Spatiotemporal oscillatory dynamics of visual selective attention during a flanker task

Timothy J. McDermott[a], Alex I. Wiesman[a,b], Amy L. Proskovec[a,c], Elizabeth Heinrichs-Graham[a,b], Tony W. Wilson[a,b,*]

[a] Center for Magnetoencephalography, University of Nebraska Medical Center (UNMC), Omaha, NE, USA
[b] Department of Neurological Sciences, UNMC, Omaha, NE, USA
[c] Department of Psychology, University of Nebraska, Omaha, NE, USA

ARTICLE INFO

ABSTRACT

The flanker task is a test of visual selective attention that has been widely used to probe error monitoring, response conflict, and related constructs. However, to date, few studies have focused on the selective attention component of this task and imaged the underlying oscillatory dynamics serving task performance. In this study, 21 healthy adults successfully completed an arrow-based version of the Eriksen flanker task during magnetoencephalography (MEG). All MEG data were pre-processed and transformed into the time-frequency domain. Significant oscillatory brain responses were imaged using a beamforming approach, and voxel time series were extracted from the peak responses to identify the temporal dynamics. Across both congruent and incongruent flanker conditions, our results indicated robust decreases in alpha (9–12 Hz) activity in medial and lateral occipital regions, bilateral parietal cortices, and cerebellar areas during task performance. In parallel, increases in theta (3–7 Hz) oscillatory activity were detected in dorsal and ventral frontal regions, and the anterior cingulate. As per conditional effects, stronger alpha responses (i.e., greater desynchronization) were observed in parietal, occipital, and cerebellar cortices during incongruent relative to congruent trials, whereas the opposite pattern emerged for theta responses (i.e., synchronization) in the anterior cingulate, left dorsolateral prefrontal, and ventral prefrontal cortices. Interestingly, the peak latency of theta responses in these latter brain regions was significantly correlated with reaction time, and may partially explain the amplitude difference observed between congruent and incongruent trials. Lastly, whole-brain exploratory analyses implicated the frontal eye fields, right temporoparietal junction, and premotor cortices. These findings suggest that regions of both the dorsal and ventral attention networks contribute to visual selective attention processes during incongruent trials, and that such differential processes are transient and fully completed shortly after the behavioral response in most trials.

Introduction

Visual selective attention has been described using different metaphors such as a filter (Broadbent, 1958; Deutsch and Deutsch, 1963; Treisman, 1964), a spotlight (Norman, 1968; Posner et al., 1980), and a zoom-lens (Eriksen and St. James, 1986). It has also been the topic of a number of neurocognitive reviews (Carrasco, 2011; Clark et al., 2015; Driver, 2001; Petersen and Posner, 2012), and a number of theories have been proposed. These theories include Feature-Integration Theory (Treisman and Gelade, 1980) and Attentional Engagement Theory (Duncan and Humphreys, 1992), among others, and while these theories have disagreed over particular details, they have generally agreed that the primary function of visual attention is to selectively process certain visual information within the larger visual field, while simultaneously blocking out distracting or unrelated stimuli (Carrasco, 2011; Driver, 2001). Visual selective attention is necessary for many goal-oriented behaviors, but its neurophysiological mechanisms, particularly the cortical dynamics, are not fully understood. The utilization of advanced technologies and methodologies could improve scientific understanding of these mechanisms, and could also be medically beneficial to a number of neurological (e.g., hemineglect) and psychiatric (e.g., attention deficit hyperactivity disorder) patient populations.

Building on decades of behavioral work, studies using functional neuroimaging methods have begun to characterize how the processes of visual attentional selection are achieved through distributed proces-

sing across widespread cortical networks (Clark et al., 2015; Petersen and Posner, 2012). Two such networks include the dorsal attention network (DAN) and the ventral attention network (VAN). The DAN is thought to facilitate top-down control of attention for voluntary and goal-directed behaviors, and includes brain regions such as the frontal eye fields (FEF) and the intraparietal sulcus bilaterally (Corbetta et al., 2008; Corbetta and Shulman, 2002). Meanwhile, the VAN is believed to facilitate stimulus detection, particularly when unexpected or distracting stimuli are present (i.e., reorienting), and includes brain regions such as the temporoparietal junction (TPJ) and the ventral frontal cortex, with a right hemispheric dominance (Corbetta et al., 2008; Corbetta and Shulman, 2002). While anatomically and functionally separate, the DAN and VAN are both necessary for normal attentional function and have been shown to interact dynamically during attentional processing (Vossel et al., 2012, 2014).

A classic cognitive task for studying visual selective attention is the Eriksen flanker task (Eriksen and Eriksen, 1974). In this task, subjects are presented with a target stimulus that is surrounded by non-target or "flanker" stimuli, and the participant is instructed to respond to the target and ignore the flanking items. The flanker task normally includes congruent trials, where the flanker stimuli match the target and facilitate task completion, and incongruent trials, where the flanker and target stimuli are opposite and thus create an interference effect that hinders task performance (i.e., prolongs reaction time). Despite this interference effect, participants generally have high accuracy rates, and this is thought to reflect successful utilization of visual selective attention functions, as participants are able to focus on the target and ignore the flanking stimuli. Previous studies using flanker tasks during functional magnetic resonance imaging (fMRI) have identified brain regions that are involved in task performance, and these include the lateral prefrontal cortices, supplementary motor area (SMA), superior parietal lobe, anterior cingulate, and other regions (Botvinick et al., 1999; Bunge et al., 2002; Fassbender et al., 2006; Hazeltine et al., 2000; Lau et al., 2006; van Veen et al., 2001). Many of these fMRI studies have focused on the role of the anterior cingulate in response-conflict monitoring during flanker-type tasks (Botvinick et al., 2001, 2004), with much less emphasis being placed on the frontal and parietal regions that likely contribute to visual selective attention processes during flanker performance. Findings from neurophysiological studies using flanker tasks during electroencephalography (EEG) have been widely similar to the fMRI work, with emphasis on the anterior cingulate and its putative role in conflict monitoring (Cavanagh and Allen, 2008; Cavanagh et al., 2009; Clayson and Larson, 2011; Cohen and Cavanagh, 2011; Cohen and van Gaal, 2014; Danielmeier et al., 2009; Gulbinaite et al., 2014; Herrmann et al., 2004; Hochman et al., 2014; Larson et al., 2012; Nigbur et al., 2011, 2012; Padrao et al., 2015; Pastotter et al., 2013; Tillman and Wiens, 2011). Several of these EEG studies have focused on frontal midline theta oscillations observed during flanker task performance (Cavanagh et al., 2009; Cavanagh and Frank, 2014; Cohen and Cavanagh, 2011; Cohen and van Gaal, 2014; Gulbinaite et al., 2014; Nigbur et al., 2011, 2012; Padrao et al., 2015; Pastotter et al., 2013), and these studies have generally found that increased conflict leads to greater frontal midline theta activity. Such findings have been obtained using both the classic flanker paradigm and variants of the flanker task that were designed specifically to increase conflict monitoring (for a review, see Cavanagh and Frank, 2014; Cohen, 2014). However, these previous EEG studies have not generally imaged their electrophysiological responses, and thus the contribution of the anterior cingulate and/or other generator(s) is not entirely clear. One notable exception was an electrocorticography (ECoG) study that also used direct cortical stimulation during the flanker task (Usami et al., 2013). Their key findings indicated that the pre-SMA held an important role in conflict processing, although other regions were likely involved. Of note, Usami and colleagues were not able to evaluate lateral frontal or parietal areas due to the absence of ECoG electrodes in these areas.

As noted above, the network level dynamics serving selective attention and successful performance during the flanker task remain largely unknown. The temporal resolution of fMRI does not allow parsing out the inherent dynamics of short tasks like the flanker, and regardless such studies have tended to focus on the anterior cingulate and conflict monitoring processes, and not the visual attention component more generally. In the current study, we utilize the high spatiotemporal precision of magnetoencephalography (MEG) to quantify the oscillatory dynamics that underlie selective visual attention function in the context of the classic flanker task. While one MEG study to date has used a flanker paradigm to probe the neurophysiological correlates of movement selection (Grent-'t-Jong et al., 2013), no previous MEG study has utilized this task to probe the neural dynamics serving visual selective attention. Our primary hypotheses were that participants would exhibit significant neural oscillations in brain regions previously associated with flanker task performance in fMRI studies, and that the parietal and occipital cortices involved in selective attention processing would exhibit stronger oscillations during the more difficult incongruent trials. In addition, we hypothesized that both congruent and incongruent conditions would elicit significant theta oscillations in a network of prefrontal areas.

Methods

Subject selection

Twenty-five healthy adults (15 males; mean age: 32.60 years, range: 22–45 years) were recruited from the local community. Exclusionary criteria included any medical diagnosis affecting CNS function (e.g., psychiatric and/or neurological disease), known brain neoplasm or lesion, history of significant head trauma, current substance dependence, and ferromagnetic implants. Written informed consent was obtained from each participant following the guidelines of the University of Nebraska Medical Center's Institutional Review Board, who approved the study protocol. This study was carried out in accordance with the Declaration of Helsinki.

Experimental paradigm and stimuli

Participants performed an arrow-based version of the Eriksen flanker task while seated in a nonmagnetic chair within the magnetically-shielded room. Each trial began with a fixation that was presented for an interval of 1450–1550 ms. A row of 5 arrows was then presented for 2500 ms and participants were instructed to indicate with their right hand whether the middle arrow was pointing to the left (index finger) or right (middle finger). The 200 total trials were pseudo-randomized and equally split between congruent and incongruent conditions (Fig. 1), with left and right pointing arrows being equally represented in the congruent and incongruent conditions. Overall MEG recording time was about 14 min for the task.

Before analyzing accuracy and reaction time data, we performed standard data-trimming procedures. First, we excluded incorrect and no response trials. Next, we calculated each participant's mean and SD of reaction times across congruent and incongruent conditions separately. We trimmed trials that were 2.5 SD or more away from the participant's response mean. This trimming procedure eliminated a mean percentage of 2.95% congruent trials and 2.75% incongruent trials, and this difference was not significant, $t(20) = 0.847$; $p = 0.408$. After this trimming procedure, we used the remaining trials to calculate the mean accuracy and reaction times for each condition separately. We used paired-sample t-tests to compare the means between conditions, and we also computed the effect size for both accuracy and reaction time using Cohen's d for within-group effects (Morris and DeShon, 2008; Cohen, 1988).