



Characterizing the roles of alpha and theta oscillations in multisensory attention



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ABSTRACT

Cortical alpha oscillations (8–13 Hz) appear to play a role in suppressing distractions when just one sensory modality is being attended, but do they also contribute when attention is distributed over multiple sensory modalities? For an answer, we examined cortical oscillations in human subjects who were dividing attention between auditory and visual sequences. In Experiment 1, subjects performed an oddball task with auditory, visual, or simultaneous audiovisual sequences in separate blocks, while the electroencephalogram was recorded using high-density scalp electrodes. Alpha oscillations were present continuously over posterior regions while subjects were attending to auditory sequences. This supports the idea that the brain suppresses processing of visual input in order to advantage auditory processing. During a divided-attention audiovisual condition, an oddball (a rare, unusual stimulus) occurred in either the auditory or the visual domain, requiring that attention be divided between the two modalities. Fronto-central theta band (4–7 Hz) activity was strongest in this audiovisual condition, when subjects monitored auditory and visual sequences simultaneously. Theta oscillations have been associated with both attention and with short-term memory. Experiment 2 sought to distinguish these possible roles of fronto-central theta activity during multisensory divided attention. Using a modified version of the oddball task from Experiment 1, Experiment 2 showed that differences in theta power among conditions were independent of short-term memory load. Ruling out theta's association with short-term memory, we conclude that fronto-central theta activity is likely a marker of multisensory divided attention.

1. Introduction

At least since James (1890), intentional ignoring has been recognized as integral to selective attention. Numerous studies have investigated intentional ignoring by asking subjects to selectively attend to one stream of information while ignoring other information (e.g., Stroop, 1935). Additionally, investigations of selective attention's neural underpinnings suggest that the prefrontal cortex biases visual gating in the visual thalamic reticular nucleus (Wimmer et al., 2015), thus performing a critical role in selective attention. Recent work identified cortical oscillations in the alpha band (8–13 Hz) as markers of intentional ignoring (for review, Payne and Sekuler, 2014). Specifically, increased power in the alpha band has been associated with suppression of distracting signals within separate sensory streams, such as vision or audition (Kelly et al., 2006; Payne et al., 2013; Dubé et al., 2013; Mazaheri et al., 2014).

Demonstrating alpha oscillations' role in perceptual discrimination, Mazaheri et al. (2014) found that pre-stimulus alpha power in distinct brain regions predicted the speed of visual and auditory discrimination.

Finally, application to the scalp of transcranial magnetic stimulation (TMS) within the alpha frequency range, showed that alpha oscillations were not simply *correlated* with selective attention but are actually *causally* involved in the suppression of distracting sensory information (Romei et al., 2010).

While much previous work on alpha oscillations' role in sensory suppression has concentrated on task-related oscillatory power (Worden et al., 2000; Kelly et al., 2006; Thut et al., 2006; Romei et al., 2008, 2010), recent research has suggested that oscillatory phase and phase-resetting may be critical for attention and ignoring (VanRullen et al., 2011). For example, posterior alpha phase is shifted just prior to an anticipated visual distractor (Bonnetfond and Jensen, 2012), and pre-stimulus phase of posterior alpha activity predicts the success or failure of stimulus detection (Mathewson et al., 2009). It seems, therefore, that fluctuations in cortical excitability, which have been termed “pulsed inhibition” of cortical activity, influence whether information from the environment reaches conscious awareness. Although the relationship between alpha oscillations (both power and phase) and selective attention has been repeatedly demonstrated in a

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wide variety of tasks, it remains to be clearly demonstrated that alpha oscillations are sustained over time if the sensory input that must be suppressed is a continuous one. We hypothesize that alpha power and phase synchrony will reflect ongoing ignoring of distracting visual information when a task demands attention to an auditory stimulus for an extended period.

For many everyday tasks, selective attention to one sensory modality at a time is critical. However, when attention is directed toward one modality, it may not always be possible to shut out completely inputs from a different modality. For example, Keller and Sekuler (2015) presented subjects with simultaneous visual and auditory sequences, instructing them to attend the visual sequence while ignoring the accompanying auditory sequence. Despite this instruction, and despite the performance cost associated with failure to comply, subjects were unable to completely filter out the auditory sequences. Moreover, in tasks that do not entail distracting information in one sensory modality, it is often advantageous to share attention between multiple, concurrent sensory inputs. For example, a driver barreling down the highway while having an urgent conversation on a mobile phone tries to attend to both streams of information, visual and auditory; after all, completely ignoring one in favor of the other would have consequences. Because so many situations require division of attention between audition and vision, we felt it was imperative to investigate the neural mechanisms underlying processing of concurrent auditory and visual sensory streams.

One early study of shared attention's neural substrate made use of functional magnetic resonance imaging to characterize the neural basis of shared attention (Johnson and Zatorre, 2006). The overall results suggest that while unimodal selective attention involves modulation of sensory specific cortical regions, shared attention recruits frontal areas of the brain. Though this work identifies some brain *locations* that are involved in multisensory divided attention, the actual mechanism underlying shared attention remains unknown.

Despite abundant, separate research on cortical oscillations and on multisensory attention, little has been done to systematically associate particular cortical oscillations with the allocation of attention among multiple sensory streams. Given the idea proposed by Kopell et al. (2010) that particular frequency bands of cortical oscillations participate differentially in various cognitive functions, as well as recent research into the mechanisms by which oscillations give rise to cognition (Cannon et al., 2014), we hypothesize that different types of attentional allocation would be associated with different frequency bands of oscillatory activity. Specifically, we hypothesize that theta oscillations (4–7 Hz) play a role in multisensory divided attention, similarly to the way that alpha oscillations play a role in selective ignoring of distracting sensory information. This hypothesis reflects the fact that theta oscillations have been implicated in various functions related to multisensory divided attention, such as audio-visual integration (Sakowitz et al., 2000) and cognitive control (Cooper et al., 2016; Cavanagh and Frank, 2014; Cavanagh et al., 2010).

A recent review by Cavanagh and Frank (2014) summarized the current understanding of theta oscillations' functional role in what the authors characterized as “cognitive control.” The review noted that studies in humans, monkeys and rats had all implicated frontal-midline theta oscillations in functions such as novelty detection (Cavanagh et al., 2011) and top-down control of memory encoding (Rutishauser et al., 2010). That top-control can be viewed as a function that prioritizes “goal directed bias over habitual responses” (Cavanagh and Frank, 2014). It appears that phase resetting of theta oscillations enhances communication among disparate brain regions during cognitive control processes. According to this view, theta oscillations promote the cognitive control needed to prepare the brain's response to uncertainty about stimulus conditions (Cavanagh et al., 2010). Klimesch (1996) presented an alternative view of theta cortical oscillations, arguing for a link between those oscillations and memory processes. That view takes account of the fact that anterior theta

oscillations have been associated with short-term memory (Klimesch et al., 1996; Arnolds et al., 1980). In particular, theta power was increased during the encoding of words that would later be correctly recognized, and theta synchrony was higher during a correct recognition response (Klimesch et al., 1997). Although previous research on the role of theta oscillations has focused on theta generated in the hippocampus, Klimesch (1996) points out strong bidirectional connections between hippocampus and neocortex, which could explain how recordings of scalp EEG could be able to capture theta activity originating sub-cortically, in the hippocampus. So, several studies have reported increased theta oscillations during various cognitive tasks, but few have tried to select between competing hypotheses for the function of theta oscillations. And none has done so successfully. Therefore, an important next step will be to differentiate or reconcile these competing views.

2. Experiment 1

To investigate oscillatory activity associated with multi-sensory divided attention, we used a high-density array of scalp electrodes to capture electroencephalographic (EEG) signals while subjects were presented with Auditory, Visual, or concurrent Audio-Visual sequences. Into a few of these sequences, an unusual (“oddball”) stimulus was occasionally inserted (Squires et al., 1975; Noyce and Sekuler, 2014). Subjects attended to each sequence, but made a response only when an oddball occurred. Responses were signaled by pressing a key on a keyboard.

For Auditory sequences, the oddball was an unusual auditory stimulus; for Visual sequences, the oddball was an unusual visual stimulus; for the divided-attention Audio-Visual condition, the oddball could occur in either the auditory or the visual domain. This required that in the Audio-Visual condition, attention be paid to both modalities. As performance at the oddball task would be undermined by a lapse in attention, we fashioned the characteristics of the oddball task so that subjects were likely to perform at ceiling in all conditions, rarely missing or responding slowly to an oddball stimulus. We took this as a marker of successful sustained attention.

In our experiments, stimuli were presented as sequences of events. We took care that the sequences of all types would be presented at a rate that was slow enough not to advantage auditory processing, which has a high temporal frequency cut off, over visual processing, which has a relatively low temporal frequency cut off (Freides, 1974; Welch and Warren, 1980; Noyce et al., 2016).

3. Methods

3.1. Subjects

Twenty-seven subjects gave written informed consent and completed the experiment. Data from eight of these subjects were excluded from analysis because of excessive EEG artifacts, that is epoch rejection rate >20%. Additionally, one subject's data was excluded because after testing, he acknowledged having an attentional deficit. Of the remaining eighteen subjects, 9 were female and 9 were male. All subjects were between 18 and 24 years old, were right-handed as characterized by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected-to-normal visual acuity (Snellen visual acuity 20/40 or better), and had clinically-normal hearing, *e.g.*, pure tone thresholds at 0.25, 0.5, 1, 2, 4 and 8 kHz of at least 20 dB_{SPL} in the better ear (Mueller and Hall, 1998). Each received \$30 (U.S.) for participation.

3.2. Stimuli

An experimental session comprised 360 trials organized into six blocks, with two blocks devoted to each type of sequence. Fig. 1 shows schematic representations of events in each sequence type, Visual,

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