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Research Paper

Association between resting-state brain network topological organization and creative ability: Evidence from a multiple linear regression model

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ABSTRACT

Previous studies have indicated a tight linkage between resting-state functional connectivity of the human brain and creative ability. This study aimed to further investigate the association between the topological organization of resting-state brain networks and creativity. Therefore, we acquired resting-state fMRI data from 22 high-creativity participants and 22 low-creativity participants (as determined by their Torrance Tests of Creative Thinking scores). We then constructed functional brain networks for each participant and assessed group differences in network topological properties before exploring the relationships between respective network topological properties and creative ability. We identified an optimized organization of intrinsic brain networks in both groups. However, compared with low-creativity participants, high-creativity participants exhibited increased global efficiency and substantially decreased path length, suggesting increased efficiency of information transmission across brain networks in creative individuals. Using a multiple linear regression model, we further demonstrated that regional functional integration properties (i.e., the betweenness centrality and global efficiency) of brain networks, particularly the default mode network (DMN) and sensorimotor network (SMN), significantly predicted the individual differences in creative ability. Furthermore, the associations between network regional properties and creative performance were creativity-level dependent, where the difference in the resource control component may be important in explaining individual difference in creative performance. These findings provide novel insights into the neural substrate of creativity and may facilitate objective identification of creative ability.

1. Introduction

Creativity is commonly defined as the generation of novel and original ideas in a divergent and manifold manner, which is the basis of human civilization and culture development (Guilford, 1950). A growing body of neuroimaging research has demonstrated that an individual's creative ability is highly related to patterns of resting-state functional connectivity. For example, higher creativity measured by tests of divergent thinking is associated with resting-state functional connectivity (RSFC) between the medial prefrontal cortex (mPFC) and the posterior cingulate cortex (PCC), both key nodes of the default mode network (DMN) (Takeuchi et al., 2012). Similarly, Beaty et al. found greater RSFC between the left inferior frontal gyrus (IFG) and the entire default mode network in a high creativity group (Beaty et al., 2014). Furthermore, research also suggests that increased RSFC between the mPFC and the middle temporal gyrus (mTG), which are both located in the DMN, might be crucial to creativity, and that mPFC − mTG connectivity can be improved by cognitive stimulation (Wei et al., 2013). All of these studies suggest the importance of increased functional interactions among distributed regions thought to underlie creativity. Nevertheless, the architecture of these large-scale functional networks contributing to creativity remain unclear.

Many previous studies have demonstrated that the intrinsic activity of brain regions are complexly interconnected when individuals are in a resting state, forming functional networks (Bullmore & Sporns, 2009; van den Heuvel & Hulshoff Pol, 2010). The topological architecture of resting-state networks can be depicted and explored using a graph-based network analysis approach, which has shown that these networks

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are organized in a "small-world" and "scale-free" way (Bullmore & Sporns, 2009). These properties not only ensure that the human brain efficiently transmits information but is also robust in the face of an attack (Watts & Strogatz, 1998; Barabási & Albert, 1999). Of note, high clustering and high efficiency in a small-world architecture contribute to cognitive functions that require either segregated or integrated information processing. On one hand, segregated processes, such as visual processes, benefit from highly clustered connections; on the other hand, integrated processes, such as executive functions, benefit from high global efficiency of information transferred across the whole network (Tononi, Sporns, & Edelman, 1994; Tononi & Sporns, 2003; Bullmore & Sporns, 2012). Recent studies have demonstrated that creativity is highly dependent on functional integration (Dietrich & Kanso, 2010; Wu et al., 2015); however, as yet few studies have investigated how the topological characteristics of resting-state functional networks contribute to creative ability. More importantly, previous research has shown that brain network properties are tightly associated with an individual's cognitive abilities, such as level of intelligence (van den Heuvel, Stam, Kahn, & Hulshoff Pol, 2009), working memory (Langer, von Bastian, Wirz, Oberauer, & Jäncke, 2013) and attentional capacity (Markett et al., 2014). Given that these cognitive abilities are all important components of creativity, it is essential to investigate the relation between creativity and the multiple brain networks which have been linked with creative performance (Beaty, Benedek, Barry Kaufman, & Silvia, 2015; Beaty, Benedek, Silvia, & Schacter, 2016), including the DMN which underpins spontaneous imagination and self-generated thought (Andrews-Hanna, 2012; Andrews-Hanna, Smallwood, & Spreng, 2014) and the executive control network (ECN) which is related to working memory, inhibition, integration, and switching (Seeley et al., 2007). Therefore, the complexity of creativity and the wide involvement of multiple brain networks both converged to suggest the rationality of the network perspective in creativity studies.

The current study aimed to investigate the relationships between the topological attributes of resting-state brain networks and individual differences in creativity. We used the Torrance Tests of Creative Thinking (TTCT) to identify high-creativity (n = 22) and low-creativity (n = 22) groups (HG and LG, respectively) from one hundred and eighty participants. Resting-state fMRI data were collected from HG and LG participants, and network analyses based on graph theory were implemented to measure the architectural properties of resting-state functional networks. These network properties were compared between the two groups, and within each group, associations between network topological attributes and behavioral performance were computed using multiple linear regression models.

2. Materials and methods

2.1. Participants

One hundred and eighty healthy volunteers (age = 18.88 ± 1.05 years, 85 males), which are all students enrolled at South China Normal University (Guangzhou, China), participated in the behavioral assessment; the results of this assessment were used to identify 22 high-creativity and 22 low-creativity individuals according to the TTCT scores distribution (see below for a detailed description of this process), a method used in previous studies (Carlsson, Wendt, & Risberg, 2000; Villarreal et al., 2013; Beaty et al., 2014). The HG and LG individuals were well-matched with respect to age, gender, and intelligence (see Results). These 44 participants, who completed a resting-state fMRI scan, were all right-handed, with no history of neurological or psychiatric problems. Exclusion criteria included an implant, device, or object in the body. All participants provided written informed consent, and the protocol was approved by the Research Ethics Review Board of South China Normal University.

2.2. Behavioral assessment

The TTCT-figural version was used to identify high-creativity and low-creativity individuals. The TTCT is widely used to measure key aspects of creativity, such as divergent thinking. The TTCT has high validity with respect to the measurement of divergent thinking (Kim, 2008) and is more predictive of creative achievements in different fields than other divergent thinking tests (Kim, 2005). The TTCT-figural version consists of three tasks: The first task requires participants to imagine a picture or story based on an egg-shaped line figure; the second task instructs participants to draw interesting things based on 10 unfinished pictures; and the third task instructs participants to draw different objects by adding lines to 30 parallel lines. All tasks require participants to imagine and draw novel answers as quickly as possible. The TTCT total creativity score is based on scores for the following dimensions of the creative process (each summed across all three tasks): 1) Fluency is measured by the number of relevant responses and is related to the ability to produce many alternatives. 2) Flexibility is measured by the number of categories that relevant responses can be assigned to (according to specific criteria) and reflects the ability to change perspective. 3) Originality is based on the degree of the ideas produced that differ from others, and is measured by the number of uncommon ideas generated (based on normative data) (De Souza et al., 2010). Consistent with previous studies (Takeuchi et al., 2012; Wei et al., 2013), our analysis only used the total creativity score. There is a high association among the subscales in the TTCT; thus, each subscale could not provide meaningfully different information (Heausler & Thompson, 1988), and some have argued that independent interpretations of TTCT subscores should be avoided (Treffinger, 1985).

Intelligence is associated with divergent thinking (Nusbaum & Silvia, 2011; Benedek, Franz, Heene, & Neubauer, 2012; Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Silvia & Beaty, 2012); thus, we also assessed intelligence using the Raven's Standard Progressive Matrices (RSPM)-Chinese version. This version of RSPM has good split-half reliability (0.95), and good test-retest reliabilities (0.82 and 0.79 over intervals of 15 days and 30 days, respectively).

Participants with TTCT total scores in the top 12% (*n* = 22, 11 males and 11 females) of the total sample were assigned to the high-creativity group, while the participants in the bottom 12% (*n* = 22, 11 males and 11 females) were assigned to the low-creativity group. Of note, we selected 12% as cut-off point for magnifying the difference of creative ability between two groups and minimizing the influence of gender differences on our results (Matud, Rodríguez, & Grande, 2007; Lin, Hsu, Chen, & Wang, 2012).

2.3. MRI acquisition

All MRI data were obtained on a 3 T Siemens Trio Tim MR scanner with a 12-channel phased-array head coil at South China Normal University. The fMRI data were acquired using a gradient-echo echo-planar imaging (EPI) sequence with the following parameters: repetition time (TR) = 2000 ms, echo time (TE) = 30 ms, flip angle = 90°, matrix = 64 × 64, field of view (FOV) = 224 × 224 mm^2, thickness/gap = 3.5/0.8 mm, and 32 axial slices covering the whole brain. During resting-state scanning, participants were instructed to keep their eyes closed. Two hundred and forty functional volumes were obtained during the 8-min scan.

In addition, 3D high-resolution structural images were obtained using a 3D T1-weighted MP-RAGE sequence with the following parameters: TR = 1900 ms, TE = 2.52 ms, flip angle = 90°, matrix = 256 × 256, FOV = 230 × 230 mm^2, thickness = 1.0 mm, and 176 sagittal slices.