Attentional inhibition by alpha power is modulated by faster theta rhythm and audio-visual congruency during natural speech perception

Gabriel Byczynski[1], Hyojin Park[2]*

[1] School of Medicine, Division of Neurology, University of Geneva & University Hospitals of Geneva, Switzerland

[2] School of Psychology, Centre for Human Brain Health (CHBH), University of Birmingham, Birmingham, UK

* Corresponding author: Dr. Hyojin Park, h.park@bham.ac.uk

Abstract

Audio-visual speech processing is a fundamental aspect of human communication; however, the neural oscillatory mechanisms, particularly those involving alpha rhythms, that underlie attention in tasks requiring attention and suppression remain unclear. To investigate this, we employed a complex audio-visual paradigm designed to explore how alpha rhythms, along with slower frequencies, monitor and integrate audio-visual information under congruent and incongruent conditions. Participants were presented with a TED Talk video while listening to auditory stimuli under three conditions: (1) congruent audio delivered to both ears, (2) congruent audio in one ear and incongruent audio in the other, with attention directed toward the congruent audio, and (3) congruent audio in one ear and incongruent audio in the other, with attention directed toward the incongruent audio. To examine lateralized attention effects, participants were divided into left-attending and right-attending groups across individuals. By analysing fluctuations in alpha power with regards to audio-visual congruency and the side of attention, we observed a notable finding: alpha power fluctuations falling within the faster delta/theta range. This aspect also emerged exclusively in the left-attending group. This result indicates a lateralized relationship between low-frequency rhythms and alpha-band activity, highlighting the role of alpha rhythms as a mediator of attention in audio-visual speech processing. Indeed, the concept of inhibitory alpha power fluctuation follows previous observations of sensory filtering or information sampling rates. These findings underscore the importance of lateralized neural dynamics in tasks involving selective attention and suppression, providing new insights into the oscillatory mechanisms underlying audio-visual integration in human communication.

Keywords: audiovisual speech, audiovisual congruence, alpha, theta, selective attention, temporal sampling, functional inhibition, MEG/EEG

Introduction

Auditory and visual information are both important aspects of communication, and thus there is a wide field of research investigating how the brain perceives, processes, integrates, and stores auditory and visual information streams. To better understand audio-visual processing, and how the brain interprets both matching (congruent) and unmatching (incongruent) inputs between audio-visual stimuli, researchers utilize paradigms that require directed attention to specific modalities. One such investigation, known as the cocktail party paradigm, reproduces a real-life scenario in which auditory and visual information are provided, but not necessarily congruently (Golumbic et al., 2013; Park et al., 2016). This task produces scenarios in which either visual or auditory information is obscured or supplemented with other inputs, creating a complex scenario in which the brain must attend to a specific speaker. In these scenarios, several neural mechanisms become essential to extracting relevant information and suppressing the processing of irrelevant information. One such mechanism includes functional inhibition by alpha rhythm (Jensen and Mazaheri, 2010). During such functional inhibition, brain regions that are unrelated to the processing or storage of activity are inhibited, and thus information is actively directed through areas that remain engaged. Reasonably, paying attention to all incoming auditory and visual information in a given moment is metabolically and cognitively non-optimal, and thus attention can be considered as an act of resource management by directing relevant information to relevant brain areas (Oberauer, 2019).

There are numerous theories of how the brain directs attention, however here we focus on two major perspectives relevant to our hypotheses. The first suggests that attention enhances neural activity in areas responsible for processing stimuli. The second proposes that attention operates by suppressing activity in regions unrelated to the stimuli through inhibitory mechanisms (Foxe and Snyder, 2011). We expand on these hypotheses by considering that attention may not function as a continuous, steady-state process but rather as an intermittent, periodic sampling of the external environment. This sampling is suggested to follow rhythmic fluctuation (Helfrich et al., 2018; Fiebelkorn and Kastner, 2019). Fiebelkorn and Kastner (2019) propose that theta oscillations (4–8 Hz) play a crucial role in visual attention by enhancing temporal resolution and facilitating periodic sampling of visual stimuli. Helfrich et al. (2018) provide evidence that saccadic eye movements are synchronized with sensory input, and that this synchronization can be influenced by precisely timed stimulus presentations, indicating a rhythmic pattern in attentional sampling. While these findings have advanced our understanding of rhythmic attention in the visual domain, there is a lack of research exploring similar mechanisms in auditory processing. In this study, we investigate whether rhythmic attention operates in the auditory domain, focusing on low frequency (< 8 Hz) and its relationship with the role of alpha oscillations (8–12 Hz) in functional inhibition. We manipulate the lateralization of attention and the congruency between audio-visual stimuli to test our hypothesis.

Recent research has addressed the gap in understanding rhythmic attention in the auditory domain. Plöchl et al. (2022) demonstrated that theta band activity (4–7 Hz) is associated with target detection in both visual and auditory modalities, providing evidence for theta oscillations in rhythmic attention. Additionally, alpha band activity appears to be coupled with theta rhythms in a counter-phasic manner, suggesting that alpha oscillations may inhibit task-irrelevant stimuli, potentially through theta-driven alpha modulation. In the visual domain, alpha rhythms are thought to reflect the sampling rate of perception and are cross-frequency coupled with theta during attention tasks (Samaha and Postle, 2015). Cross-frequency coupling (CFC) refers to the interaction between neuronal oscillations of different frequencies, where one frequency modulates another through various methods, including phase–amplitude, phase–phase, and amplitude–amplitude coupling (Jensen and Colgin, 2007). This phenomenon allows for the integration of information across different temporal and spatial scales in the brain, facilitating complex cognitive functions and enables the coordination of activity between distributed brain regions, serving as a mechanism for attentional control and the integration of sensory information (Canolty and Knight, 2010; Doesburg et al., 2012). Low-frequency oscillations, such as theta, have been linked to conditions requiring both auditory and visual monitoring, playing roles in attention and short-term memory (Keller et al., 2017). Therefore, theta-driven modulation of alpha activity may direct top-down attention by functionally inhibiting irrelevant information.

In our study, we employed a classical cocktail party paradigm to investigate audio-visual attention using magnetoencephalography (MEG). Our findings reveal asymmetric alpha power correlates of auditory attention within the theta frequency range. Consistent with previous visual domain studies, we observed that alpha band oscillations may serve as a 'sampling rate' mechanism, enhancing information intake. This mechanism appears to function by increasing sampling directed toward attended stimuli and/or decreasing sampling toward unattended or irrelevant stimuli. Further lateralization of this effect suggests regional contributions, underscoring the significance of top-down signaling through cross-frequency coupling in directing attention under complex audio-visual conditions.

Materials and Methods

Participants

We employed four experimental conditions as described in our previous study (Park et al., 2016). For complete methodology and detailed protocol, please refer to the original publication. Data were collected from 46 healthy right-handed participants (26 females, mean age 20.54 ± 2.58 years). All participants provided written consent and received monetary compensation for their participation. All participants had normal or corrected-to-normal vision and no history of developmental, psychological, or neurological disorders. Due to the nature of the task, only British English native speakers were recruited. Two subjects were removed, as one fell asleep and the other had excessive MEG noise. This left dataset from 44 participants (25 females, mean age: 20.45 ± 2.55 years). This study was approved by the local ethics committee (CSE01321; University of Glasgow, College of Science and Engineering) and conducted in conformity with the Declaration of Helsinki.

Data acquisition

Neuromagnetic signals were obtained using a 248-magnetometer MEG system (MAGNES 3600 WH, 4-D Neuroimaging) in a shielded room with a sampling rate of 1017 Hz. Pre-processing included denoising using the Fieldtrip Toolbox (Oostenveld et al., 2011), and removal of electrooculogram (EOG) and electrocardiogram (ECG) artifacts using independent component analysis (ICA) and bad sensors according to the MEG analysis guidelines (Gross et al., 2013).

Stimuli and task

Participants were presented with a visual stimulus and two auditory stimuli. The stimuli used were video and audio clips of a male speaker talking for between 7-9 minutes. Stimuli were sourced from TED talks (www.ted.com/talks/) and were edited to remove references to visual materials or referring to the gender of the speaker. Video clips were filmed by a professional filming company with a high-quality audio-visual device and recorded in 1920 x 1080 pixels at 25 fps (frame per second) for video and a sampling rate of 48 kHz for audio.

Three conditions were used in the present study: ‘All congruent’ condition, ‘AV congruent’ condition, and ‘AV incongruent’ condition. Here, congruency refers to the alignment between auditory and visual stimuli. In the ‘All congruent’ condition, participants were presented with congruent audio-visual stimuli in both ears. ‘AV congruent’ and ‘AV incongruent’ conditions followed a dichotic listening paradigm, where participants received different auditory stimuli in each ear. In the ‘AV congruent’ condition, participants were presented with congruent audio-visual stimuli on either the left or right side and instructed to attend to the congruent audio. In contrast, the ‘AV incongruent’ condition maintained the same stimulus presentation as the ‘AV Congruent’ condition; however, participants were required to attend to the side where the audio was incongruent with the visual input (Figure 1A). Participants were divided into two groups (22 participants each for the left- and right-attending groups), and a fixation cross color at the beginning of the visual stimulus cued them to attend to either the left or right auditory stimulus. Throughout the task, participants were instructed to maintain their gaze on a fixation cross, which was positioned over the speaker’s lips. Their eye movements and gaze behaviors were continuously monitored using an eye-tracking device to ensure compliance with the fixation requirement.

Extraction of alpha power fluctuation

We first acoustically segmented the speech recordings into discrete chunks using the Syllable Nuclei (de Jong and Wempe, 2009) script in Praat (Boersma and Weenink, 2018) (see Fig. 1D). Acoustic silences were identified based on a minimum pause duration of 0.25 seconds and a silence threshold of 25 dB. Each resulting speech chunk had a minimum duration of 1 second. The corresponding MEG data were then segmented to align with these speech chunks for subsequent analysis.

To determine the rhythms of the alpha power fluctuation in each condition, we used Fast Fourier Transform (FFT) of a subset frequency range of the alpha power. Using the FieldTrip toolbox (Oostenveld et al., 2011) in MATLAB2021b, data analysis was carried out following the Flux Pipeline for MEG analysis (Ferrante et al., 2022). Data were baseline corrected using -1.5 to 0 seconds before the onset of speech. After the time-frequency analysis, alpha power (8-12 Hz) was extracted from left and right auditory sensors in each participant. This produced a single trace representing the fluctuation of alpha power over time for the subset of auditory sensors. We then applied a Fast Fourier Transform (FFT) to determine at which frequencies the alpha power was oscillating (Figure 1). We investigated the peaks of FFT of alpha power fluctuation falling under theta and delta range (0.1 – 7 Hz).

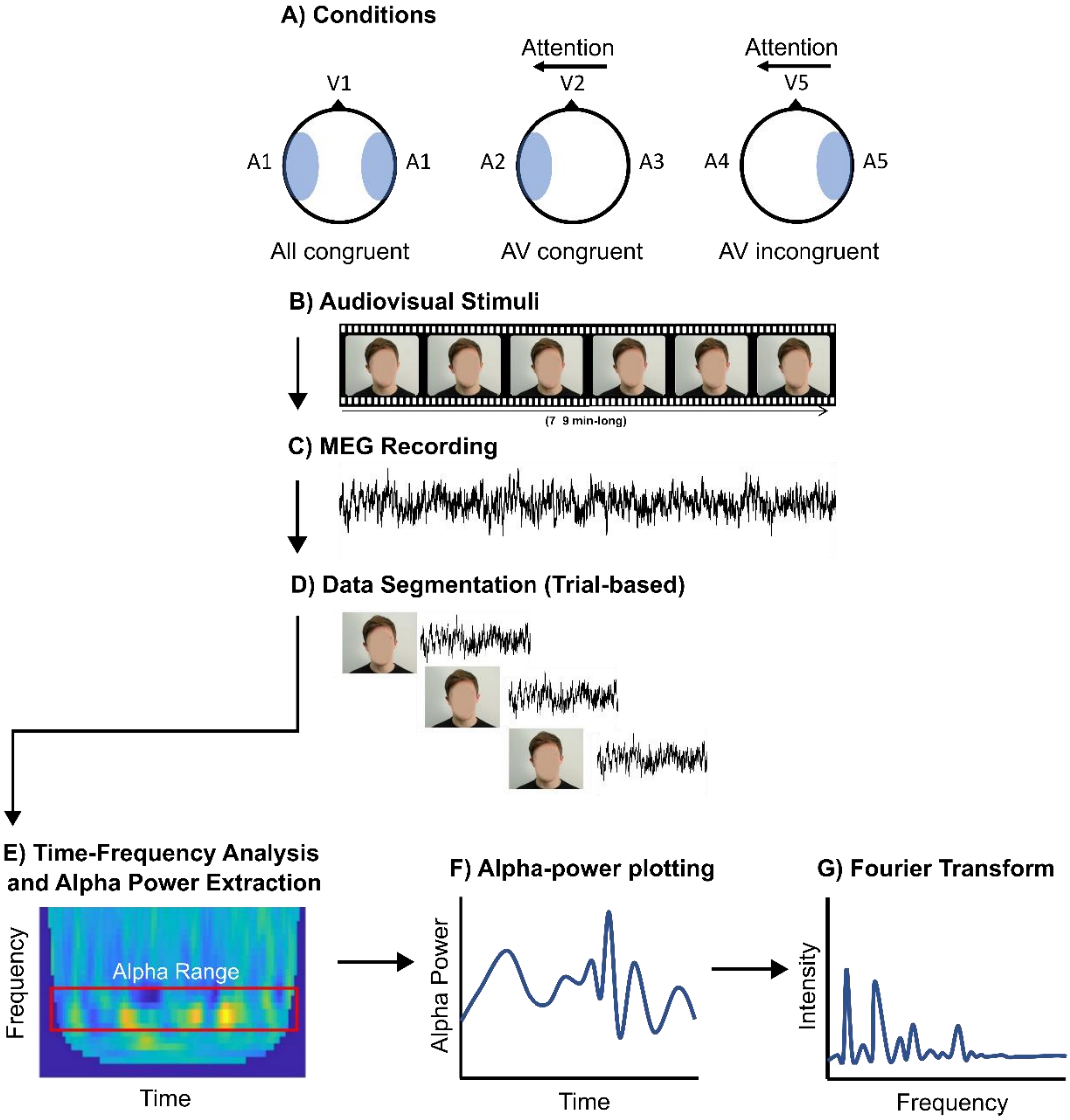

Figure 1. A) Conditions used in the present study, where the direction of attention is indicated by arrows, and the shaded region indicates the side in which auditory information is congruent with visual

information (examples of the left-attending group). B) Audio-visual stimulus appearance. C) Continuous MEG recording during stimulus. D) MEG data were segmented into ~3-second trials aligned with acoustically segmented speech chunks. E) Time-frequency analysis was performed for each trial. F) Alpha power was extracted over time, and G) Fast-Fourier Transform results on alpha power fluctuation.

Statistical analysis

Statistical analyses were performed on data from all 44 participants, separated by attending direction (n = 22 per group). When comparing alpha power fluctuation, paired t-tests between experimental conditions for within-group and unpaired t-tests for between-group contrasts were used. Only significant results ($p < 0.05$) are reported. For statistical differences between the attending groups shown in Figure 5, cluster-based permutation tests were performed in Fieldtrip (Oostenveld et al., 2011). An independent samples t-test was calculated for each sensor-time sample with an alpha threshold of 0.05 as the cluster-building threshold (two-tailed). Only significant results ($p < 0.05$) are reported.

Results

No differences in the rhythms of alpha power fluctuation in the AV congruent condition

In the AV congruent condition, where the participants paid attention to the auditory speech that matched the video, rhythms of alpha power fluctuation had no differences between left and right auditory sensors for any of the major underlying frequencies in theta and delta range (0.1 – 7 Hz). Neither the left group nor the right group had significantly different fluctuation frequencies. Alpha power in the left auditory sensors exhibits a trend of fluctuation at higher theta frequencies for the left group and vice versa for the right group; however, this difference was not significant (Figure 2).

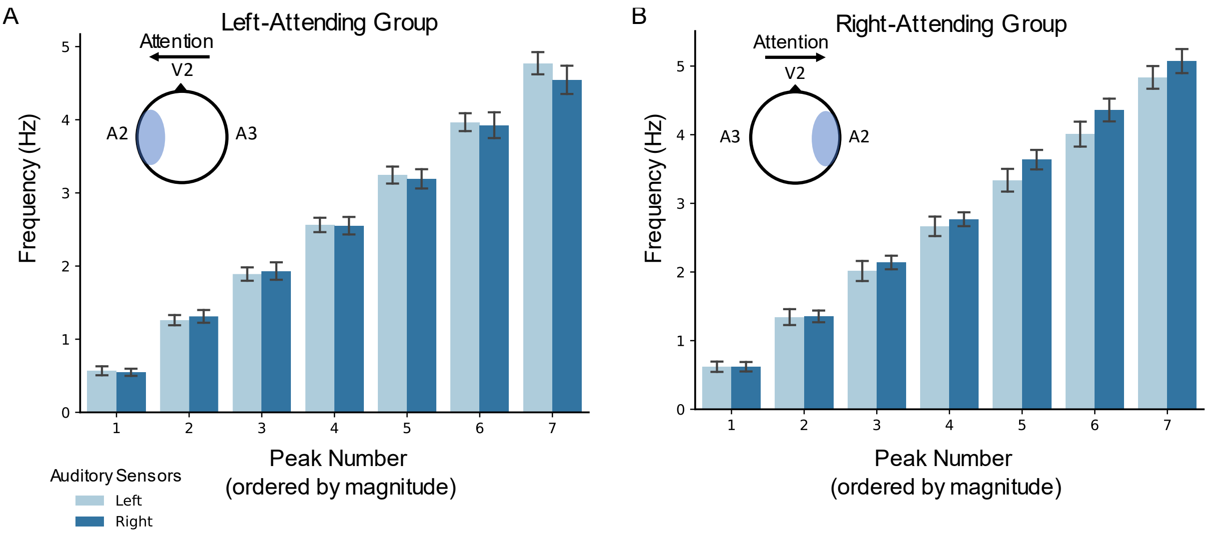

Figure 2. Alpha power fluctuation frequency of the left-attending group (A) and right-attending group (B) in the AV congruent condition. The blue circle indicates the side of congruency, while the arrow indicates the direction of attention during the task. Boxplots depict alpha power fluctuation of the left and right auditory regions. Error bars represent the standard error of the mean (SEM).

Differences in the rhythms of alpha power fluctuation in the AV incongruent condition for the left-attending group

In the AV incongruent condition, where the participants paid attention to the auditory speech that unmatched the video, the left-attending group had significantly higher left-sided alpha power fluctuation at peak 2 (t_{21} = 2.44, p = 0.023), peak 3 (t_{21} = 2.45, p = 0.023), and peak 4 (t_{21} = 2.19, p = 0.039) (Figure 3). However, the right-attending group did not exhibit any significant peaks albeit there was a noticeable trend of alpha power fluctuations at higher theta frequencies in the right auditory sensors.

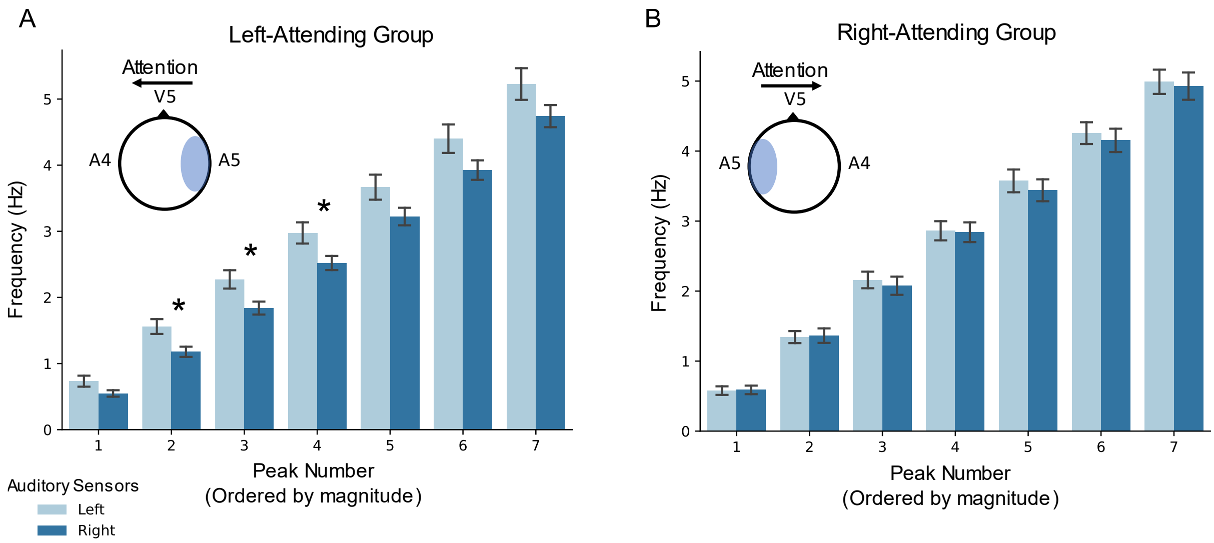

Figure 3. Alpha power fluctuation frequency of the left-attending group (A) and right-attending group (B) in the AV incongruent condition. The blue circle indicates the side of AV congruency, while the arrow indicates the direction of attention during the task. Boxplots depict alpha power fluctuation of the left and right auditory regions. *$p < 0.05$ via paired t-test. Error bars represent the standard error of the mean (SEM).

To determine if this difference was also statistically significant when compared to the All congruent condition, which serves as a control condition involving congruent audio-visual stimuli without a specific direction of attention, we analysed changes in frequencies from the All congruent to the AV congruent, and All congruent to the AV incongruent condition (Figure 4). This validated peaks 3 to 6 being a significance change from the All congruent condition (paired t-test; peak 3: $t_{21} = 2.517$, $p = 0.02$; peak 4: $t_{21} = 2.74$, $p = 0.01$; peak 5: $t_{21} = 2.34$, $p = 0.03$; peak 6: $t_{21} = 2.23$, $p = 0.037$ shown in Figure 4C) in the left-attending group for AV incongruent condition. However, there was no significant change from the All congruent condition in the right-attending group for both conditions.

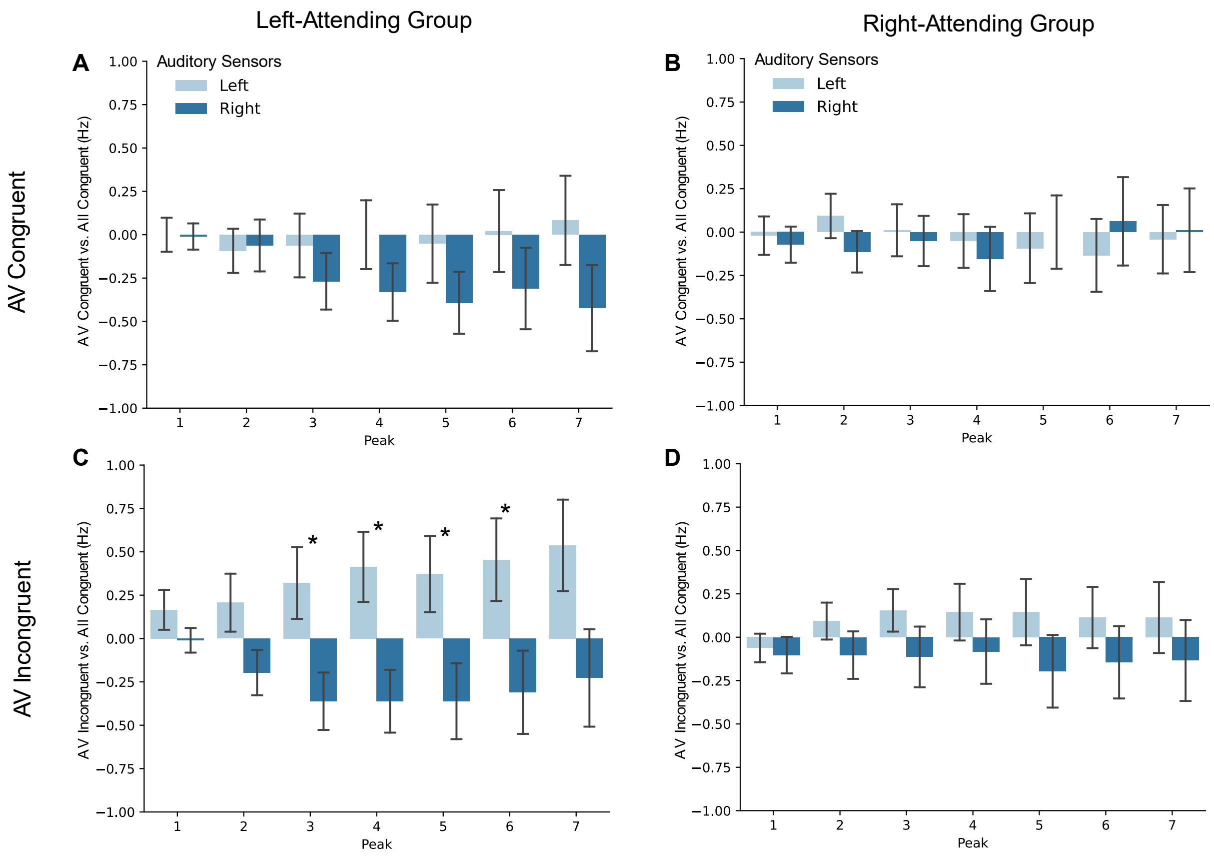

Figure 4. Alpha power fluctuation frequency for the AV congruent (upper) and AV incongruent (lower) conditions compared to the All congruent (control condition) in the left-attending group (A, C) and right-

attending group (B, D). *$p < 0.05$ via paired t-test. Error bars represent the standard error of the mean (SEM).

Global alpha power differences between attending groups across the sensor array

The difference between the attending groups prompted further investigation of global alpha (8-12 Hz) power differences between the left- and right-attending groups for each audiovisual conditions: AV congruent (Figure 5A) and AV incongruent (Figure 5B). Statistical comparisons between the groups were conducted separately for each condition using cluster-based permutation tests ($p < 0.05$), applied at 500 ms time intervals. For the AV congruent condition, alpha power was significantly increased in the left auditory and temporal areas in the left-attending group compared to the right-attending group, suggesting enhanced suppression of the to-be-ignored speech on the right side. For the AV incongruent condition, alpha power was significantly increased in the central and bilateral parieto-occipital regions, as well as in the auditory and temporal areas, suggesting suppression of lip movements that were congruent with the to-be-ignored speech. Significant effects were observed between 2-2.5 seconds after the onset of the speech chunks for both conditions.

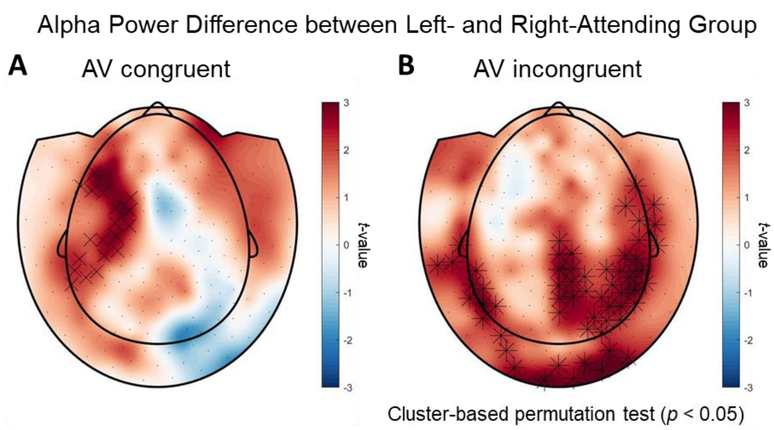

Figure 5. Topographical maps of alpha power (8–12 Hz) differences between the left-attending and right-attending groups for each condition: AV congruent (A) and AV incongruent (B). Statistical comparisons between the groups were performed separately for each condition using two-tailed cluster-based permutation tests ($p < 0.05$). Significant effects were observed between 2-2.5 seconds after the onset of the speech chunks for both conditions.

Discussion

In this study, we investigated how alpha-band (8–12 Hz) oscillations are modulated by attention and audio-visual congruency during natural speech perception. By analyzing alpha power fluctuations and overall alpha power under congruent and incongruent listening conditions, we aimed to understand the role of oscillatory dynamics - particularly cross-frequency interactions - in supporting selective attention in complex audio-visual environments.

Our findings reveal two key aspects of alpha dynamics: First, alpha power fluctuation frequency differed between the left- and right-attending groups, but only in the AV incongruent condition. Specifically, the left-attending group exhibited significantly faster fluctuations of alpha power in the left auditory sensors, with frequencies falling into the delta-theta range (2–5 Hz). This pattern was absent in the right-attending group and under the AV congruent condition. These results align with previous theories proposing that attentional sampling may operate rhythmically, modulated by low-frequency oscillations such as theta (Helfrich et al., 2018; Fiebelkorn and Kastner, 2019). It may represent an increased temporal sampling of perceptual information which becomes necessary when visual information no longer provides congruent information. This pattern has been observed before, wherein sensing organs alternate between operational modes resulting in low and high modal frequencies (Morillon et al., 2019), and in the visual domain as well (Samaha and Postle, 2015). Second, overall alpha power also differed between attending groups. In the AV congruent condition, alpha power was significantly greater in the left auditory and temporal areas of the left-attending group compared to the right-attending group, supporting the notion that alpha oscillations facilitate functional inhibition of task-irrelevant inputs (Jensen and Mazaheri, 2010; Foxe and Snyder, 2011). Interestingly, in the AV incongruent condition, alpha power increases were observed not only in auditory areas but also in bilateral parieto-occipital regions, suggesting that suppression was extended to visual inputs - particularly lip movements congruent with the to-be-ignored auditory stream. Such findings support broader models of cross-modal suppression during audiovisual processing (Janssens et al., 2018; Ro, 2019), and illustrate how alpha-band activity is recruited flexibly depending on the sensory modality and attentional demands. As such, alpha dynamics subserve distinct cognitive mechanisms: fluctuation frequency may govern temporal sampling of attended information (Samaha and Postle, 2015; Morillon et al., 2019), while overall alpha power may regulate inhibition of distractors (Jensen and Mazaheri, 2010). These two dimensions of alpha control may operate independently depending on task complexity.

Moreover, the faster alpha fluctuation rate falling into the delta-theta range raises the possibility of cross-frequency coupling between theta phase and alpha amplitude, a phenomenon proposed to coordinate information processing across temporal scales (Jensen and Colgin, 2007; Canolty and Knight, 2010; Doesburg et al., 2012). Phase-amplitude coupling between delta/theta oscillations and alpha power has previously been shown in other studies (e.g., Cohen et al. (2009)), and is proposed to represent a coordinated timing of neuronal firing within local networks (Szczepanski et al., 2014). Taking this effect into consideration, our findings align with those of Gomez-Ramirez et al. (2011), suggesting that delta-entrained rhythms can modulate alpha power during auditory and visual paradigms. While our study does not directly investigate phase-amplitude coupling but rather examines the frequency of alpha power, it is possible that the observed alpha power oscillation results from delta/theta-phase modulated alpha-amplitude coupling. Our results suggest that the speed at which the alpha power oscillates (perhaps via operationalizing theta/delta-oscillation frequency), reflects a top-down attentional mechanism of information processing that could reflect the temporal sampling theory in the visual domain. Faster theta-modulated coupling results in faster information sampling, thus preferentially directing and attentional control of incoming information.

Lastly, the absence of significant alpha fluctuation changes under the AV congruent condition suggests that top-down attentional modulation may be less necessary when auditory and visual streams are congruent and mutually supportive. When audiovisual inputs align, attentional demands may decrease, and inhibition through alpha dynamics may not be actively recruited (Park et al., 2016; Klatt et al., 2020). This interpretation is supported by previous behavioral findings showing that comprehension performance is higher under congruent audiovisual conditions compared to incongruent ones (Park et al., 2016).

In summary, our results demonstrate that alpha oscillations play a flexible, dynamic role in supporting selective attention during complex audiovisual speech perception. Faster fluctuations of alpha power reflect enhanced temporal sampling when attentional control is necessary, while increases in overall alpha power indicate suppression of irrelevant information across sensory modalities. These findings extend current models of attention by highlighting how cross-frequency dynamics and hemispheric asymmetries contribute to the neural basis of communication in naturalistic environments.

Conclusion

Our results provide the first evidence that alpha power fluctuation frequency is modulated by delta/theta rhythm when greater attentional control is required during a naturalistic speech perception task. Furthermore, this effect was more pronounced in the left-attending group compared to the right-attending group. Our study suggests a novel neural cross-oscillatory correlate of complex auditory attention in association with audio-visual congruency. Future research may further investigate specifically the directionality of delta/theta coupling with alpha power fluctuation and explore the plausibility of this fluctuation as an information ‘filter’ which appears to be lateralized.

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