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Attentional modulation of perceptual comparison for feature binding

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ABSTRACT

We investigated the neural correlates of attentional modulation in the perceptual comparison process for detecting feature-binding changes in an event-related functional magnetic resonance imaging (fMRI) experiment. Participants performed a variant of a cued change detection task. They viewed a memory array, a spatial retro-cue, and later a probe array. Their task was to judge whether the cued item had changed between the two arrays. Change type was manipulated to be a color-location binding or a color feature change. The retro-cue onset time in the retention interval was manipulated to be early or late. As a consequence of strong inter-item competition, we found strong prefrontal activation for late cues when contrasting the binding-change with the color-change condition. In contrast, we observed a comparable behavioral and neural effect between the two types of change detection when retro-cue was presented early. More importantly, we demonstrated a significant inter-regional correlation between the prefrontal and parietal regions in both binding- and color-change conditions for late cues. In addition, extensive prefrontal–parietal–visual functional connectivity was showed for detecting binding changes in the late-cueing condition. These results support the critical role in prefrontal–parietal–visual functional coupling for resolving strong inter-item competition during the comparison process in the binding-change condition. We provide direct evidence that attention modulates neural activity associated with perceptual comparison, biasing competition in favour of the task-relevant information in order to detect binding changes.

1. Introduction

Change detection, reflecting conscious awareness of deviation in the environment, is of considerable importance for survival in an ever changing world. Successful detection of changes from within the dynamic visual space often depends on the ability to compare preceding internal representations held in visual short-term memory (VSTM) with the incoming perceptual events (Hollingworth, 2003; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Luck & Vogel, 1997; Rensink, 2000, 2002). The success of change detection also relies on what type of information must be compared, ranging from simple features such as color or location, to feature-location binding (Wheeler & Treisman, 2002). However, little is known about the neural substrates underpinning the perceptual comparison processes for detecting binding changes. In the current study, we explored the comparison process in successful detection of feature binding changes in an event-related functional magnetic resonance imaging (fMRI) experiment. Moreover, we investigated whether and how top-down attention can affect the neural responses in this comparison process of binding-change detection.

Accumulating neural evidence of successful change detection has revealed the involvement of a distributed neural network including frontal, parietal, and temporal–occipital regions when compared to activity associated with correct rejection or change blindness (Beck, Muggleton, Walsh, & Lavie, 2006; Beck, Rees, Frith, & Lavie, 2001; Huettel, Güzeldere, & McCarthy, 2001; Pessoa & Ungerleider, 2004; Pollmann & Manginelli, 2009). In these studies, changes were manipulated in faces or outdoor scenes (Beck et al., 2001, 2006), in complex natural scenes (Huettel et al., 2001), in orientation among bars (Pessoa & Ungerleider, 2004; Sligte, Scholte, & Lamme, 2009), in everyday objects (Busch, Frund, & Herrmann, 2010; Sligte, Vandenbroucke, Scholte, & Lamme, 2010), or in implicitly learned spatial contexts (Pollmann & Manginelli, 2009). These findings highlight not only the importance of right parietal cortex in conscious change detection (Beck et al., 2001, 2006), but also the involvement of prefrontal–parietal neural network in controlling the deployment of attention to the location of change (Beck et al., 2001; Pessoa & Ungerleider, 2004).

Change detection requires comparing ongoing perceptual inputs with preceding VSTM representations to detect any differences. Hyun et al. (2009) were the first to characterize the comparison process of detecting a feature change (color or orientation) using event-related potential (ERP) measure. However, how the neural activity in prefrontal and parietal regions relates to different types

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of perceptual comparison remains unclear. VSTM is the function by which configuration-based relational information is maintained (Jiang, Olson, & Chun, 2000). Wheeler and Treisman (2002) found that behavioral performance in change detection, based on relational information (e.g. binding-change detection) was worse than that based on a non-relational change (e.g. color-change detection). The difficulty of detecting binding changes may arise because cross-feature or cross-dimensional relations are changed but the elements still remain identical in each feature map between perceptual and mnemonic representations. Relational information of all items must be compared and, hence, inter-item competition is strong. In this study, we manipulated the type of change (color feature versus color-location binding) (Treisman & Zhang, 2006; Wheeler & Treisman, 2002), to test whether change type during the comparison process can affect prefrontal or parietal activation in supporting successful change detection. Although a previous study had incorporated this manipulation (Yeh, Kuo, & Liu, 2007), their design is less appropriate for examining the neural correlates of comparison processes because participants could predict the change type and so they could adopt certain strategies prior to perceptual comparison.

More importantly, we tested whether early deployment of attention during retention can strengthen the task-relevant representation to facilitate the comparison process in detecting binding changes and its underlying neural mechanisms. Selective attention supports the transfer of sensory inputs into VSTM (Sperling, 1960). After the presentation of a memory array, attention can be directed by a spatial cue to a specific location retrospectively during the retention period (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Yeh, Yang, & Chiu, 2005), thus effectively reducing the memory load. This process appears to occur in a similar way to the direction of attention by a pre-cue to a location in the external world (Posner, 1980). Recent evidence has showed that early deployment of attention can strengthen sensory representations, optimize later VSTM retrieval functions, and suppress the task-irrelevant representations for later comparison (Matsukura, Luck, & Vecera, 2007; Nobre, Griffin, & Rao, 2008; Sligte et al., 2010; Yeh et al., 2005, 2007). Directing attention to cued representations may facilitate perceptual comparisons by reducing inter-item competition (Scalf & Beck, 2010), even in the binding-change condition. To verify this hypothesis, we manipulated the deployment of attentional orienting by varying the onset time of a retro-cue during the retention interval to be early or late.

We focused on the difference in neural activity in the comparison process between binding- and feature-change conditions for each cueing condition. In the late-cueing condition, attentional orienting was engaged late in the retention interval and shortly before the presentation of the probe array. We hypothesize that attentional modulation instigated by the late cue may not re-orient attention in time to retrieve and transfer the cued iconic representation into VSTM (Yeh et al., 2005, 2007), protect the cued representation from subsequent interference imposed by testing displays (Makovski & Jiang, 2007), and reduce memory load prior to the comparison. Late cueing may also disrupt the probe comparison. Inter-item competition is strong for detecting binding changes during the comparison process. Thus, we expect greater activation in the prefrontal or parietal regions for detecting binding changes in contrast to color changes as a consequence of resolving inter-item competition via top-down control mechanisms. When cued early in the retention period, attentional signals can be deployed early to retrieve and strengthen iconic representation into a stable VSTM representation and thereby, increasing the probability of recall for perceptual comparison. The inter-item competition in detecting binding changes is, therefore, reduced during the perceptual comparison process. We expect to observe, both behaviourally and neurally, a comparable effect of attention for detecting the two types of change. Finally, a standard psychophysiological interaction (PPI) analysis was conducted to test the prefrontal–parietal functional connectivity because these areas have been shown to be critical in top-down control (Corbetta & Shulman, 2002; Hopfinger, Buonocore, & Mangun, 2000), and change detection (Beck et al., 2001, 2006; Pessoa & Ungerleider, 2004). Under late-cueing condition, we expect more extensive prefrontal and parietal functional coupling to be employed for resolving inter-item competition and cognitive control during the perceptual comparison of binding changes compared to the perceptual comparison of color features, In contrast, no such difference between binding- and color-change conditions would be observed under early cueing because early deployment of attention can mitigate inter-item competition at the perceptual comparison stage.

2. Materials and methods

2.1. Participants

Sixteen right-handed (Oldfield, 1971) volunteers participated in this study. The participants were recruited from the undergraduate and graduate students at National Taiwan University and National Taiwan University of Science and Technology. All participants were healthy and without any neurological or psychiatric history. Informed written consent was obtained from all participants prior to the study. We analyzed data from 13 participants (5 females, mean age = 21.70 ± 2.75 years) because one participant showed excessive head movement in the scanner (greater than 2 mm) and data sets from two participants were partially lost due to technical failures. The methods and procedures used in the study were non-invasive and had ethical approval from the local ethics committee at the Department of Psychology, National Taiwan University.

2.2. Design and task

The experimental design followed a 3 (change type: binding-change, color-change, and no change) $\times$ 2 (retro-cue onset time: early cue and late cue) factorial design. Participants viewed a memory array, followed by a spatial retro-cue, and later by a probe array and were instructed to judge whether the cued item of the probe array had changed relative to the preceding memory array. The manipulation of the binding- or color-change condition altered whether integrated color-location information or novel color features were evaluated for detecting changes respectively (Wheeler & Treisman, 2002). Deployment of attention was varied by the manipulation of the retro-cue onset time during retention prior to the test array (Yeh et al., 2005, 2007). In each cueing condition, the encoding and cueing processes during retention were identical between feature- and binding-change conditions. The procedure is shown in Fig. 1a.

2.3. Stimuli

Stimulus arrays were composed of four colored squares with the colors randomly selected from a set of six colors: red, green, yellow, blue, cyan, and magenta. Each stimulus subtended a visual angle of approximately $0.52^\circ \times 0.52^\circ$ (edge-to-edge) and was positioned randomly in one of the eight possible peripheral locations of an invisible 3×3 matrix that subtended approximately $6.2^\circ \times 6.2^\circ$. The memory array was presented first and was followed by the presentation of the probe array after a retention interval. In color-change trials, two new colors replaced the original colors of two items from the memory array. In binding-change trials, two