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Short Communication

The neural substrates associated with inattentional blindness

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ABSTRACT

Inattentional blindness is the failure to perceive salient stimuli presented at unattended locations. Whereas the behavioral manifestation of inattentional blindness has been investigated, the neural basis of this phenomenon has remained elusive. In the current study, event-related fMRI was used to identify the neural substrates associated with inattentional blindness. During central fixation, participants named colored digits presented at a peripheral location. On a subset of trials, an unexpected checkerboard circle (the critical stimulus) was presented at the same eccentricity along with the colored digits (a post-scan questionnaire assessed participants' awareness of the critical stimulus). Neural activity during inattentional blindness was observed in the prefrontal cortex. Together with previous findings, these results call into question the widespread view that activity in the prefrontal cortex reflects conscious processing.

1. Introduction

Inattentional blindness is the failure to perceive salient visual stimuli presented at unattended locations (Mack & Rock, 1998). While several studies have focused on the behavioral manifestation of inattentional blindness (Cartwright-Finch & Lavie, 2007; Koivisto, Hyona, & Revonsuo, 2004; Koivisto & Revonsuo, 2008; Most, Scholl, Clifford, & Simons, 2005; Newby & Rock, 1998; Simons & Chabris, 1999; Thakral & Slotnick, 2010), the neural basis of inattentional blindness, to date, has remained elusive. During an inattentional blindness paradigm, only a single unaware trial can be acquired from each participant. This is due to the increased expectation of the unexpected salient stimulus presented after the first trial. Moreover, it is generally assumed that numerous trials must be averaged to extract a reliable neural signal, and thus the neural basis of inattentional blindness has not been evaluated. Nevertheless, robust functional magnetic resonance imaging (fMRI) activity has been reported based on few or even single trials (Blamire et al., 1992; Richter et al., 2000; for discussion see, Huettel & McCarthy, 2001). Based on this, the current aim was to investigate the neural basis of inattentional blindness using fMRI.

Of relevance, conventional theories have posited that neural activity in the prefrontal cortex is associated with conscious processing (Baars, 2003; Beck, Rees, Frith, & Lavie, 2001; Crick & Koch, 1995, 1998; Dehaene et al., 2001; Dehaene & Changeux, 2005; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Naccache, 2001; Jack & Shallice, 2001; Rees, 2007; Rees, Kreiman, & Koch, 2002). Crick and Koch (1995, 1998), for example, stated that the prefrontal cortex holds a privileged role in conscious processing, due to its association with planning, language production, and motivated behaviors (Fuster, 2001; Miller, 2000; Sakai, 2008). This stands in contrast to activity in striate cortex (visual cortical area V1) which is presumed to not necessarily lead to consciousness due to its distinct lack of direct connections to the prefrontal cortex (Crick & Koch, 1995, 1998). Similar to striate cortex, neural activation in the ventral and dorsal visual processing streams is presumed to be necessary but not entirely sufficient for conscious visual processing (Rees, 2007; Rees et al., 2002; Tong, 2003). For example, activation of the parahippocampal cortex in the ventral stream has been observed for visual

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scenes in the absence of awareness during attentional blink (Marois, Yi, & Chun, 2004). Dorsally, activation of the parietal lobe has been observed for objects rendered invisible through interocular suppression (Fang & He, 2005). For a review of evidence in support of the role of the ventral and dorsal visual streams (in addition to striate cortex) during unconscious processing see Rees (2007).

In opposition to the notion that the prefrontal cortex is directly involved with conscious processing, recent studies have reported evidence of neural activity occurring in this higher-cortical region during unconscious processing. Using behavioral paradigms such as change blindness (Beck et al., 2001), binocular fusion (Moutoussis & Zeki, 2002) and priming (Dehaene et al., 2001; Lau & Passingham, 2007), neural activity has been observed in the frontal cortex. To further this idea, experimental studies investigating the neural activity associated with previously seen but unrecognized items provides parallel findings for unconscious activity in this higher-cortical region (Henson, Hornberger, & Rugg, 2005).

The aim of the present study was to determine the neural underpinnings of inattentional blindness. Inattentional blindness related activity was defined as neural activity, independent of awareness (i.e., activity consistent across both conscious and unconscious processing of the unexpected critical stimulus). Awareness related activity was identified by contrasting trials where participants were aware versus unaware of the critical stimulus. To anticipate the results, inattentional blindness related activity independent of awareness was revealed to be significant in the prefrontal cortex, a region more traditionally associated with conscious processes.

2. Materials and methods

2.1. Participants

The experimental and imaging protocol was approved by the Massachusetts General Hospital Institutional Review Board. Informed consent was obtained before the experiment commenced. Twenty-eight participants (with normal or corrected-to-normal visual acuity) completed the study with nine participants included in the final analysis; nineteen participants were not included due to awareness of the critical stimulus in the *inattention* condition.

2.2. fMRI stimuli and tasks

As illustrated in Fig. 1, each trial began with a central fixation cross presented on a grey background (for 1500 ms), followed by two colored digits (each for 350 ms, ranging in value from 1 to 9, and subtending 0.5° of visual angle) located 11° of polar angle from the horizontal meridian and 3.2° of visual angle from fixation, and ended with a mask (for 500 ms, Koivisto et al., 2004; Thakral & Slotnick, 2010). Participants were instructed to maintain fixation and name each digit (ranging from 1 through 9) and its corresponding color (red, orange, green, purple, blue, pink, black, or yellow) requiring participants to focus attention at the location of the digits. Participants completed two non-critical trials (each followed by the mask) where only the colored digits were presented, and on the third trial, the critical trial, the critical stimulus – a black and white checkerboard circle – was presented along with the digits (for 700 ms; see Fig. 1). The critical stimulus subtended 1° of visual angle in diameter and was presented 1.5° of visual angle from the attended location at the same eccentricity as the digits.

Participants completed three attention conditions (*inattention*, *divided attention*, and, *full attention*; see also, Koivisto et al., 2004; Thakral & Slotnick, 2010). Each of these conditions included the three trials described above (*inattention* condition: trials 1–3; *divided attention* condition: trials 4–6; *full attention* condition: trials 7–9). The first condition was classified as the *inattention* condition because there was no expectation of the critical stimulus (trials 1–2, non-critical *inattention* trials and trial 3, critical *inattention* trial). The second condition was classified as the *divided attention* condition because the questions asked after the previous *inattention* condition signaled participants to the possibility that an extra stimulus might appear, even though there were no direct instructions to look for the critical stimulus (trials 4–5, non-critical *divided attention* trials and trial 6, critical *divided attention* trial). The third condition was classified as the *full attention* condition because participants were explicitly told to detect the occurrence of anything new appearing on the screen, and were thus expected to attend more diffusely, including the location of the critical stimulus (trials 7–8, non-critical *full attention* trials and trial 9, critical *full attention* trial). This *full attention* condition served as the control because observers were expected to perceive the critical stimulus. Across the three conditions, the digits and critical stimulus were always presented at the same location in the upper right quadrant as shown in Fig. 1 (Thakral & Slotnick, 2010). Each condition began and ended with a period of fixation (for 14 s).

After each of the three conditions (i.e., *inattention*, *divided attention*, and *full attention*), participants answered three questions to determine whether they had been aware of the critical stimulus (Koivisto et al., 2004; Thakral & Slotnick, 2010). The first question asked if the participant had detected something new that had not been previously presented. The second question asked participants to choose the critical stimulus from five possible shapes (square, circle, star, triangle, or diamond). The third question asked participants to select the quadrant in which the critical stimulus appeared. Participants were classified as aware of the critical stimulus if they answered yes to the first question and either correctly identified it, or correctly selected its spatial location (and were otherwise classified as unaware of the critical stimulus). Questions were administered visually in the scanner and participants responded via button box placed in their left hand. These behavioral responses along with the presence or absence of the critical stimulus yielded three event types: (1) 'no-critical stimulus', where only the