



# Plasticity of the resting-state brain: static and dynamic functional connectivity change induced by divergent thinking training

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Published online: 13 March 2019

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## Abstract

Creativity is very important and is linked to almost all areas of our everyday life. Improving creativity brings great benefits. Various strategies and training paradigms have been used to stimulate creative thinking. These training approaches have been confirmed to be effective. However, whether or not training can reshape the resting-state brain is still unclear. The present study examined whether or not the divergent thinking training intervention can reshape the resting-state brain functional connectivity (FC). Static seed-based and dynamic approaches were used to explore this problem. Results demonstrate significant changes in static and dynamic FCs. FCs, such as dorsal anterior cingulate cortex-inferior parietal lobule, dorsal anterior cingulate cortex-precuneus and left and right dorsolateral prefrontal cortex, was significantly improved through the training. Furthermore, the temporal variability of the supplementary motor area and middle temporal gyrus was improved. These results indicate that divergent thinking training may lead to resting-state brain plasticity. Considering the role of these regions in brain networks, the present study further confirms the close relationship between the brain networks' dynamic interactions and divergent thinking processes.

**Keywords** Plasticity · Resting-state · Functional connectivity · Divergent thinking · Training

## Introduction

Creativity is very important and is linked to almost all areas of our everyday life (Dietrich and Kanso 2010; Mumford 2002). Previous studies about geniuses showed that individuals with high creativity appear to have a special brain. Einstein's brain has an increased expansion of the inferior parietal region and a thicker corpus callosum than controls (Men et al. 2014; Witelson et al. 1999). Distinguished exceptional groups, such as scientists and artists, seem to have different brain mechanisms compared with ordinary people (Andreasen and Ramchandran 2012; Japardi et al. 2018). Their brains seem to work in a creative way. Creativity is important in being a genius or at least closer to becoming one. The question of

whether or not creativity can be improved by training has long attracted the attention of researchers. Various strategies and training paradigms have been used to stimulate creative thinking (Scott et al. 2004; Smith 1998). These training approaches have been confirmed to be effective (Ma 2006; Scott et al. 2004). Thus, another question is whether or not such training can reshape the resting-state brain.

Previous studies exploring the difference between experts and novices provide insights into the training inducing brain plasticity. Professional individuals in a field have different brain activity patterns than novices in profession-related process and creative processes (Fink et al. 2009b; Gibson et al. 2009; Limb and Braun 2008). Fink, Graif, et al. (2009) observed that professional dancers exhibited greater alpha synchronization during an improvisation dance than novices. Furthermore, professional dancers had stronger alpha synchronization in posterior parietal brain regions than novices during the generation of alternative uses task. Trained musicians had enhanced creativity and greater bilateral frontal activity during creative tasks (Gibson et al. 2009). Kowatari et al. (2009) found that subjects who had been formally trained in design (experts) had different intercortical interactions

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compared with novice subjects. Furthermore, compared with inexperienced writers, experts with professional training experience in creative writing showed increased left caudate nucleus and left dorsolateral and superior medial prefrontal cortex activation during creative writing (Erhard et al. 2014).

Most of these findings are based on comparisons between groups, causing difficulty in inferring causality. Therefore, several longitudinal training studies have been conducted to explore the creativity training that induces brain plasticity. Different kinds of training procedures and brain imaging approaches have been used to explore this problem (Beaty et al. 2018b; Q. Chen et al. 2014; Fink et al. 2006; Gibson et al. 2009; Sun et al. 2016; H. Takeuchi et al. 2011; Zhu et al. 2013). Fink et al. (2006) found that participants who were trained for approximately two weeks on various divergent thinking tasks displayed comparatively higher synchronization of frontal electroencephalogram (EEG) alpha activity compared with their pre-training performance. Their recent study found that verbal creativity training modulates brain activities of the language and memory related regions, such as the left inferior parietal cortex (IPL) and left middle temporal gyrus (MTG) (Fink et al. 2015). Divergent thinking training was found to reshape the activation patterns during creative processes (Sun et al. 2016). In addition, changes in alternative uses fluency induced by divergent thinking training were positively associated with changes in superior lateral prefrontal cortex (LPFC) activation over time (Kleibeuker et al. 2017). Another study used design-thinking-based training to enhance the creative capacity of participants and found a significant difference in brain activities between the training group and control group during spontaneous improvisation task (Saggar et al. 2017). Furthermore, a recent study found that resting-state brain network connectivity can be modulated through verbal divergent thinking training (Fink et al. 2018). Schlegel et al. (2015) found that students became more creative via the reorganization of prefrontal white matter during taking art courses.

Although several studies have showed that creativity training has an effect on the function and structure of the brain, its effect on the spontaneous neuronal activity of the brain, especially the dynamic resting-state brain activity, is still unknown. Previous studies have shown that divergent thinking is related to the resting-state functional connectivity (FC) (Li et al. 2016; Hikaru Takeuchi et al. 2012). Moreover, recent studies have emphasized the dynamic interaction of the brain network in creative processes (Beaty et al. 2016). A recent study showed that the dynamic character of the resting-state brain is related to creativity (Sun et al. 2019). They found that verbal creativity correlates with temporal variability of the FC patterns of the LPFC, precuneus, and parahippocampal gyrus. Furthermore, verbal creativity correlates with the temporal variability of FC patterns within the default mode network (DMN) and between the DMN and several networks.

Several studies have also showed that cognitive abilities, such as cognitive flexibility and personality characteristics, such as openness, are related to the dynamic FC (Beaty et al. 2018a; Braun et al. 2015; T. Chen et al. 2016).

On the basis of the findings discussed above, the present study investigated the effects of a 20-session divergent thinking training intervention. In line with our previous studies, we employed divergent thinking tasks that are widely used to measure creativity (Fink and Benedek 2014; Scott et al. 2004). We also proposed several hypotheses based on previous studies (Ma 2006; Scott et al. 2004). First, we hypothesized that FC pattern changes would be observed after training. Our previous study showed that the training increased the activity of brain regions, such as dorsolateral prefrontal cortex (DLPFC), IPL and dorsal anterior cingulate gyrus (dACC) (Sun et al. 2016). After the training, the FC among these regions and other brain regions was reshaped. Second, we hypothesized that the changes in the dynamic character of brain regions and networks would be observed. After training, the brain FC patterns were more flexible.

## Materials and methods

### Participants

A total of 40 participants were recruited from Southwest University, China (Sun et al. 2016). They were randomly assigned either to the training group (TG) or control group (CG). All participants were right-handed and none of them had a history of neurological or psychiatric illness. The study was approved by the Southwest University Brain Imaging Center Institutional Review Board. In accordance with the Declaration of Helsinki (1991), written informed consent was obtained from all participants. One participant in the TG gave up after the pre-test, and one participant in the CG was absent at the post-test. One participant in the TG did not follow the instructions during scanning. Two participants (one in the TG and one in the CG) were excluded because of the head motion >3 mm maximum translation or 3° rotation during the resting-state scanning at pre-test or post-test. As such, a total of 17 participants in the TG and 18 participants in the CG remained in the final analysis.

### Procedure

The procedure has been described in our previous study. Participants completed cognitive assessments and fMRI scanning during the pre-test and post-test.

During cognitive simulation training, participants were first presented with an everyday object (e.g., “umbrella”) and were asked to generate as many novel and unusual uses of these common objects as possible within three minutes. Then, a

cognitive simulation was realized through exposure to external ideas, which were obtained in a preliminary experiment. Subsequently, participants had another three minutes to think of other novel and unusual answers. The training materials were presented on the computer, while the participants wrote down their ideas on paper. This procedure is known as an effective approach in group-based brainstorming techniques (Dugosh et al. 2000) and has been confirmed by previous neuroimaging studies (Fink et al. 2010). The training consisted of 20 sessions, each session took nearly 30 min long with four items.

## Image acquisition

Images were acquired using a Siemens TRIO 3-Tesla scanner. The participants were asked to lay supine, with their heads snugly fixed with foam pads to minimize head movement. Participants were instructed to keep still, close their eyes, and not fall asleep. A total of 242 BOLD images were obtained using echo planar imaging (EPI) sequence with following parameters: slices = 32; repetition time (TR)/echo time (TE) = 2000/30 ms; flip angle = 90 deg. FOV = 200 × 200 mm<sup>2</sup>; voxel size = 3.4 × 3.4 × 4 mm<sup>3</sup>; thickness = 3 mm; slice gap = 1 mm.

## Functional imaging data preprocessing

Preprocessing was performed using Data Processing Assistant for Resting-State fMRI (DPARSF\_V3.1\_141101, <http://www.restfmri.net/forum/DPARSF>). The first 10 volumes of the functional images were discarded. Next, slice timing and head motion correction were performed. Two participants who exhibited head motion of 3.0 mm maximum translation or 3.0° rotation were excluded. Then, each participant's functional image was normalized onto the Montreal Neurological Institute space (EPI template, resampling voxel size was 3 × 3 × 3 mm<sup>3</sup>). Spatial smoothing (6 mm full width at half maximum Gaussian kernel) was conducted to decrease spatial noise. Finally, linear trends were removed, and 0.01–0.1 Hz band-pass filter was applied (Cordes et al. 2001; Lee et al. 2013; Liao et al. 2013; Mokhtari et al. 2019; Plante et al. 2018; Wang et al. 2009). 24 head motion parameters (Friston, Williams, Howard, Frackowiak, & Turner, 1996), global mean signal, white matter signal, and cerebrospinal fluid signal were regressed out from BOLD signals in DPARSF.

## Static FC analysis

Seed-based FC approach was used in the static FC analysis. We used the regions that show significant activation changes in our previous task-based fMRI study as seed regions. Then, we computed the FC between the seed regions and all other voxels. The seeds used were as follows: 6-mm-radius spheres

centered on the DLPFC (MNI coordinates: −36, 39, 15), IPL/postcentral gyrus (MNI coordinates: −57, −30, 45), IPL (MNI coordinates: −39, −48, 48), DLPFC (MNI coordinates: 36, 27, 30), and dACC (MNI coordinates: 3, 21, 21). For each participant, the mean time series of the seed regions was calculated and then correlated with the time series of all other voxels in the whole brain. The correlation coefficients were transformed to Fisher z-scores to form a z-functional connectivity map for each participant for further analysis.

Paired t-tests were used to estimate the FC differences between the pre-test and post-test. The voxel-wise threshold was set at  $P < 0.001$ . We defined the ROIs according to the prior neuroimaging studies about divergent thinking (Abraham et al. 2012; Beaty et al. 2016; Fink et al. 2009a; Jung et al. 2013; Wu et al. 2015). The ROIs were used for multiple comparisons. The Wake Forest University (WFU) Pick Atlas (Maldjian et al. 2003) was used to define the following areas: the bilateral ACC, bilateral precuneus, left and right DLPFC, left and right IPL, and left and right MTG. Small-volume corrections were performed across the ROIs. The family-wise error (FWE) method was used for multiple comparisons, and significance level was set at  $P < 0.05$  (Figs. 1 and 2).

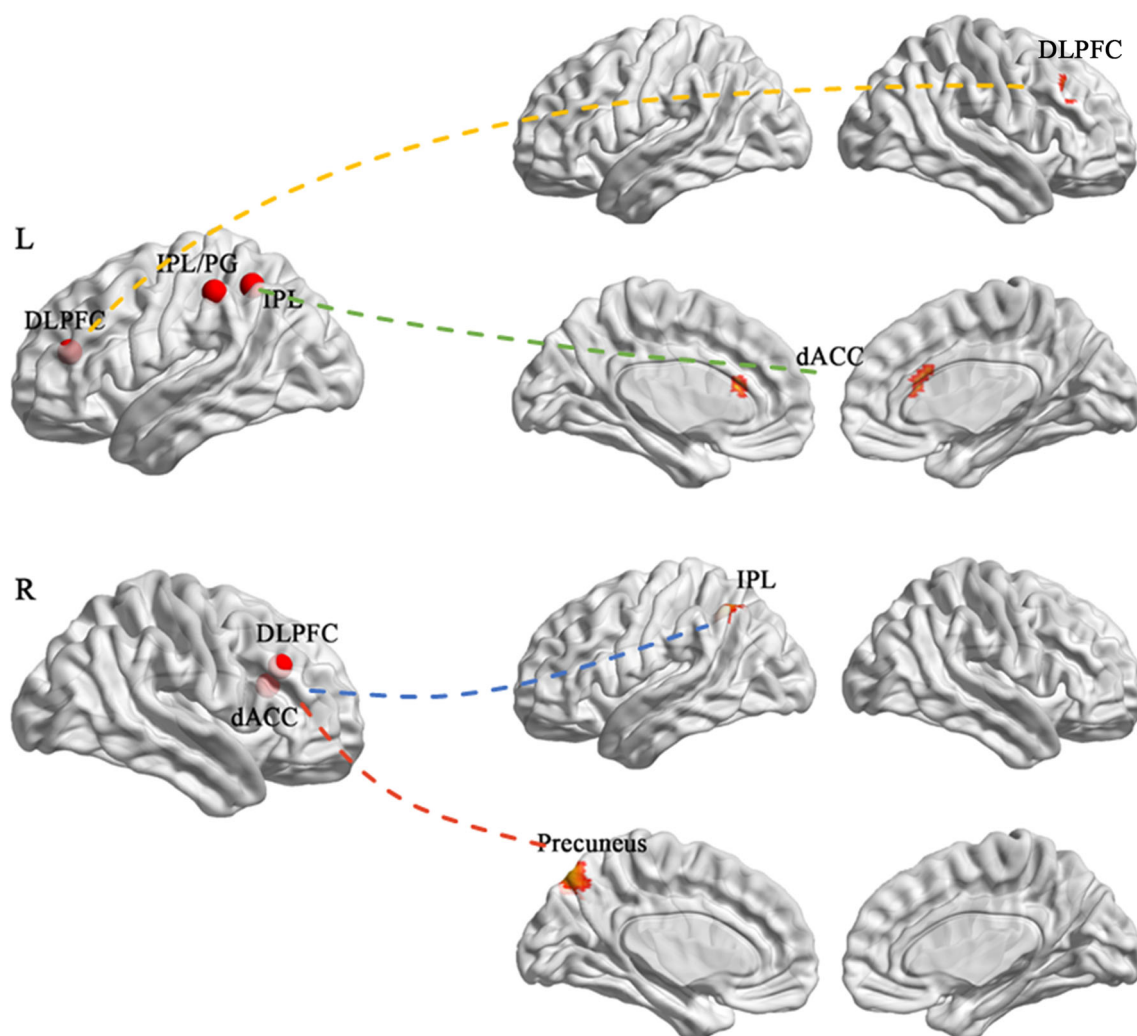
Further ANOVAs were conducted in the significant clusters with groups (TG and CG) and time periods (pre and post-test) as factors.

## Dynamic FC analysis

The temporal variability of a brain region was consistent with our previous study (Sun et al. 2019). This index reflects the dynamic reconfiguration of a brain region into distinct functional modules at different times, and is indicative of brain flexibility and adaptability (Zhang et al. 2016). We adopted the Power-264 module parcellation as ROIs (Power et al. 2011). To characterize the temporal variability of a given ROI, we first segmented all BOLD signals into  $n$  non-overlapping windows with length  $l$ . The whole-brain FC network  $F_i$  (an  $m \times m$  matrix, with  $m = 264$  nodes) in the  $i$ th time window was then constructed, with the Pearson correlation being the measure of FC. The FC profile of region  $k$  at time window  $i$  is denoted by  $F_i(k, :)$  (shortened as  $F_{i,k}$ ), which is an  $m$ -dimensional vector that represents all the functional connections of region  $k$ . The variability of a ROI  $k$  is defined as:

$$V_k = 1 - \overline{\text{corrcoef}(F_{i,k}, F_{j,k})} \quad i, j = 1, 2, 3, \dots, n, i \neq j$$

We calculated  $V_k$  at a number of different window lengths ( $l$  = equal to 40, 42, 44, ... 50 s) and then take the average value as the final variability to avoid arbitrary choice of window length. The variability associated with a region characterizes the flexibility of the region's functional architecture. The larger the temporal variability of a ROI, the more



**Fig. 1** Static functional connectivity change induced by divergent thinking training. The left of the figure showed the seed regions used in functional connectivity analysis. The right of the figure showed the

clusters whose functional connectivity with seed regions were significantly changed. All effects are corrected by FWE

functional communities/systems this region will be involved in at different times.

Paired t-tests were used to estimate the dynamic FC differences between the pre-test and post-test. The FWE method was used for multiple comparisons for the regions in each network. The significance level was set at  $P < 0.05$ .

Further ANOVAs were conducted in the significant regions with groups (TG and CG) and time periods (pre and post-test) as factors.

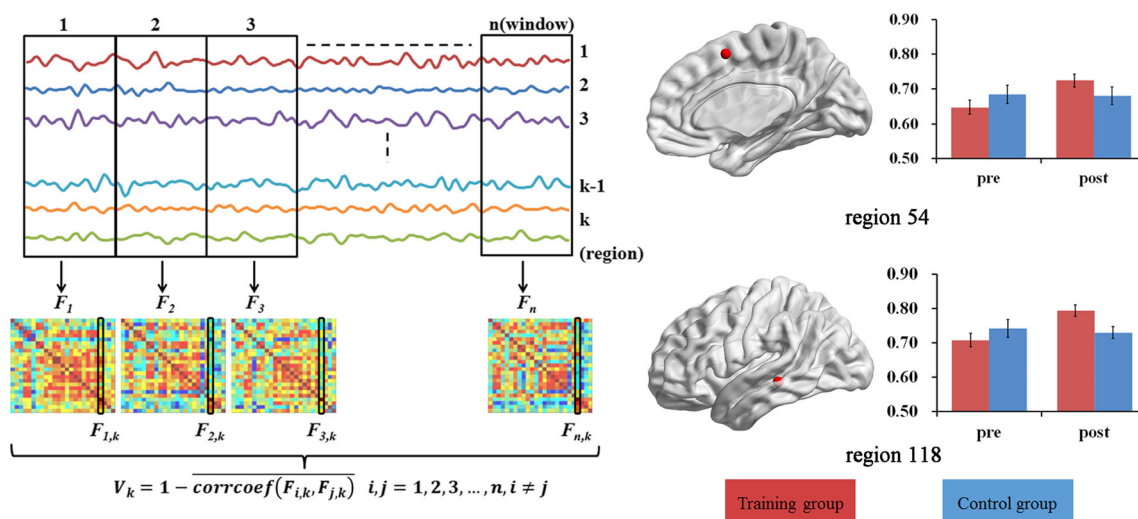
## Results

### Static FC analysis

The seed-based whole brain FC analysis revealed that the FC patterns of TG had changed after training. Using the left DLPFC as the seed region, the connectivity between

the left and right DLPFC was significantly increased (cluster size = 46 voxels; peak coordinates in MNI: 57, 30, 30;  $t = 5.55$ ; Table 1). By using the left IPL/PG as seed region, the connectivity between the left IPL/PG and MTG was significantly increased (cluster size = 21 voxels; peak coordinates in MNI: 63, -30, 0;  $t = 5.30$ ; Table 1). By using the left IPL as the seed region, the connectivity between the left IPL and dACC was significantly increased (cluster size = 12 voxels; peak coordinates in MNI: -3, 24, 15;  $t = 5.00$ ; Table 1). When the right DLPFC was used as the seed region, the connectivity between the right DLPFC and IPL (cluster size = 41 voxels; peak coordinates in MNI: -45, -51, 42;  $t = 5.75$ ; Table 1) and the connectivity between the right and left DLPFC (cluster size = 50 voxels; peak coordinates in MNI: -54, 18, 9;  $t = 5.80$ ; Table 1) were significantly increased. The dACC-IPL connectivity (cluster size = 56 voxels; peak coordinates in MNI: -42, -54, 48;  $t = 4.78$ ; Table 1) and dACC-precuneus





**Fig. 2** Dynamic functional connectivity change induced by divergent thinking training. The left of the figure showed the dynamic functional connectivity analysis process. The right of the figure showed the regions

whose temporal variability were significantly changed. All effects are corrected by FWE

connectivity (cluster size = 87 voxels; peak coordinates in MNI:  $-9, -75, 57$ ;  $t = 7.03$ ; Table 1) were also significantly increased when the dACC was used as the seed region.

Following ANOVA analysis revealed significant group  $\times$  time period interaction for the left DLPFC-right DLPFC [ $F(1, 33) = 6.98$ ;  $P < 0.05$ ,  $\eta^2 = 0.18$ ], the IPL-dACC [ $F(1, 33) = 13.53$ ;  $P < 0.05$ ,  $\eta^2 = 0.29$ ] and the dACC-IPL connectivities [ $F(1, 33) = 4.91$ ;  $P < 0.05$ ,  $\eta^2 = 0.13$ ]. The dACC-precuneus connectivity was marginally significant [ $F(1, 33) = 3.56$ ;  $P = 0.068$ ,  $\eta^2 = 0.10$ ]. Other connectivities showed no significant interaction effect. The simple-effect analysis indicated that the connectivity of dACC-IPL, bilateral DLPFC and dACC-precuneus connectivities at the post-test were higher than those at the pre-test in the TG ( $P < 0.05$ ). However, the changes of the connectivities in the CG were insignificant. The IPL-dACC connectivity at the post-test was higher than that at the pre-test in the TG, whereas the change of the IPL-dACC connectivity in the CG was reverse.

## Dynamic FC analysis

Paired t-tests showed that the variability of the four regions from the DMN, CTCN and SN had significantly changed after training, as shown in Table 2.

Following ANOVA analysis revealed significant group  $\times$  time period interaction for the supplementary motor area [SMA, region 54,  $F(1, 33) = 9.27$ ;  $P < 0.05$ ,  $\eta^2 = 0.22$ ] and MTG [region 118,  $F(1, 33) = 8.40$ ;  $P < 0.05$ ,  $\eta^2 = 0.20$ ]. The simple-effect analysis indicated that the variability of these regions at post-test was higher than that at the pre-test in the TG ( $P < 0.05$ ), whereas the change in variability of these regions in the CG was insignificant.

## Discussion

The present study examined whether or not a divergent thinking training can reshape the FC pattern of the resting-state

**Table 1** Brain functional connectivity change induced by divergent thinking training

Seed regions	Brain areas	R/L	Maxima of cluster	t	Cluster size (voxels)
Left DLPFC	DLPFC	R	57 30 30	5.55	46
Left IPL/PG	MTG	R	63 -30 0	5.30	21
Left IPL	dACC	R, L	-3 24 15	5.00	12
Right DLPFC	IPL	L	-45 -51 42	5.75	41
	DLPFC	L	-54 18 9	5.80	50
dACC	IPL	L	-42 -54 48	4.78	56
	Precuneus	L	-9 -75 57	7.03	87

IPL inferior parietal lobule, dACC dorsal anterior cingulate cortex, MTG middle temporal gyrus, DLPFC dorsal lateral prefrontal cortex. All results were corrected by FWE

**Table 2** The change of temporal variability of brain region induced by divergent thinking training

ROI index	R/L	Brain areas (AAL atlas)	Network	t
54	R	SMA	Cingulo-opercular Task Control	3.95
56	R	IFG	Cingulo-opercular Task Control	3.76
118	L	MTG	Default mode	4.51
213	R, L	SMA	Salience	4.10

*SMA* supplementary motor area, *IFG* inferior frontal gyrus, *MTG* middle temporal gyrus. All results were corrected by FWE

brain. Seed-based static and dynamic FCs were used to answer this question. Our results demonstrated significant changes in the static and dynamic FCs. Specifically, several connectivities such as dACC-IPL and dACC-precuneus, were significantly improved through the training. Furthermore, the temporal variability of several regions, such as SMA and MTG, was improved. These regions are the key regions of DMN, control network, and salience network. These results indicated that divergent thinking training may lead to resting-state brain plasticity in the static and dynamic manners.

A number of studies have confirmed the role of the dACC, IPL, and precuneus in divergent thinking. Task-based fMRI showed that the activity of these regions is involved in creative processes. For example, Abraham et al. (2012) proposed that reconsidering the function of ACC in divergent thinking task is necessary. Fink et al. (2010; 2012) concluded that temporoparietal brain regions and precuneus were particularly sensitive to creative cognitive stimulation. Meta-analysis combining different creative tasks also confirmed this point (Wu et al. 2015). Aside from the task-related brain activity, off-line resting-state studies also showed the close relationship between creativity and these regions. For example, high creative ability was related to great resting-state FC in the inferior frontal cortex and DMN (Roger E Beaty et al. 2014). The significant increase of FC in the brain regions after the training was also found in previous studies (Beaty et al. 2015, 2016; Takeuchi et al. 2011). Furthermore, our results confirm that the FCs of these regions in brain networks are sensitive to divergent thinking training.

The dACC is commonly thought to be related to response conflict monitoring, error detection and response selection (Holroyd et al. 2004; Mansouri et al. 2009). The dACC may contribute to a cognitive top-down control mechanism that enhances the process of evaluation and exploration of generated ideas during creative thinking. The IPL has been linked to the attention state during the generation of original ideas (Sun et al. 2016). Lastly, the precuneus was the core region of DMN that is related to the generation of original ideas (Beaty et al. 2016; Jung et al. 2013). The present study further showed that the training-induced plasticity mechanism of these regions may also extend to the spontaneous neuronal activity of the brain.

The FCs of the bilateral DLPFC were also improved. This area plays an important role in creative processes (Abraham et al. 2012). This finding was also supported by our recent study, which found that the posterior DMN and right FPN connectivity strength in the divergent thinking task was positively correlated with the connectivity strength between anterior DMN and left FPN during the resting-state (Shi et al. 2018). Increased FC of the bilateral DLPFC may be related to the enhanced top-down process which is related to divergent thinking.

The present study also found that the temporal variability of SMA and MTG was also improved after training. Our previous studies showed that the dynamic character of brain regions and networks is related to verbal divergent thinking (Sun et al. 2019). The dynamic interaction of brain networks is closely related to creativity (Beaty et al. 2016). SMA is related to task switching, whereas MTG is related to semantic processing, representation and control (Badre et al. 2005; Nachev et al. 2008; Whitney et al. 2011). These regions were activated during the creativity tasks (Bashwiler et al. 2016; de Manzano and Ullen 2012). In Power's study, SMA belongs to the cingulo-opercular task control network, whereas MTG belongs to the DMN (Power et al. 2011). Our finding is consistent with previous studies emphasizing the role of brain networks in creative processes (Beaty et al. 2016; Jung et al. 2013; Sun et al. 2019). Furthermore, our results confirm the relationship between dynamic FC and divergent thinking. Improved temporal variability of the key regions showed that the FC patterns of these regions and other regions of the brain were changed. After the training, the brain showed more flexible connectivity patterns.

The present study explored the divergent thinking-related brain functional plasticity. A number of previous studies focused on brain structure plasticity (Bezzola et al. 2011; Colcombe et al. 2006; Colom et al. 2016; Draganski et al. 2004). The relationship between the brain's structure and function is complex (Honey et al. 2010; Sun et al. 2016). The present study extended the research on training-related brain function plasticity. Furthermore, the present study used complex cognitive training procedure. Observing that the brain function can be reshaped by complex cognitive abilities training is encouraging.

This study, however, has some limitations. One limitation is that only divergent thinking training was used. Although the longitudinal design we used can provide direct evidence for the neural basis of creativity training and its plasticity effects, studies using different training approaches are needed in the future. Another limitation is that this study did not investigate possible transfer effects of creativity training on other cognitive abilities, such as cognitive control or working memory. Future studies that examine transfer effects may give insights into the causal explanation of creative and other cognitive abilities. Furthermore, future studies also need to use an active control group to explore the specific divergent thinking training effect.

## Conclusion

In summary, the results of the present study showed the effects of creativity training on brain function through short-term divergent thinking training. Our results offer insights into the neural plasticity of the resting-state brain. The observation that neural plasticity can be achieved through training, not only by task-related brain activity but also by resting-state brain is encouraging. Human creativity training that can reshape the brain function shows a promising potential as it may have positive effect on the external behavioral performance.

**Acknowledgments** This research was supported by the National Natural Science Foundation of China (31470981; 31571137; 31500885; 31600878; 31771231), Project of the National Defense Science and Technology Innovation Special Zone, Chang Jiang Scholars Program, National Outstanding Young People Plan, the Program for the Top Young Talents by Chongqing, the Fundamental Research Funds for the Central Universities (SWU1709568, SWU1609177), the Postgraduate Science Innovation Foundation of Chongqing (CYB18109), Natural Science Foundation of Chongqing (cstc2015jcyjA10106), Fok Ying Tung Education Foundation (151023), the Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University.

## Compliance with ethical standards

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** All procedures performed in studies involving human participants were in accordance with the ethical standards of the Brain Imaging Center Institutional Review Board of Southwest China University and with the standards of the Declaration of Helsinki (1991).

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

报告编号: 202011-055

# 检索报告


项目名称: 论文被 SCI 收录情况证明

委托人: 西南大学心理学部 孙江洲

日期: 2020 年 11 月 5 日

认证单位: 教育部科技查新工作站 N08

二〇二〇年制

检索项目名称	委托人孙江洲提交论文被 SCI 收录情况			
查新机构	名称	教育部科技查新工作站 N08	邮编	400715
	地址	重庆市北碚区西南大学图书馆	电话	023-68253283
委托文献目录	<p>标题: Plasticity of the resting-state brain: static and dynamic functional connectivity change induced by divergent thinking training</p> <p>作者: Sun, JZ (Sun, Jiangzhou); Zhang, QL (Zhang, Qinglin); Li, Y (Li, Yu); Meng, J (Meng, Jie); Chen, QL (Chen, Qunlin); Yang, WJ (Yang, Wenjing); Wei, DT (Wei, Dongtao); Qiu, J (Qiu, Jiang)</p> <p>来源出版物: BRAIN IMAGING AND BEHAVIOR 卷: 14 期: 5 页: 1498-1506</p>			
检索的数据库范围	<p>1. Science Citation Index Expanded (SCIE) - 1900 年至今</p> <p>2. 中科院-JCR 期刊分区数据在线平台</p>			
检索结论	<p>经检索, 孙江洲提交的论文(第一作者)被 SCI 收录; 检索结果详细情况见附件 1 和附件 2。</p> <p>检索人(签名): 周剑  职称: 研究馆员</p> <p> 教育部科技查新工作站 N08</p> <p>2020 年 11 月 5 日</p>			
备注	1、影响因子及分区为论文发表当年或当前最新的影响因子和分区。			

# 附件 1: SCI 收录情况

题名 作者等信息	检索号	影响因子	分区(中科院)	出版时间						
<p>标题: Plasticity of the resting-state brain: static and dynamic functional connectivity change induced by divergent thinking training</p> <p>作者: Sun, JZ (Sun, Jiangzhou); Zhang, QL (Zhang, Qinglin); Li, Y (Li, Yu); Meng, J (Meng, Jie); Chen, QL (Chen, Qunlin); Yang, WJ (Yang, Wenjing); Wei, DT (Wei, Dongtao); Qiu, J (Qiu, Jiang)</p> <p>来源出版物: BRAIN IMAGING AND BEHAVIOR 卷: 14 期: 5 页: 1498-1506</p>	000579512100019	IF <sub>2019</sub> =3.491	<table><tr><td>小类</td><td>NEUROIMAGING 神经成像</td><td>3区</td></tr><tr><td>大类</td><td>医学</td><td>2区</td></tr></table>	小类	NEUROIMAGING 神经成像	3区	大类	医学	2区	2020
小类	NEUROIMAGING 神经成像	3区								
大类	医学	2区								

## 附件 2:

标题: Plasticity of the resting-state brain: static and dynamic functional connectivity change induced by divergent thinking training

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来源出版物: BRAIN IMAGING AND BEHAVIOR 卷: 14 期: 5 页: 1498-1506 DOI:

10.1007/s11682-019-00077-9 出版年: OCT 2020

Web of Science 核心合集中的 "被引频次": 1

被引频次合计: 1

入藏号: WOS:000579512100019

PubMed ID: 30868403

语言: English

文献类型: Article

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Web of Science 类别: Neuroimaging

研究方向: Neurosciences & Neurology

IDS 号: OC9YM

ISSN: 1931-7557

eISSN: 1931-7565



基金资助致谢:

基金资助机构 授权号

National Natural Science Foundation of China

31470981

31571137

31500885

31600878

31771231

Project of the National Defense Science and Technology Innovation Special Zone

Chang Jiang Scholars Program

National Outstanding Young People Plan

Program for the Top Young Talents by Chongqing

Fundamental Research Funds for the Central Universities

SWU1709568

SWU1609177

Postgraduate Science Innovation Foundation of Chongqing

CYB18109

Natural Science Foundation of Chongqing

cstc2015jcyjA10106

Fok Ying Tung Education Foundation

151023

Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University

This research was supported by the National Natural Science Foundation of China (31470981; 31571137; 31500885; 31600878; 31771231), Project of the National Defense Science and Technology Innovation Special Zone, Chang Jiang Scholars Program, National Outstanding Young People Plan, the Program for the Top Young Talents by Chongqing, the Fundamental Research Funds for the Central Universities (SWU1709568, SWU1609177), the Postgraduate Science Innovation Foundation of Chongqing (CYB18109), Natural Science Foundation of Chongqing (cstc2015jcyjA10106), Fok Ying Tung Education Foundation (151023), the Research Program Funds of the Collaborative Innovation Center of Assessment toward Basic Education Quality at Beijing Normal University.