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NEURAL DYNAMICS UNDERLYING VARYING ATTENTIONAL CONTROL FACING INVARIANT COGNITIVE TASK UPON INVARIANT STIMULI

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Abstract—Even when performing invariant behavioral task repeatedly on invariant physical stimuli, our behavioral performance always changes as manifested in varying response times (RTs), which is associated with fluctuations in attentional control and thus the underlying self-organization states of the human brain. In a visuospatial task of the present fMRI study, physical stimuli differed across six levels of spatial scope, but were kept invariant within each level. The slower RTs with larger spatial area attended suggested higher demands on visuospatial attention. The slower RTs within each level, however, implicated worse attentional control since both the task and the physical stimuli were kept invariant within each level. The imaging results showed that slower RTs within each of the six levels were associated with higher but later activations in the frontoparietal network, and higher but later deactivations in the default-mode network (DMN). These findings thus for the first time suggested that the within-level variance of attentional control corresponded to dynamic changes in the frontoparietal network and the DMN, in terms of not only the height but also the latency of neural activity. Moreover, although the two networks are anti-correlated in terms of the height of neural activity, they are tightly coupled in terms of the temporal dynamics. Based on the current results, we proposed a tentative hypothesis on the optimal working mode of the frontoparietal attentional control system in the human brain: even a lower height of neural activity in frontoparietal network can significantly improve behavioral performance as long as it starts relatively early.
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Key words: within-level variance, parametric modulation effect, fMRI, attentional control, frontoparietal network, default-mode network.

INTRODUCTION

Human beings perform invariant cognitive task differently from time to time, even with the sensory inputs being invariant, indicating fluctuations in attentional control and thus the underlying self-organization states of the frontoparietal and the default-mode network (DMN) (Bellgrove et al., 2004; Castellanos et al., 2005; Gilbert et al., 2006; Hahn et al., 2007; Weissman et al., 2009; Prado et al., 2011). Functionally speaking, with both the cognitive task and the sensory inputs being kept invariant, longer RTs and higher error rates indicate worse attentional control (Weissman et al., 2006; Prado et al., 2011), rather than increased task difficulty or cognitive loads.

It has been well documented that the frontoparietal network, including bilateral dorsolateral prefrontal cortex (DLPFC) and bilateral parietal cortex, is involved in modulating attentional control and shows enhanced neural activity during a variety of attention-demanding cognitive processes (Cabeza and Nyberg, 2000; Corbetta et al., 2000, 2002; Zanto and Gazzaley, 2013; Di and Biswal, 2014). In contrast, orbital prefrontal cortex (OPFC), posterior cingulate cortex (PCC)/precuneus, and angular gyrus (AG) are "active" during the so-called "resting state" and show task-induced deactivations (TID) during the performance of various goal-directed tasks. Therefore, the latter areas have been associated with the so-called "default-mode" of the human brain (Gusnard et al., 2001; Raichle et al., 2001; Fox et al., 2005; Dosenbach et al., 2006). The height of neural activity increases in the frontoparietal network and decreases in the DMN proportionally to the cognitive loads (Gould et al., 2003; McKiernan et al., 2003, 2006).

If higher activations in the frontoparietal network and higher TID in the DMN with increasing cognitive loads reflect the recruitment of more neural resources, what, if

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Abbreviations: ACC, anterior cingulate cortex; AG, angular gyrus; BOLD, blood oxygen level-dependent; DLPFC, dorsolateral prefrontal cortex; DMN, default-mode network; GLM, general linear model; HRF, hemodynamic response function; IFG, inferior frontal gyrus; IPC, inferior parietal cortex; ITI, inter-trial intervals; OPFC, orbital prefrontal cortex; PCC, posterior cingulate cortex; PCG, bilateral precentral gyrus; RTs, response times; TD, temporal derivative; TID, task-induced deactivations.

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any, is their functional implication for the variance of RTs facing invariant cognitive task and stimuli? In the present event-related fMRI study, the within-level variance of attentional control was defined as the trial-by-trial variance of RTs. In order to investigate the neural mechanisms underlying the within-level variance of attentional control, we used a parametric design in which the trial-by-trial variance of RTs was associated with both the height and the latency of neural activity in the frontoparietal network and the DMN.

Visual inputs in each trial consisted of two parallel line segments separated by a horizontal gap. The behavioral task was to discriminate whether or not the two line segments were collinear. Six sizes (width) of the horizontal gap (spatial scope) randomly changed across trials and there were three levels of vertical distance for each size of horizontal gap, which accordingly varied the spatial area over which participants had to spread their attention in a given trial (Chen et al., 2009). Thereby, a parametric design with six levels of horizontal gap was employed and there were two sources of variance of RTs in this parametric design (Fig. 1A). First, there was the between-level variance corresponding to the six different sizes of the horizontal gap. The second source of variance was the within-level one. We, accordingly, focused on the neural mechanisms underlying the within-level variance of attentional control in our current analysis. Correct trials on each of the six levels of the horizontal gap were modeled as one of six events in the general linear model (GLM) analysis of the fMRI data. More importantly, in order to examine the positive and the negative parametric modulation effects of the within-level variance of attentional control on both the height and the latency of blood oxygen level-dependent (BOLD) responses: (1) Each of the six events was separately modeled by the canonical hemodynamic response function (HRF) and its first order temporal derivative (TD) (Henson et al., 2002); (2) RTs on correct trials of each of the six levels of the horizontal gap (i.e., the within-level variance of attentional control) were included as covariates in corresponding events; (3) The vertical deviations of each of the six levels were included as covariates in corresponding events. Parametric modulation effects of the within-level variance of RTs on both the height and the temporal delay of the BOLD responses were calculated to characterize the neural dynamics underlying the within-level variance of attentional control in both the spatial and the temporal dimensions.

EXPERIMENTAL PROCEDURES

Participants

Twelve healthy, right handed volunteers (4 female, 8 male, aged 26 ± 3.5) without any history of neurological or psychiatric illness participated in the study. Handedness was tested by the “Edinburgh Handedness Inventory” (Oldfield, 1971). All participants had normal or corrected-to-normal vision. Informed consent was obtained from the volunteers prior to participation in accordance with the Helsinki declaration. This study was approved by the local ethics committee.

Stimuli and experimental design

In each trial, a pair of black line segments was presented on a white background and was separated by a blank gap. In total, there were six levels of horizontal gap between the two line segments: 0.5°, 3°, 5.5°, 8°, 10.5°, and 13° of visual angle and the size of the horizontal gap randomly varied across trials (Fig. 1A). The length of each line segment was 2.5° of visual angle. The two line segments were either collinear or not in each trial and non-collinear and collinear trials were randomly interspersed (Fig. 1B). For each of six levels, there were three levels of vertical distance, i.e. collinear trials with zero vertical distance, non-collinear trials with a smaller vertical distance (non-collinear_small), and non-collinear trials with a larger vertical distance (non-collinear_large). Specifically speaking, the vertical deviation within each of the six levels is listed as below: 0°, 0.15° and 0.6° of visual angle for the first level; 0°, 0.4° and 0.6° for the second level; 0°, 0.6° and 0.8° for the third level; 0°, 0.6° and 1° for the fourth level; 0°, 0.65° and 1.3° for the fifth level; and 0°, 0.65° and 1.8° for the sixth level. The target stimuli were presented randomly at the center of the screen or at one of

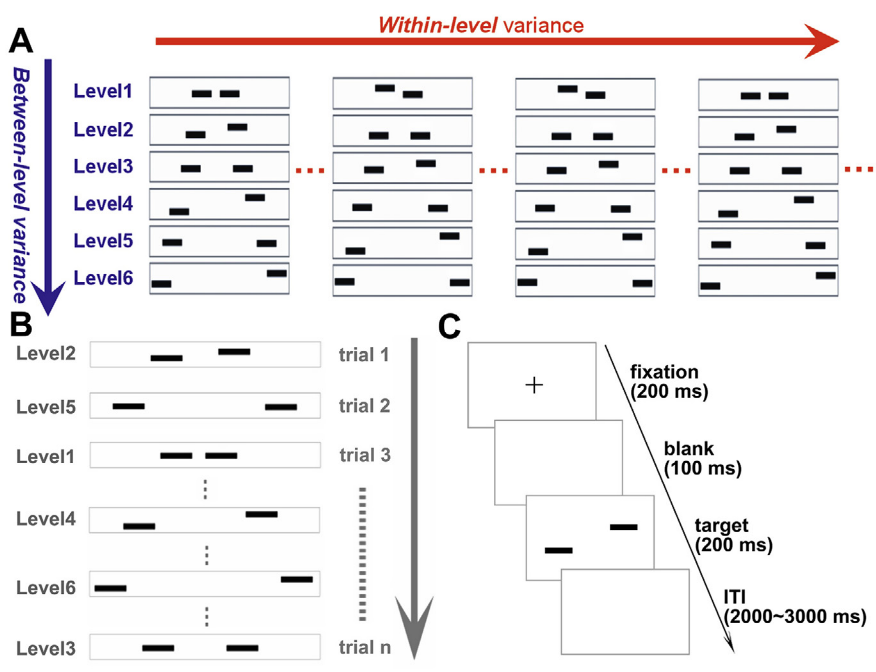

Fig. 1. (A) Illustration of the between-level and the within-level variance of RTs in the present parametric event-related fMRI design with six levels. (B) Example of the event-related experimental paradigm. (C) Example of the experimental procedure of one trial.

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