Brain Networks: Structural and Dynamic Substrates of Cognitive Architectures?

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Network Neuroscience

- Social networks
- Perception-action coupling
- Brain-behavior interactions
- Whole-brain functional networks (EEG, MEG, fMRI, fNIRS, ECOG)
- Diffusion MR imaging
- Histological tract tracing
- Connectome networks
- Optical imaging
- EM imaging and reconstruction
- Metabolic pathways
- Transcriptional and gene regulatory networks
- Interactome networks

Spatial scale:
- Environment
- Organism
- Brain
- System
- Circuit
- Neuron
- Synapse
- Molecule

Timescale:
- Millisecond
- Second
- Minute
- Hour
- Day
- Month
- Year

Changing Views of Human Brain Anatomy

Ludwig Klingler - 1956
Patric Hagmann - 2008
Network Analysis of the Human Connectome

Prominent network attributes of the human connectome (Hagmann et al. 2008)

- Unique regional connectivity fingerprints
- Broad (log-normal?) degree distribution
- High clustering, short path length
- Existence of modules interlinked by hub regions
- A prominent structural core
In some networks, highly connected/central hub nodes have a tendency to be highly connected to each other (“rich-club” organization).

Hubs, cores and rich clubs may play important roles in global communication:
- By creating short (efficient) paths
- By supporting integration of information across diverse brain systems

Rich-Club Organization of the Human Connectome

High proportion (89%) of short communication paths travel through at least one RC node (66% through an RC edge).

RC damage (node/edge deletion) has large effects on network integrity and efficiency.

The human connectome exhibits rich club organization.
Modular organization

Swanson, Hahn, Sporns (2017) PNAS
Cost-Efficiency Trade-Off

Two major driving forces shaping brain connectivity:

- **Minimization of cost** (wiring volume, energy use)
- **Maximization of efficiency** (communication, information flow)

Cost minimization and efficiency maximization promote different network attributes.

Hypothesis: The architecture of brain networks represents an **optimal trade-off** between the competing demands of cost and efficiency.

Linking Anatomy and Dynamics

Hagmann et al. (2008)  
Structural Connectivity  

Vincent et al. (2007)  
Functional Connectivity
Resting-State Networks

Patterns of coherent brain activity during extended periods of resting-state: “resting-state networks” (functional brain modules)...

Betzel et al. (2014) Neuroimage 102, 345

Power et al. (2011) Neuron

Yeo et al. (2011) J Neurophysiol.

Generative Models for Functional Networks

Structural connectivity (SC) constrains & shapes functional connectivity (FC)

macaque rs-fMRI (Adachi et al, 2012)  
biophysical neural model  
empirical FC  
modeled FC (R = 0.55)

Human rs-fMRI (Goni et al, 2014)  
analytic network model  
empirical FC  
predicted FC (R = 0.60)
Going from Nodes to Edges

“Classic” fMRI functional connectivity is based on similarity of (node-based) activation patterns (Pearson correlation of node time series)

Proposal: “edge functional connectivity” based on similarity of (edge-based) co-fluctuation patterns (Pearson correlation of edge time series)

Classic FC is the average of this edge time series
High-Resolution fMRI Dynamics

Edge time series deliver moment-to-moment co-fluctuations

Edge time series exhibit “bursty” behavior (events)

...unrelated to head motion or cardiac/respiratory cycles

Events are intermittent, short-lasting, present in movie data, can be extracted from “standard” BOLD time series, and are present in all individuals

Esfahlani et al (2020) PNAS  
Sporns et al (2021) Netw Neurosci
High-Resolution fMRI Dynamics

Esfahlani et al (2020) PNAS
Sporns et al (2021) Netw Neurosci
Networks Link Structure and Function

- **Structural connectivity**: anatomical links (weighted, directed, multi-scale)

- **Communication dynamics**: the spatiotemporal flow of communication events unfolding along structural connections

- **Functional connectivity**: expresses the effect of communication dynamics in statistical dependencies among time series

Cognition emerges from **Brain Networks**

Many Features of Brain Networks are **shared across Species**

Evolving Networks trade off **Cost and Efficiency** – Cognition is subject to same Constraints

Functional Connectivity (Rest and Task) is **Dynamic and Flexible**