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# Brain oscillations in Switching vs. Focusing audio-visual attention

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***Abstract*— Selective attention contributes to perceptual efficiency by modulating cortical activity according to task demands. The majority of attentional research has focused on the effects of attention to a single modality, and little is known about the role of attention in multimodal sensory processing. Here we employ a novel experimental design to examine the electrophysiological basis of audio-visual attention shifting. We use electroencephalography (EEG) to study differences in brain dynamics between quickly shifting attention between modalities and focusing attention on a single modality for extended periods of time. We also address interactions between attentional effects generated by the attention-shifting cue and those generated by subsequent stimuli. The conclusions from these examinations address key issues in attentional research, including the supramodal theory of attention, or the role of attention in foveal vision. The experimental design and analysis methods used here may suggest new directions in the study of the physiological basis of attention.**

## I. Introduction

The ability to selectively attend to a subset of all the stimuli that continually impact our senses is at the heart of human cognition. The alternative, whereby all stimuli reaching our senses are processed to the level of conscious appraisal may be partially involved in disorders such as Autism Spectrum Disorder [1] and attention deficit disorder [2].

To some degree humans have executive control over what aspects of their environment their attention is directed to [3]. This endogenous form of attention is distinct from the attention that is captured by salient stimuli in the environment in an involuntary fashion (exogenous attention).

This investigation addresses the role of oscillations accompanying endogenous orienting of attention. In particular, we study neurophysiological differences between rapidly switching attention among the visual and auditory modalities, and focusing attention for extended periods of time on either vision or audition.

Two types of effects of attention on cortical oscillations measured using the electroencephalogram have been carefully studied in the literature of attention shifting: effects of attention on oscillations following the stimulus on which attention is engaged [4], and anticipatory effects on oscillations occurring between the attention-shift cue and the attended stimulus [5]. These effects have been studied separately. Here, a unique characteristic of our experimental design allows us to examine how anticipatory attentional oscillations affect stimulus-related ones.

Shomstein and Yantis [6] used a similar experimental design as ours. However, they measured hemodynamic activity that is not sensitive to effects at the near-millisecond resolution reported here. Also, they did not study the interactions between anticipatory and stimulus-related effects of attention on brain processes.

The remainder of the manuscript is organized as follows. We first describe a spectral signature of attention shifting between the visual and auditory modalities (Section III). Then we show that visual stimuli immediately following the attention-shift cue generates enhanced attention-related EEG activity when subjects are quickly switching their attention between different modalities, but not when they are focusing it for extended periods of time on a single modality (Section IV). Next we investigate the dynamics of this attentional-related enhancement of EEG activity, and show that it tapers off as the delay between the cue and the following stimulus increases (Section V). Sections III through V showed attentional-related enhancements of EEG responses to visual stimuli following a switch-to-vision cue. In Section VI we show a similar attentional enhancement for visual stimuli following a switch-to-audition cue, representing a cross-modal interaction in the domain of multi-modal attention shifting. The final section discusses these results in the context of the existing literature.

## II. Methods

*Experimental design* A schematic of the experiment is shown in Figure 1, and details are provided in [7]. Briefly, the experiment consisted of FOCUS VISION, FOCUS AUDITION, and SWITCH blocks. In each block the same visual and auditory stimuli streams were presented, with occasional interspersed audio-visual attention-shift cues. Target (10%) and non-target (90%) stimuli were presented in each stimulus stream. In FOCUS VISION (or AUDITION) blocks, the task of the subjects was to detect visual (or auditory) targets. In SWITCH blocks, audio-visual LOOK (or HEAR) cues, interspaced among the stimuli, instructed subjects to respond to visual (or auditory) targets.

*Subjects* Nineteen individuals, aged 20 to 40.

*EEG recording* 33 channels arranged in the International 10-20 system and digitized at a rate of 250 Hz.

*EEG analysis* Data were analyzed using EEGLAB [8]. For each subject, after digitally filtering the EEG data to remove frequencies above 50 Hz, ICA decompositions were computed using AMICA [9]. After manually removing non-brain ICA components, we obtained an average of 26 components per subject.

*Event Related Spectral Perturbation (ERSP)* Data were separated into epochs of 6000 msec around events of interest (e.g., LOOK and HEAR cues in SWITCH and FOCUS blocks in Figure 2). These epochs comprised data from 1000 msec before to 5000 msec after the event of interest. Each single-trial epoch was transformed into a spectrographic image using three-cylce Morlet wavelets in the

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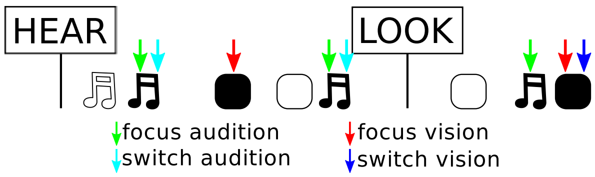


Fig. 1. Experimental design. In FOCUS VISION (AUDITION) blocks subjects had to detect visual (auditory) targets. In SWITCH blocks subjects had to detect visual (auditory) targets after the audio-visual LOOK (HEAR) cue. Visual (auditory) targets are represented by dark squares (musical notes). Red/green/blue/cyan arrows point to targets in focus vision/focus audition/switch vision/switch audition blocks.

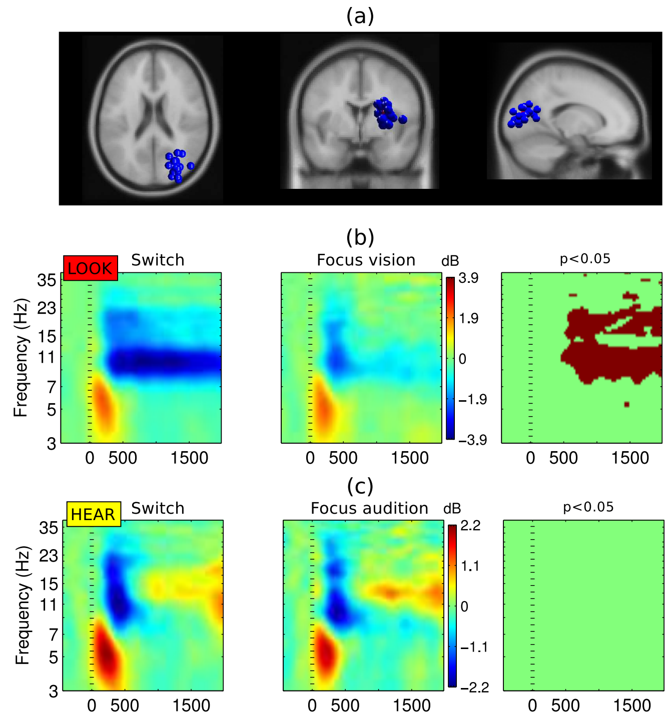


Fig. 2. (a) Parieto-occipital cluster characterized in this article. (b,c) ERSPs epoched around the (b) LOOK and (c) HEAR cues. The left and center plots show the ERSPs for the SWITCH and FOCUS blocks, respectively. Dark pixels in the right plot represent significant statistical differences between the left and center plots ($p < 0.05$, corrected for multiple comparisons). The LOOK but not the HEAR cue in SWITCH blocks generated a deep and long-lasting alpha band desynchronization in this visual cluster, suggesting that this desynchronization represents a signature of attention shift.

frequency range between 2 and 50 Hz. Then the log mean power in a baseline period of 1000 msec before the event of interest was subtracted from each single-trial spectrographic image. Finally, the spectrographic images of all the trials were averaged, yielding the *ERSPs* shown in Figures 2 and 3.

*ERP-images* For each subject and each condition in Figure 4, three single-trial spectrographic images were constructed, by using epochs time-locked to the first, second, and third non-target visual stimuli occuring after the attention-shift cue. The ERP-images in Figure 4 were then constructed by concatenating the time series of power at 10 Hz extracted from the three single-trail spectrographic images of every subject. Each time series was shifted in time so that the non-target stimulus presentation time aligned with the median of all non-target stimuli presentation times, indicated by the vertical black line in Figure 4. Then, the aligned times series for every trial were plotted together, and sorted by increasing delay between the shift cue and the subsequent stimulus presentations.

*Independent Component Clustering* Independent component (IC) clustering across subjects was based on two measures for each selected IC from each subject: ERSPs and equivalent dipoles locations. ERSPs were compressed by principal components analysis (PCA) into a 10 dimensional vector. The equivalent dipoles location were inherently three dimensional but, to compensate, were multiplicatively weighted by a factor of 10. These measures for a given IC of a given subject represent a point in an 13-dimensional space. The points for all ICs were then clustered using a K-means algorithm implemented in EEGLAB. A free parameter in K-means is the number of clusters. We set this parameter to 17 to obtain clusters with approximately one component per subject.

*Right parieto-occipital cluster characterized in this article* Of the estimated 17 clusters, the right parieto-occipital cluster, shown in Figure 2a, was the only one displaying oscillatory modulation to the attention shift cues, as well as to the subsequent non-target visual stimuli. This manuscript focuses on the characterization of this cluster. It contained 21 dipoles from 16 subjects, and its centroid was located in the middle occipital gyrus of the right hemisphere in Boradmann area 18.

Further details on the EEG data analysis, calculation of ERSPs, and component clustering are provided in [10].

## III. Deeper and longer-lasting alpha desynchronization in switching than in focusing attention

Comparing the EEG spectral power following a LOOK cue between SWITCH blocks (where the LOOK cue instructs subjects to switch their attention to the visual modality) and FOCUS VISION blocks (where the LOOK cue is irrelevant) shows a significantly deeper and long-lasting alpha desynchronization in SWITCH blocks (Figure 2b).

One could argue that in SWITCH blocks the audio-visual LOOK cue is a behaviorally relevant stimuli, while in FOCUS blocks it is not. Then, in SWITCH (but not in FOCUS) blocks the LOOK cue should generate a late positivity (P300) in brain regions included in the parieto-occipital cluster (Figure 2a). Thus, the prolonged alpha desynchronization shown in Figure 2b could just be a spectral manifestation of the P300 activity [11]. However, if this were the case, the audio-visual HEAR cue in SWITCH blocks, being as behaviorally relevant as the LOOK cue in these blocks, should also generate a similar long-lasting alpha desynchronization. But, as shown in Figure 2c, this is not the case. Therefore the long-lasting alpha desynchronization illustrated in Figure 2b does not merely reflect the behavioral relevance of the LOOK cue and may be a consequence of the shift of attention to the visual modality.

Here we have shown that attention-shifting cues generate deeper attention-related EEG changes in SWITCH blocks than in FOCUS VISION blocks. Do visual stimuli following these cues also elicit this effect? We address this question next.

## IV. More attention-related EEG activity in SWITCH than in FOCUS conditions

Figure 3 shows that in the right parieto-occipital cluster the first visual stimulus after the LOOK cue generates a significantly deeper alpha and delta desynchronization in

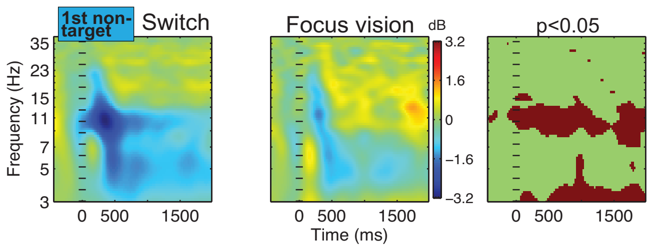


Fig. 3. ERSPs epoched around the first non-target visual stimulus after the LOOK cue in (a) SWITCH and (b) FOCUS VISION blocks. SWITCH blocks generate a deeper and longer-lasting alpha desynchronization than FOCUS VISION blocks, suggesting that rapid switching attention between vision and audition capture more attention than extended periods of focusing attention on the visual modality.

SWITCH than in FOCUS VISION blocks. Thus, the first visual stimuli after the LOOK cue may attract more attention in SWITCH than in FOCUS VISION blocks. The same holds for a middle occipital and a left occipital cluster (data not shown).

Do visual stimuli presented subsequent to the first one also generate enhanced attention-related EEG activity in SWITCH compared to FOCUS VISION blocks? We investigate this question below.

## V. Attention-related EEG activity decays after the attention-shift cue

We studied the dynamics of the enhancement of attentional-related EEG activity using trial-by-trial analysis based on ERP-images. Figure 4a shows that non-target visual stimuli presented shortly after the LOOK cue (figure bottom) triggered deeper and longer-lasting alpha desynchronization than non-target visual stimuli presented longer time after the LOOK cue (figure top). This suggests that the levels of attention-related EEG activity produced by visual stimuli after the LOOK cue in SWITCH blocks decreases progressively as the delay between the cue and the ensuing stimuli increases. Figure 4b is similar to Figure 4a, but displays single trials in FOCUS VISION blocks. Here the delay between the LOOK cue and the non-target visual stimuli does not modulate the attention-related activity triggered by the visual stimuli.

The enhanced attention-related activity generated by visual stimuli presented close to the LOOK cue was generated by switching attention to the visual modality. Is this enhanced activity also observed when switching attention to the auditory modality? We address this question below.

## VI. Switching attention to audition also generates enhanced attention-related EEG activity

Figure 4c is similar to Figure 4a, but for visual stimuli presented in blocks in which subjects switched their attention to the auditory modality. Alpha synchronization is a well-known indicator that this visual brain region is disengaged, here after a switch of attention to the auditory modality [11]. What is not know is that, even after a switch of attention

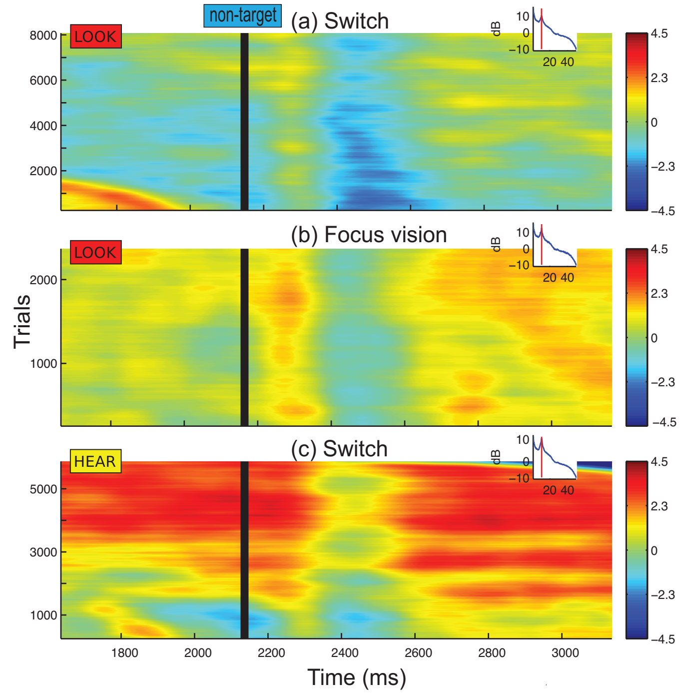


Fig. 4. ERP-images (see methods) epoched around the first, second, and third non-target visual stimulus for trials after the (a) LOOK cue in SWITCH blocks, (b) after the LOOK cue in FOCUS VISION blocks, and (c) after the HEAR cue in SWITCH blocks. In the SWITCH (a), but not in the FOCUS VISION block (b), trials where the visual stimuli follow closely the LOOK cue (bottom trials) generated deeper and longer-lasting alpha desynchronization than trials locked to later visual stimuli (top trials). This effect on a visual brain region (Figure 2a) was also evident when subjects switched their attention to the auditory modality (c).

to the auditory modality, visual stimuli presented close to the attention-shift cue (bottom of the figure) elicited deeper and longer-lasting alpha desynchronization than later stimuli following the cue (top of the figure). This figure suggests that attention shifts act as a "wake-up signal" that trigger enhanced levels of attention in all the modalities involved in multi-modal tasks.

## VII. Discussion

This study examined physiological differences between quickly shifting attention between auditory and visual modalities and focusing attention for extended periods of time in one modality. We reported four observations:

1) Audio-visual cues generate a long-lasting alpha desynchronization when they instruct subjects to switch their attention to vision, and not when they are behaviorally irrelevant (Figure 2).
2) EEG attention-related activity following the first visual stimulus after the cues is greater in blocks where subjects quickly switch their attention between vision and audition than in blocks where they keep their attention focused on a single modality (Figure 3).
3) When subjects quickly switch their attention between vision and audition (Figure 4a), but not when they keep it focused on the visual modality (Figure 4b),

the attention-related EEG change (alpha desynchronization) weakens as the delay between the cue and the visual stimulus increases.

4) The previous attentional decay in visual brain regions holds even when switching attention to the auditory modality (Figure 4c), suggesting a new type of cross-modal interaction between vision and audition.

Previous investigations of anticipatory attentional effects [5] have used a fixed delay between the cue and the following stimulus. Our experiment differed in that this delay was random. These randomness allowed us to show, for the first time, interactions between changes in oscillations related to the attention-shifting cues and those related to the subsequent stimuli (Figure 4).

The right parieto-occipital cluster that we characterized here was the only cluster (out of the 17 we identified – see methods) that displayed oscillatory modulations to the attention-shifting cues as well as to the subsequent non-target visual stimuli. This observation is consistent with the conclusions of Banerjee et al. [14], that indicated that a right parieto-occipital region is involved in both visual and auditory spatial attention, acting in effect as a supramodal attention system.

EEG recordings have shown that attention to peripheral stimuli modulates sensory processing in early visual cortex [15]. This effect can be described in terms of sensory gain control. Differently, for visual stimuli presented in the fovea, two event-related potential studies [16], [17] indicated that there is no attentional gain control. Hence, most studies of selective attention present the visual stimuli to be attended in the periphery. However, recently Frey and collaborators [18] have shown that foveal stimuli elicited event related potential (ERP) modulations similar to those generated by peripheral stimuli. Here we showed that foveal stimuli generated attentional modulations compatible to those reported using peripheral visual stimuli by Banerjee et al. [14], supporting the claim that foveal stimuli also modulate sensory processing in early visual cortex.

That the attention-related activity triggered by the first-visual stimuli is larger in SWITCH than in FOCUS blocks (Figure 3), and that this activity decays progressively when switching attention to the visual (Figures 4a) or to the auditory modality (Figure 4c), but not when focusing attention in the visual modality (Figures 4c), suggests that cross-modal attention shifts generate a transient arousal. This arousal may briefly elicit larger attentional levels, no only in the modality where attention is switched to, but also in other modalities involved in the task.

In summary, in this manuscript we have used a novel experimental design to study neural oscillations in cross-modal switching of attention. We reported novel attentional modulations to the switch cues and the subsequent stimuli, as well as interactions between them. We envision that the study of these interactions will open a new branch in attentional research, one that we plan to explore in future publications.

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