Behavioural Brain Research 320 (2017) 233–243

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

Mental rotation task specifically modulates functional connectivity strength of intrinsic brain activity in low frequency domains: A maximum uncertainty linear discriminant analysis

Mengxia Gao [a,1], Delong Zhang [a,1], Zengjian Wang [a], Bishan Liang [b], Yuxuan Cai [a], Zhenni Gao [a], Junchao Li [a], Song Chang [a], Bingqing Jiao [a], Ruiwang Huang [a,*], Ming Liu [a,*]

[a] Center for the Study of Applied Psychology, Key Laboratory of Mental Health and Cognitive Science of Guangdong Province, School of Psychology, South China Normal University, Guangzhou, China
[b] College of Education, Guangdong Polytechnic Normal University, China

HIGHLIGHTS

- MLDA method effectively discriminates the resting and task state based on FCS.
- The modulation of FCS is observed in the low frequency band 0.05–0.1 Hz.
- Imagery-based and executive-control function are differently involved in mental rotation.
- Exploration of modulation effect provides full view of the neural basis of mental rotation.

ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form
12 December 2016
Accepted 15 December 2016
Available online 20 December 2016

Keywords:
Mental rotation task
Resting-state fMRI
Discriminant analysis
Voxel-wise functional connectivity strength
Frequency-bandwidth

ABSTRACT

Neuroimaging studies have highlighted that intrinsic brain activity is modified to implement task demands. However, the relation between mental rotation and intrinsic brain activity remains unclear. To answer this question, we collected functional MRI (fMRI) data from 30 healthy participants in two mental rotation task periods (1st-task state, 2nd-task state) and two rest periods before (pre-task resting state) and after the task (post-task resting state) respectively. By combining the spatial independent component analysis (ICA) and voxel-wise functional connectivity strength (FCS), we identified FCS maps of 10 brain resting state networks (RSNs) within six different bands (i.e., 0–0.05, 0.05–0.1, 0.1–0.15, 0.15–0.2, 0.2–0.25, and 0.01–0.08 Hz) corresponding to the four states for each subject. The maximum uncertainty linear discriminant analysis (MLDA) method showed that the FCS within the low frequency bandwidth of 0.05–0.1 Hz could effectively classify the mental rotation task state from pre-/post-task resting states but failed to discriminate the pre- and post-task resting states. Discriminative FCSs were observed in the cognitive executive-control network (central executive and attention) and the imagery-based internal mental manipulation network (default mode, primary sensorimotor, and primary visual). Imagery manipulation is a stable mental element of mental rotation, and the involvement of executive control is dependent on the degree of task familiarity. Together, the present study provides evidence that mental rotation task specifically modifies intrinsic brain activity to complement cognitive demands, which provides further insight into the neural basis of mental rotation manipulation.

1. Introduction

Recent functional imaging studies have shown that intrinsic brain activity is the baseline of cognition processes, in which resting-state brain activity is modified to implement cognition demands [1,2]. The modification of intrinsic brain activity is depending on the task demand, such as the goal-directed task [3] and the internally directed tasks [4,5]. In particular, the mental

* Corresponding authors at: Center for the Study of Applied Psychology, Key Laboratory of Mental Health and Cognitive Science of Guangdong Province, School of Psychology, South China Normal University, Guangzhou 510631, China.
E-mail addresses: ruiwang.huang@gmail.com (R. Huang), lium@scnu.edu.cn (M. Liu).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.bbr.2016.12.017
0166-4328/

rotation task in which participants make a decision about orientating visual images by manipulation during mental imagining [6], is not only a classical "internally directed" task [7] but also embodies goal-directed attributes [8]. However, the linkage between the mental rotation state and intrinsic brain activity still remains largely unclear.

It is well established that intrinsic brain activity is self-organized into a spatial structure [9] and the evoked neural responses to tasks are embedded in this functional architecture [10]. First, intrinsic brain activity has been observed to be highly trait-related, in which many studies have shown that it is significantly modified by many traits, such as brain disease [11–13], intelligence [14], personality [15], age [16], and gender [17]. At the same time, intrinsic brain activity exhibits dynamically adaptive reconfiguration during active task performance [18]. Recently, many studies have showed the existence of the modulation effect on intrinsic brain activity from task engagements, including simple visual tasks [19–21], auditory task [22], attention task [23], memory task [24], and motor learning task [25]. Of note, most of the modulatory effects on intrinsic brain activity from different cognitive tasks were found in the low-frequency bandwidth (0.01–0.1 Hz) [1,26–28]. Although the significant modulation effect of task demands on intrinsic brain activity has been widely reported, distinct task demands have been rarely studied, which may induce different modifications. Particularly, many studies found that the default mode network (DMN) was deactivated during some externally goal-directed tasks [29–31]. In contrast to these observations, it was recently found that the involvement of internal processing cognition task could cause activation of the DMN [4,5], and during the maintenance period of a working memory task, brief task-unrelated visual stimuli increased the activity of the DMN [32].

As a specific task demand, the mental rotation task allows one to judge an object's orientation in their mind and was first proposed by Shepard and Metzler [6]. The completion of an mental rotation task requires at least 5 cognitive steps [33]: (I) visually perceiving and encoding the presented object, (II) imagining the object and its orientation, (III) rotating the object mentally, (IV) making a judgment whether the object is similar to the target object, and (V) making the final decision. Regarding the behavior response aspect, it has been widely proven that the reaction time (RT) required to make a judgment always increases in a near-linear fashion with increasing numbers of angles [8,34,35]. To explore the neural substrates of mental rotation, neuroimaging studies have identified many brain regions responding to mental rotation task [8], in which the prefrontal and parietal cortex have been suggested to be highly associated with mental rotation task demands [36–40]. The activation of prefrontal regions is thought to be involved in comparing the target object with the mentally rotated object [41], whereas the parietal cortex is thought to participant in mediating visual and somatosensory input message and generating of rotated movements in the visual space [42]. More specifically, the secondary motor areas (i.e., the premotor cortex and supplementary motor area) are thought to be involved in computing rotation angles, matching objects and making the final decision [43]. These observations provide evidence for the complex mental components involved in mental rotation task and shed light upon the neural basis that underlies mental rotation perception process. However, few studies have focused on the neural response of the intrinsic brain activity modified by mental rotation task.

To fill this gap, the present study aimed to explore the changes of the functional connection architecture of intrinsic brain activity in the pre-/post-task resting states and mental rotation task state and investigate the modulation effect of the specific task on resting-state brain activity. To this end, we collected fMRI data from 30 healthy subjects during four states: a pre-task resting state, two mental rotation states (1st-task state and 2nd-task state), and a post-task resting state. Then, we estimated the voxel-wise functional connectivity strength (FCS) based on a graph theoretical method [44,45] related to different frequency bands (i.e., 0–0.05 Hz, 0.05–0.1 Hz, 0.1–0.15 Hz, 0.15–0.2 Hz, 0.2–0.25 Hz, and 0.01–0.08 Hz) [46] to measure the brain functional connection architecture. To further depict the details of the brain connections, we performed a spatial independent component analysis (ICA) to identify the resting-state networks (RSNs) and to further calculate the FCS maps of these RSNs. Meanwhile, a pattern recognition method, a maximum uncertainty linear discriminant analysis (MLDA) [47–49], was applied to detect the changes in the FCS of these RSNs within each frequency band between any two of the four states. Finally, we validated the findings of the present study using an anatomical automatic labeling (AAL) atlas [50].

2. Materials and methods

2.1. Participants

Thirty right-handed, healthy participants (15 males, age 19–25 years) were recruited from the South China Normal University (SCNU) for the present study. All participants had normal or corrected-to-normal vision. None had a history of neurological or psychiatric disorders according to their self-reports. The protocol was approved by the Research Review Board of SCNU. Written informed consent was obtained from each participant.

2.2. Experiment stimuli

In the present study, the letter "R" was selected from the rotation-arrow task devised by Shah and Miyake [51] and was used in the mental rotation task. The stimuli were presented as normal or as mirror-image in 4 orientations: (1) 0°, (2) 45°, (3) 90°, and (4) 135° (Fig. 1).

2.3. Behavioral task and procedure

Fig. 2 shows the stimuli and the procedure of the mental rotation task which corresponded to a previous study [51]. Briefly, the present study contained 4 experimental conditions (i.e., 0°, 45°, 90°, and 135°), which were presented using an event-related design with 2 parts. A total of 128 trials were presented randomly per part (80 trials in the 1 st task and 48 trials in the 2nd task). A rest period of approximately 2 min was allowed between the 2 parts to prevent fatigue. For each trial, a fixation point (500 ms) was first presented, followed by a first letter (normal-R or mirror-R, 1000 ms), then a mask (5000 ms), and finally a second letter (rotated normal-R or mirror-R). The participants were asked to decide whether the second letter was the same to the first letter (normal or mirror) by pressing a button within 5000 ms using the right thumb to indicate the same and the left thumb to indicate a difference. Stimuli were presented using *E*-prime software (http://www.e-prime.pl). Before fMRI scanning, participants performed practice sessions until they reached an accuracy of 90% outside the scanner.

There were a total of three scans during the MRI scanning. During the first and third scans, we acquired resting-state fMRI (R-fMRI) data for 8 min. The participants were instructed to lie quietly with their eyes fixed at the black fixation cross on the screen. During the second scan, we obtained the task-state fMRI (T-fMRI) data while the participants performed the mental rotation task.

A median absolute deviation estimator [52] based on the correct response time (RT) was applied to eliminate outlier trials, and the average RTs of the correct responses were subsequently calculated for each participant. A one-way ANOVA with a rotation angle