Economical brain networks

Ed Bullmore

Behavioural & Clinical Neuroscience Institute, University of Cambridge

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How did we start thinking about brain networks?

Macro

Mayo (1827)

Micro

Ramón y Cajal (1890)
Brain network disorder is an old idea in medicine

Theodor Meynert
(1833-1892)
Anatomy of white matter

Carl Wernicke
(1848-1905)
Aphasia and psychosis as disorders of large scale brain connectivity

Sigmund Freud
(1856-1939)
*Project for a Scientific Psychology*
Mental states represented by flow of libido through cellular circuits
Brain networks are expensive and tend to minimize their physical costs

**Cajal’s conservation principle:**

“We realized that all of the various conformations of the neuron and its various components are simply morphological adaptations governed by laws of conservation for time, space, and material.”

has been approximately verified many times since it was first stated c 1900.

Chen, Hall & Chklovskii (2006) *Proc Natl Acad Sci USA*
Garcia-Lopez (2010) *Front Neuroanatomy*
Why now for the connectome?
Topological complexity exists at all biological scales of space and time and in all kinds of brain networks.

Worm cellular connectome

Cat micro functional network

Human macro anatomical and functional networks

Monkey macro anatomical network

Bullmore & Sporns (2009) *Nat Rev Neurosci*
Economical brain networks: definition and talk plan

• “Economical” means that the brain network represents a trade-off between its physical cost and its topological value
  – Cost
    • Wiring cost or physical distance of edges
    • Metabolic rate of nodes
  – Value
    • Topological properties that support integrative processing and, ultimately, adaptive behaviour

• Economics of human connectome
• Economics of worm connectome
• Implications for brain disorders
From neuroimaging to brain graphs

1. Estimate an association matrix from the data
   - What are the nodes?
   - What metric of connectivity?

2. Generate an adjacency matrix from the association matrix
   - What are the edges?

3. Measure topological properties of each graph

4. Make comparisons between graphs

Brain graphs are statistical models entailing assumptions and trade-offs which influence parameter values

Brain graph parameters make sense relativistically, not absolutely; comparison between graphs is not trivial

Consistent topological properties of connectomes

**Small worldness**
- high clustering
- short path length or high efficiency

**Hub nodes**
- fat-tailed degree distributions

**Rich club**
- hubs are highly connected to each other to form a small elite core in a larger periphery of network nodes

**Modularity**
- nodes are more densely connected to other nodes in the same module than to nodes in other modules
- connector hubs mediate a large proportion of inter-modular connections

Meunier et al (2010) *Front Neurosci*
Hierarchical modularity of the human brain

Adult human brain has “modules-within-modules”

Meunier et al (2010) *Frontiers Neuroscience*

Hierarchical modularity is common to many information processing systems

Long-haul connector hubs in airline and brain networks: inter-modular connector hubs have high wiring cost

Airline systems are cost constrained, physically embedded, modular networks with most long-haul (inter-modular) flights through a few connector hubs...

...the precuneus is the brain’s equivalent of London Heathrow?

The rich club of the human brain anatomical network: a high cost / high capacity elite group of hubs

Network hubs also have high metabolic cost / blood flow

Topological properties

Metabolic cost
(rCBF = regional cerebral blood flow)

Liang et al (2013) Proc Natl Acad Sci USA
Expensive, long-range integrative connections may be “worth it” for extra cognitive capacity

Greater efficiency (shorter path length) of brain networks is correlated with higher IQ


Global (neuronal) workspace theory predicts integrative processing will be required for conscious, effortful, cognitive functions

Baars (1993) *A cognitive theory of consciousness*
Working memory load “breaks modularity” and drives workspace re-configuration of functional brain networks.

β-band frequency networks recorded using MEG in healthy volunteers performing N-back working memory task.
A drug that improves cognitive performance also increased the cost and efficiency of brain functional networks

Giessing et al (2013) *J Neurosci*
Functional brain networks at rest (correlation) and at work (coactivation)

Crossley et al (2013) in review
The rich club of the human brain functional network is co-activated by diverse, executive tasks.

This co-activation network is based on meta-analysis of 1,641 primary fMRI studies in the BrainMap database, each primary study including at least 5 healthy adults.
Generative models of distance-topology trade-offs can simulate fMRI network statistics

The probability of a connection between two nodes was modelled as:

1) A function of distance only: longer distance, less probability of connection
2) A function of topology only: e.g., greater probability of connection to high degree nodes
3) A function that trades-off distance versus topology

- The distance-topology trade-off models were a better fit to brain network statistics than either distance-only or topology-only models


\[ P_{i,j} \propto (k_{i,j})^\gamma (d_{i,j})^{-\eta} \]
Has brain network organization evolved to optimise a trade-off between cost and efficiency?

Strictly minimizing wiring cost of the *C. elegans* connectome adversely impacts topological efficiency

Naturally wired

Minimally wired


Bullmore & Sporns (2012) *Nat Rev Neurosci*
The rich club of the worm brain:
a high cost / high value system for coordinated movement

Towlson et al. (2013) J Neurosci
Economically modeled growth of the *C. elegans* connectome

Nicosia et al (2013) *Proc Natl Acad Sci*
Some economical principles of brain networks

• Brain networks are spatially embedded and topologically complex (like airline networks)

• The high costs of brain networks are nearly (but not strictly) minimized

• Some of the most expensive topological features of brain networks are hubs, often comprising rich clubs

• The high costs of hubs-and-clubs are **worth it** because these integrative network components add value behaviourally (let the worm move)

In general, brain networks negotiate (and re-negotiate over time) an economical trade-off between physical cost and topological value

Bullmore & Sporns (2012) *Nat Rev Neurosci*
How do economical principles of the connectome matter to psychiatry and neurology?

- High cost network components are likely to be most vulnerable to disease processes
  - Trauma
  - Hypoxia
  - Infection...

- High value network components are most likely to cause functional deficits, or symptoms, if lesioned

- Therefore, high cost / high value components of the connectome may be central to many brain disorders
The hubs of brain networks are most vulnerable to amyloid deposition in Alzheimer’s disease

Grey matter atrophy in neurodegenerative disorders impacts hubs preferentially and may propagate trans-synaptically.

Increasing gray matter atrophy in patient groups

Increasing weighted degree in healthy fMRI networks

Coma due to acute brain injury is associated with radical disruption of hubs

In schizophrenia, greater-than-normal long distance connections to hubs “break modularity”

Distance-topology trade-off models simulate abnormal fMRI network statistics in schizophrenia

Conclusions

• Economical brain networks negotiate a trade-off between physical cost and topological value

• Hubs and clubs are high cost network components that add value by supporting integrative processing and, ultimately, adaptive behaviour

• Economy of brain network organization is conserved across scales and species

• Brain network growth can be simulated by simple generative models of distance / topology trade-off

• High cost / high value hubs are the most vulnerable to brain disease and the most likely, if lesioned, to generate cognitive or behavioural symptoms
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etb23@cam.ac.uk

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