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

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Abstract

Audio-visual processing is an essential aspect of human communication, however the mechanisms that underlie attention and processing in the auditory and visual domains are still limited. In order to understand how the brain attends to and processes information while ignoring irrelevant information, we employed a complex audio-visual paradigm to understand how the brain monitors and integrates audio-visual information in congruent and incongruent conditions. In three conditions, participants watched a Ted Talk presentation while listening to 1) congruent audio in both ears, 2) congruent audio in one ear and incongruent in the other (attending to congruent) or 3) congruent audio in one ear and incongruent audio in the other (attending to the incongruent). In order to investigate correlates of attention and audio-visual processing, we developed a novel method of detecting audio-visual congruency in the fluctuation rhythms of alpha power during each condition. Employing this method, we found that higher frequency alpha power fluctuation, falling in the delta-theta range, corresponded regionally to the side of attention, suggesting a novel mechanism of processing in that alpha-band activity may act as a temporal filter or attentional mechanism during audio-visual attention.

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, 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 (O'Sullivan et al., 2015; Park et al., 2016a; Park et al., 2018; Har-Shai Yahav and Zion Golumbic, 2021). This reproduces 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 specific speakers. In these scenarios, several neural mechanisms become essential to extracting relevant information, and suppressing the processing of irrelevant information. One such mechanism includes alpha wave function inhibition (Klimesch et al., 2007; Jensen and Mazaheri, 2010). During such functional inhibition, regions of the brain that are unrelated to the processing or storage of activity are inhibited, and thus, information is actively directed through areas that remain active. 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 active areas (Oberauer, 2019). There are numerous theories of attention, however here we restrict our discussion to two major theories relevant to our hypotheses: first, that attention is controlled by increasing activity responsible for processing stimuli, or second, those areas not relevant for stimuli processing are deactivated via inhibition (Foxe and Snyder, 2011). We amend these hypotheses with an additional consideration, which is that attention is likely not a consistent process, but rather occurs as a sampling of the external environment. This sampling is suggested to follow rhythmic fluctuation (Helfrich et al., 2018; Fiebelkorn and Kastner, 2019). In their review, Fiebelkorn and Kastner (2019) include in their discussion that theta oscillations specifically play a role in visual attention, increasing temporal resolution by promoting sampling from a neural location. The work that investigates the so-called *Rhythmic Theory of Attention* in the visual domain puts forth that saccadic eye movements are coupled with sensory input direction, and can be manipulated with precise stimulus presentation intervals, which suggests a pattern of attention sampling (Helfrich et al., 2018). Interestingly, there is minimal literature that translates the possibility of rhythmic attention in the

auditory domain, thus here we test the hypothesis that a similar mechanism exists in auditory processing, albeit possibly via an alternative underlying mechanism.

Research has somewhat amended this gap, with work by Plöchl et al. (2022) illustrating theta band activity (4-7Hz) reflects target detection occurring in both visual and auditory domains, positing evidence for theta oscillations in rhythmic attention. Alpha band activity also appears to be counter-phasic-ally power-coupled with theta rhythms, suggesting the inhibition of task-irrelevant stimuli, and perhaps as the authors note, theta-driven alpha modulation. The role of alpha in both auditory and visual streams has numerous explanations, however it seems consistent that alpha rhythms reflect the 'sampling rate' of visual perception and are cross-frequency coupled with theta during visual attention (Samaha and Postle, 2015). Cross-frequency coupling (CFC) describes a method where one frequency wave may modulate another, via several methods including power-power, phase-phase, power-phase, etc. (Jensen and Colgin, 2007; Park et al., 2011; Park et al., 2016c). Information can be shared across frequencies, cross-modally, and interregionally via CFC, with some studies investigating audio-visual attention finding cross-frequency modulation as a mechanism for control (Canolty and Knight, 2010; Doesburg et al., 2012).

Using a classical paradigm in audio-visual attention, we test the hypothesis that there exist alpha-power correlates of auditory attention by using magnetoencephalography (MEG) and a novel method for measuring alpha power dynamics. We expect that, consistent with previous studies in other modalities, patterns representing a 'sampling rate' in the alpha band may reflect an attentional mechanism employed to increase the quantity of information input. We expect that this pattern may occur as either an increase in sampling directed toward the attended stimuli, and/or a downsampling to the unattended/irrelevant stimuli.

Materials and Methods

Participants

We employed four experimental conditions as described in our previous study (2016b). 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, no history of developmental, psychological, or neurological disorder. 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

In brief, 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 and electrocardiogram artifacts using independent component analysis (ICA) 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. Eleven video clips were filmed by a professional filming company with 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, an 'All congruent' condition, 'AV congruent' condition, and an 'AV incongruent' condition. In the All congruent condition, participants were presented with congruent audio-visual stimuli in both ears. In the AV congruent condition, the participant was presented with congruent audio-visual information on the side of attention, and in the AV incongruent condition, the stimulus presentation is the same as the congruent condition, however the participant attended to a side where incongruent auditory information was presented (Figure 1). Participants were split evenly into two groups, and a fixation cross colour at the start of the visual stimulus indicated to attend to the left side or the right side for the experiment. Participants fixated on a fixation cross which was placed over the speaker's lips, and gaze behavioural was monitored via eye-tracking.

Extraction of alpha power fluctuation

To determine the rhythms of the alpha power fluctuation in each condition, we used an analysis procedure which utilized Fast Fourier Transform of a subset frequency range. 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 from -1.5 to 0 seconds before the onset of speech. Alpha power (8-12 Hz) was extracted from left and right auditory sensors (n = 22 and 26, respectively) in each participant (an equivalent number of sensors were chosen initially, and those which were discarded from a participant due to artifact or poor data were then removed from all participants). 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) on each of the left and right auditory region data for each participant to determine at which frequencies the alpha power was oscillating (Figure 1). We investigated the peaks falling under theta and delta range (0.1 – 7 Hz), revealing the major low frequencies of the alpha power fluctuation.

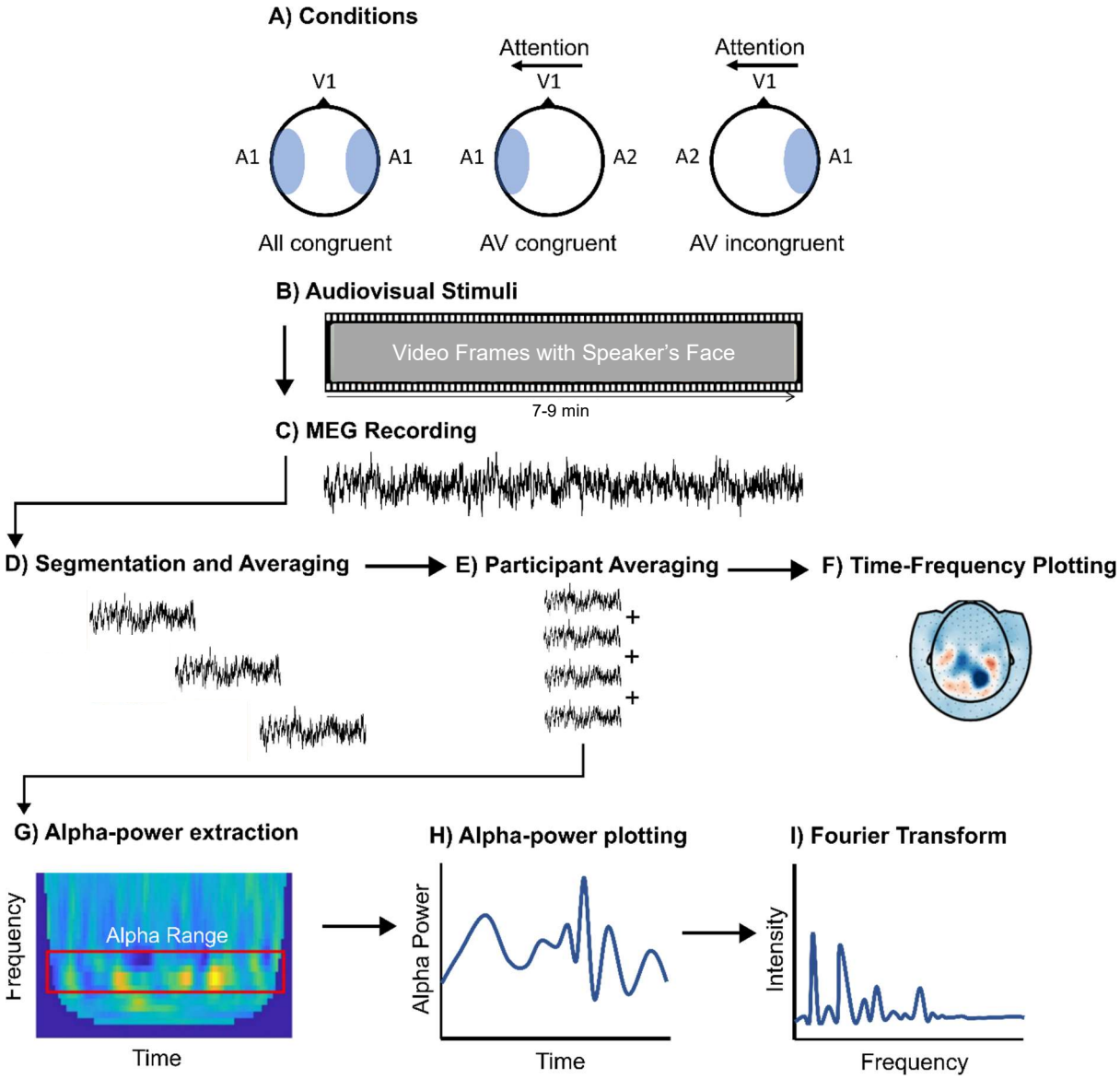

Figure 1. A) Conditions used in the present paradigm, where the direction of attention is indicated by arrow, and the shaded region indicates the side which auditory information is congruent with visual information. B) Audio-visual stimulus appearance. C) Continuous MEG recording during stimulus. D) Segmentation of recording into ~3 second segments based on speech onset and averaging of segments for each participant. E) Averaging all participants within the group for plotting: F) Time-frequency topoplot representation. G) Individual-level alpha power extraction, H) alpha power plotting over time and I) 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 values, paired -tests for between-condition and unpaired t-tests for between groups were used. Only significant results ($p < 0.05$) are reported. Change from All congruent to AV congruent or AV incongruent conditions was calculated as the

subtractive difference between conditions within each individual, and this difference was averaged across participants. For statistical differences between these conditions shown in Figure 6, non-parametric (Monte Carlo) randomization statistics was used in Fieldtrip (Oostenveld et al., 2011). A dependent samples t-test was calculated for each channel-time sample with an alpha threshold of .05 as the cluster-building threshold (two-tailed). The null distribution was estimated using 2000 randomizations and multiple comparison corrections was performed using FDR (False Discovery Rate). Only significant results ($p < 0.05$, FDR corrected) are reported.

Results

No differences in rhythms of alpha power fluctuation in matched attention and AV congruency condition

In AV congruent condition where the direction of auditory attention and AV congruency are matched, 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 fluctuated at higher theta frequencies for the left group, and vice-versa for the right group, however this difference was not significant (Figure 2).

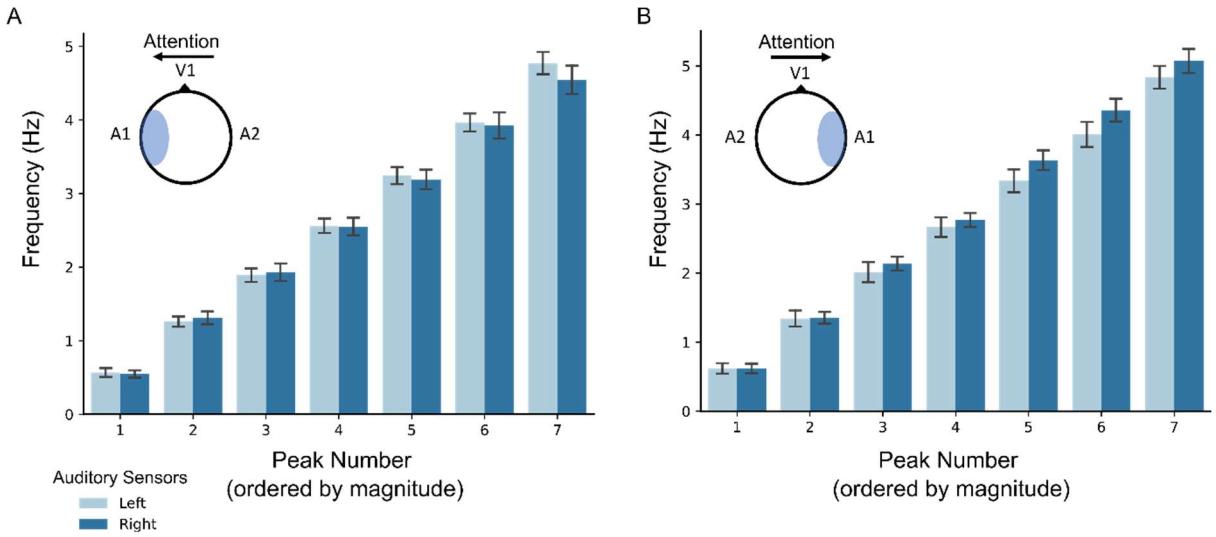

Figure 2. Alpha power fluctuation frequencies of the left-attending group (A) and right-attending group (B) in the AV congruent condition. Blue circle indicates the side of congruency, while the arrow indicates the direction of attention during the task. Boxplots depict alpha power fluctuation of left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

Differences in rhythms of alpha power fluctuation in mismatched attention and AV congruency condition

In the AV incongruent condition, in which the direction of auditory attention and AV congruency were mismatched, 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).

179 However, the right-attending group did not exhibit any significant peaks albeit there was a noticeable
180 trend of alpha power fluctuations at higher theta frequencies in the right auditory sensors.

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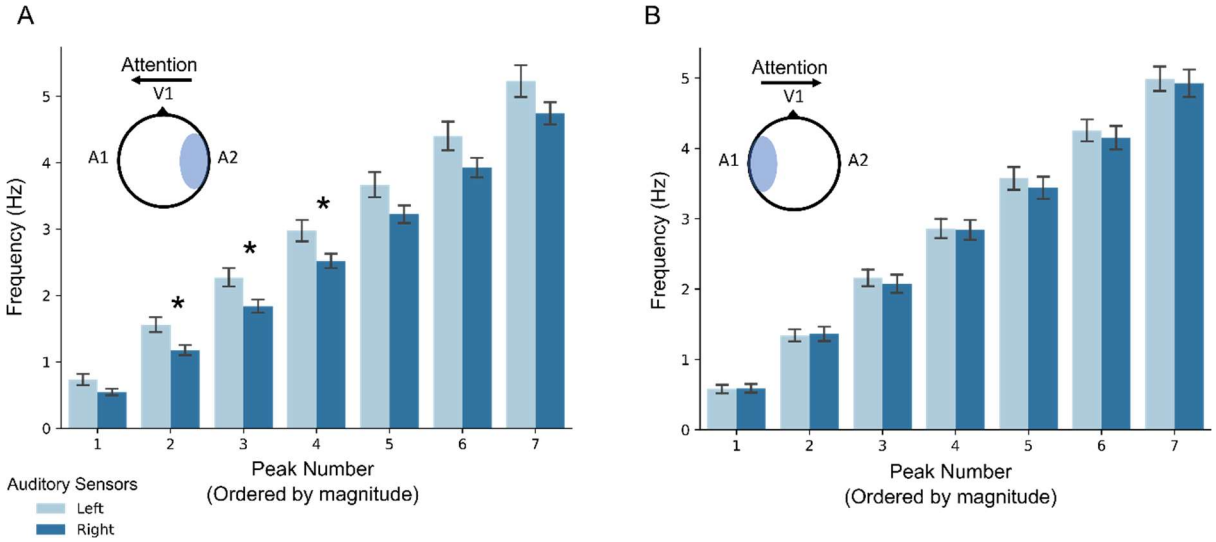

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183 **Figure 3**. Alpha power fluctuation frequencies of the left-attending group (A) and right-attending group
184 (B) in the AV incongruent condition. Blue circle indicates the side of AV congruency, while the arrow
185 indicates the direction of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

188

189 To determine if this difference was also statistically significant when compared to the All congruent
190 condition, which serves as a control condition involving congruent audio-visual stimuli without a specific
191 direction of attention, we analyzed changes in frequencies from the All congruent to the AV congruent,
192 and All congruent to the AV incongruent condition, using the subtractive difference between the
193 conditions (e.g., AV congruent – All congruent) (Figure 4). This validated peaks 3 to 6 being a
194 significance change from the All congruent condition (paired t-test; peak 3: $t_{21} = 2.517$, $p = 0.02$; peak
195 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
196 the left-attending group. However, there was no significant change from the All congruent condition in
197 the right-attending group.

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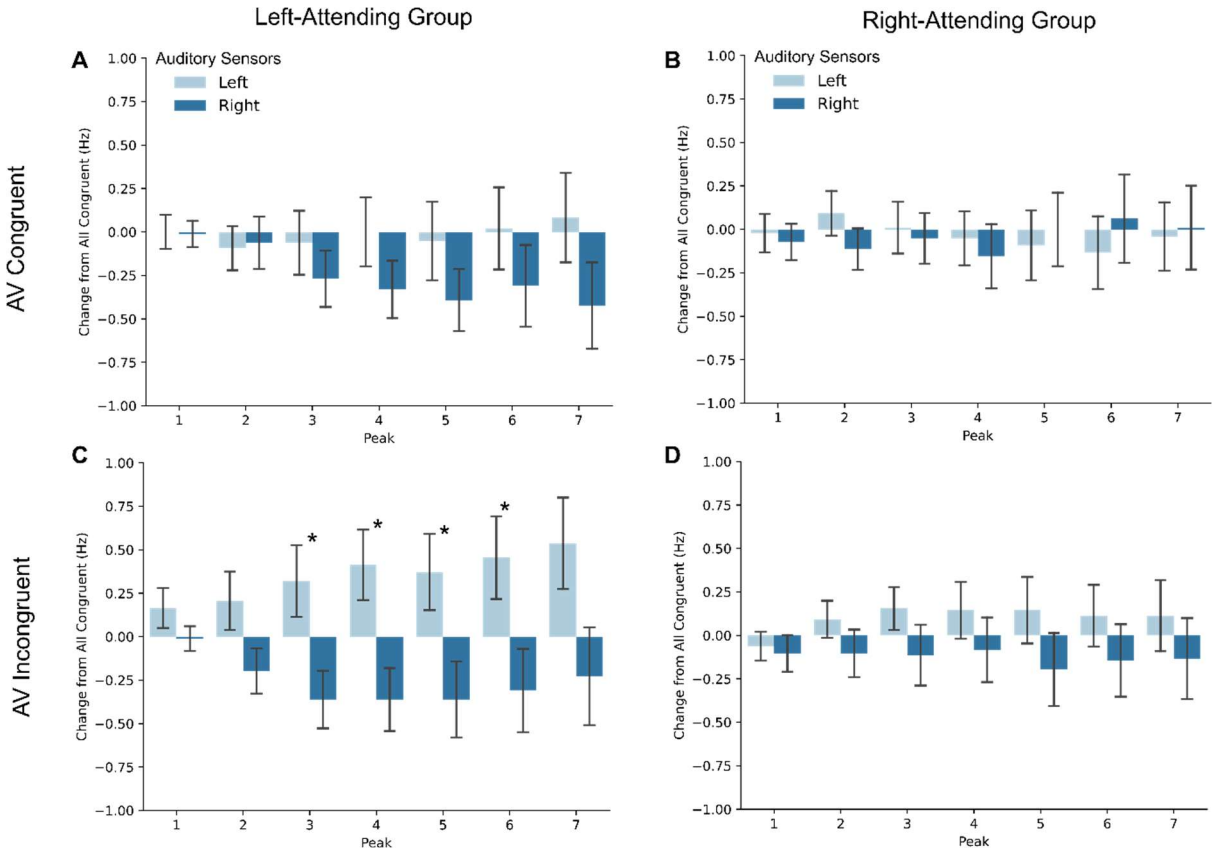


Figure 4. Changes in alpha power fluctuation frequency from the All congruent (control) condition for the AV congruent (upper) and AV incongruent (lower) conditions of the left-attending group (A, C) and right-attending group (B, D). *$p < 0.05$ via paired t-test. Error bars represent the standard error of the mean (SEM).

Alpha power differences by group and condition

We here show grand-averaged alpha power (8-12 Hz) for AV congruent and AV incongruent conditions after the speech chunk onset for the left-attending (Figure 5A) and right-attending (Figure 5B) groups. For the left-attending group during the AV congruent condition, the alpha power was prominent in the left auditory sensors which is suggested to inhibit the input from the right ear that matches visual information (lip movement, i.e., matched AV congruency) (lower plot in Figure 5A). However, this pattern is not as clearly represented in the right-attending group (lower plot in Figure 5B) as well as in AV congruent condition (upper plots in Figure 5A and B).

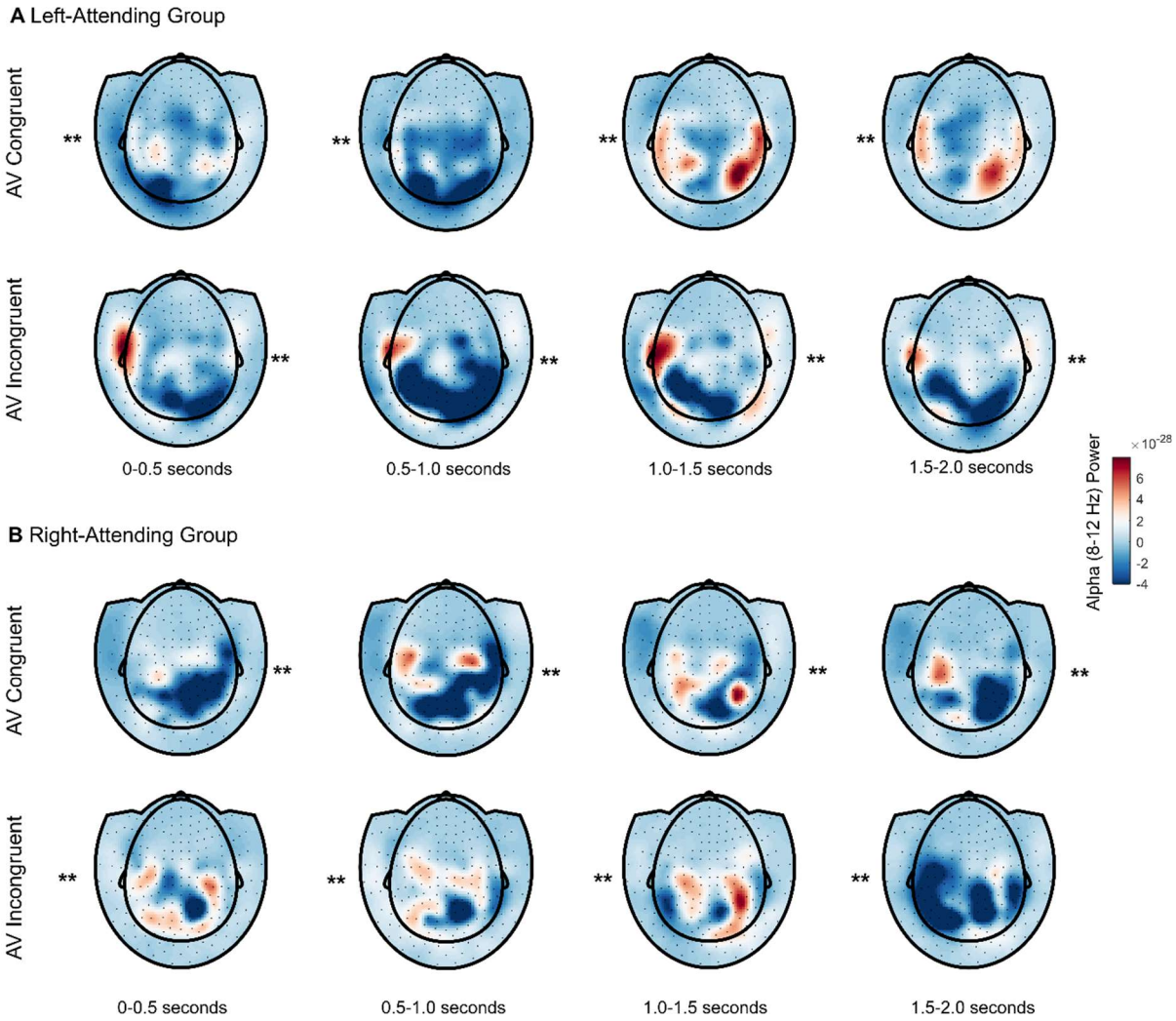
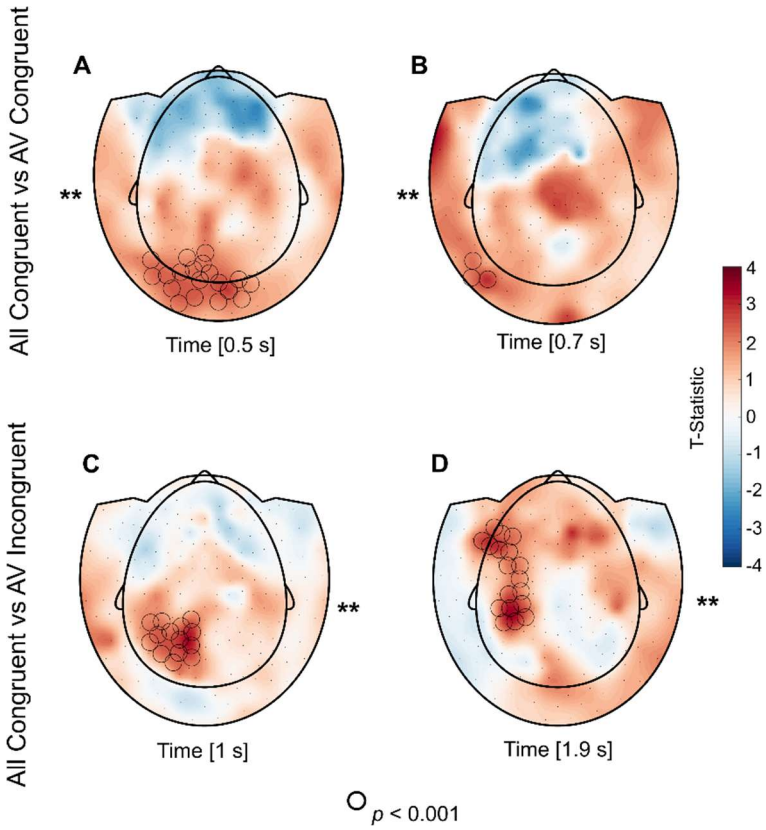


Figure 5. Topoplots of alpha power after the speech chunk onset for the left-attending group (A) during AV congruent (upper) and AV incongruent (lower) conditions and the right-attending group (B) during AV congruent (upper) and AV incongruent (lower) conditions. ** denotes the side of congruent audio-visual information.

222 We performed a statistical comparison between All congruent compared to each AV congruent and AV
223 incongruent conditions. Figure 6 shows the significant time points and conditions where alpha power
224 differed significantly. Specifically, we found that there was reduced alpha power in posterior sensors
225 during the AV congruent condition compared to the All congruent condition, although only significant
226 for the left group. During the All congruent vs AV incongruent comparison, we found that in the left-
227 attending group, there was reduced alpha power in the left-posterior sensors at 1 second, which moved
228 to a general left-hemispheric (side of incongruent information) reduction in alpha power at about 2
229 seconds.



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232 **Figure 6**. Alpha power topoplots of *T*-statistic at each electrode are created through cluster
233 randomization. Circles denote significant sensor differences at the given time point and condition. A-B)
234 Left-attending group, All congruent vs AV congruent condition. C-D) Left-attending group, All congruent
235 vs AV incongruent condition. ** denotes the side of congruent audio-visual information.

Discussion

In this study, we present results that suggest that oscillating alpha power in auditory regions may represent a correlate of attention during complex audio-visual conditions, possibly indicating a method of attentional control in the auditory domain. Our analysis procedure determined the oscillation frequencies of alpha power in the left and right auditory sensors during MEG recording. We compared the alpha power fluctuation (frequency) in the left and right attending groups during congruent and incongruent listening conditions, as a pseudo-measure of cross-frequency coupling with theta and delta oscillations. During the AV incongruent condition, the left group showed increased fluctuation frequency on the side of attention, only during conditions in which congruent audio-visual information was presented on the unattended side. Furthermore, this left-right hemispheric difference was further validated when compared to the All congruent (control) condition, which found that the attended side had increased fluctuation frequency, while the unattended (congruent) side had reduced fluctuation frequency. While this finding was not statistically mirrored in the right-attending group, the pattern of left-right attending fluctuation difference was visible. Interestingly, although alpha power was found to have faster fluctuation on the attended side, this did not necessarily translate to higher alpha power overall. The topoplots of Figure 5 instead suggest that alpha power is generally higher on the unattended side during AV congruent conditions. However, when comparing the alpha power between the All congruent and AV congruent condition, significant differences arose more posteriorly, which could be interpreted as decreased alpha in visual regions when visual information becomes more important. It may be that during the All congruent condition, identical auditory information from both sides makes visual information redundant, while the AV congruent condition elicits more information through increased visual attention (marked by a reduction in alpha power). Interestingly, while the topoplots in Figure 5 show that incongruent conditions have increased alpha power on the side of irrelevant information, this effect is inverted when statistically tested against All congruent condition (Figure 6). That is, there is higher alpha power in the left hemisphere during the All congruent condition, compared to the AV incongruent condition. This pattern may arise for several reasons. For instance, variability in listening strategy during All congruent condition could produce differences in alpha power during the comparison conditions. Likewise, generally higher or lower alpha power across the scalp could produce within-condition differences which do not survive the comparison to a control condition.

Our interpretation of the results is two-fold. Firstly, it may be that increased alpha power fluctuation represents a theta- or delta-coupled effect. In a previous paper, Park and Ince note that there is a canonical left-lateralization for speech production, but also for speech perception. They put forth that top-down control is more left-lateralized, and is predominantly controlled via low-frequency oscillations, which we propose is corroborated at the alpha power level here (Figure 4B-D). We then introduce the second aspect of the interpretation, which would posit that the occurrence of increased alpha-power fluctuation frequency in the delta-theta range during the AV incongruent condition 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 is a present mechanism in the visual domain (Samaha and Postle, 2015). Indeed, the alpha power in general, and the alpha power fluctuation, appear to be independent, suggesting that alpha power may perform two simultaneous mechanisms, the first being increasing the fluctuation to increase information sampling, and the second being using alpha to inhibit irrelevant information processing.

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 appear to fit in context with those of Gomez-Ramirez et al. (2011), where it was found 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 looks at the frequency of the alpha power, it may be that the alpha power oscillation produced is a result of delta/theta-phased alpha-amplitude coupling. Our method and results ultimately suggest that, through an undetermined mechanism, the speed at which the alpha power oscillates (perhaps operationalizing theta/delta-oscillation frequency via coupling) reflects a top-down mechanism of information processing that could replicate the temporal resolution theory in the visual domain. The patterns presented suggest that when conflicting information is presented visually, or to each ear, top-down attentional processes governed by low-frequency bands may influence oscillations that improve perception. The results in Figure 3 also illustrate a pattern in which the attended side has faster alpha fluctuation relative to control (All congruent), however the unattended side has lower alpha power fluctuation relative to control. Thus, it

295 may be that top-down delta/theta modulation of auditory alpha power not only increases filtering (and
296 thus information input) to the attended side, but also decreases the irrelevant/unattended information.
297 Again, a similar mechanism exists in the visual stream, as it has been shown that when presented with
298 visuo-proprioceptive incongruency, beta power decreases in the occipital regions, suggesting
299 contextual gating of information (Limanowski et al., 2020).

300 One important note is that our results may therefore appear conflicting, since the alpha power fluctuation
301 changes were not present in the AV congruent condition, where it might be expected that on the side
302 of incongruent/unattended information, would be lower alpha power fluctuation speed reflecting reduced
303 auditory filtering or possibly an active suppression of irrelevant information. One interpretation is that
304 since one auditory stream is congruent in the AV congruent condition, integration of auditory and visual
305 information provides sufficient information and requires relatively less attention, and thus the top-down
306 attentional control is not as necessary as in conditions where both an auditory and visual stream of
307 information must be ignored (e.g., the AV incongruent condition). Reductions in comprehension
308 accuracy during the AV incongruent condition corroborate this theory, as it was shown that ignoring
309 congruent visual and auditory information requires more attentional control (Park et al., 2016b). Indeed,
310 the results of Figure 5 suggest that in instances where the attention required is minimal, alternative
311 mechanisms such as alpha power inhibition can act on their own to prevent unnecessary information
312 processing. It could even be suggested that (based on the hierarchy of difficulty from AV congruent to
313 AV incongruent condition), the individual and independent mechanisms of alpha power inhibition and
314 alpha power fluctuation are hierarchically recruited as attentional demand is increased, however this
315 hypothesis would require further investigation.

Conclusion

Our results provide evidence of a combined effect of left-lateralized speech perception, alpha-power (frequency) modulation, alpha power inhibition, and information filtering processes. While preliminary, the developed methodology and results suggest a novel correlate of complex auditory attention, and a potential mechanism from the visual domain for information processing in the auditory modality. Future work may investigate more specifically the possibility of delta/theta coupling with alpha power fluctuation, and the plausibility of this fluctuation as an information 'filter' which appears bilaterally independent and recruited on an attentional basis.

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