Mesoscopic Structure of the Resting-State Small-World Brain Network

LCBN
Laboratory for Complex Brain Networks

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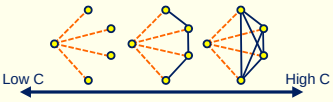
Introduction

Small-world networks are a class of networks that exhibit (a) efficient long-distance communication and (b) tightly interconnected local neighborhoods. In recent years, network theory-based examinations of neuroimaging data have demonstrated that structural and functional brain networks exhibit small-world properties. However, such analyses are often based on region-based networks with ~90 nodes corresponding to regions of interest (ROI), providing only a macroscopic representation of the brain network with limited spatial localization of important nodes. For a finer mesoscopic representation of the brain network, a voxel-based network can be constructed with each voxel treated as a network node, enabling more precise spatial localization of important nodes in a 3D brain space. The goal of this work is to demonstrate advantages of modeling the functional connectivity network as a voxel-based network in comparison with a region-based network. To do so, the same resting-state fMRI data were used to construct region-based networks and voxel-based networks.

Metrics for Small-World Networks

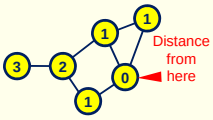
Clustering coefficient (C):

A measure of tight local interconnection



Path length (L):

A measure of efficient long-distance communication
→ Average steps between two nodes



Efficiency:

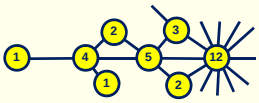
Alternative metrics to C & L, scaled from 0 (least efficient) to 1 (most efficient)
- Local efficiency E_{loc}: for tight local interconnection
- Global efficiency E_{glob}: for efficient long-distance communication

Small-world metric (σ):

An indicator of a small-world network, calculated relative to a random network.
- $\sigma > 1$ → small-world network
- $\sigma >> 1$ → • more local clustering
  • shorter path length

Degree (k):

Number of edges at each node



Degree distribution:

A histogram of degrees. It describes relative abundance of high or low degree nodes.

Resting fMRI Data Processing

The data set for this study consisted of fMRI experiment data from 5 subjects. For each subject, a series of 120 BOLD fMRI images was acquired during 5 minutes of resting. The time series data were spatially normalized and corrected for motion and physiological noises. From the pre-processed data, a region-based network and a voxel-based network were generated (see Fig 1).

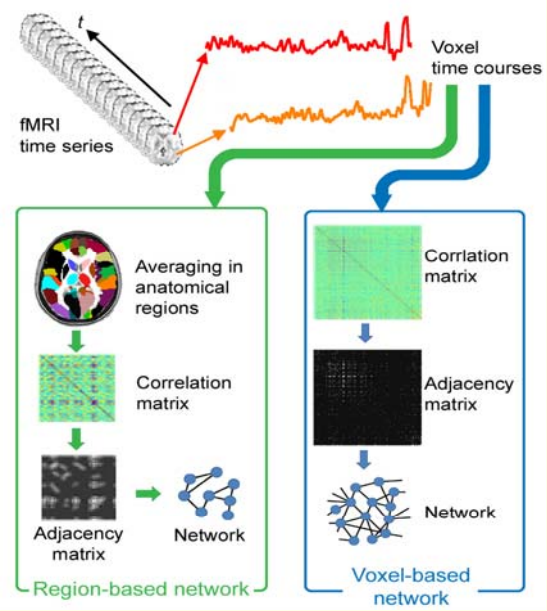


Fig 1
A schematic of generating a region-based network and a voxel-based network from an fMRI time series.

Results

Both region-based and voxel-based networks were small-world networks (σ>1), with the voxel-based networks exhibiting higher small-world metric (see Table 1). The degree distributions from both types of networks followed an exponentially truncated power law distribution, with a small number of high-degree nodes (see Fig 2).

Table 1
Average network characteristics of region-based and voxel-based networks

Network	# Nodes	C	L	σ
Region-based	103.2	0.40	5.05	5.3
Voxel-based	20474.4	0.24	4.86	9.0

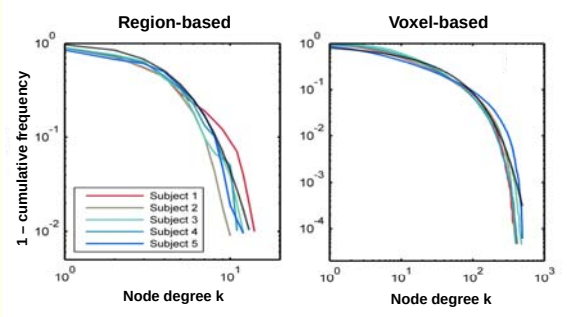


Fig 2
Degree distributions of region-based (left) and voxel-based (right) networks

However, the voxel-based networks allowed localization of important network nodes with finer granularity in a 3D brain space, allowing visualization of important nodes in a mesoscopic scale. A close examination of a voxel-based network revealed that some high-degree nodes and high-efficiency nodes spatially coincided (see Fig 3). It was also found that nodes with high degree and high efficiency occurred consistently in the similar brain areas across subjects (see Fig 4).

Fig 3
Surface plots of node degree (height) and efficiency (color-scale) of a voxel-based network

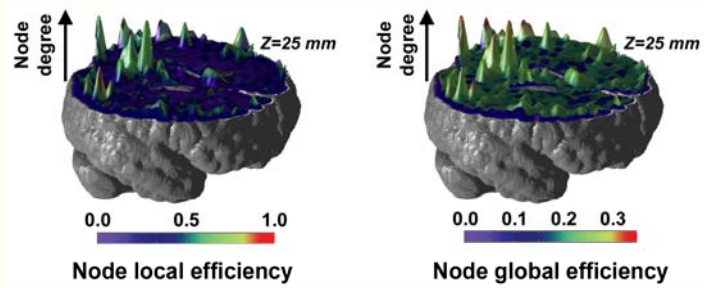
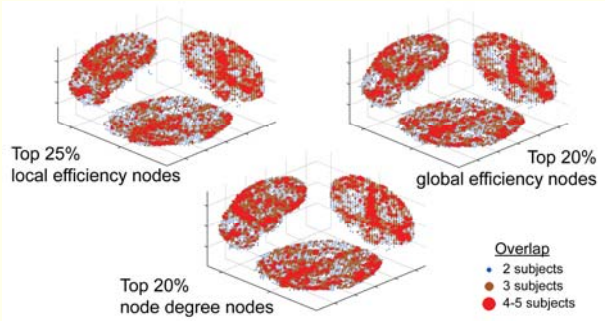


Fig 4
Population-based localization of high degree and high efficiency nodes. The maximum intensity projections of overlap across subjects are displayed in three orthogonal planes.



Conclusion

Our examination of resting-state fMRI data revealed small-world characteristics both in the region-based and voxel-based networks. The voxel-based networks were able to localize important network nodes with finer precision, producing a mesoscopic representation of the functional connectivity network. Moreover, we were able to localize the important nodes consistently occurring in similar areas across subjects. Based on these findings, we conclude that voxel-based networks are highly desirable.

Supported by:
Wake Forest University (Kulynych Memory and Cognition Research Center, GCRC (RR07122), Translational Science Institute)
National Institute of Health (NS 042658)