

Economical brain networks

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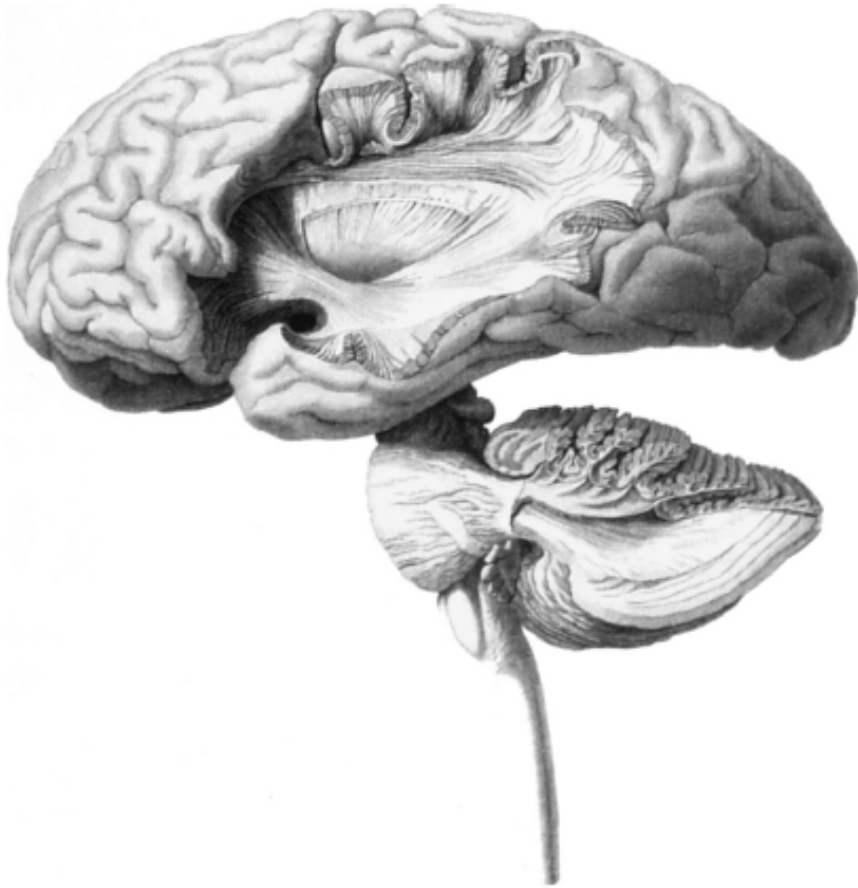
7 May, 2013



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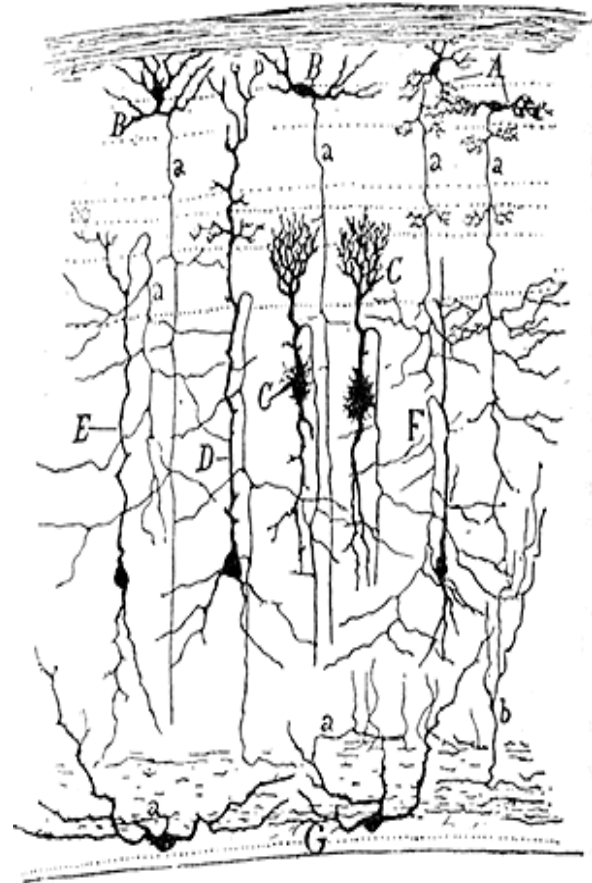
How did we start thinking about brain networks?

Macro



Mayo
(1827)

Micro



Ramón y Cajal
(1890)

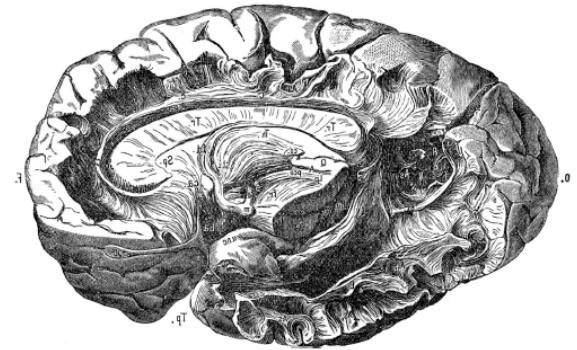
Brain network disorder is an old idea in medicine



Theodor Meynert

(1833-1892)

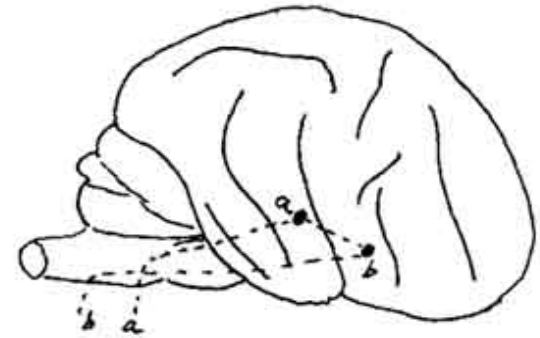
Anatomy of white matter



Carl Wernicke

(1848-1905)

Aphasia and psychosis as disorders of large scale brain connectivity

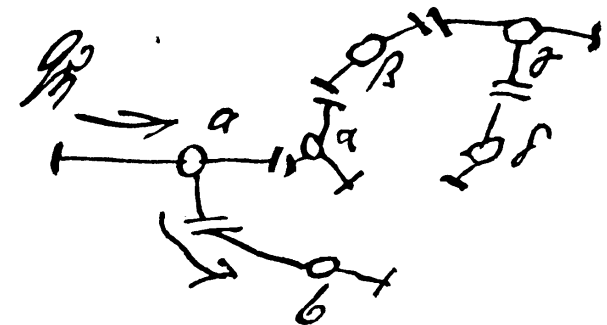


Sigmund Freud

(1856-1939)

Project for a Scientific Psychology

Mental states represented by flow of libido through cellular circuits



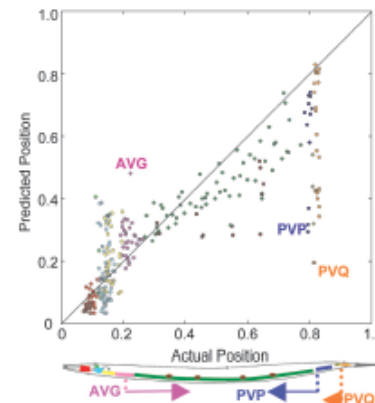
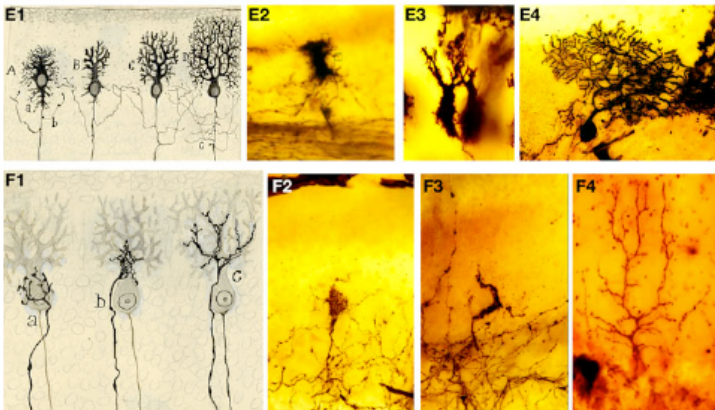
Brain networks are expensive and tend to minimize their physical costs



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."

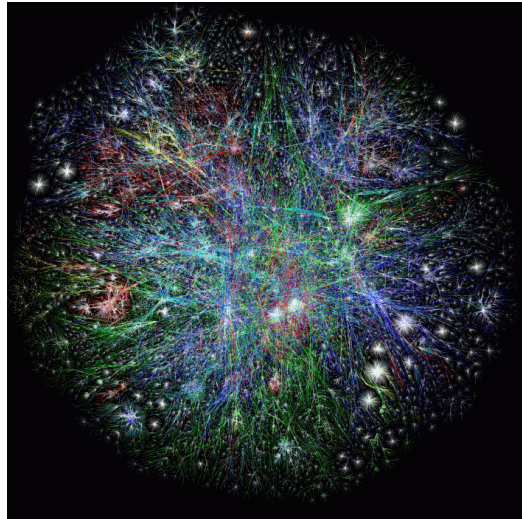
has been approximately verified many times since it was first stated c 1900.



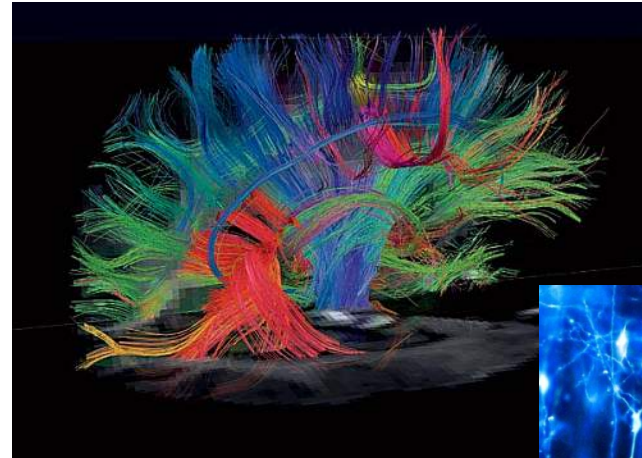
Chen, Hall & Chklovskii (2006) *Proc Natl Acad Sci USA*

Garcia-Lopez (2010) *Front Neuroanatomy*

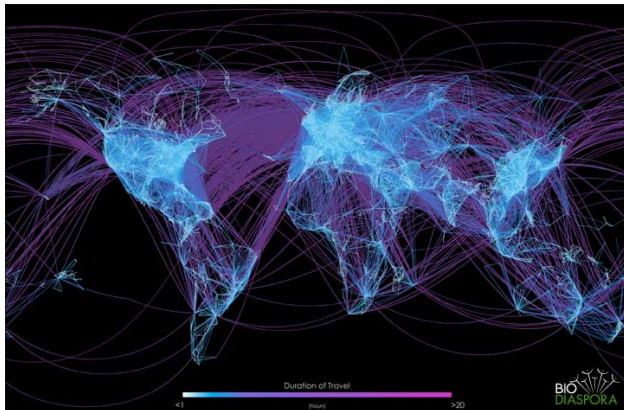
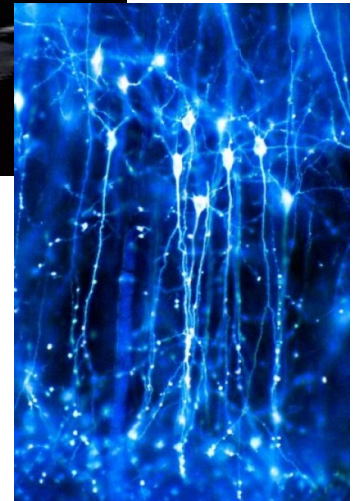
Why now for the connectome?



World Wide Web



Brains



Global Airlines

OPEN ACCESS Freely available online

PLOS COMPUTATIONAL BIOLOGY

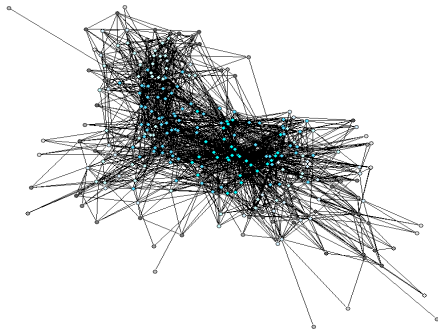
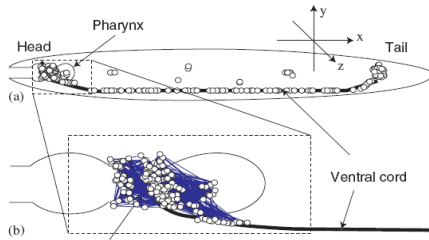
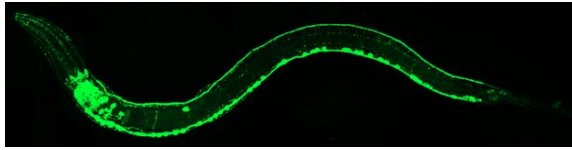
Review

The Human Connectome: A Structural Description of the Human Brain

Olaf Sporns*, Giulio Tononi, Rolf Kötter

(2005)

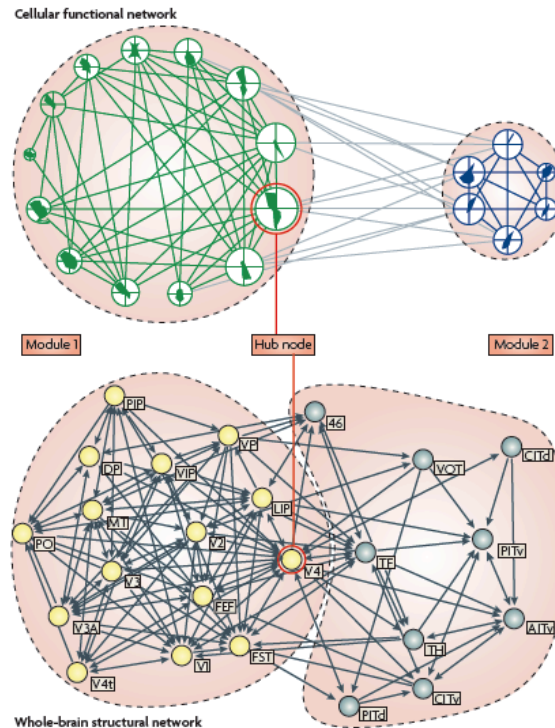
Topological complexity exists at all biological scales of space and time and in all kinds of brain networks



Worm
cellular connectome

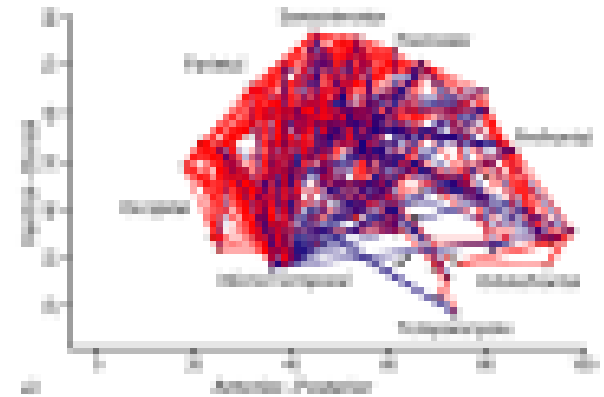
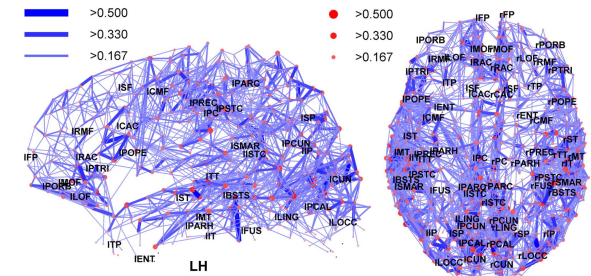
Watts & Strogatz (1998) *Nature*
Achard et al (2006) *J Neurosci*
Hagmann et al (2008) *PLoS Biol*
Bullmore & Sporns (2009) *Nat Rev Neurosci*

Cat
micro functional network



Monkey
macro anatomical network

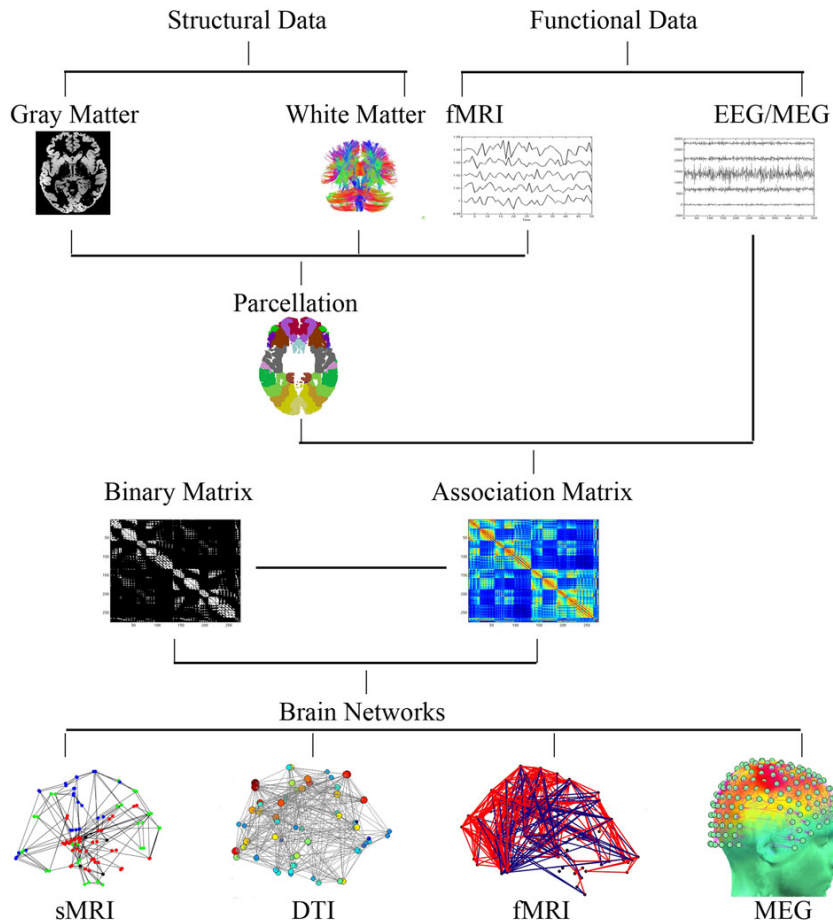
Human
macro anatomical and
functional networks



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

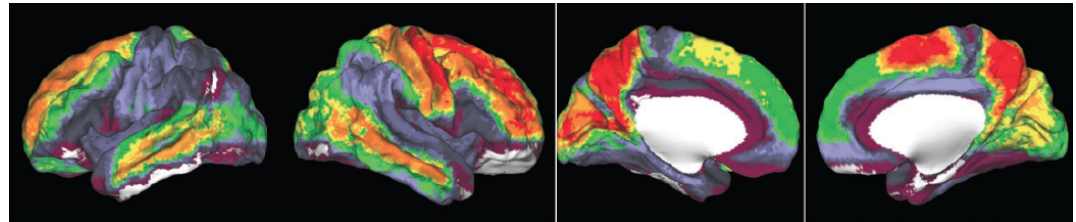
Rich club

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

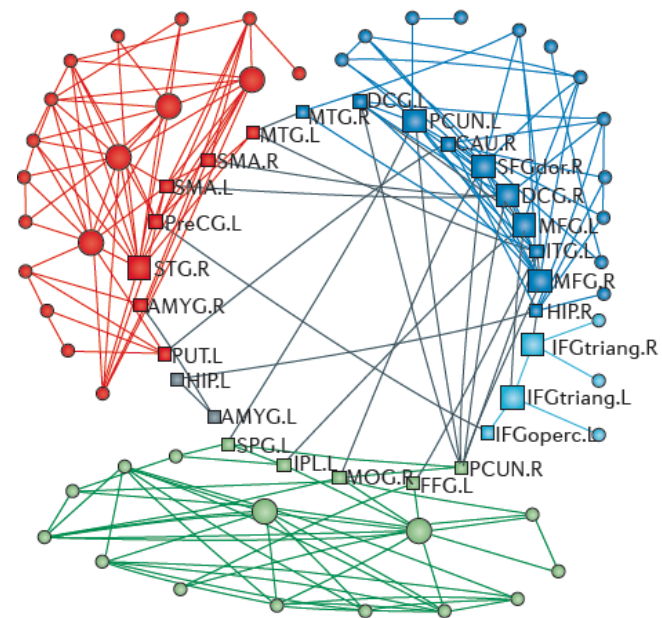
Modularity

- 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

Anatomical map of hubs



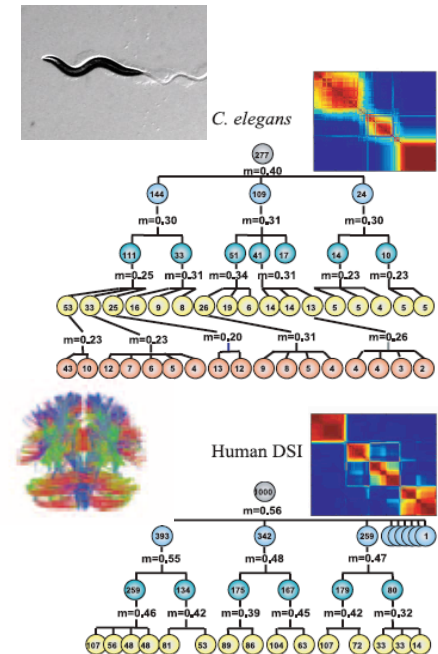
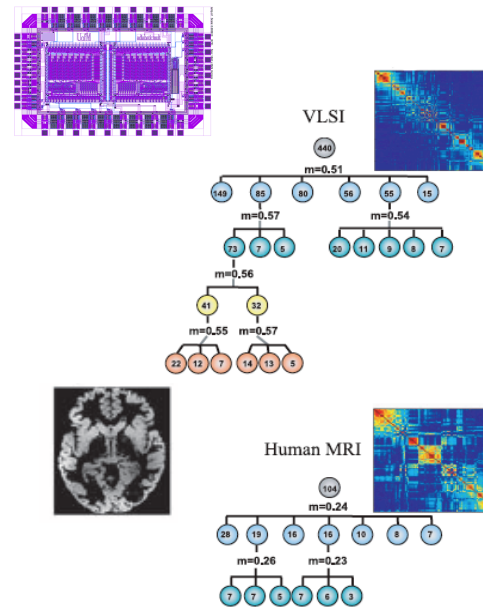
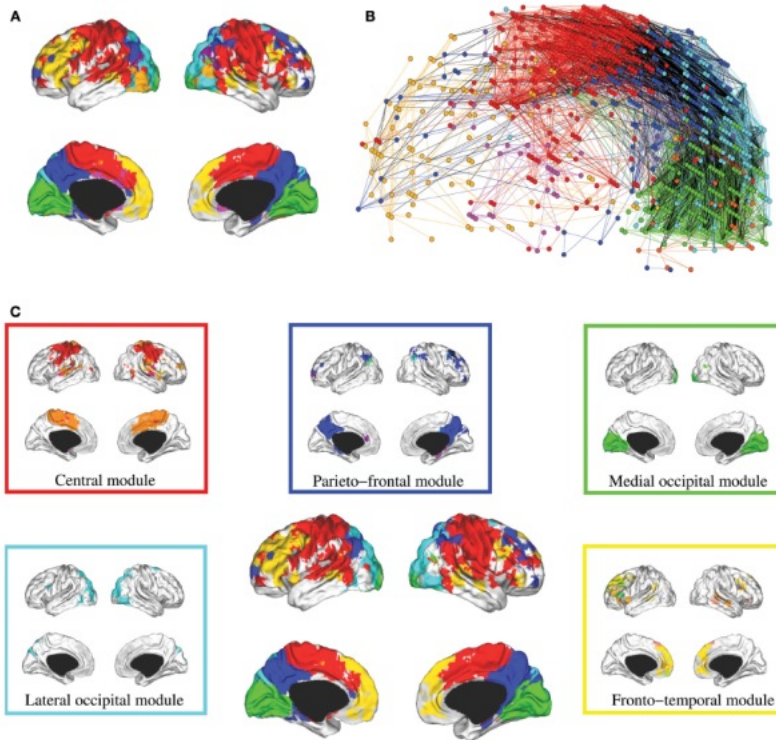
Topological map of modules



Bullmore & Bassett (2009) *Annu Rev Clin Psychol*

Meunier et al (2010) *Front Neurosci*

Hierarchical modularity of the human brain



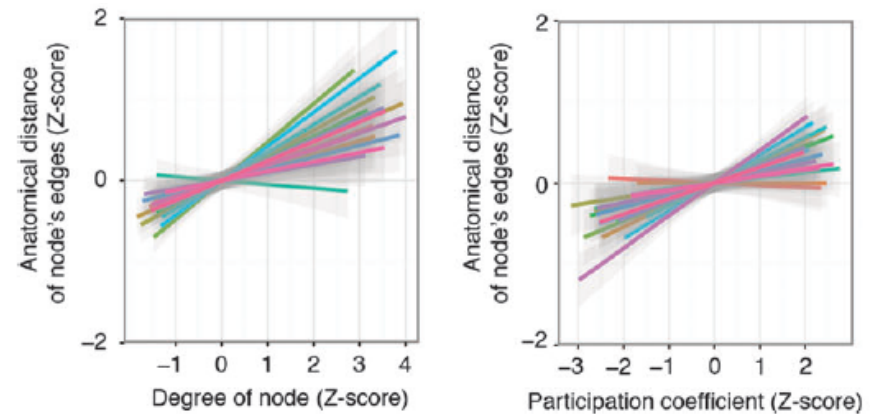
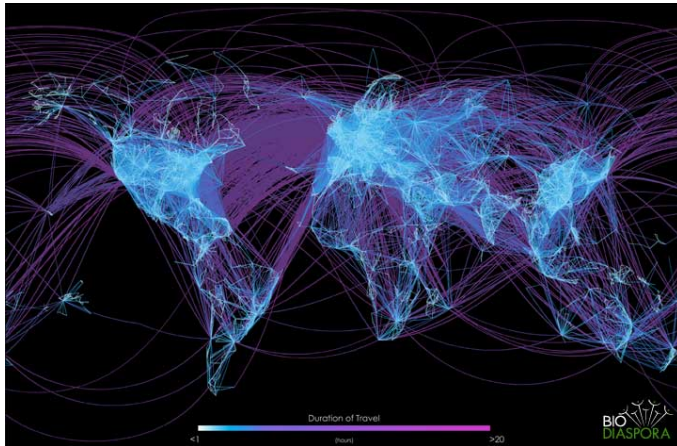
Adult human brain has “modules-within-modules”

Meunier et al (2010) *Frontiers Neuroscience*

Hierarchical modularity is common to many information processing systems

Bassett et al (2010) *PLoS Computational Biology*

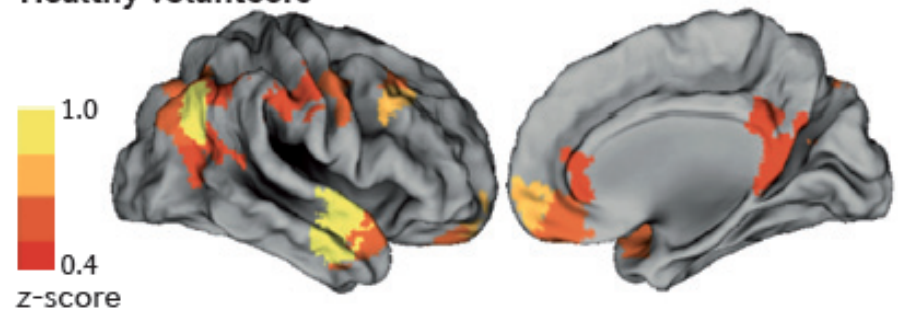
Long-haul connector hubs in airline and brain networks: inter-modular connector hubs have high wiring cost



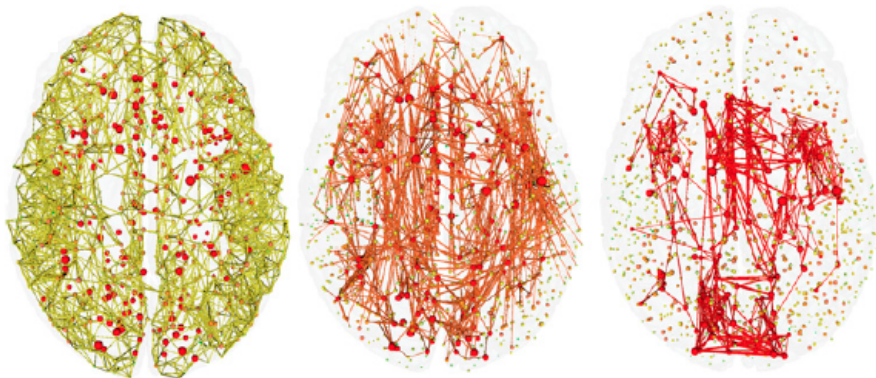
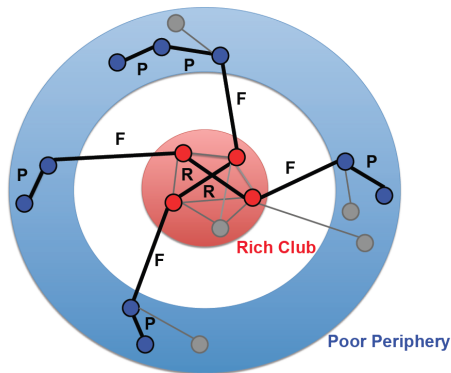
Airline systems are cost constrained, physically embedded, modular networks with most long-haul (inter-modular) flights through a few connector hubs...

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

Healthy volunteers



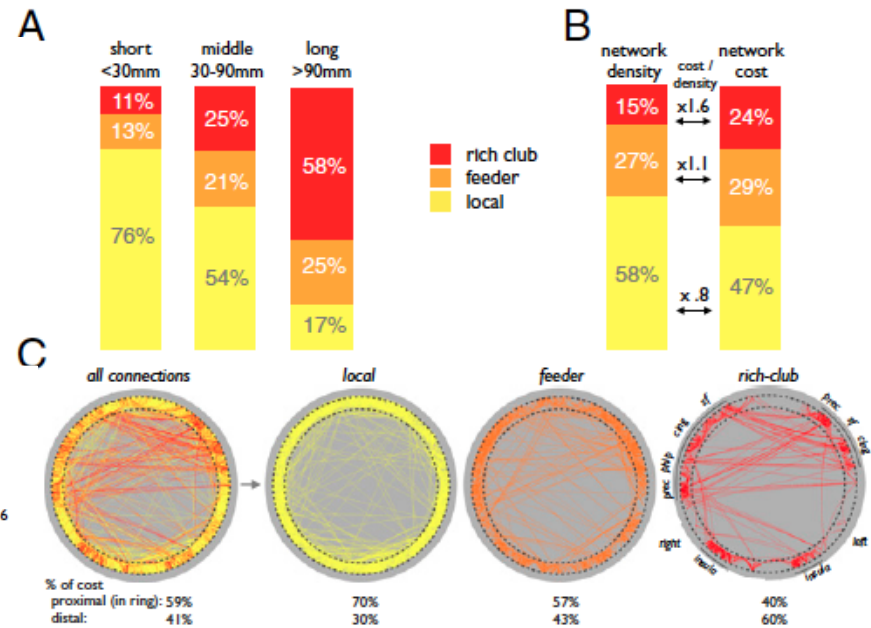
The rich club of the human brain anatomical network: a high cost / high capacity elite group of hubs



Poor

Feeder

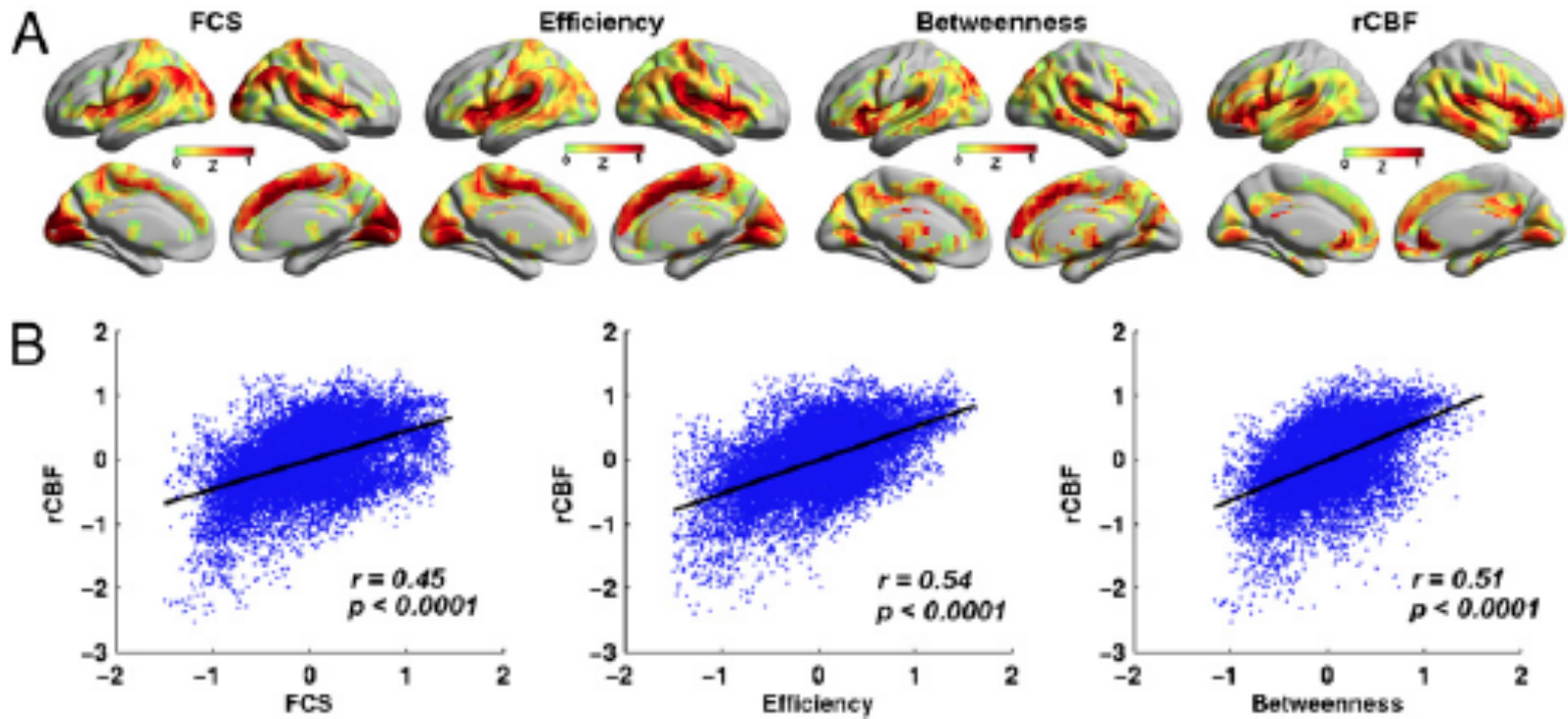
Rich



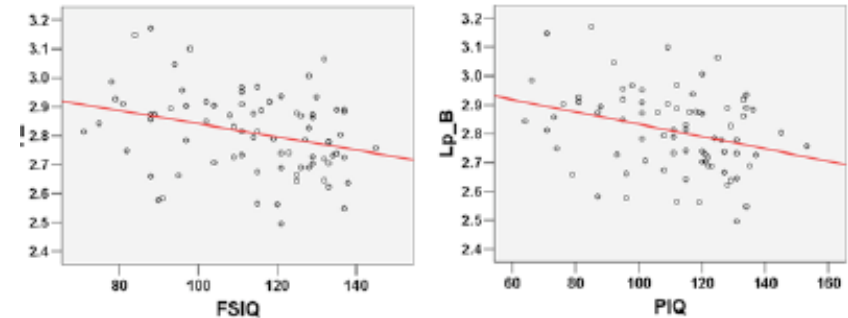
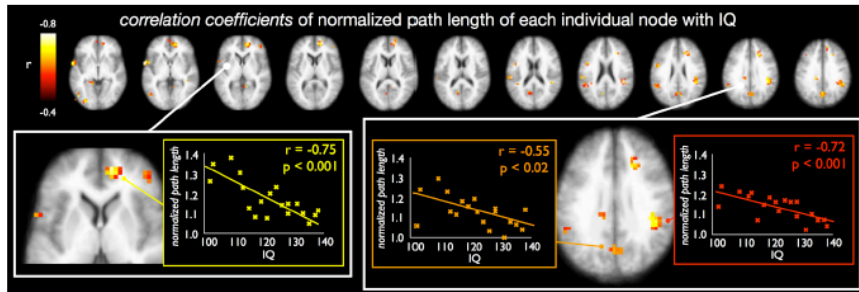
Network hubs also have high metabolic cost / blood flow

Topological properties

Metabolic cost
(rCBF = regional cerebral blood flow)

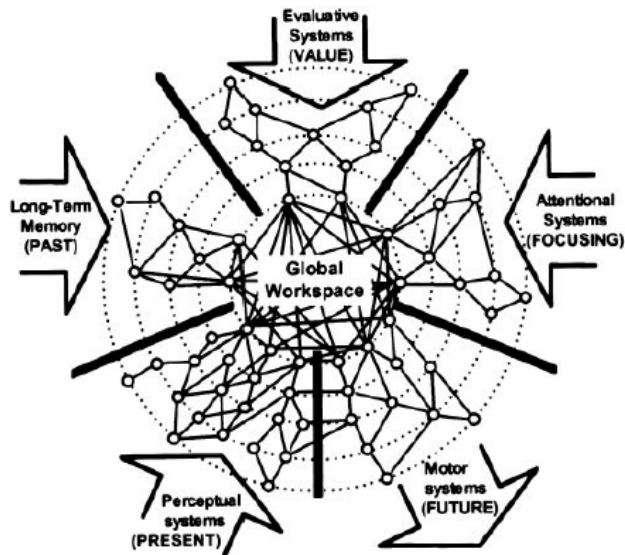


Expensive, long-range integrative connections may be “worth it” for extra cognitive capacity



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

Van den Heuvel et al (2009) *J Neurosci*; Li et al (2009) *PLoS Comp Biol*; Bassett et al (2010) *PLoS Comp Biol*;

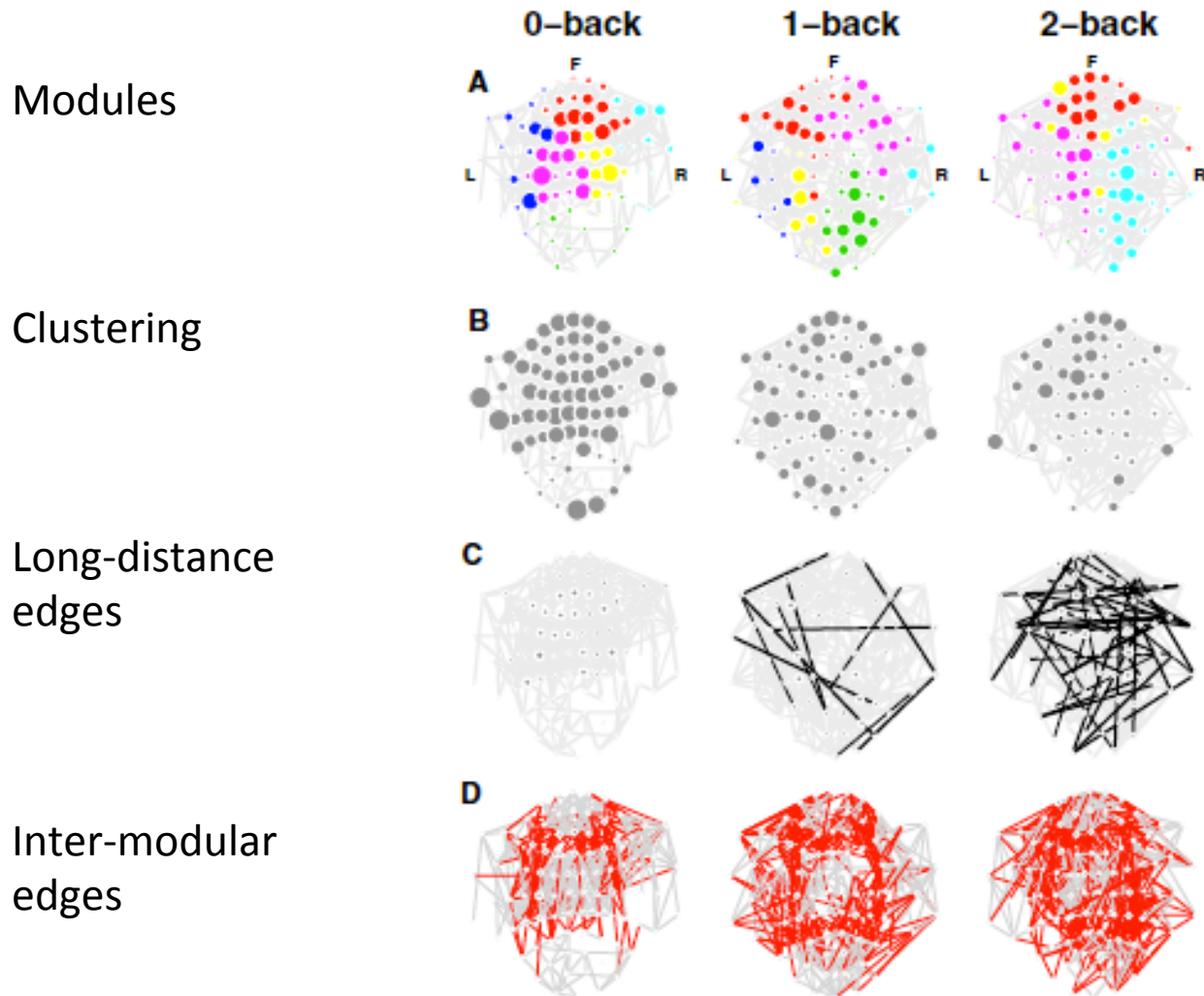


Global (neuronal) workspace theory predicts integrative processing will be required for conscious, effortful, cognitive functions

Dehaene et al (1998) *Proc Natl Acad Sci*

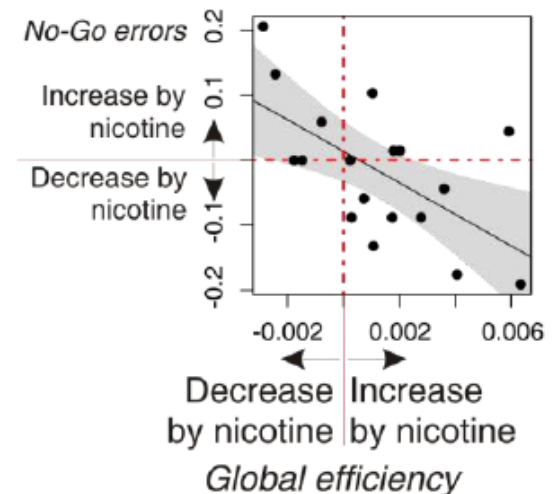
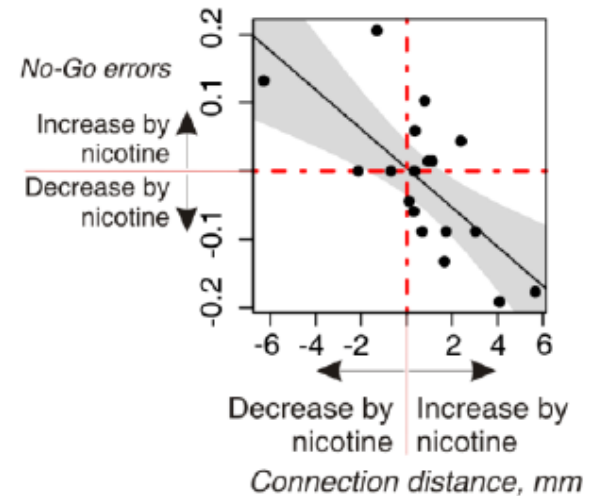
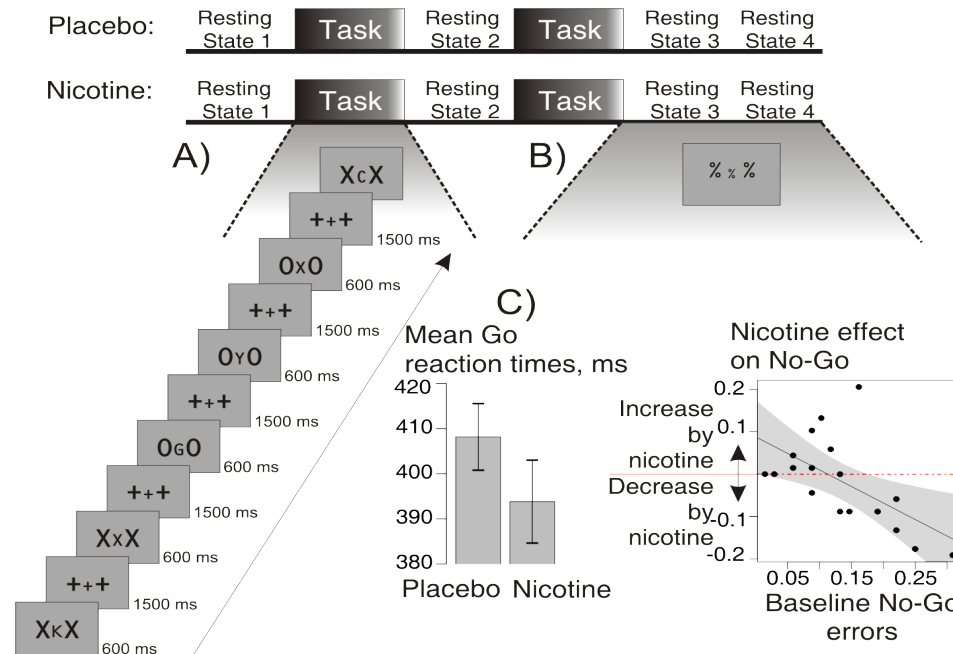
Baars (1993) *A cognitive theory of consciousness*

Working memory load “breaks modularity” and drives workspace re-configuration of functional brain networks

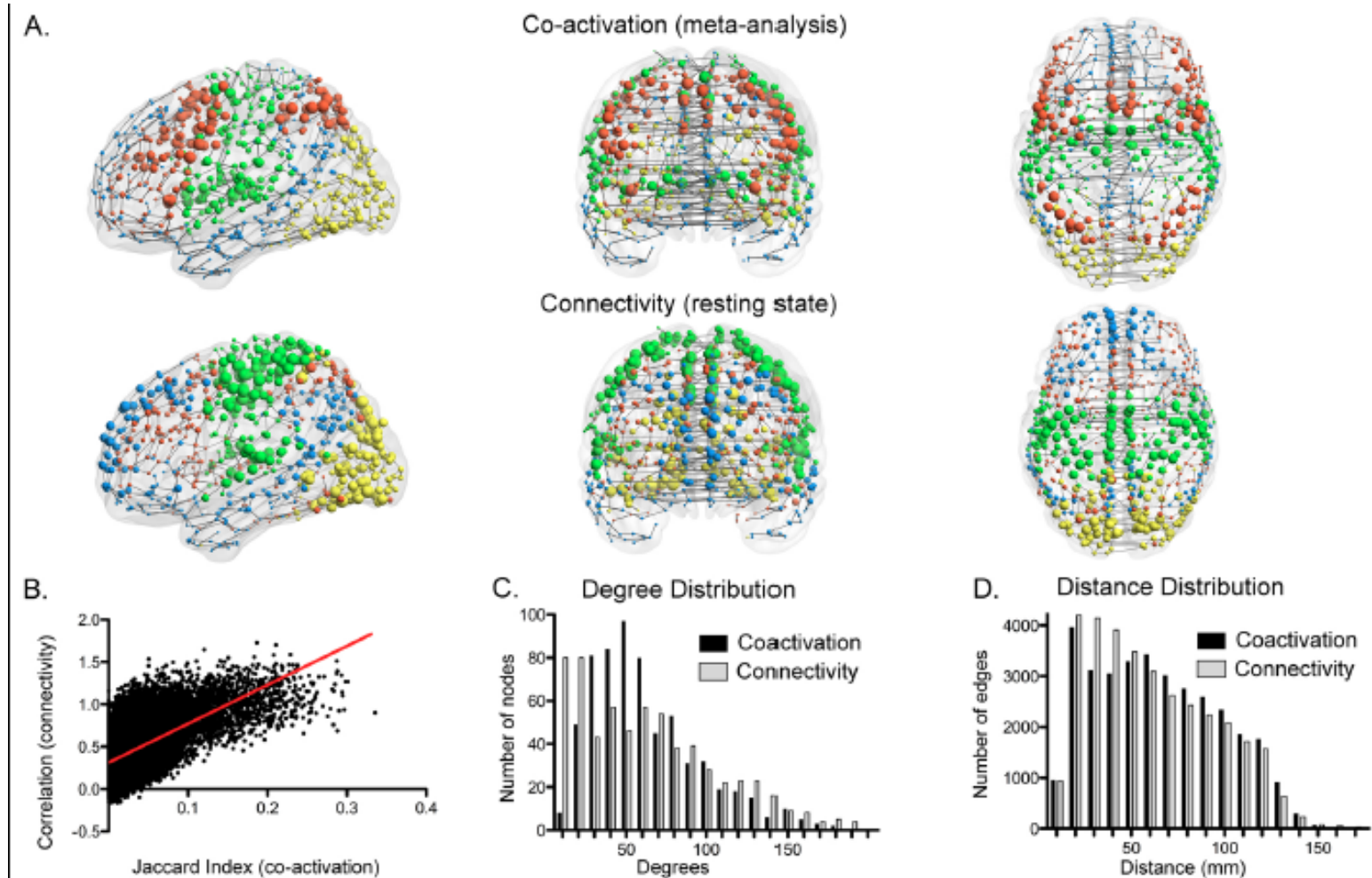


β -band frequency networks recorded using MEG in healthy volunteers performing N-back working memory task

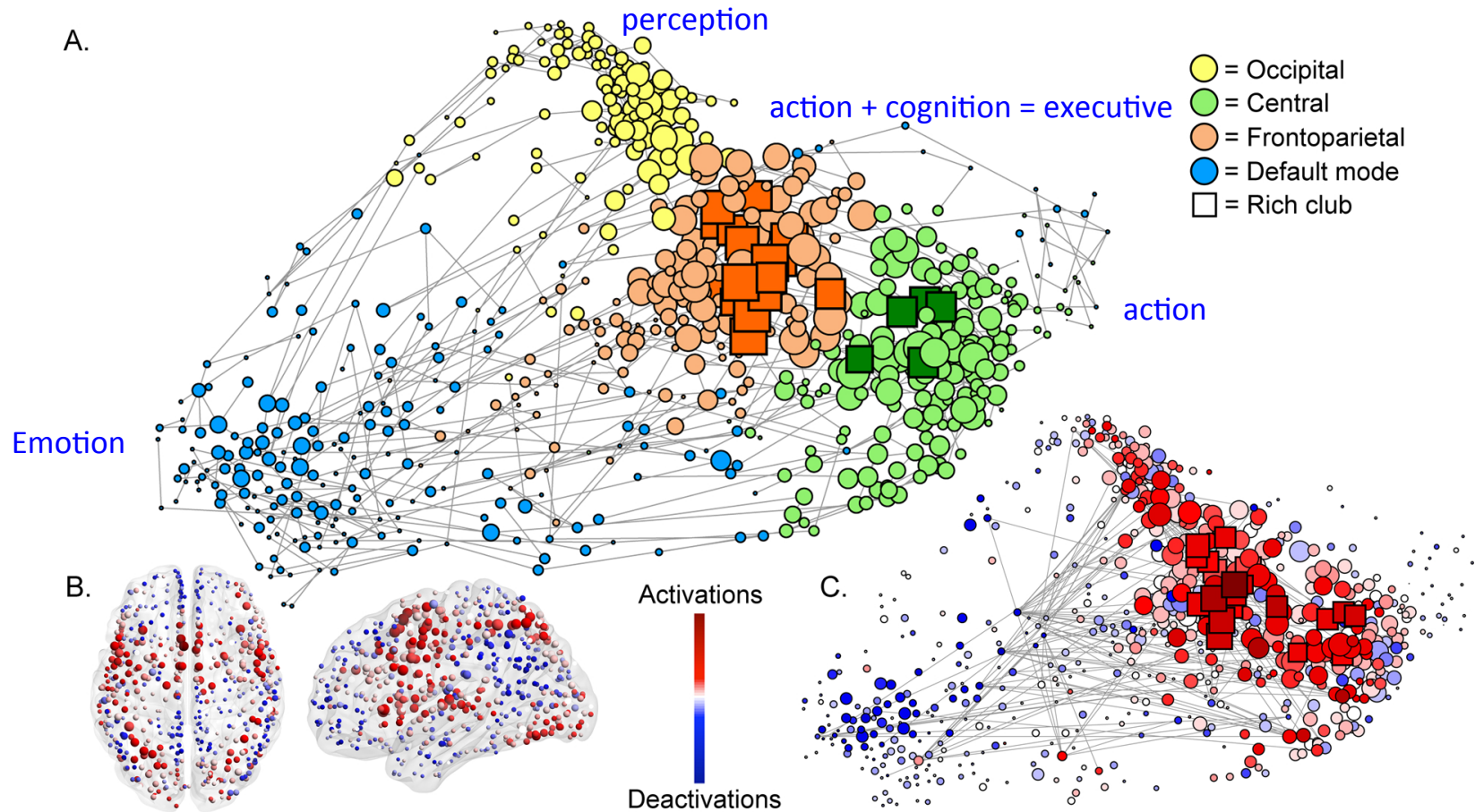
A drug that improves cognitive performance also increased the cost and efficiency of brain functional networks



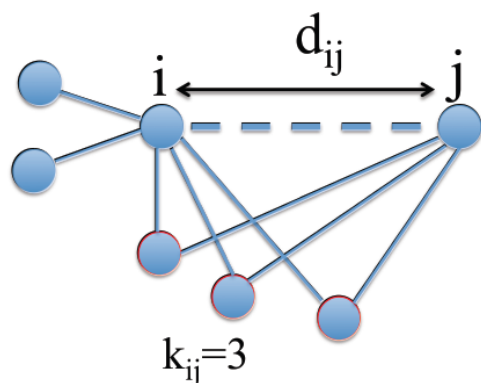
Functional brain networks at rest (correlation) and at work (coactivation)



The rich club of the human brain functional network is co-activated by diverse, executive tasks



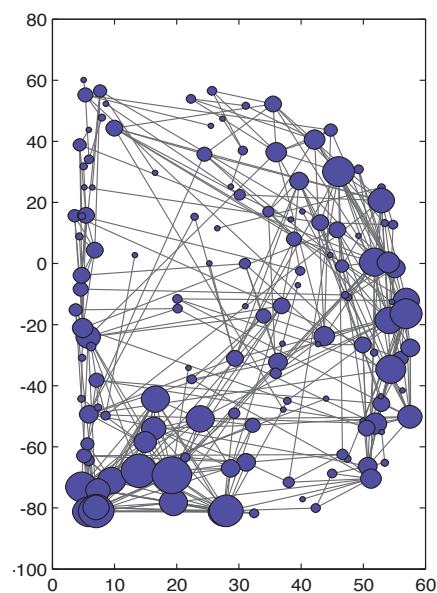
Generative models of distance-topology trade-offs can simulate fMRI network statistics



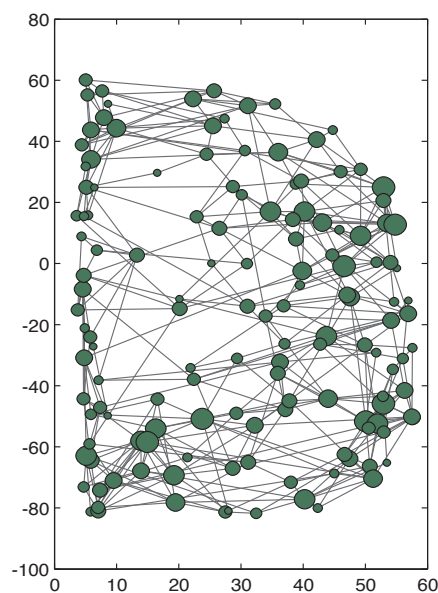
The probability of a connection between two nodes was modelled as:

- 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

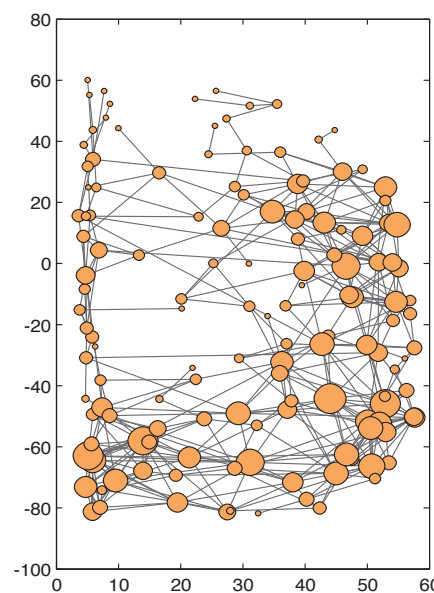
Vertes et al (2012) *Proc Natl Acad Sci*



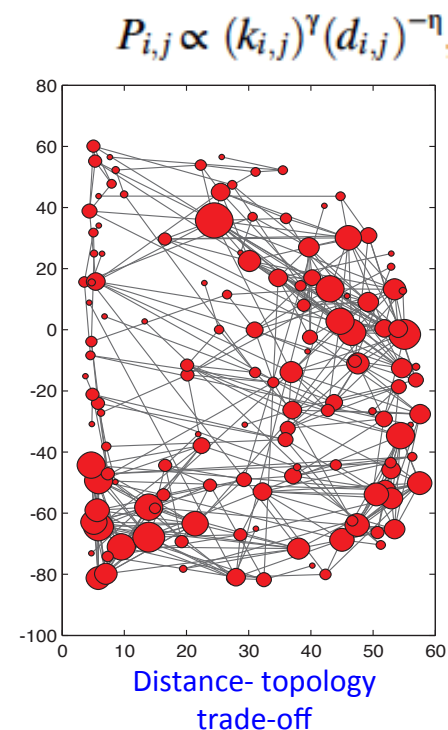
Brain



Distance only

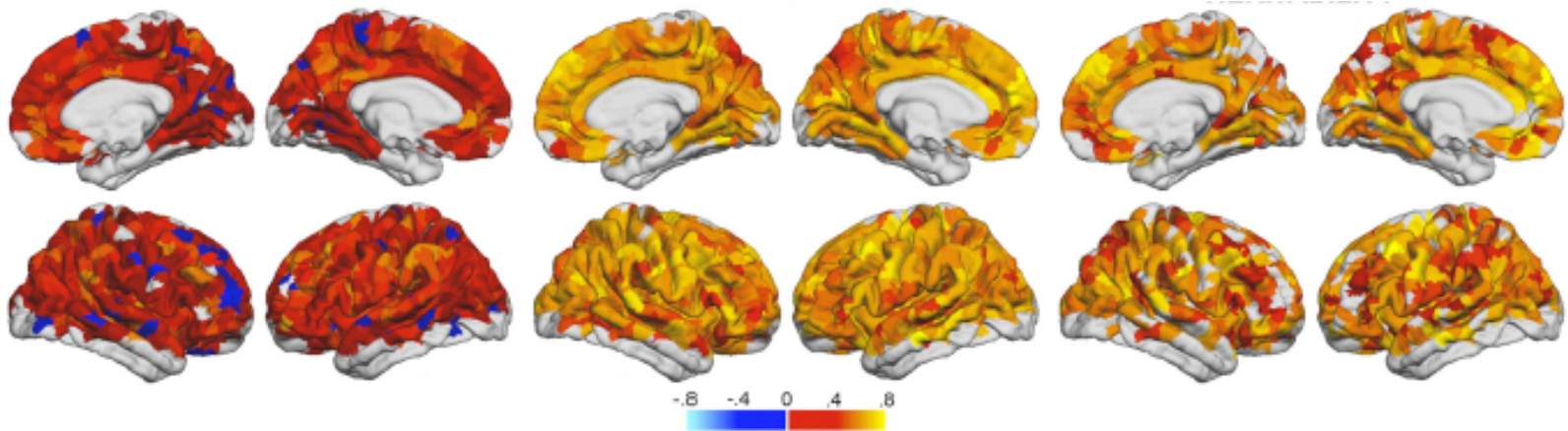


Topology only



Distance-topology
trade-off

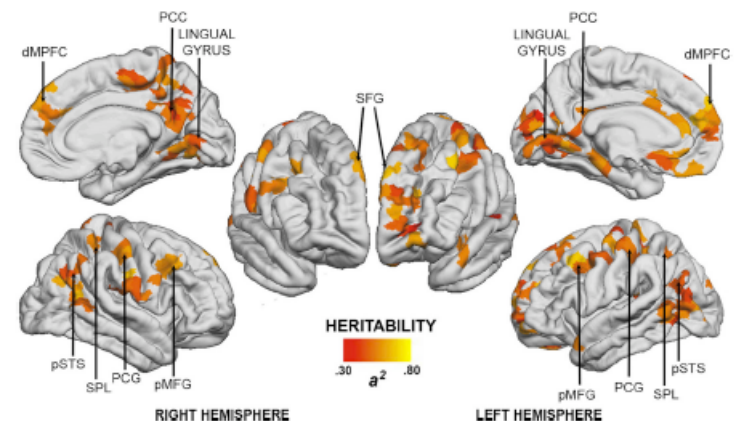
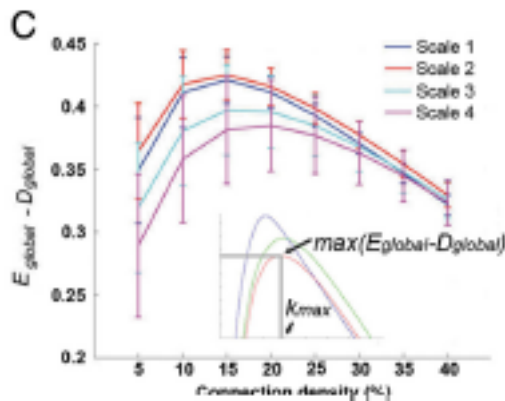
Has brain network organization evolved to optimise a trade-off between cost and efficiency?



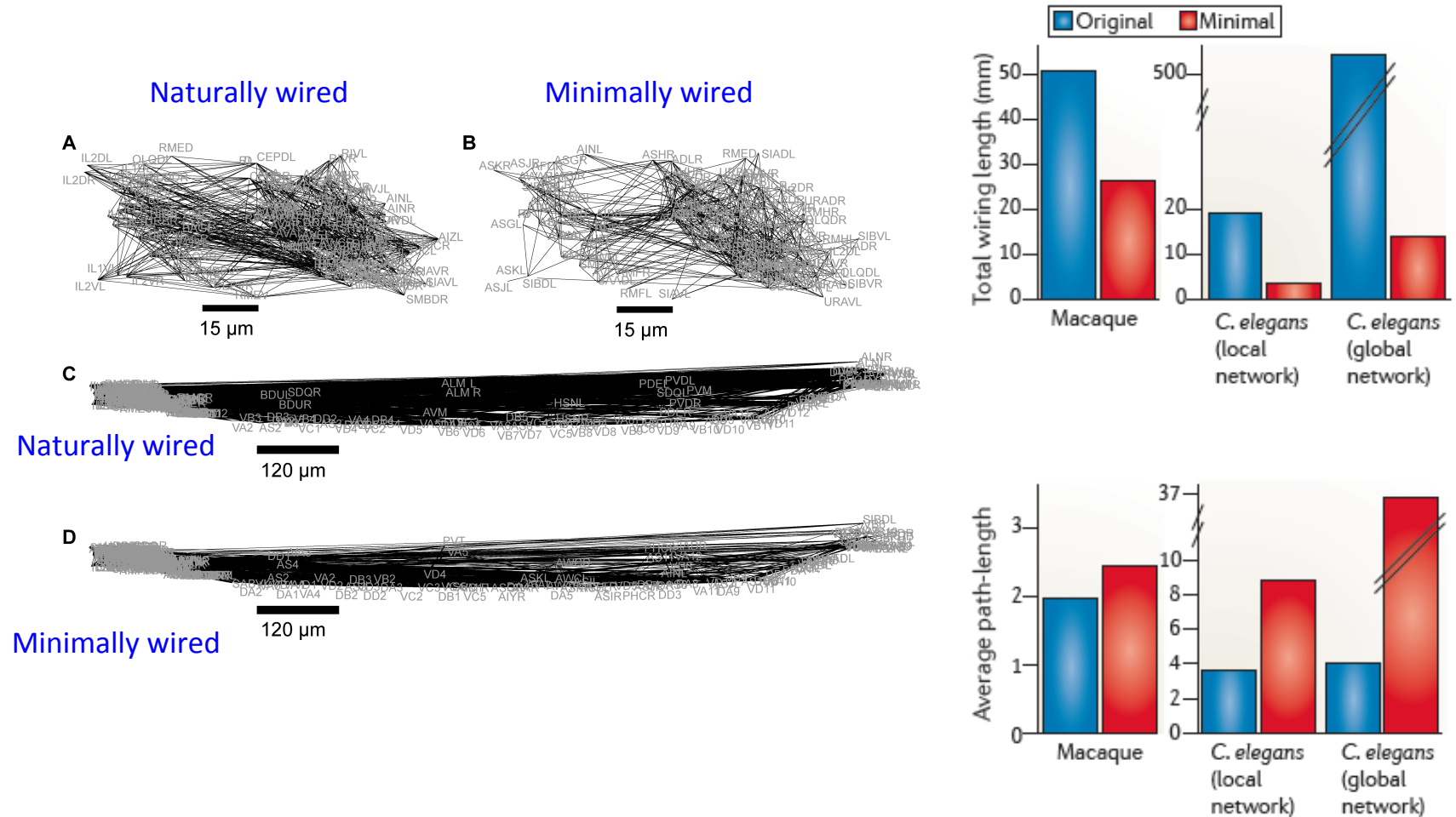
Similarity of
Non-identical Twins

Similarity of
Identical Twins

Heritability



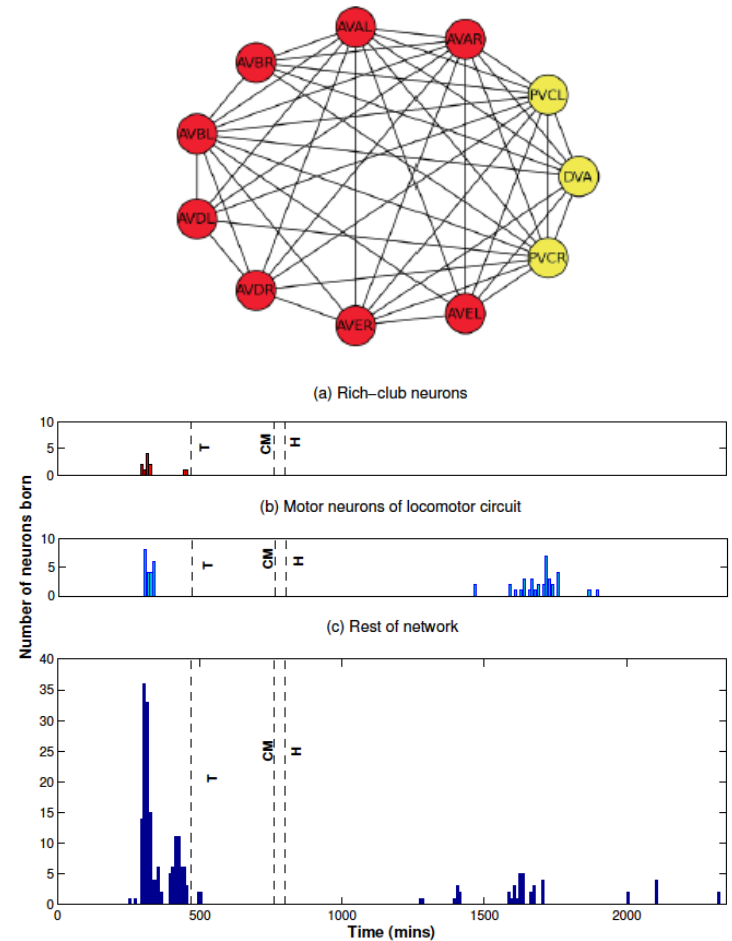
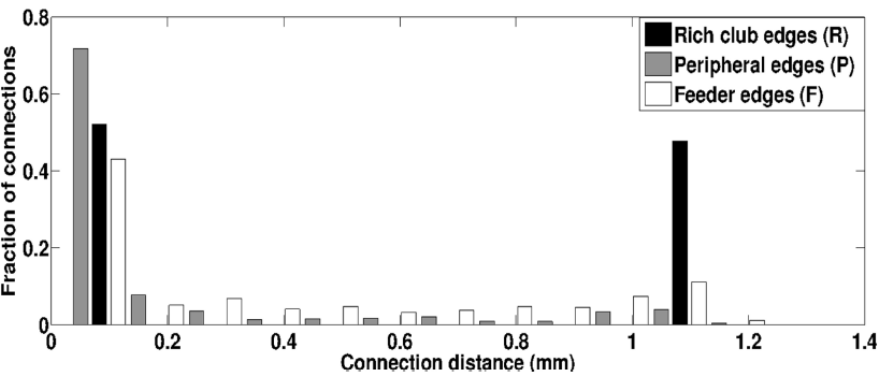
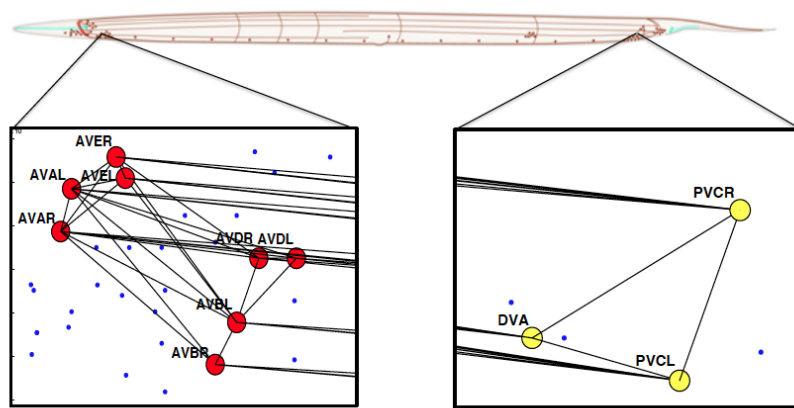
Strictly minimizing wiring cost of the *C. elegans* connectome adversely impacts topological efficiency



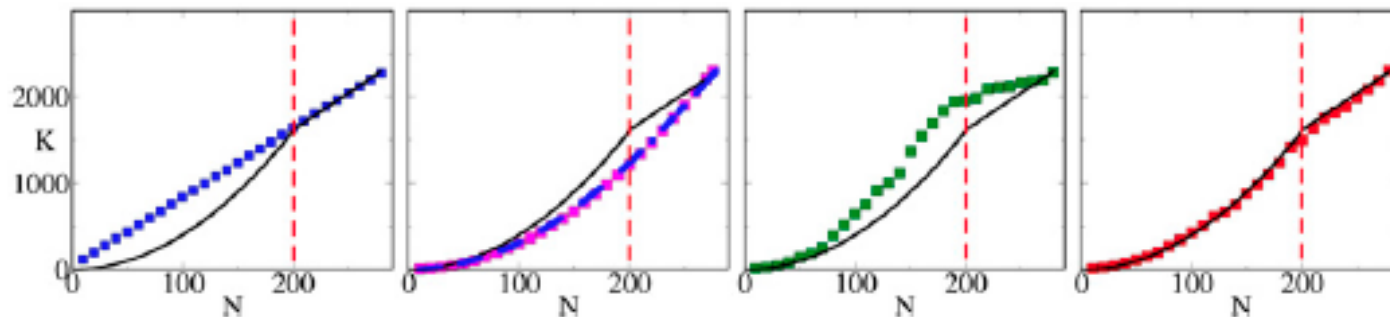
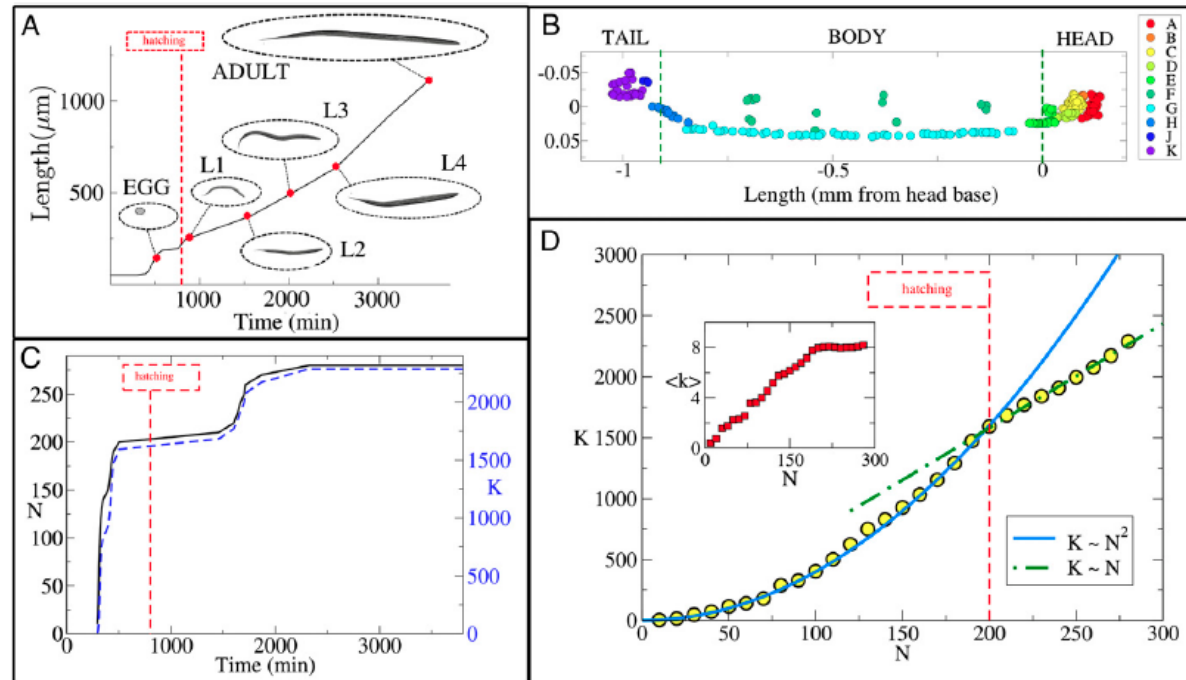
Kaiser & Hilgetag (2006) *PLoS Comp Biol*

Bullmore & Sporns (2012) *Nat Rev Neurosci*

The rich club of the worm brain: a high cost / high value system for coordinated movement



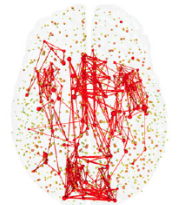
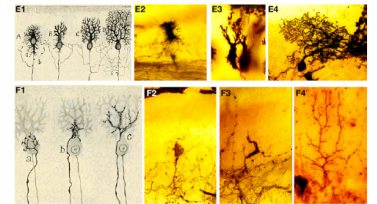
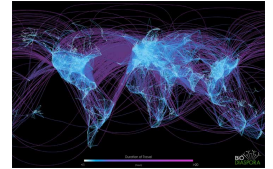
Economically modeled growth of the *C. elegans* connectome



$$\Pi_{i \rightarrow j}^{\text{ESTG}} = \frac{h_j}{h_{\max}} e^{-\frac{d_{ij}(t)}{b}},$$

Some economical principles of brain networks

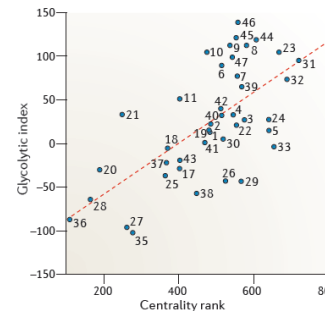
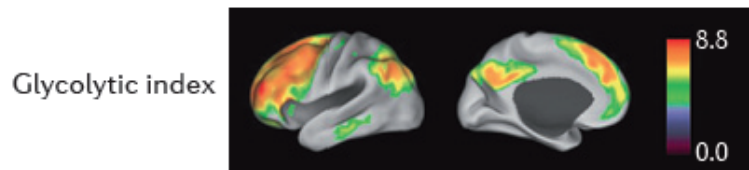
- Brain networks are spatially embedded and topologically complex (like airline networks)
- The high costs of brain networks are nearly (but not strictly) minimized
- Some of the most expensive topological features of brain networks are hubs, often comprising rich clubs
- The high costs of hubs-and-clubs 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

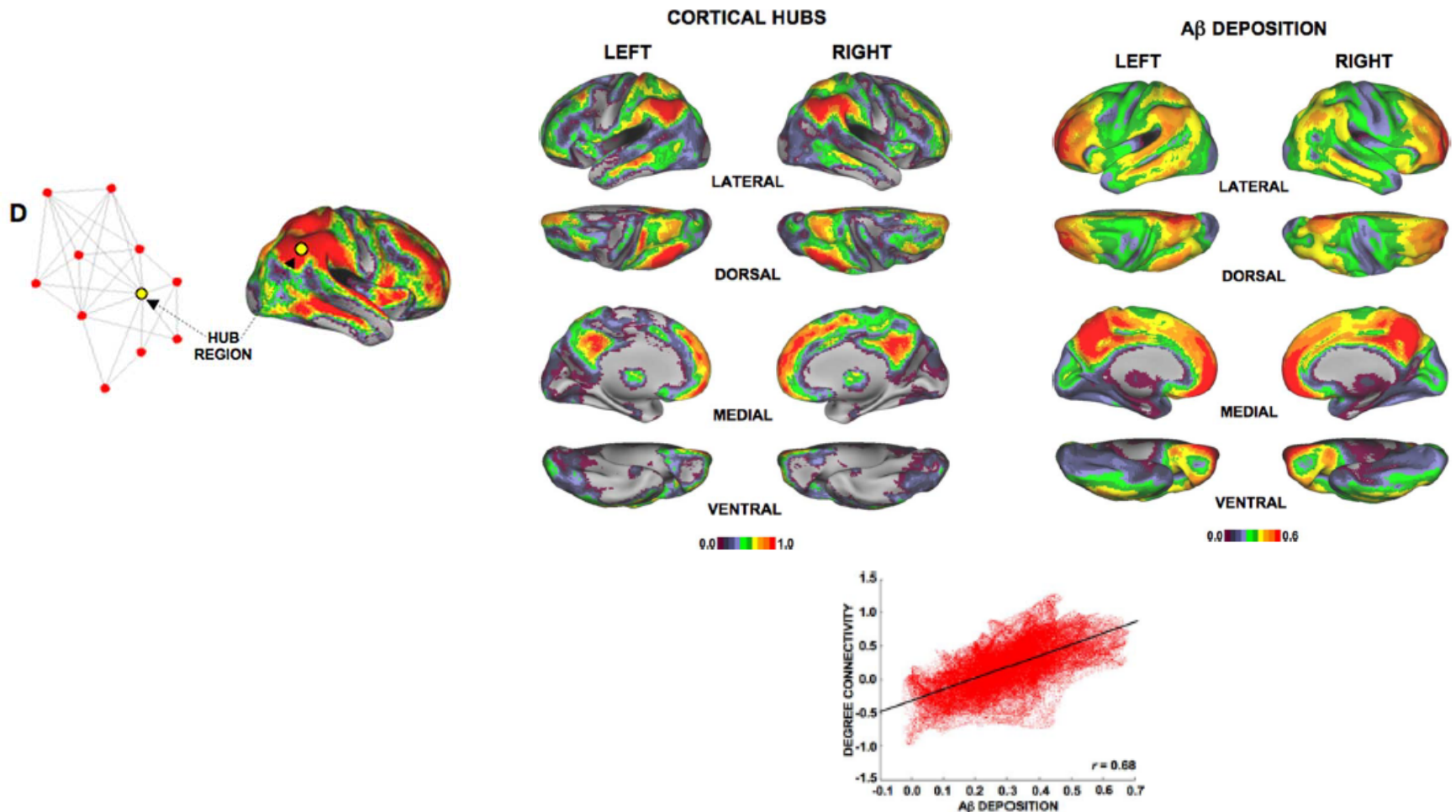
How do economical principles of the connectome matter to psychiatry and neurology?

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

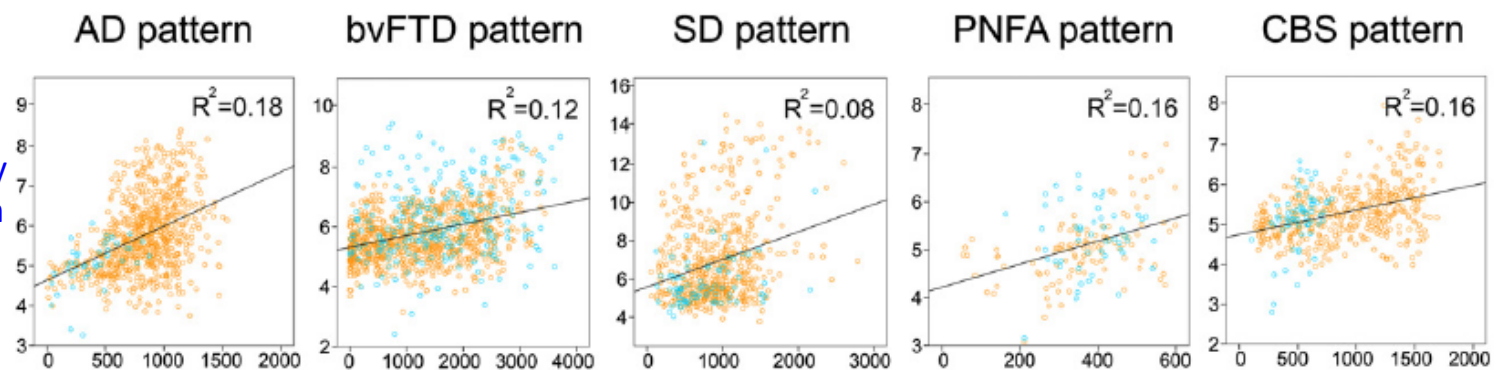
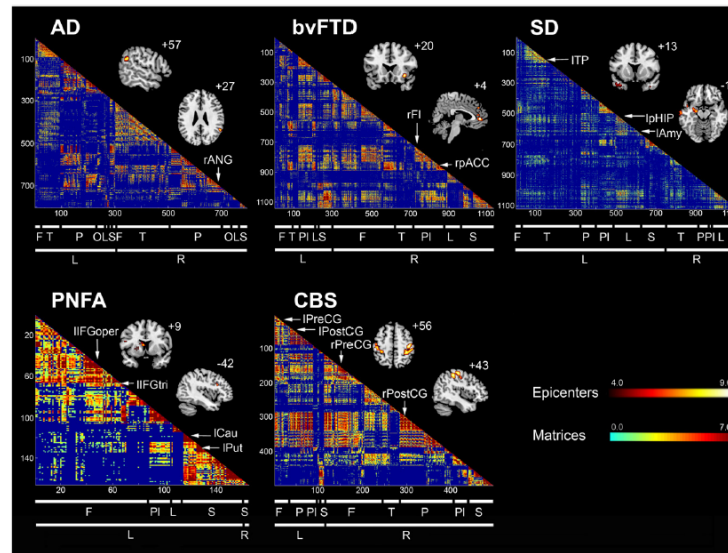


- High value network components are most likely to cause functional deficits, or symptoms, if lesioned
- Therefore, high cost / high value components of the connectome may be central to *many* brain disorders

The hubs of brain networks are most vulnerable to amyloid deposition in Alzheimer's disease

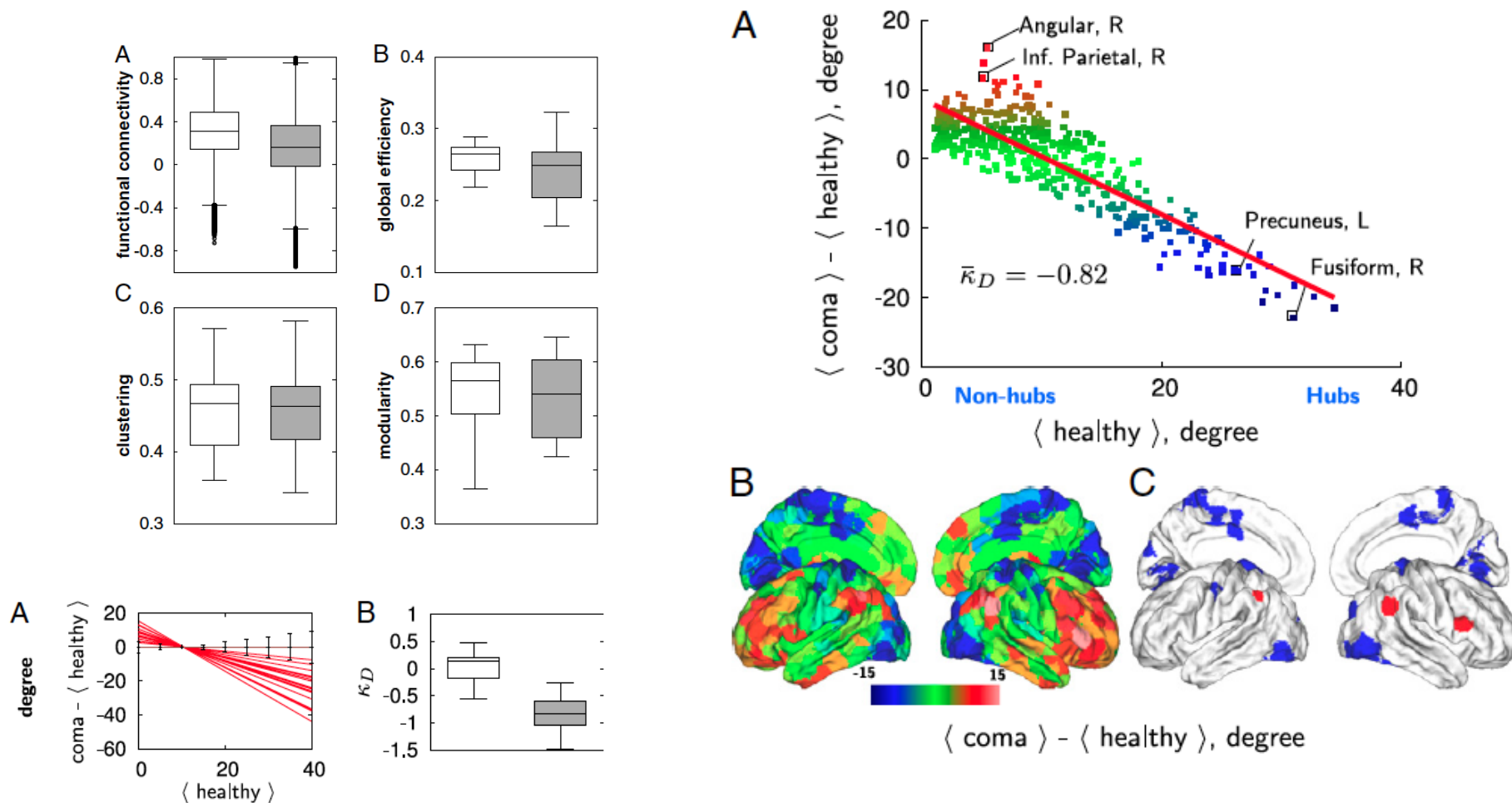


Grey matter atrophy in neurodegenerative disorders impacts hubs preferentially and may propagate trans-synaptically

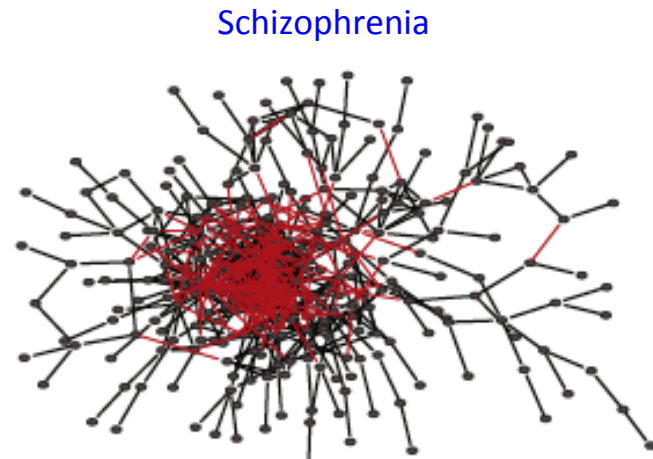
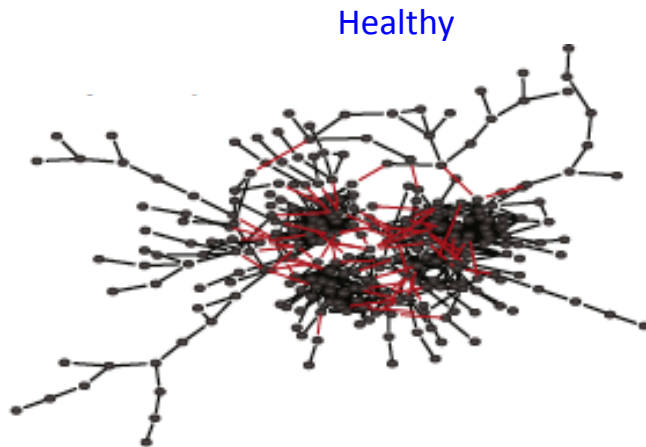
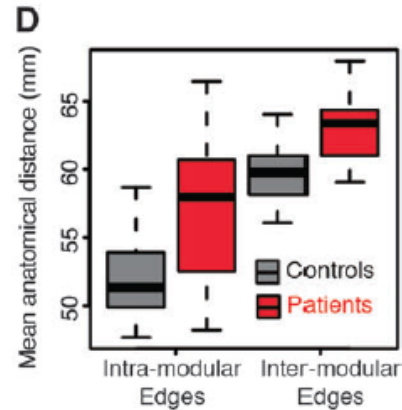
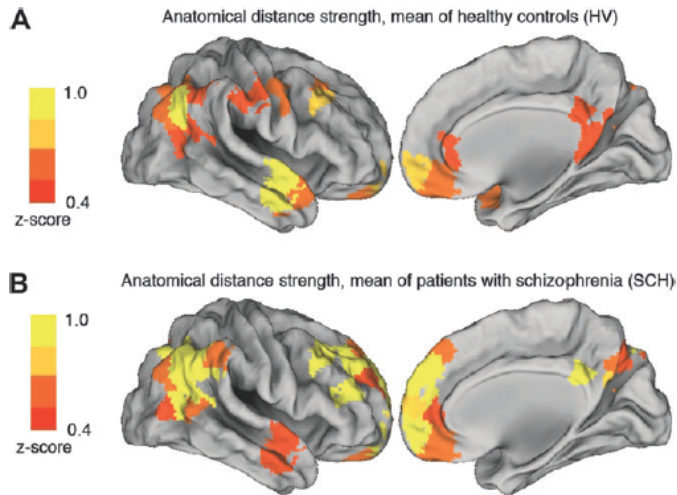


➔ Increasing weighted degree in healthy fMRI networks

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



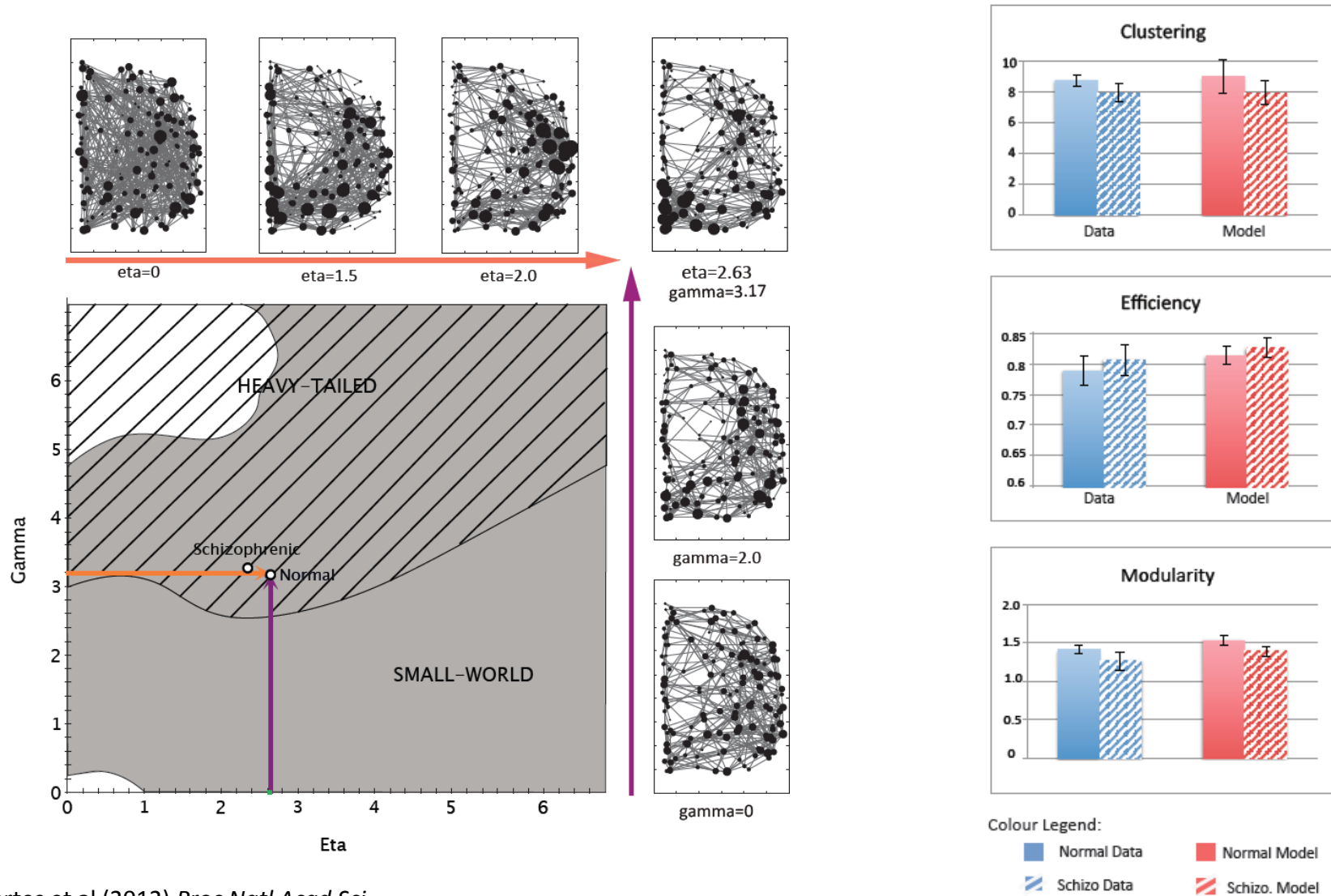
In schizophrenia, greater-than-normal long distance connections to hubs “break modularity”

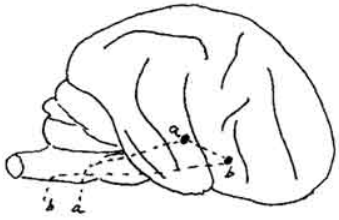


Alexander-Bloch et al (2012) *Cereb Cortex*
Alexander-Bloch et al (2012) *NeuroImage*

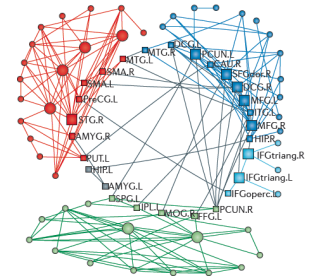
▣ Intra-modular edges
▣ Inter-modular edges

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

Many Thanks!

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- Vincenzo Nicosia
- Vito Latora
- Trevor Robbins
- Bill Schaffer
- Manuel Schroeter
- Olaf Sporns
- Christiane Thiel
- Emma Towlson
- Nicolas Crossley
- Petra Vertes

Human Brain Project, NIBIB/NIMH
NIH/Cambridge PhD Program



wellcometrust

