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Subcortical Structures and Creative Divergent Thinking: A Resting-state functional MRI Analysis

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Author Contributions

Z. G., X. L., D. Z., M. L., and N.H. conceived the experiment. Z.G., X.L., and D. Z. performed the research. X. L., and Z. G. analyzed the data. Z. G., X. L., and N. H. wrote the paper.

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Abstract

This study aimed to testify whether spontaneous fluctuations in the subcortex contribute to creative divergent thinking. Individuals at high- and low levels of creativity were recruited and the resting-state fMRI data was collected. Seed-wise and dynamic functional connectivity (FC) were used to identify differences between the two groups. The topological properties of the subcortical network were measured, and their relationship with performance of creative divergent thinking was calculated using brain-behaviour correlation analyses. The results revealed higher FC between the putamen, pallidum, and thalamus in high creativity group (HCG) compared to low creativity group (LCG) within the subcortex. Whole-brain FC results showed stronger connection across subcortical (i.e., the thalamus and pallidum) and cerebral regions (i.e., the insula, middle frontal gyrus, and middle temporal gyrus) in HCG compared to LCG. In addition, the subcortical FC demonstrated a positive correlation with performance of creative thinking across the pallidum, putamen, and thalamus. Our findings may provide novel insights into the relationship between creative divergent thinking and the activities of the subcortex. It is likely that not only fronto-striatal dopaminergic pathways, but also “motor” pathways, are involved in creative thinking processing.

Keywords: creative thinking, subcortex, functional connectivity, resting-state fMRI

Introduction

Creativity includes a series of complex cognitive processes, which induce activity within multiple cortical structures, such as the prefrontal cortex (PFC) (Beaty et al., 2015; Wei et al., 2014), middle frontal gyrus (MFG) (Bechtereva et al., 2004; Chávez-Eakle et al., 2007), middle temporal gyrus (MTG) (Kounios et al., 2008), and insula (Gao et al., 2017). It has been hypothesized that dopamine-coupled brain areas contribute to creative thought (Heilman, Nadeau, & Beversdorf, 2003). On one hand, the idea suggests that many creative traits (such as extraversion and openness) result from the neural activity of dopamine-coupled regions (Schuler et al., 2019). On the other hand, some researchers have suggested that higher dopamine receptor levels cause greater cognitive flexibility, resulting in better creative performances (Ashby, Isen & Turken, 1999; Chermahini, & Hommel, 2010).

Neuroimaging techniques have been widely used to examine potential morphological and functional changes within subcortical regions associated with creativity. An increasing number of studies have investigated the important role of dopamine-related subcortical regions in creative thinking processing (Boot et al., 2017; Chen et al., 2019). For example, increased regional grey matter volumes in the caudate nucleus and midbrain are significantly related to divergent thinking performances (Takeuchi et al., 2010). The recent burgeoning of research on creative thinking is indicative of a growing conviction that subcortical regions, such as the putamen and nucleus accumbens (NAcc), are involved in the process of insight, which is a crucial process in problem solving (Shen et al., 2018; Tik et al., 2018). Similar results have been found in a very

recent publication by Chen et al. (2019), and the results of the resting-state fMRI (r-fMRI) study have demonstrated that verbal divergent thinking is associated with neural activity within subcortical regions, such as the thalamus and putamen. In summary, creativity appears to be correlated with subcortical regions (Chen et al., 2019; Shen et al., 2018). Although the impact of dopamine levels underlying creativity has been found not only in behavioural experiments but also in relevant neuropsychiatric disorders (i.e. Parkinson's disease) (Faust-Socher et al., 2014; Salvi et al., 2015), the neural basis of these subcortical regions relating to individual creativity based on spontaneous fluctuations of the human brain is still unclear.

Generally, there are two different dopamine loops for information transmission across subcortical regions. One is a “motor” loop passing largely through the putamen, which receives inputs from the sensorimotor cortex and whose influences are ultimately returned to the premotor areas (Alexander, Crutcher & DeLong, 1986, 1990). Another is an “association” loop passing through the caudate nucleus, which receives input from association areas and whose influences are ultimately returned to portions of the PFC (Alexander, DeLong & Strick, 1986). Based on current available results, however, studies investigating subcortical areas that are involved in creative thinking are mainly focused on one aspect — the “association” loop. For example, Boot et al. (2017) demonstrated that creative thinking is strongly based on fronto-striatal dopaminergic pathways, which contributes to flexibility in increasing creativity. However, it does not suggest whether other regions, such as the pallidum and thalamus, are involved in the process of creativity. Moreover, researchers have found that intranasal administration

of oxytocin boosts divergent thinking, flexibility, and creative insight performance (De Dreu and Kret, 2016). This may be caused by decreased cortisol responses and fear signals in the amygdalar-hippocampal circuit. Thus, increased creative performance may be due to other neurotransmitters. However, it is unclear whether other neurotransmitters such as norepinephrine and oxytocin contribute to creative thinking.

Neurons in the brain form complex networks (Cajal, 1995), which are thought to underlie the physiological basis of information transfer and mental representation (Strogatz, 2001). The human brain needs to expend 20% of the body's energy, and oxygen consumption by the brain is no lower at rest than during task performance (Sokoloff, Wechsler, Mangold, Balls, & Kety, 1953). Before Biswal and colleagues (1995) published findings about spontaneous fluctuations in the human brain using functional magnetic resonance imaging (fMRI), scientists had suggested that the spontaneous fluctuations in the human brain are noise. However, the study published by Biswal and colleagues indicated that blood oxygen level-dependent signals show low frequency fluctuations in the bilateral motor cortex (Biswal, Yetkin, Haughton, & Hyde, 1995). That is, in the absence of explicit external or internal stimuli, the human brain maintains a specific level of fluctuations. Many studies have found that spontaneous activity in the human brain can shape most neural activity underlying behaviour (Dietrich & Kanso, 2010; Wei et al., 2014), indicating that spontaneous fluctuations could provide resources for our behaviour. Therefore, the neural basis of behaviour can be explored by examining the brain networks underlying spontaneous fluctuations (Zou et al., 2013), it seems to be effective that the neural basis of creativity

can be explored using resting-state data. A recent study indicated that creative divergent thinking trainings give rise to changes in functional connectivity patterns of human brain networks using resting-state data (Fink et al., 2018). This provides further evidence that there is a consistency between resting-state and task-state connectivity patterns related to creative thinking. On the other hand, the human brain is a complex system and never in a static state (Marusak et al., 2017). Previous fMRI researches have revealed the variations of static functional connections during the whole scanning (Allen et al., 2014; Calhoun et al., 2014). Generally, static functional connectivity was regularly divided into several continuous sections that are considered as dynamic functional connectivity. Recent evidence has shown that dynamic functional connectivity may reveal a great deal of information in time-varying neural activity of the human brain (Calhoun et al., 2014; Rashid et al., 2016). Therefore, it provides a comprehensive insight that we used both static and dynamic functional connectivity to explore the basis of creative brain network.

Although previous studies have investigated the relationship between special dopamine loops and creativity, subcortical-wide regional connectivity with cortical regions contributing to individual creativity ability has been neglected. Additionally, dopamine loops within subcortical regions are more complex than between subcortico-cortical regions. Whether the interactions of these subcortical regions are involved in creativity should also be examined. In addition, more information could likely be obtained to investigate the interactions between subcortical regions by using dynamic functional connectivity. The primary purpose of this study was to address each of the

following issues. First, to identify the subcortical brain regions that contribute to our creative abilities. Second, whether highly creative individuals show different functional connectivity compared to individuals with low creativity. Third, whether the network efficiency of the cortico-subcortical network exhibits differences between individuals with high and low levels of creativity.

In the present study, we recruited a high creativity group (HCG, $n = 22$) and a low creativity group (LCG, $n = 22$) based on divergent thinking test scores. We calculated functional connectivity (FC) maps based on resting-state functional magnetic resonance imaging (r-fMRI) data. Meanwhile, the topological properties of the whole-brain network, which showed differences between the two groups, were measured using graph-based analyses. We explored the relationship between subcortical regions and creative divergent thinking by using functional connectivity and graph-based analyses. We hypothesized that the dopamine-coupled regions may show group differences, and high creativity individuals show increased functional connectivity and network efficiency compared to low creativity individuals.

Methods

Participants

One hundred and eighty healthy and right-handed undergraduates (90 males and 90 females, aged 18 to 22 years old) took part in the study. In this study, we used the total scores of the figural Torrance Tests of Creative Thinking (f-TTCT) test to measure the creative thinking ability of all subjects (the sum of originality, flexibility, fluency, and

elaboration scores). The Torrance Tests of Creative Thinking test has shown good predictive validity ($r > 0.57$) and high reliability ($r > 0.90$) (Torrance, 1988, 1990). Based on the f-TTCT scores, we selected 22 subjects from the top 12% of f-TTCT scores (11 males, 18.86 ± 1.08 years old) and 22 subjects from the bottom 12% of f-TTCT scores (11 males, 19.13 ± 0.99 years old) as the high creativity group (HCG) and low creativity group (LCG), respectively. Next, we collected the r-fMRI data of all 44 subjects in the two groups. During fMRI scanning, we asked participants that they should remain awake and not be asleep. Meanwhile, we also required them to try not to think systematically. The present study was approved by the Institutional Review Board of South China Normal University.

Resting-state fMRI data acquisition

All participants were scanned using a 3T Siemens Trio Tim MR scanner at the Brain Imaging Center at SCNU, Guangdong, China. The r-fMRI data were collected using a GE-EPI sequence: 32 axial slices, repetition time (TR) = 2 s, echo time (TE) = 30 ms, slice thickness = 3.5 mm, no gap, flip angle (FA) = 90° , matrix = 64×64 , and field of view (FOV) = $192 \text{ mm} \times 192 \text{ mm}$. The subjects were instructed to lie down with their eyes closed, and to remain quiet during the scans while thinking of nothing in particular. After scanning, a total of 240 volumes were obtained from each participant.

Resting-state fMRI data preprocessing

The r-fMRI data were preprocessed using DPARSF (Yan, et al., 2009) based on

SPM8 (<http://www.fil.ion.ucl.ac.uk/spm/software/spm8>). First, we discarded the first 10 volumes for signal equilibrium. Second, the time delay of the intra-volume in slices, as well as head movements resulting in geometrical displacements, were corrected (none of the subjects were excluded based on the criterion of displacement of > 1 mm or angular rotation of $> 1^\circ$ in any direction). Third, the image data were normalized to the standard Montreal Neurological Institute (MNI) space at 3-mm isotropic resolution with an echo-planar imaging (EPI) template. The data were then band-pass filtered (0.01 – 0.1 Hz) to decrease the effects of low-frequency drift and high-frequency physiological noise. We also removed the linear trend and spatially smoothed the data with an 8 mm FWHM Gaussian kernel. Nuisance covariates, including head motion via the Friston 24-parameter model (Friston et al., 1996; Yan et al., 2013), white matter (WM), and cerebrospinal fluid (CSF) signals, were removed using regression.

Regions of interest (ROIs)

The regions of interest (ROIs) for subcortical regions were extracted using the Harvard-Oxford subcortical structural probabilistic atlas from Data Processing & Analysis for Brain Imaging (DPABI, <http://rfmri.org/dpabi>). We extracted all ROIs based on the 25% probability map, including the bilateral amygdala, accumbens, brainstem, caudate, hippocampus, pallidum, putamen, and thalamus (16 ROIs in total). We then resampled these selected ROIs to a voxel size of 3 mm for further analyses. Figure 1 shows the different anatomical orientations of the subcortical regions in this study.

Functional connectivity maps

We constructed the whole-brain functional connectivity (FC) map of each subcortical region by using a standard seed-voxel approach. In this step, each ROI was considered as a seed region. For each participant, we extracted the averaged time series of all voxels within a given seed region and the time series of each voxel in the whole brain. We then calculated FC (i.e. Pearson's correlation coefficient r) between the time series of selected seed regions and each voxel in the whole brain. Through the above analyses, we obtained a whole-brain FC map of a given subcortical region for each participant. Finally, we performed the Fisher's r -to- z transformation to convert these FC maps to z -value maps for further statistical analyses.

Constructing subcortical network

We constructed the subcortical network using a standard seed-wise method in this study. For each participant, we extracted averaged time series of all voxels within each seed region and calculated Pearson's correlation coefficient r between any two time series of these seed regions to generate the FC. Based on the above calculations, we generated a 16×16 FC matrix for each participant. By taking all seed regions as nodes, and all FC between any two seed regions as edges, we constructed the subcortical network for each participant in the study.

Topological properties of the subcortical network

We estimated the topological properties of the subcortical network by using the

GRETNA software (Wang et al. 2015) (<http://www.nitrc.org/projects/gretna/>). Because of the confounding effects of noisy correlations on network analyses, we set a threshold of a significance level for FC to reduce the effects. Specifically, we only kept those FCs whose corresponding p -values satisfied a statistical threshold of $p < 0.05$ (family-wise error, FWE-correction) compared to all others in a given FC matrix. Because the clustering coefficient (C_p), characteristic path length (L_p), global efficiency (E_{glob}), and local efficiency (E_{loc}) describe the local and global information communication of the networks and provide the altered information transferring within the brain networks, we hence selected these four parameters to examine the topological properties of the networks in this study. Based on the corrected FC matrix, we finally calculated topological properties of the subcortical network including four global parameters: C_p , L_p , E_{glob} and E_{loc} for each subject. Graph theory have been widely used to measure the topological properties of brain networks (Bullmore and Bassett, 2009; Wang et al., 2010), including the creativity-related networks (Gao et al., 2017; Kenett et al., 2020). In addition, we also estimated the nodal parameters including the nodal strength (S_i^w) and nodal efficiency (E_i^w) of the subcortical network. Detailed definitions and mathematical descriptions of these global parameters are listed in Table S1.

Dynamic measures of the subcortical network

We estimated dynamic FC (dFC) and dynamic topological properties as dynamic measures of subcortical networks in this study. The sliding-window approach (Allen et al. 2014; Gao et al., 2020; Liu et al., 2020) was applied to dynamic measures by using

the DynamicBC toolbox (Liao et al. 2014). Specifically, we first segmented the whole time series of each seed region into several sliding windows. Then, the fixed length of the sliding window was set to 22 TRs (i.e. 44 s) and the subsequent sliding-window began with the step of 1 TR. The entire scanning lasted for about 8 min, including 240 TRs. After removing 10 TR in the preprocessing step, only 230 TRs were conserved for this analysis. We hence obtained 209 sliding windows based on the above calculations for each subject. Next, we extracted the time series (22 TRs, 44 s) of each seed region in each sliding window and calculated the Pearson's correlation coefficient r between any two time series of seed regions to generate the dynamic FC (dFC) of the subcortical network. We also calculated four global parameters in each sliding window, which were considered as dynamic topological properties of subcortical networks. Finally, we estimated both the mean (i.e. averaged) and the variance of dFC, as well as the variance of dynamic topological properties across all sliding windows for each subject.

Brain-behavior correlation analyses

We used Spearman's correlation analysis to examine correlations between brain measures (i.e. FC and global parameters) and f-TTCT scores. We only considered those FC or global parameters that showed significant between-group differences in the correlation analyses. We also explored a partial correlation (Pearson's correlation) between the subcortical nodal degree and f-TTCT scores. Age and sex were controlled, and the statistical significance was set to $p < 0.05$ (false discovery rate, FDR correction).

Statistical analyses

We used a two-sample *t*-test to detect between-group differences in whole FC maps of the subcortical region. We determined that the clusters showed statistical differences between HCG and LCG with two criteria: 1) significant threshold $p < 0.05$, with a strict multiple comparison correction strategy, Threshold-Free Cluster Enhancement correction (TFCE-correction); 2) the number of voxels in each cluster should be more than 50 voxels.

In addition, a nonparametric permutation *t*-test was used to determine the between-group differences in each FC within the subcortical network, topological properties of the subcortical network, as well as the mean and variance of dynamic measures. In the calculation, for a given parameter (either FC or global parameter), we randomly paired the parameter values between HCG and LCG to generate two new groups. Subsequently, we calculated the mean value of each new group and estimated their differences. This permutation was repeated 5,000 times to obtain the empirical distribution of the difference between new paired groups. We then selected a significance level at $p < 0.05$ to determine significant differences between HCG and LCG at 95% of the empirical distribution in a two-tailed test. Given the small sample size of the participants in our study (22 participants in each group), when significant between-group differences were determined in any parameter, we also calculated the corresponding effect size (Cohen's *d*) according to Cohen (2013).

Results:

FC maps of subcortical regions

Figure 2 and Table S2 show significant differences in the whole-brain FC maps of the subcortical regions between the HCG and LCG. To illustrate our results conveniently, we have used L. to denote the left hemispheric lobules and R. to denote the right hemispheric lobules below. We found significantly ($p < 0.05$, TFCE-correction) higher FC between the left thalamus (L.THA) and left insula (L.INS) in the HCG compared to the LCG. In addition, statistical analyses showed that the right pallidum (R.PAL) was more strongly connected to five regions, including the bilateral parahippocampal gyrus (L/R.PHG), left fusiform gyrus (L.FFG), left middle temporal gyrus (L.MTG), and left middle frontal gyrus (orbital part, ORBmid), in the HCG compared to the LCG.

FC within the subcortical network

Figure 3A and Table S3 illustrate the significant between-group differences ($p < 0.05$, FDR-correction) of FC within the subcortical network. We found significantly higher FC between the putamen (PUT), PAL, and THA in the HCG than in the LCG. In particular, we found significantly higher FC between the bilateral PUT ($p = 0.0012$), between the L.PUT and R.PAL ($p = 0.0006$), between the L.THA and the R.PUT ($p = 0.0002$) and R.PAL ($p = 0.0010$), as well as between the R.PUT and R.PAL ($p = 0.0014$) in the HCG than in the LCG.

Topological properties of the subcortical network

Global parameters of the subcortical network for both HCG and LCG are shown in Figure 4A and Table S4. Statistical analysis ($p < 0.05$) revealed a significantly higher clustering coefficient ($p = 0.0330$) and local efficiency ($p = 0.0190$) in the HCG compared to the LCG. Moreover, we found a marginally significant difference in global efficiency ($p = 0.0550$) between HCG and LCG. In addition, we found that the nodal strength was significantly lower ($p = 0.0008$) in the L.PUT for HCG than in the LCG.

Dynamic measures of the subcortical network

Averaged dFC. Significant ($p < 0.05$, FDR-correction) differences in the averaged dFC of the subcortical network between HCG and LCG are shown in Figure 3B and Table S5. Across all sliding windows, we found significantly higher dFC between the PUT, PAL, and THA in the HCG than in the LCG. These results were consistent with the findings of FC within the subcortical network. We additionally found a significantly higher dFC between the R.THA and R.PAL ($p = 0.0006$), as well as between the R.THA and R.PUT ($p = 0.0010$).

Variance of dFC. We found significant ($p < 0.05$, FDR-correction) between-group differences in the variance of dFC across all sliding windows between the HCG and LCG (Figure 3C, Table S6). We found that HCG showed significantly decreased variance of dFC between the left amygdala (L.AMY) and the L.PAL ($p = 0.0002$), L.THA ($p = 0.0012$), and R.THA ($p = 0.0002$) than LCG. Meanwhile, significant between-group differences (HCG < LCG) were found in the variance of dFC between

the left hippocampus (L.HIPP) and the L.PAL ($p = 0.0020$) and L.PUT ($p = 0.0008$). Moreover, significantly decreased variance of dFC between the bilateral THA ($p = 0.0024$), between the L.PAL and R.AMY ($p = 0.0024$), between the R.HIPP and R.PAL ($p = 0.0008$), and between the R.THA and R.AMY ($p = 0.0016$) were found in the HCG compared to the LCG.

Variance of global parameters. We found significantly decreased variance of clustering coefficient ($p = 0.0180$), characteristic path length ($p = 0.0196$), and local efficiency ($p = 0.0052$) in the HCG compared to the LCG. Figure 4B and Table S7 show detailed results of variance of global parameters of the subcortical network for both HCG and LCG.

Brain–behavior correlation analyses

A significant ($p < 0.05$, FDR-correction) positive correlation was found between the FC values between the subcortical network and the f-TTCT scores (Figure S1). We found that FC between the bilateral PUT ($r = 0.48$, $p = 0.0010$), the L.PUT and R.PAL ($r = 0.43$, $p = 0.0050$), the L.THA and R.PUT ($r = 0.44$, $p = 0.004$), the L.THA and R.PAL ($r = 0.42$, $p = 0.006$), and between the R.PUT and R.PAL ($r = 0.42$, $p = 0.006$) were all significantly positively correlated with the f-TTCT scores. We found a significant ($p < 0.05$, FDR-correction) positive correlation between the nodal strength of the L.PUT and f-TTCT scores.

Discussion

The present study investigated the cortico-subcortical network involved in creativity from a novel point of view, and examined the functional brain connectivity of subcortex and cortico-subcortical regions underlying creative thinking in terms of brain-behavior correlations and group differences. The main results are summarized as follows. First, static/dynamic functional connectivity between the bilateral putamen, between the right pallidum and bilateral putamen, and between the left thalamus and the right putamen and right pallidum indicated group differences within the subcortex. Second, information translation efficiency was higher in the HCG than in the LCG, along with network stabilization in the subcortical network. Third, the voxel-wise functional connectivity results showed group differences across the subcortical (i.e. the left thalamus and right pallidum) and cerebral regions (i.e. insula, MFG, and MTG). Fourth, the variance of dFC indicated significant differences between HCG and LCG across the putamen, thalamus, pallidum amygdala, and hippocampus. Fifth, the FC between the bilateral putamen, between the right pallidum and bilateral putamen, and between the left thalamus and the right putamen and right pallidum demonstrated a positive correlation with f-TTCT scores. Additionally, the f-TTCT scores and nodal degree of the subcortical regions showed a significantly positive correlation in the left putamen.

The results of graph-based network analyses showed group differences within the subcortical regions. We explored the subcortical topological network organization using two different creativity groups to analyse path length and network efficiency potentially underlying group differences. Our results demonstrated that the subcortical network of participants with higher creativity exhibited better network efficiency. That is,

information translation efficiency was higher in the HCG than in the LCG. In total, the subcortical network of participants with high creativity indicated better optimized network organization compared with participants with low creativity. Furthermore, the indicator of subcortical network variance was smaller in the HCG, indicating that individuals with high creativity exhibit a more stable subcortical network. This is consistent with our expectations.

In particular, the FC of three subcortical regions, the putamen, pallidum, and thalamus, showed group differences. Cortical signals are transmitted through the basal ganglia-thalamocortical circuits. The elements of each circuit include the cortex, striatum, pallidum, and thalamus (Alexander, DeLong & Strick, 1986). Each circuit receives multiple, partially overlapping cortico-striate inputs, which are progressively integrated during their subsequent passage through the pallidum to the thalamus and from the thalamus back to cortex (Alexander, DeLong & Strick, 1986). Our FC results indicate that participants with higher creativity exhibited better functional connectivity strength within the information transmission circuit.

Many previous studies have linked the dopaminergic system to creative performance (De Manzano et al., 2010; Mayseless et al., 2013; Zabelina et al., 2016). Creativity appears to be associated with the neural activity of the striatum, which is involved in dopaminergic modulation (Boot et al., 2017). The release of dopamine in the striatum is thought to be beneficial for cognitive flexibility, broadening attentional focus, and perspective switching, which are important for creativity (Boot et al., 2017). Furthermore, the putamen, which is a part of the striatum, is found to have a high

density of D2 dopaminergic receptors (Willeit et al., 2016). In addition, the putamen contributes to behavioural inhibition (Sweitzer et al., 2018). A study by Peterson and colleagues (2002) found that behavioural inhibition is a gating process that allows ignoring prior related information; individuals with decreased behavioural inhibition are more likely to develop their creative potential. However, it is worth noting that previous studies have drawn attention to fronto-striatal pathways underlying dopaminergic modulation of creativity (Boot et al., 2017; Schuler et al., 2019), which is an “association” loop passing through the prefrontal cortex, association areas, and caudate nucleus (another part of the striatum) (Alexander, DeLong & Strick, 1986).

Although the putamen is found to have a high density of D2 receptors and is highly involved in creative performance, it participates in the “motor” loop, where signals pass through the putamen, which receives inputs from sensorimotor cortex, and whose influences were ultimately returned to premotor areas. (Alexander, DeLong & Strick, 1986). In addition, we also found group differences between the insula (sensorimotor cortex) and thalamus. The results further suggest that modulation of the “motor” pathway may be involved in the process of creative thinking. Previous studies (de Manzano & Ullén, 2012; Pinho, Ullén, Castelo-Branco, Fransson & de Manzano, 2015) found the sensorimotor cortex is related to visuospatial creative activity. Meanwhile, the insula plays an important role in planning, motor execution, and goal-directed behavior during visual divergent thinking (de Manzano & Ullén, 2012; Huang et al., 2013; Pinho et al., 2015). Studies revealed a tendency for greater activities in the thalamus during creative task compared to control task (Gilbert et al., 2010; Park et al.,

2015). In addition, mental imagery is thought to rely on sensorimotor experiences of motor states, which is involved in generating images of objects in their absence, via retrieving, modifying and recombining sensory information from memory (Kosslyn et al. 2001). And, the ability of mental imagery plays a fundamental role in visual creative divergent thinking (LeBoutillier & Marks, 2003). Taken together, these findings strongly suggest an important role of sensorimotor regions in visual creative divergent thinking. We did not find group differences in FC in the caudate. This, however, does not necessarily imply that dopaminergic modulation of the fronto-striatal pathway is not involved in creative thinking. Although there were no differences in the caudate, we found group differences between the pallidum and association areas (FFG and MTG) and the PFC (i.e. ORBmid). Creative processing requires persistence, which involves focused, convergent, and systematic thinking and longer idea searching (Baas et al., 2013). Effortful and focused creative thinking has been implicated in the activation of the PFC pathway (Benedek et al., 2014). Further, activation in the PFC enhances creative insightful behaviour and increases original idea generation (Mayseless and Shamay-Tsoory, 2015). Nonetheless, there may be more complex mechanisms involved in the process of creative thinking, which need to be further explored.

Our results showed group differences between the respective “motor” pathways in the HCG and the LCG, which has not been previously demonstrated. The differences between the “motor” loop pathways may be a result of other neuromodulators, such as noradrenaline and oxytocin. Although previous studies have focused on dopamine (fronto-striatal pathway) as the key neurotransmitter involved in creative thinking (Boot

et al., 2017; Schuler et al., 2019), cognition and behaviour are modulated by other neurotransmitters such as noradrenaline (Aston-Jonnes and Cohen, 2005; Berridge and Waterhouse, 2003), in addition to dopamine. Noradrenaline is thought to modulate the balance between exploitation and exploration by promoting stabilization of salient information in working memory and in attention shifting (Aston-Jonnes and Cohen, 2005; Berridge and Waterhouse, 2003) and may enable the persistence of creative thinking. In addition, oxytocin facilitates flexibility and divergent thinking, which are crucial for creative thinking (De Dreu et al., 2014). Moreover, the differences may be caused by decreased cortisol responses and fear signals in the amygdalar-hippocampal circuit. Our results showed that the variance of dFC indicated significant differences between the HCG and LCG across the amygdala and hippocampus. It offers the possibility that not only a single neurotransmitter (i.e. dopamine), but also additional neurotransmitters (such as norepinephrine and oxytocin) contribute to creative thinking.

Our findings provide some insight into the results and possibilities. First, we used static/dynamic functional connectivity and graph theory methods to explore group differences in brain subcortical regions. In addition to the brain regions of the fronto-striatal pathway, we also found that other regions of the “motor” loop exhibited group differences. These results extend existing known findings. In addition, we also found significant differences between the HCG and LCG in the amygdalar-hippocampal circuit. Thus, there may be other neurotransmitters that contribute to creative behaviour in addition to dopamine.

Although the present study has some limitations and could be improved, the results

of our study have some theoretical and practical implications. The study provides a new perspective on the relationship between subcortical regions and creativity. A limitation of the study is that the analyses were based on using resting-state data. It is not clear how subcortical regions would perform during creative thinking tasks and what the interaction is between the cortex and subcortex during creative thinking. This will be explored through further research.

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Figure Captions

Figure 1 Locations of subcortical regions. Each region is labeled with different colors.

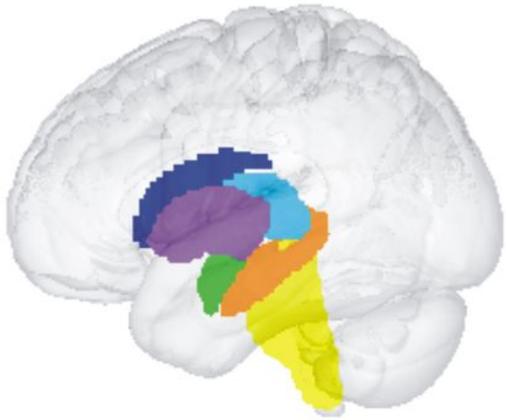
Figure 2 Cluster corresponding to the significant difference ($p < 0.05$, Threshold-Free Cluster Enhancement correction, TFCE-correction) in the whole-brain map of subcortical region between high creative group (HCG) and low creative group (LCG). Abbreviation: THA, thalamus; PAL, pallidum; L (R), left (right) hemisphere.

Figure 3 Significant differences ($p < 0.05$, false discovery rate correction, FDR-correction) in A) function connectivity (FC) and B) averaged dynamic FC (dFC) between high creativity group (HCG) and low creativity group (LCG).

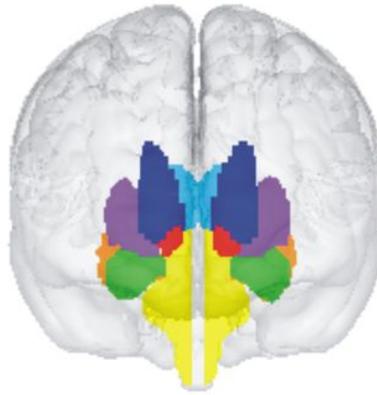
Figure 4 A) Global parameters of subcortical network for both high creativity group (HCG) and low creativity group (LCG). B) The variance of global parameters of subcortical network for both HCG and LCG. $*p < 0.05$.

Figures

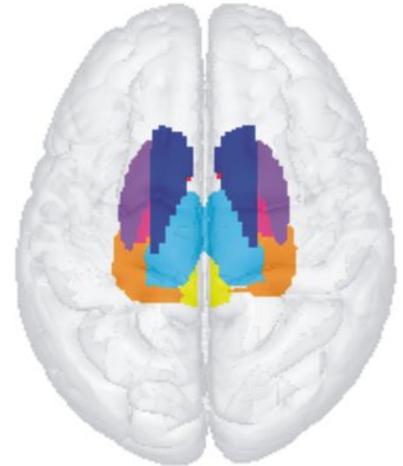
Sagittal



Coronal



Axial



■ Caudate ■ Amygdala ■ Thalamus ■ Brain-Stem
■ Putamen ■ Hippocampus ■ Accumbens ■ Pallidum

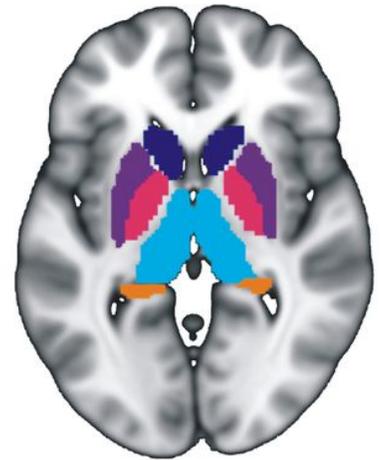
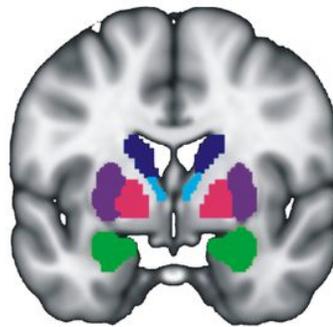
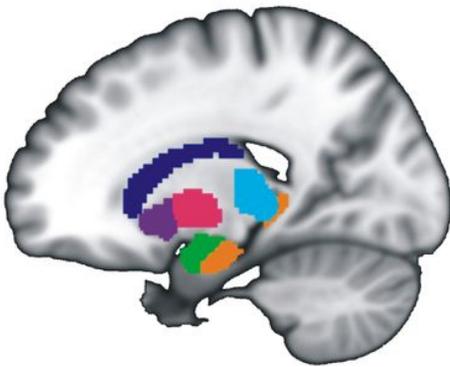


Figure 1

Locations of subcortical regions. Each region is labeled with different colors.

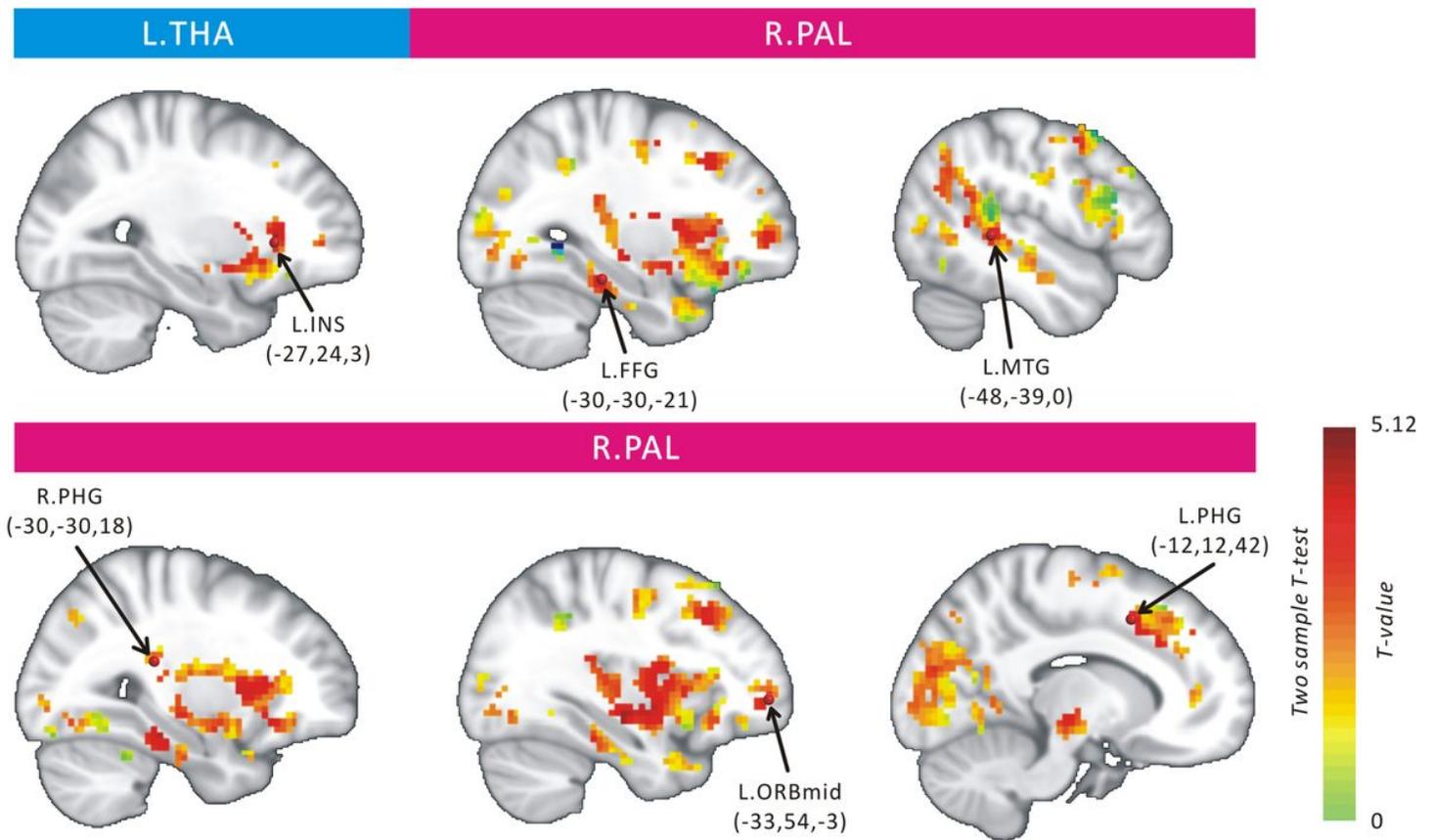


Figure 2

Cluster corresponding to the significant difference ($p < 0.05$, Threshold-Free Cluster Enhancement correction, TFCE-correction) in the whole-brain map of subcortical region between high creative group (HCG) and low creative group (LCG). Abbreviation: THA, thalamus; PAL, pallidum; L (R), left (right) hemisphere.

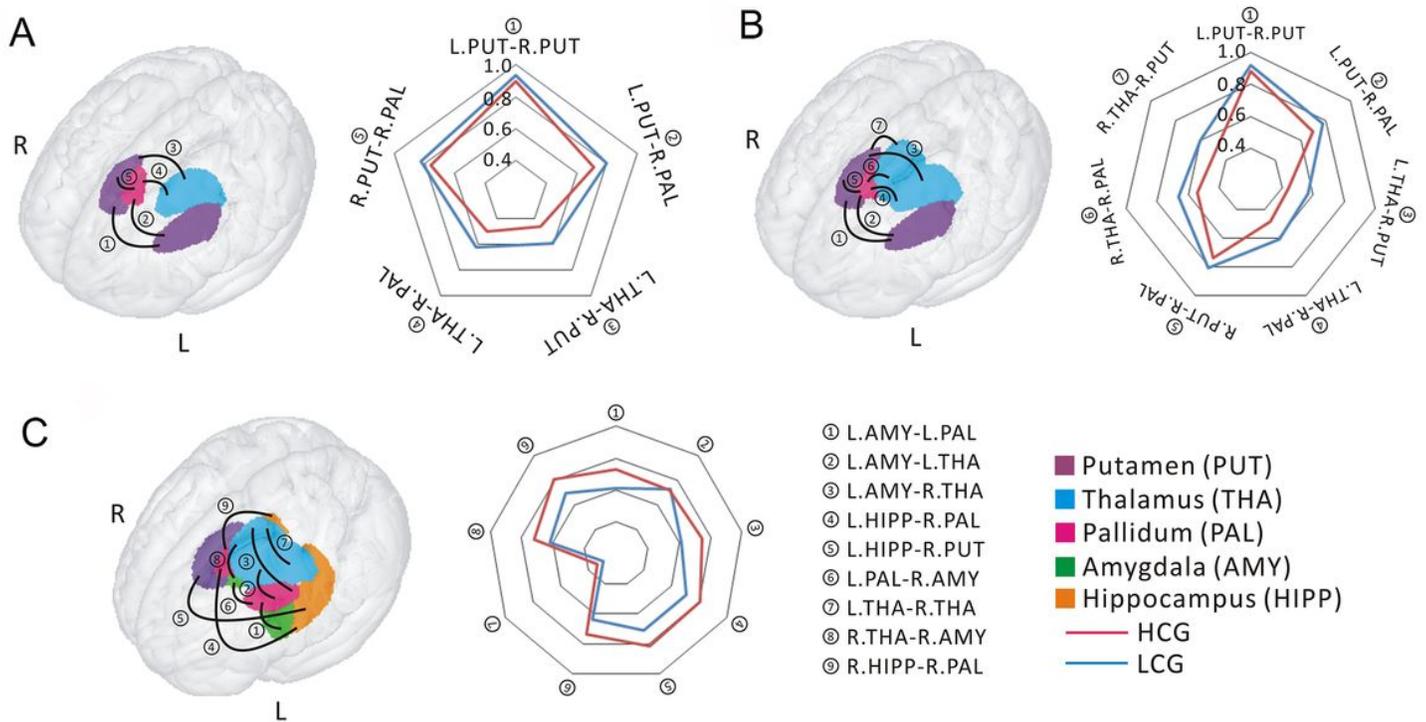


Figure 3

Significant differences ($p < 0.05$, false discovery rate correction, FDR-correction) in A) function connectivity (FC) and B) averaged dynamic FC (dFC) between high creativity group (HCG) and low creativity group (LCG).

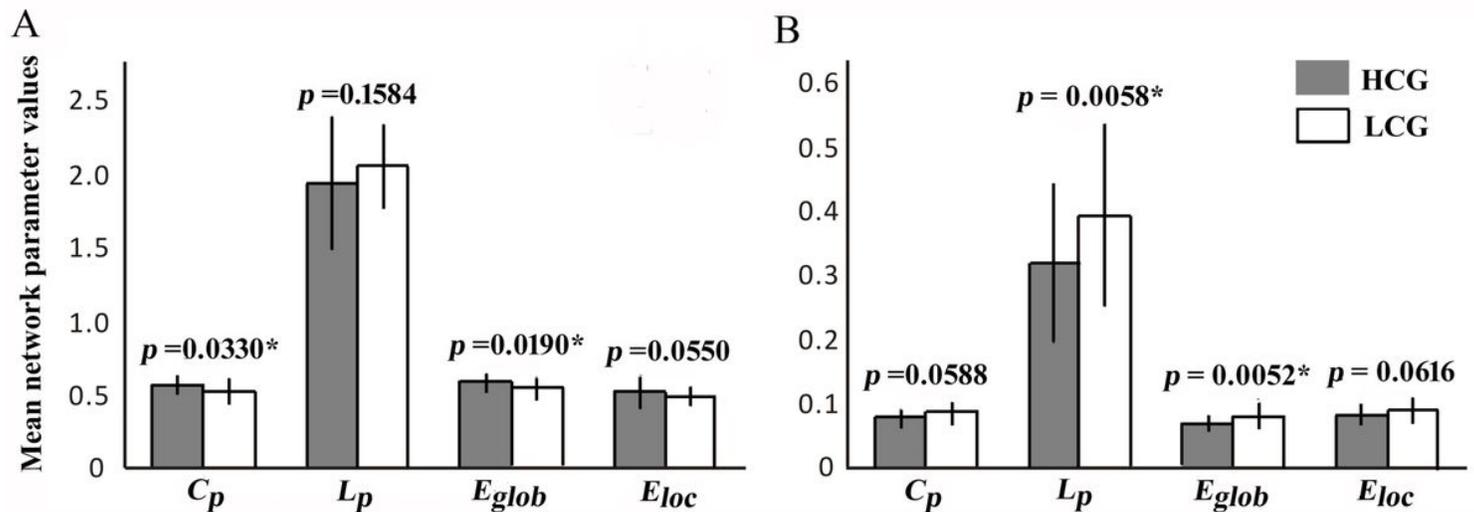


Figure 4

A) Global parameters of subcortical network for both high creativity group (HCG) and low creativity group (LCG). B) The variance of global parameters of subcortical network for both HCG and LCG. * $p < 0.05$.

Supplementary Files

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