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Hub recognition for brain functional networks by using multiple-feature combination☆

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A B S T R A C T

Hubs in complex networks can greatly influence the integration of network functions, and recognition of hubs helps to better understand the interaction between pairs of network nodes. This paper proposes a new hub recognition method with multiple-feature combination for the brain functional networks constructed by resting-state functional Magnetic Resonance Imaging (fMRI). Three single-feature methods, including degree centrality, betweenness centrality and closeness centrality, are used to calculate hubs of the brain functional network separately. For reordering the nodes, a composite equation is constructed based on the three recognition parameters. Network vulnerability and average shortest path length are used to evaluate the importance of the hubs recognized by above four methods. Experimental result demonstrates that, the hubs recognized by multiple-feature combination have more significant differences from ordinary nodes than those by single-feature methods, and they have an important impact on the global efficiency of brain functional networks.

1. Introduction

Many complex systems in the real world can be characterized as networks. Individuals of complex systems are often taken as nodes, and interactions between individuals are treated as edges of networks [1]. Complex network, a new discipline for studying complex systems, has attracted much attention in different disciplines of scientific research personnel in the past few years [2,3]. The brain is one of the most complex organs of human in structure and function, and could be regarded as a complex structure network composed of multiple neurons, neuron clusters and multiple brain regions [4]. Neurons in each part cooperate with each other to complete various functions of the brain [5]. Recent functional neuroimaging studies have shown that the brain can be divided into several spatially separate, functionally distinct sub-regions [6]. The different functional sub-regions are abstracted into corresponding nodes, and the connections between the brain sub-regions are considered as the edges between nodes [7,8]. As a result, all of these nodes and edges will make up a brain functional network which is comparable to many other complex networks [9].

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Network analysis helps to better understand the relationship between functional sub-regions and their topological roles in brain networks. Hence it has been applied to structural and functional brain networks derived from neuroimaging data to quantify the topological characteristics of the network using complex network metrics, such as clustering coefficient, the shortest path length, small-worldness, and node centrality [10]. Although these metrics provide useful information regarding global and local properties of brain networks, they do not provide any information about the intermediate scale of the network [11]. Additionally, it is notable that most of the brain diseases are later proved to be abnormalities of one or part of the brain areas, no abnormalities of the whole brain [12]. Like complex networks, brain networks in nature often show hierarchical, modular organization. As such, hubs are generally characterized by their high degree of connectivity to other regions and their central placement in the network [13]. Importantly, they play indispensable roles in brain functional networks, and some features or abnormalities of them can be preliminaries used to diagnosis cerebral damages and diseases.

In the last decade, complex network theory has been more prevalent in brain networks, and thereby many scholars started studying the importance of major nodes in brain functional networks [14]. Sporns et al. assumed betweenness centrality and closeness centrality can recognize the hubs of human brain networks, and analyzed its functions in the brain functional network and structure network [15]. Van den Heuvel et al. utilized the modular method to recognize the nodes in the human brain network, and apply the recognized hubs to cognitive function [11]. Geetharamani et al. have taken different node centrality indicators to analyze the importance of nodes in the human brain network [16]. On the one hand, these above scholars did not give a comparison of the importance of nodes from the entire network, and they merely used a single-feature to recognize the hubs. On the other hand, the recognition of hubs can lay the foundation for the next simplification which helps to reduce the feature dimension of whole brain networks [17], and more advanced theories such as machining learning can be introduced into this field of investigation [18].

Nowadays, hubs recognition methods of brain functional network are mainly based on degree centrality and based on betweenness centrality. Generally, these methods only complete the extraction, comparison and analysis of hubs, while it is not common to combine different hub recognition methods to sort nodes from multiple dimensions. Thus, this is a significant limitation to the recognition of hubs. Gattal et al. recognized isolated handwritten digits using combination of multiple-feature method, which has higher recognition rates comparing with traditional methods [19]. Burghouts et al. have applied multiple-feature methods into human actions that can detect 48 kinds of actions from simple actions such as walk to complex actions such as exchange [20]. These findings show that the combination of multiple-feature method usually can greatly enhance the recognition rates in different research directions. However, the multiple-feature combination has not been greatly used in brain network researches. In this paper, a new hub recognition method with multiple-feature combination is proposed to study the brain functional networks constructed by resting-state functional Magnetic Resonance Imaging (fMRI). On this basis, three single-feature methods are used simultaneously to calculate the values of node centrality separately, and a composite equation is constructed based on the single-feature recognition parameters. The nodes of brain functional network are reordered by means of the proposed method, in which network vulnerability is taken as an evaluating indicator of hub recognition.

The rest of the paper is organized as follows. In Section 2, the basic theory on hub recognition is presented. Section 3 introduces the preliminary work of this research. The experimental results of single-feature method and multiple-feature combination are given in Section 4, respectively. Section 5 discusses the importance of hubs via network vulnerability and average shortest path length. Finally, Section 6 concludes all the paper and suggests a direction for future work.

2. Basic theory

2.1. Recognition parameters

Recently, some studies have been carried out on the importance of nodes in complex networks [21,22]. Freeman summarizes the relevant research systematically and gives three main evaluation features about the importance of nodes respectively from different sides [23], including degree centrality, betweenness centrality and closeness centrality. However, there is not any uniform standard and method for defining nodes, especially the core nodes.

The calculation of degree centrality is based on the degree itself, and the number of adjacent edges k_i of node v_i is called the degree of the node. The more nodes link with node v_i, the greater the degree of node v_i, which means node v_i has a higher priority in the network. It is mainly used to measure local importance of nodes in the network. The nodes with high degree are likely to be important transportation hubs in brain networks, and they usually undertake a great deal of information transfer and conversation work. Therefore, the degree is a hub recognition parameter with higher application frequency. Its formula for node i is as follows:

$$K_i = \sum_{j=1, j\neq i}^{N} k_{ij} \tag{1}$$

where N indicates the number of nodes in the network; k_{ij} is the number of edges between node i and node j.

Betweenness centrality is defined as the fraction of shortest paths between any pair of nodes traveling through the node. It is not merely can measure the global characteristics of nodes in the network, but also can reveal the importance of the brain nodes in the information transfer process of the whole network, which highlights its global control capability and

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