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Controllability of Structural Brain Networks in Dementia

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Abstract

The dynamics of large-scale neural circuits is known to play an important role in both aberrant and normal cognitive functioning. Describing these phenomena is extremely important to understanding of the aging processes and of the evolution of neurodegenerative diseases such as Alzheimer's Disease (AD). Modern systems and control theory offer a wealth of methods and concepts which can be easily applied to facilitate an insight into the dynamic processes governing disease evolution at the patient level, treatment response evaluation and revealing some central mechanism in a network that drives the progression of these diseases.

Introduction

Fusing modern network theory and control strategies yields a novel transformational paradigm in dementia research. One research direction is determining the leader nodes in disease networks, which can be directly manipulated via external inputs to influence the overall network trajectory and simulate the dynamic progression of the disease.

Certain areas of the brain or nodes in the connectivity graph (either structural or functional) can act as "drivers" which can move or "drive" the system (brain) into specific states of action. To determine these areas we conduct a novel application of "exact controllability" to determine the minimum set and the location of driver nodes in brain networks in various stages of cognitive impairment. Our results, applied on structural brain networks in dementia, suggest that this novel technique can accurately describe the roles of different brain regions in controlling the trajectories of brain networks, and show the transition of some driver nodes and the conservation of others in the course of this disease.

Main Objectives

1. Conduct a novel examination of the exact controllability of structural brain networks with various degrees of cognitive impairmentin a computationally efficient manner.
2. Determine the disease leader nodes by relying only on the network structure (algebraic multiplicity of system's matrix) to determine the location of a minimum set of driver nodes.
3. Identify differences and similarities between the controllability of various networks, which could be useful for early diagnosis and perhaps inform the targeting of a therapeutic solution to different brain regions.

Materials and Methods

We examine 249 subjects with FDG-PET and T1-weighted MRI images consisting of 68 control, 111 mild cognitive impairment (MCI) and 70 Alzheimers disease (AD). We consider only 42 out of the 116 from the AAL in the frontal, parietal, occipital and temporal lobes. In a departure from previous work on controllability of disease networks, we determine the disease leader nodes by relying only on the network's structure, particularly the graph distances between the nodes, and not on the existing connection weights.

Mathematics

The brain is represented as a graph network with N nodes, system matrix A , input matrix of nodes to be controlled B, and a vector u of controller inputs.

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

For an undirected graph with arbitrary weights, the minimum number of driver nodes N_D is equal to the maximum algebraic multiplicity of the eigenvalues of A in (1), i. e.,

$$N_D = max_i[\rho(\lambda_i)], \tag{2}$$

$\rho(\lambda_i)$ is algebraic multiplicity of λ_i. This condition is valid for general undirected networks when A is a diagonalizable matrix. There are fewer driver nodes than nodes in the system; mathematically we have $N_D < N$ for any nontrivial network. Inputs to the driver nodes can lead the others' states towards any desired reference evolution.

Each node i has a certain number of links k_i, called its "structural degree". Structural degree does not account for link weights. Denote the average degree of the network as $\langle k \rangle$, defined as

$$\langle k \rangle = \frac{1}{N} \sum_{i=1}^{N} k_i \tag{3}$$

We will also observe the average degree of driver nodes, to compare to the average degree in the network. The average degree of driver nodes in the network is denoted as $\langle k_D$. Also we consider the "controllability density" of the network. This is a measure $0 < \delta_D \leq 1$ which shows which fraction of the nodes are drivers. In other words we have:

$$\delta_D = \frac{N_D}{N} \tag{4}$$

Controllability density is useful to observe how the network will become more difficult to control as the disease progresses.

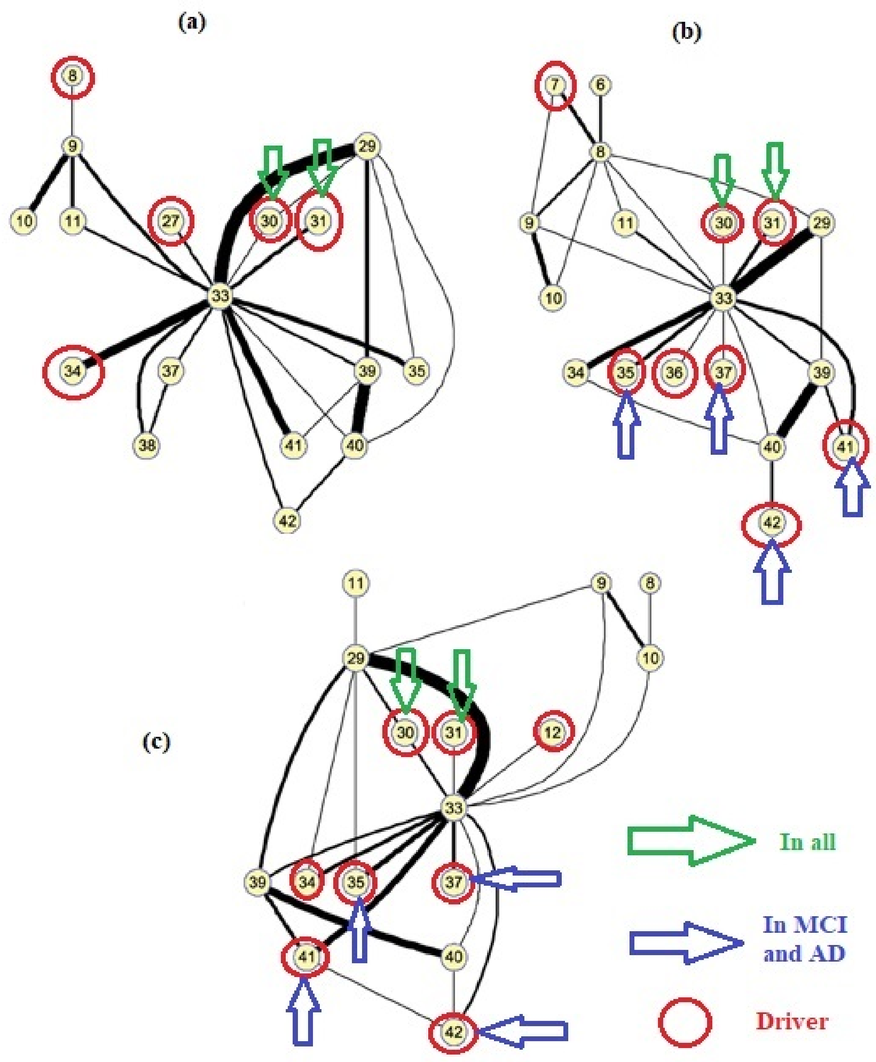

Figure 1: Leader nodes for structural data. (A) Controls, (B) Mild cognitive Impairment (MCI), (C) AD subjects. Leaders are highlighted by a red circle. Colored arrows highlight drivers which are shared between all networks, and which drivers are present in both MCI and AD networks.

Results and Conclusions

Network	$\langle k \rangle$	$\langle k_D \rangle$	δ_D
Control	2.882	1.200	0.294
MCI	2.833	1.250	0.444
AD	3.125	1.875	0.500

Table 1: Network statistics for Control, MCI, and AD

We show that there are two common leader nodes in the temporal lobe for all structural networks and a decreasing number of leader nodes from MCI to AD being located in the temporal and frontal lobe. Table 1 shows the average degree of nodes in each network, average degree of driver nodes, and the controllability density of the networks for Control, MCI, and AD.

- Driver nodes tend to have a below-average number of links.
- The fraction of nodes in the network which are driver nodes increases with disease progression; making the network more difficult to control.
- There are two leader nodes in the temporal lobe which are common in all three networks – controls, MCI, and AD.
- For controls, MCI, and AD, all but one driver node are located in the temporal lobe with the rest in the frontal lobe.
- Both MCI and AD brain networks share four common driver nodes located in the temporal lobe.

References

[1] L. Xiang abd F. Chen, W. Ren, and G. Chen. Advances in network controllability. *IEEE Circuits and Systems Magazine*, 19:8–32, 1 2019.

[2] S. Gu, F. Pasqualetti, M. Cieslak, Q. Telesford, A. Yu, A. Kahn, J. Medaglia, J. Vettel, M. Miller, S. Grafton, and D. Bassett. Controllability of structural brain networks. *Nature Communications*, 6:1–10, 1 2015.