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THE NEURAL CORRELATES OF PERCEPTUAL LOAD INDUCED ATTENTIONAL SELECTION: AN FMRI STUDY

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Abstract—The neural correlates of perceptual load induced attentional selection were investigated in an functional magnetic resonance imaging (fMRI) experiment in which attentional selection was manipulated through the variation of perceptual load in target search. Participants searched for a vertically or horizontally oriented bar among heterogeneously (the high load condition) or homogeneously (the low load condition) oriented distractor bars in the central display, which was flanked by a vertical or horizontal bar presented at the left or the right periphery. The search reaction times were longer when the central display was of high load than of low load, and were longer when the flanker was incongruent than congruent with the target. Importantly, the flanker congruency effect was manifested only in the low load condition, not in the high load condition, indicating that the perceptual load in target search determined whether the task-irrelevant flanker was processed. Imaging analyses revealed a set of fronto-parietal regions having higher activations in the high than in the low load condition. Anterior cingulate cortex (ACC) was more activated for the incongruent than for the congruent trials. Moreover, ACC and bilateral anterior insula were sensitive to the interaction between perceptual load and flanker congruency such that the activation differences between the incongruent and congruent conditions were significant in the low, but not in the high load condition. These results are consistent with the claim that ACC and bilateral anterior insula may exert executive control by selectively biasing processing in favor of task-relevant information and this biasing depends on the resources currently available to the control system.

Key words: visual search, perceptual load, flanker effect, ACC, anterior insula.

INTRODUCTION

The extent to which individuals can focus attention in face of distracting information depends on the information load imposed by the current task. The ‘perceptual load theory of attention’ (Lavie and Tsal, 1994; Lavie, 1995, 2005, 2010) provides a framework which combines the early-selection assumption (e.g., Broadbent, 1958) that perception is a limited-capacity process with the late-selection assumption (e.g., Deutsch and Deutsch, 1963) that perception is an automatic process, attempting to resolve the longstanding antagonism between early- and late-selection theories of attention. According to perceptual load theory, a task with high perceptual load that engages all available processing resources would leave effectively no spare capacity for the perception of task-irrelevant information, giving rise to a pattern of performance indicative of early attentional selection. In contrast, a task with low perceptual load would leave spare capacity that (unintentionally) spills over to irrelevant information; processing of this information could interfere with the processing of the target, yielding a pattern of performance indicative of late attentional selection.

Perceptual load theory has received much support in behavioral studies (see Lavie, 2005, 2010, for reviews). In a typical experimental situation, participants search for a target among a number of non-target items in the central display, which is flanked in the periphery by a to-be-ignored item that can be congruent (potentially requiring the same response as the target) or incongruent (potentially requiring the opposite response) with the target. Importantly, the ‘perceptual’ load of the central display is often manipulated between low and high, for example, by presenting the target surrounded by a smaller or a larger number of distractors (e.g., Lavie and de Fockert, 2003), by making the distractors visually homogeneous or heterogeneous (e.g., Johnson et al., 2002; Lavie and Cox, 1997; Wei and Zhou, 2006), or by making the ‘attentional’ processing requirements easy or difficult without changing the perceptual properties of the task-relevant stimuli (e.g., Lavie, 1995;

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Abbreviations: ACC, anterior cingulate cortex; ANOVA, analysis of variance; DLPFC, dorsolateral prefrontal cortex; FEF, right frontal eye field; FWE, family-wise error; GLM, general linear model; IFJ, inferior frontal junction; PPC, posterior parietal cortex; SPM, Statistical Parametric Mapping.

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Rees et al., 1997; Chen, 2003; Schwartz et al., 2005). The absence or presence of a congruency effect (i.e., an reaction time (RT) difference between incongruent and congruent conditions) has been taken as an indicator of whether the peripheral flanker is processed up to the response level. The flanker congruency effect has been found to be larger when processing of the central display and identifying the target are of low perceptual load, and smaller or entirely absent when the current task is of high perceptual load (Lavie, 2005; Wei and Zhou, 2006).

At the neural level, neuroimaging studies on the role of perceptual load in attentional selection have mainly shown activation in stimulus processing areas for task-irrelevant stimuli to be reduced with high, relative to low, perceptual load (Rees et al., 1997; Schwartz et al., 2005; Bahrami et al., 2007). For example, Rees et al. (1997) asked participants to perform a linguistic task of either low or high load in processing a word presented in the center of the screen, while ignoring irrelevant visual motion in the periphery. Although the linguistic task and distractor processing were unrelated, functional imaging of activity in cortical area V5 revealed reduced motion processing during the high load task. Schwartz et al. (2005) varied the attentional load in a visual monitoring task performed on a rapid serial visual presentation (RSVP) stream at central fixation and measured brain responses to task-irrelevant checkerboards in the periphery. They found that activation in the visual cortex for the irrelevant peripheral stimuli decreased when the attentional load at fixation increased. Taken together, these studies validated the load theory (Lavie and Tsal, 1994; Lavie, 2005) by showing reduced perceptual processing of the irrelevant information when the central task load was high. However, to the best of our knowledge, none of the previous neuroimaging studies did examine whether and, if so, how the neural activation related to response congruency between the target and the task-irrelevant stimuli is modulated by the perceptual load.

The need to resolve behavioral conflict arises in many everyday circumstances. A large body of neuroimaging studies has reported activations of the medial prefrontal cortex (mPFC) and especially the anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), and posterior parietal cortex (PPC) in incongruent (or conflict) conditions as compared to congruent conditions (see Nee et al., 2007, for a meta-analysis). ACC activation is widely observed in tasks requiring participants to resolve response conflict (e.g., in Flanker or Stroop tasks) elicited by automatic processing of the task-irrelevant objects/dimensions, which is consistent with the conflict monitoring theory (Botvinick et al., 1999, 2001, 2004; van Veen et al., 2001; Ridderinkhof et al., 2004; Chen et al., 2006; Botvinick, 2007; Carter and van Veen, 2007). Furthermore, ACC activation is also associated with other cognitive functions, such as detecting discrepancies between actual and intended responses (Scheffers and Coles, 2000), predicting error likelihood (Brown and Braver, 2005, 2007), biasing attentional selection toward task-relevant information (Frith et al., 1991; Paus et al., 1998; Posner and DiGirolamo, 1998; Roelofs et al., 2006; Wei et al., 2009), and implementing and maintaining task-goals (Weissman et al., 2003; Dosenbach et al., 2006, 2007; Dosenbach et al., 2008). For example, a recent fMRI study found that ACC was more activated when participants searched for a target among heterogeneous, rather than homogeneous, distractors in visual search (Wei et al., 2009). This suggests that this area may play a general role in biasing target template matching in conditions with heterogeneous distractors, as false activation of the target template by a distractor is more likely when the distractors are heterogeneous. Given this, it is of theoretical interest to examine how activation of the ACC, and related brain areas, would be modulated by the current demands of searching for a task-relevant target under different perceptual load conditions and by possible conflict elicited by the processing of the task-irrelevant flankers.

In the present fMRI experiment, we asked participants to search for a vertically or horizontally oriented bar in the central search display consisting the target and distractors, while a task-irrelevant flanker (a vertical or horizontal bar) was presented to the left or the right of the central display, creating congruent and incongruent conditions (Fig. 1). Crucially, we manipulated the perceptual load of target search by embedding the target among distractors of either the homogeneous orientation (the low load condition) or heterogeneous orientations (the high load condition) in the central display. For the main effect of perceptual load, we expected to observe higher activations in brain regions involved in attentional selection in the high load, relative to the low-load, condition. For the main effect of target-distractor congruency, we expected higher ACC activation on incongruent, compared to congruent, trials. In addition, we expected an interaction between load and congruency, characterized by a robust congruency effect in the ACC in the low-load condition, but no (or a reduced) effect in the high load condition because in that condition there should be no conflict arising from the target flanker.

EXPERIMENTAL PROCEDURES

Participants

Sixteen undergraduate and graduate students (11 female; aged between 22 and 31 years) participated in the experiment. All of them were right-handed, had normal or corrected-to-normal vision, and had no known neurological or psychiatric disorders. All participants gave written informed consent before the scanning.

Design and procedures

Fig. 1 depicts the trial sequence and sample display. Visual stimuli were presented through an liquid-crystal display (LCD) projector onto a rear projection screen located behind the participant's head. Participants viewed the screen through an angled mirror on the head-coil. Presentation of the stimuli and recording of the responses were controlled by the Presentation