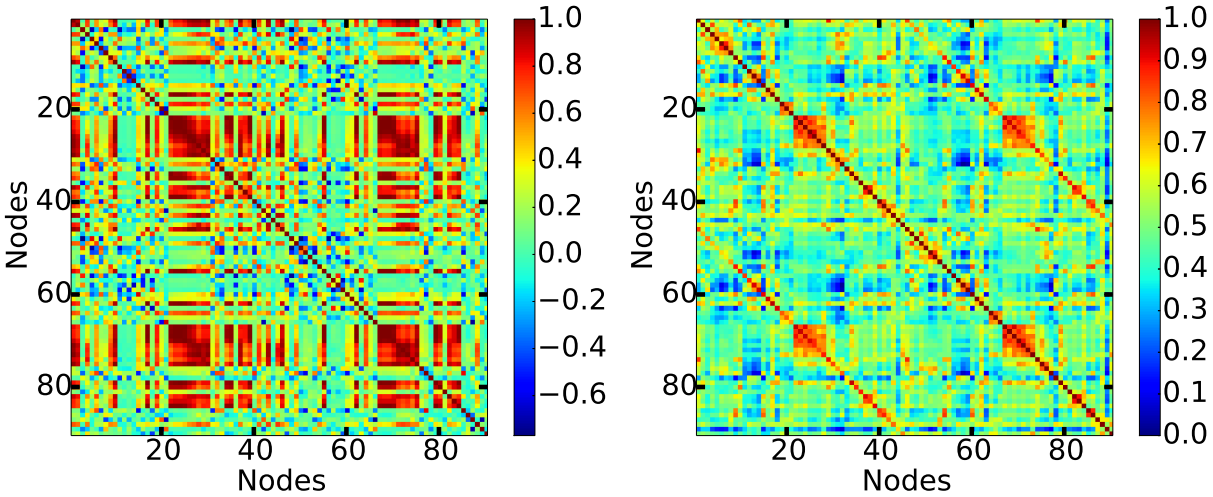
Statistical Method...

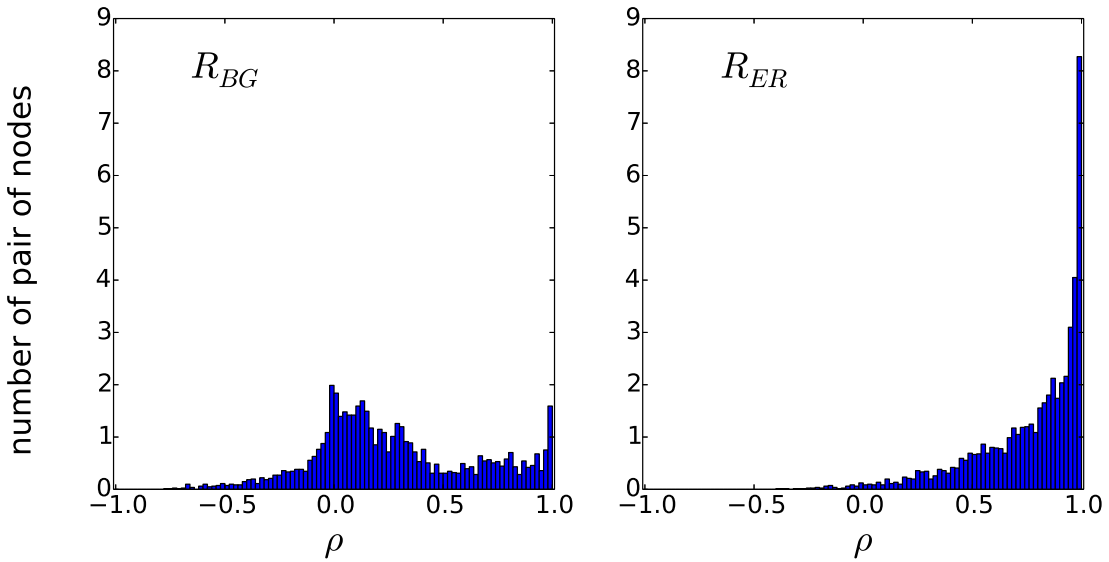
How to Compare the Modeled Temporal Dynamics of Brain Graphs to that of the Random Networks ?

- construct brain graphs and their random networks at defined r- and p-ranges for FCM and ACM based empirical data
- extract FHN network modeled time-series in each graph
- find Pearson correlation coefficients ρ between pairwise combination of $N = 90$ nodes in each graph
- distribute ρ values in histograms for each graph
- compare histograms via Bhattacharya coefficients :

$$d(H_b, H_r) = \sqrt{1 - \frac{1}{\sqrt{\bar{H}_r \bar{H}_b N^2}} \sum_i \sqrt{H_r(i) H_b(i)}} \tag{3}$$

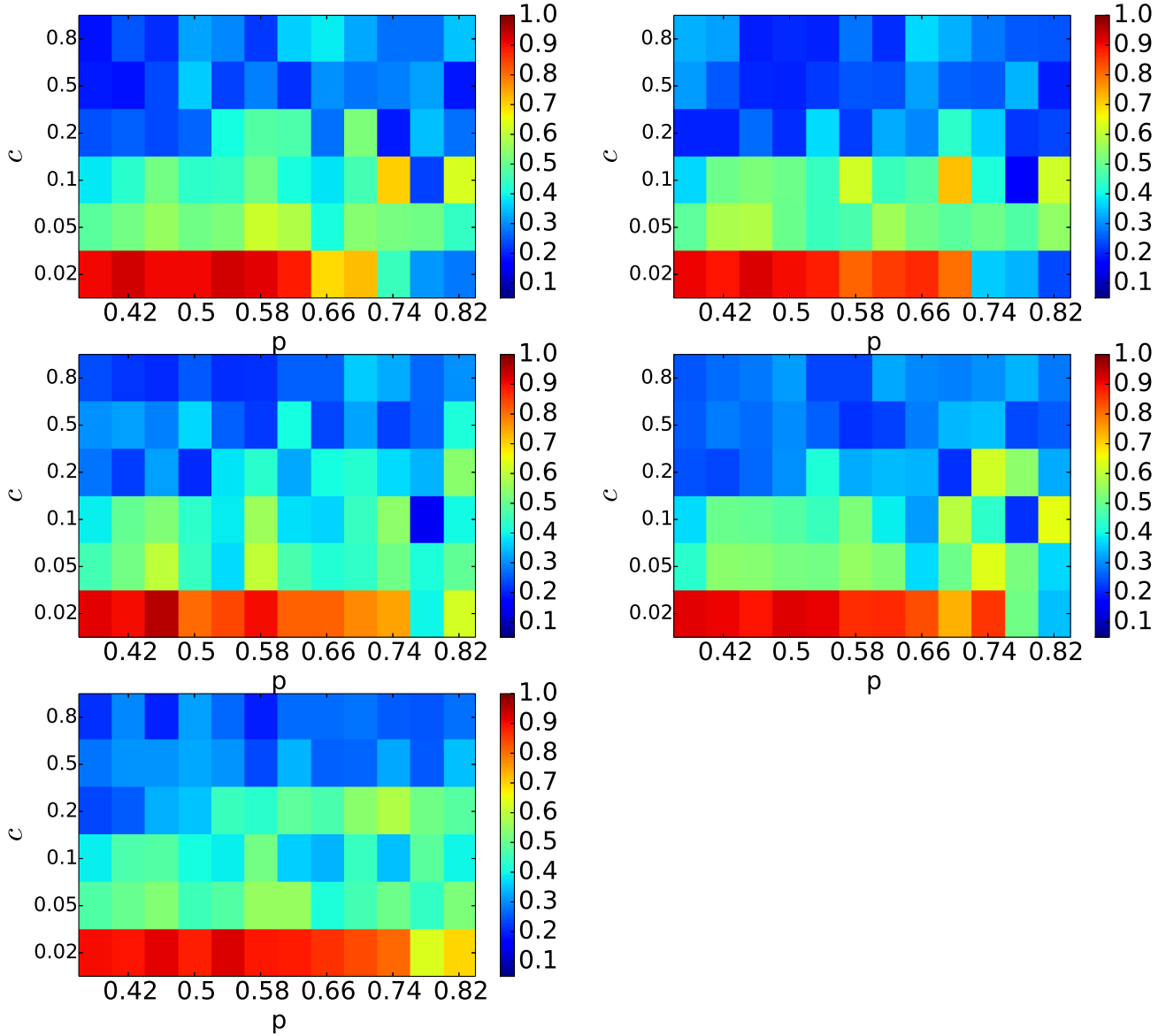
Appendix



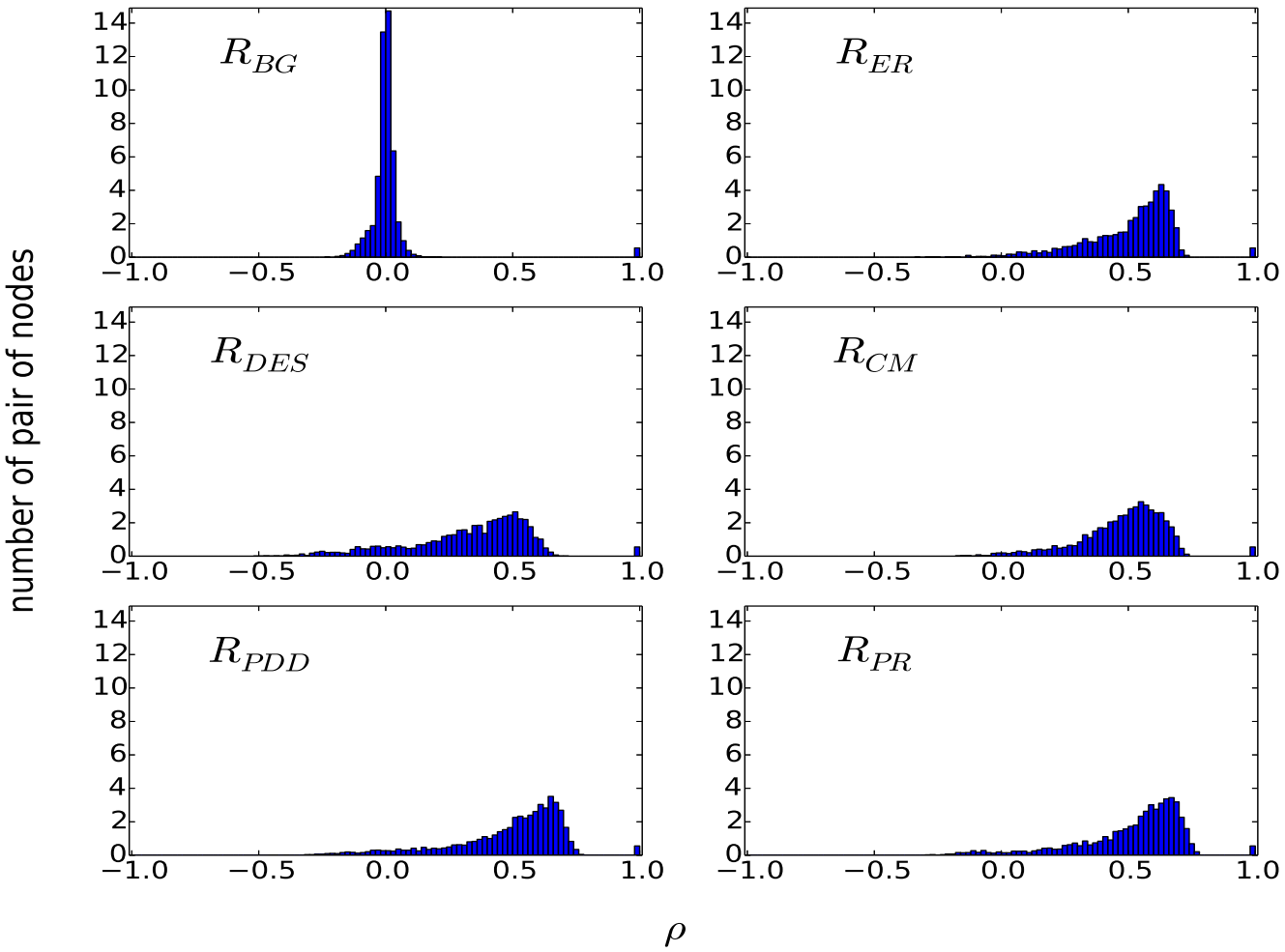


$\rho_{e,s} = 0.43$
FitzHugh-Nagumo network model,
simulation parameters :
$c = 0.2$
$v = 7$ m/s
Brain Graph Topology :
$r = 0.60$
Bhattacharya Coeff.:
$d(H_b, H_r) \approx 0.50$

Results... Comparison of ACM Related Brain Graph to the Random Networks



Results... Comparison of ACM Related Brain Graph to the Random Networks



Appendix

Distance Matrices... $\Delta t_{ij} = d_{ij}/v$