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Default network and intelligence difference

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***Abstract*— In the last few years, many studies in the cognitive and system neuroscience found that a consistent network of brain regions, referred to as the default network, showed high levels of activity when no explicit task was performed. Some scientists believed that the resting state activity might reflect some neural functions that consolidate the past, stabilize brain ensembles and prepare us for the future. Here, we modeled default network as undirected weighted graph and then used graph theory to investigate the topological properties of the default network of the two groups of people with different intelligence levels. We found that, in both groups, the posterior cingulate cortex showed the greatest degree in comparison to the other brain regions in the default network, and that the medial temporal lobes and cerebellar tonsils were topologically separations from the other brain regions in the default network. More importantly, we found that the strength of some functional connectivities and the global efficiency of default network were significantly different between the superior intelligence group and the average intelligence group, which indicates that the functional integration of the default network might be related to the individual intelligent performance.**

I. INTRODUCTION

Scientists and engineers have been attempting to simulate human cognitive mechanisms to make artificial intelligent system that exhibits mental capabilities, including perception, action and motivation. One has been concerned primarily with the processes that how information is extracted from sensory inputs in artificial system and integrated over time to make decisions and then take actions. So, researchers have paid much attention to the dynamics when the system is required to make response to and interact with the external environment. Unfortunately, it seems that the progress is not exciting enough. An interesting question is what the artificial system does when it is idle. In other words, is it necessary to explore the significance of investigating the dynamics of the artificial system when the system is not explicitly engaged in the interaction with the external environment?

On the other hand, some scientists in cognitive and system neuroscience found that a consistent network of human brain regions showed high levels of activity when no explicit task was performed. They suggested that the human brain has a default or intrinsic mode of functioning [1], [2]. The default network is comprised of a set of brain regions, including medial prefrontal cortex, posterior midbrain regions, medial temporal lobes, lateral parietal cortex and so on. These brain regions show greater neural activity during passive states in comparison to a range of cognitive task states. Although there are some argues about cognitive functions of the default network [3], some investigators suggest that the brain's default network directly contribute to internal mentation that is largely detached from the external world, including self-reflective thoughts and judgments, conceiving the mental states of other peoples and envisioning the future to make up alternative decision and so on [2]. Additionally, researchers have found that the activity of the default network was damaged in some neuropsychiatric diseases, for example, Alzheimer disease, schizophrenia, in the coma and even vegetative state. Taken together, these findings suggested that the intrinsic activity of the default network could play important role in the human cognitive functions.

In the present study, we explored the associations between different human intelligent performance and the activity of the default network when the subjects were not required to do any explicitly cognitive tasks. Using the graph theory, we modeled the default network as weighted undirected graph for each subject and then investigated the network topology of the default network of the subjects.

II. MATERIALS AND METHODS

In the present study, we used the dataset that has been described previously to carry out the present study. For more details about the dataset and the data preprocessing, please refer to [4].

A. *Subjects and imaging protocol:*

Fifty-nine healthy right-handed subjects were included in this study. The Chinese Revised Wechsler Adult Intelligence Scale (WAIS-RC) were administered to all subjects for assessing individual intelligence. The subjects were divided into two groups on basis of the individual intelligence quotient score, i.e. the superior intelligence group (FSIQ $\geq$ 120, 15 women and 17 men) and the average intelligence group (120 $>$ FSIQ $>$ 90, 15 women and 12 men). There was not significant difference in age between the two groups. All subjects were recruited by advertisement, and they gave written informed consent. This study was approved by the ethical committee of Xuanwu Hospital of Capital Medical University.

MR imaging was acquired using a 3.0-Tesla MR scanner. Functional images were collected axially by using an echo-planar imaging sequence. During the resting state scanning, the subjects were instructed to keep still with their eyes

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TABLE I
SEED REGIONS FOR DEFAULT NETWORK

Brain region	Abbreviations	MNI Coordinates
Medial prefrontal cortex (anterior)	aMPFC	(-3,54,18)
Left superior frontal cortex	L.Sup.F	(-15,54,42)
Right superior frontal cortex	R.Sup.F	(18,42,48)
Medial prefrontal cortex (ventral)	vMPFC	(-6,36,-9)
Left inferior temporal cortex	L.IT	(-60,-9,-24)
Right inferior temporal cortex	R.IT	(57,0,-27)
Left parahippocampal gyrus	L.PHC	(-24,-18,-27)
Right parahippocampal gyrus	R.PHC	(27,-18,-24)
Posterior cingulate cortex	PCC	(-3,-48,30)
Retrosplenial	Rsp	(9,-54,12)
Left lateral parietal cortex	L.LatP	(-48,-69,39)
Right lateral parietal cortex	R.LatP	(48,-66,36)
Cerebellar tonsils	Cereb	(-6,-54,-48)

closed, as motionless as possible and not to think about anything deliberately.

B. Data analysis:

1) Preprocessing: Several preprocessing steps were used, including (1) slice timing; (2) realigning; (3) spatially normalizing; (4) spatially smoothing; (5) linear regression to remove the influence of head motion, whole brain signals and linear trends; (6) temporally band-pass filtered.

2) Region definition: We used *a priori* regions of interest (ROIs) to define the default network as previous studies [5]. The coordinates of *a priori* ROIs were obtained as shown in Table I. All of ROIs were defined as a spherical region with a radius of $6\mathrm{mm}$ at the center of the obtained coordinates of *a priori* ROI.

3) Individual functional connectivity graph: After extracting the 13 ROIs for each subject, we computed the functional connectivity between each pair of the 13 ROIs. The resulting correlation then was transformed to approximate Gaussian distribution using Fisher's r-to-z transformation $z = \frac{1}{2}\ln\frac{1+r}{1-r}$. Thus, for each subject, we obtained a 13×13 matrix, with each element representing the strength of functional connectivity between the corresponding two regions within the default network. Specifically, the diagonal element was self-correlation of the corresponding region. So, for computational convenience, we set all the diagonal elements to 2, whose approximate correlation was 0.964.

In the present study, all functional connectivities within the default network were significantly greater than 0 (P< 0.05, FDR corrected), which was consistent with previous studies [5]. In addition, although we found that some of functional connectivity in some subjects were negative, the negative functional connectivity accounted for less than 5% of the number of all the functional connectivity. To adopt the common used network measures to investigate the topological characteristics of the default network, we set the negative functional connectivity to 0. These allowed us to use the undirected weighted graph to model the default network. That is, the node of graph was used to denote the brain region within the default network, and the weight of the edge between two nodes was represented as the z-valued strength of functional connectivity between the corresponding two brain regions. Thus, we constructed a complete undirected weighted graph to model the topology of the default network for each subject.

4) Median functional connectivity graph: We intuitively investigated the average topology of the default network within each of the two groups. For more robustness, we used the median, rather than the mean, of z-valued strength of each functional connectivity to represent the average strength of the functional connectivity. Thus, we obtained a median functional connectivity graph separately for each group and then analyzed the network measures and topological architecture for the median functional connectivity graph of each group.

In graph theory, the degree s_i of a node i was the number of edges linking to the node, and was defined as [6]:

$$s_i = \sum_j w_{ij} \tag{1}$$

where w_{ij} denoted the weighted edge that connected node i with node j, that is, in the present study, the z-valued strength of the functional connectivity between brain region i and brain region j. The degree s_i can be used to quantify the extent to which the node was central in the graph.

To represent the architecture of the graph, we used Kamada-Kawai algorithm (fix the first and last nodes) that was implemented in the free software *Pajek*. The layout of graph could be used to represent how close the nodes in graph were.

5) Comparison of topological properties of graph between two groups: We used two-sample t test to investigate whether there was significant difference in some network measures of the graph of the default network between the superior intelligence group and the average intelligence group. These measures included the strength of functional connectivity between any two nodes, node degree of every node, clustering coefficient of every node, the shortest path length between any pair of nodes and the global efficiency of graph. The definition and significance of degree have been stated in Equation 1.

The clustering coefficient C_i can be used to quantify how close the neighbors of the node i are. Various definitions for clustering coefficient in weighted graph have been proposed over years. In the present study, since the weighted graph was complete, we used the definition as [7]:

$$C_i = \frac{\sum_j \sum_k w_{ij} w_{jk} w_{ki}}{(\sum_j w_{ij})^2 - \sum_j {w_{ij}}^2} \tag{2}$$

where w_{ij} denoted the weighted edge that connected node i to node j.

The shortest path length refers to the length of the path of minimal length between two nodes, and it can be used to characterize how well two nodes communicate. In this study, the weight of the edge between two nodes was represented to the z-valued strength of functional connectivity, and we set all the diagonal elements of individual functional connectivity matrix to 2. Therefore, we defined the distance between two nodes in the graph by subtracting the z-valued strength of functional connectivity from the constant 2. The more general definition of the distance in this study was as follows.

$$d_{ij} = constant - w_{ij} \tag{3}$$

where w_{ij} was the z-valued strength of the functional connectivity between the brain region i to the brain region j. Here, the *constant* was set to 2. Thus, the distance was inversely related to the strength of the functional connectivity. Then, we computed the shortest path lengths with the Dijkstra's algorithms. With the shortest path lengths, we can define the so-called global efficiency of graph as [8]:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{l_{ij}} \tag{4}$$

where N was the number of nodes in the graph, and l_{ij} was the shortest path length between node i and node j. Here, we used the global efficiency to quantify the associations between intelligence differences and the functional integration of the default network.

6) Correlations between network measures and FSIQ scores across all subjects: We correlated the FSIQ scores with network measures across all subjects. These measures included the strength of the functional connectivity, node degree, clustering coefficient, the shortest path length and global efficiency.

III. Results

The median functional connectivity matrix and weighted graph for both groups were shown in Fig. 1. As shown in Fig. 1, the PCC showed the greatest degree and was situated in the center of the layout of the default network in both of the two groups. We validated that PCC was the node with the greatest degree in the default network (the paired t test, P< 0.00025). On the other hand, we used the paired t test and found that the bilateral PHC and cerebellar tonsils showed greater shortest path lengths to the *major nodes* of the default network in comparison to the nodes within *major nodes* (bilateral PHC, P< 0.0000, cerebellar tonsils, P< 0.0000).

Comparing the network measures of the default network between the superior intelligence group and the average intelligence group, we found that there were significant differences in the strength of some functional connectivities between the two groups (two-sample t test, P< 0.05, uncorrected). These results were shown in Table II. We found that there were no significant differences in any node degree and clustering coefficient between the two groups. Additionally, we found significant differences in the shortest path length between the two groups (two-sample t test, P< 0.05, uncorrected). And there was significant difference in the global efficiency of the graph of the default network (two-sample t test, P< 0.035, uncorrected).

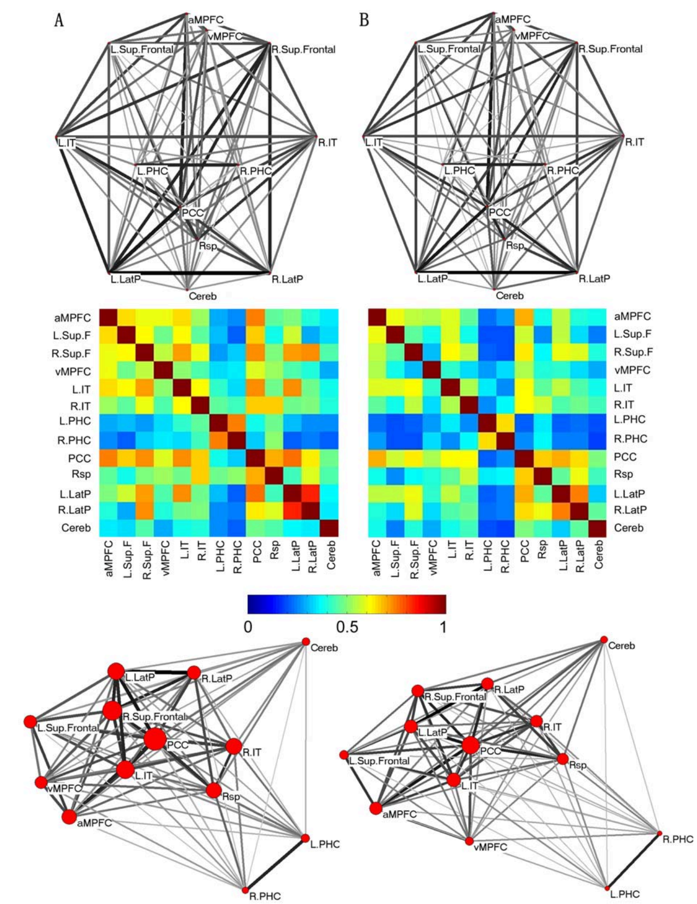

Fig. 1. The median functional connectivity matrix and graph separately for the superior intelligence group (Column A, left) and the average intelligence group (Column B, right). The first row represents the function connectivity between any pair of brain regions in the default network in a pseudoanatomical organization. The gray value of line is proportional to the connection strength. The second row represents the correlation matrices. The third row represents one layout of graph of the default network using the Kamada-Kawai algorithm. The distance between nodes roughly represents how close the brain regions functionally correlated. Node size is proportional to its node degree.

We correlated the network measures with the FSIQ scores across all subjects. We found that there were no significant correlation between the FSIQ scores and some network measures, including node degree, clustering coefficient and global efficiency (P$= 0.072$), while some functional connectivities showed significant correlations to the FSIQ scores, including PCC-vMPFC, Rsp-vMPFC, Rsp-L.PHC, Rsp-R.PHC and R.IT-L.PHC (P< 0.05, uncorrected).

IV. Discussion

In the present study, using weighted graph theory, we quantitatively confirm that PCC was the most important hub node in the default network, which suggested that PCC could be the center of information processing within the default network. At the same time, we found that the MTLs were topologically separations from the other brain regions within the default network. Additionally, we found that there were significant differences in the global

TABLE II

THE COMPARISONS OF THE STRENGTH OF FUNCTIONAL CONNECTIVITY BETWEEN THE SUPERIOR INTELLIGENCE GROUP AND THE AVERAGE INTELLIGENCE GROUP

Functional connectivity		P value
Brain region 1	Brain region 2	
L.Sup.F	R.Sup.F	0.038
L.Sup.F	L.PHC	0.031
L.Sup.F	Rsp	0.0256
R.Sup.F	vMPFC	0.0257
vMPFC	PCC	0.0453
vMPFC	Rsp	0.0229
L.IT	PCC	0.0467
L.IT	L.LatP	0.0314
R.IT	L.PHC	0.0014
L.PHC	PCC	0.0041
L.PHC	Rsp	0.001
R.PHC	Rsp	0.0385

efficiency between the average intelligence group and the superior intelligence group. As shown in *methods*, the global efficiency is inversely related to the shortest path length, which roughly means the global efficiency is related to the strength of functional connectivity in the present study. In comparison to the functional connectivity, the measure of the global efficiency is numerically easier to use to estimate the functional integration of multiple brain regions in a network. In this study, the superior intelligence group showed larger global efficiency of the default network compared to the average intelligence group, which suggest that the subjects with higher intelligence have more integrated functional architecture of the default network.

For a long time, researchers have been concerned with some explicitly intelligence demanding tasks, for example, rational planning, reasoning and working memory, in order to understand the neural basis of the intelligence[9]. In comparison, there are a few studies to investigate the associations between the intrinsic activity and the intelligent performance [10]. However, human brains are not only adaptive but also anticipatory and prospective [11]. Interestingly, we noted that some artificial cognitive architecture, for example, ACT-R (Adaptive Control of Thought–Rational) [12], had designed some modules or mechanisms to rehearse imaginary events or scenarios and then use the information from the rehearsal to modulate the actual behavior. The architectures suggest the importance of the ability to reflect on the past and predict the future, which are similar to the cognitive functions of the default network in human brain. So, we here suggest that the ongoing studies on the intrinsic activity of human brain will bring more cues not only for human cognitive functions but also for the developmental artificial cognitive system.

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