Auditory stimuli extend the temporal window of visual integration by modulating alpha-band oscillations

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Abstract

In multisensory environments, how inputs from different sensory modalities interact to shape perception is not fully understood. In this study, we investigated how auditory stimuli influence the temporal dynamics of visual processing using electroencephalography (EEG). We found that the presence of auditory stimuli led to poststimulus alpha frequency degradation, which positively correlated with the prolonged temporal window of visual integration. This was accompanied by a diminished predictive role of prestimulus alpha frequency while enhancing the predictive role of prestimulus alpha phase in shaping perceptual outcomes. To probe the underlying mechanisms, we developed a computational model that successfully replicated the core findings and revealed that auditory input extends the temporal window of visual integration by resetting alpha oscillations in the visual cortex, leading to alpha frequency reduction and an altered perception of visual events.

Keywords: Multisensory perception; fusion illusion; alpha oscillations; phase reset

Introduction

In our daily lives, we are constantly bombarded with information from various senses. Our brains face the challenge of organizing and integrating these signals into coherent perceptual experiences, and this becomes more complex due to the interactions between different sensory modalities (Cooke et al., 2019; Shams et al., 2002). Numerous studies consistently highlight the noteworthy influence of sound signals on visual perception, particularly in the temporal domain (Shipley, 1964; Walker & Scott, 1981).

Temporal windows, a fundamental attribute of the visual system, refer to time intervals during which discrete stimuli interact to influence perception (Samaha & Romei, 2023). A simple example is the fusion of two brief stimuli into a unified percept when they occur within a certain time range. The rhythmic patterns of alpha oscillations serve as a potential mechanism for defining this temporal window. Both the phase (Busch et al., 2009; Busch & VanRullen, 2010) and frequency (Han et al., 2023; Samaha & Postle, 2015; Shen et al., 2019) of alpha oscillations influence whether stimuli are perceived as distinct events or as a single, fused percept.

In audiovisual processing, the presentation of two visual flashes with an auditory stimulus leads to an increased likelihood of perceiving them as a single flash, inducing fusion illusions (Andersen et al., 2004). This suggests that cross-modal stimulation can influence the temporal window of visual perception. Evidence from both human and animal studies indicates that auditory stimuli affect early visual cortex activity through phase-resetting mechanisms, particularly within the alpha frequency range (Lakatos et al., 2007; Mercier et al., 2013).

Building upon these findings, one potential hypothesis is that cross-modal sound stimuli may influence the temporal window of visual integration by exerting an influence on alpha oscillations. To test this, we conducted an EEG experiment where participants performed a visual flash discrimination task. Then, we analyzed the frequency and phase of alpha oscillations to determine their role in cross-modal temporal integration.

Method

Thirty-four participants performed a two-alternative forced-choice task, reporting whether they perceived one or two flashes. The study included two conditions: F2, with two visual stimuli, and F2B1, where the first flash was consistently paired with an auditory beep (Figures 1A and B). A psychophysical pretest determined individual fusion thresholds, which were then used in bistable trials during the EEG experiment.

To assess whether single-trial perception is influenced by the frequency and phase of ongoing oscillatory activity, we analyzed EEG data by computing instantaneous alpha frequency (IAF) (Cohen, 2014) and phase opposition sum (POS) (VanRullen, 2016a) for bistable 1-flash and 2-flash trials in both conditions. Additionally, we developed a computational model based on perceptual cycle theory (VanRullen, 2016b) and the phase-resetting hypothesis to estimate the intricate interplay between frequency and phase in shaping visual perception while ensuring that pure phase resetting is not confounded with evoked phase locking (details see Xu et al., 2025).

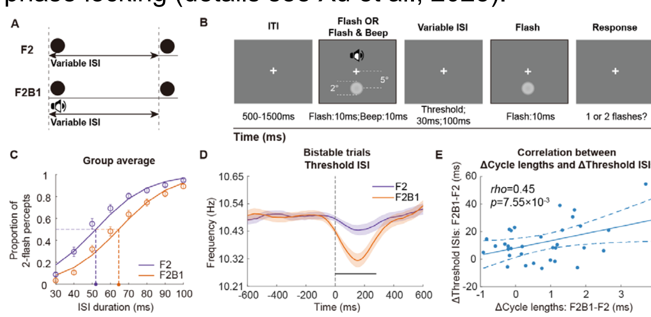

Figure 1. (A) Schematic illustration of the F2 and F2B1 conditions. (B) Illustration of one trial sequence. On each trial, the first visual stimulus presented below the fixation, either accompanied by an auditory beep or without it. After a variable ISI, the second visual stimulus was presented. Participants were required to report whether they perceived one or two flashes. (C) Psychometric curves showing the best fit of the average probability of perceiving two flashes as a function of ISIs in F2 and

F2B1. (D) The within-subject findings of the IAFs revealed that the post-stimulus alpha frequency of F2B1 decreased more than that of F2. (E) The relationship between the post-stimulus IAFs difference of F2B1 and F2 in the main EEG experiment and the threshold ISIs difference of F2B1 and F2 in the psychophysical pretest.

Results

Behavioral analysis showed a significantly longer fusion threshold in the F2B1 condition than in F2 (Figure 1C), indicating that auditory input extended the temporal integration window. At the neural level, F2B1 exhibited a significantly lower frequency than F2 after auditory stimulus presentation (p = 1.00×10^{-3}; Figure 1D). Consistent with our hypothesis, the reduction in alpha frequency significantly correlated with the increased fusion threshold in the F2B1 condition. (r = 0.45, p = 7.55 × 10^{-3}; Figure 1E), suggesting that a lower alpha frequency may underlie the extended temporal window.

To compare different frequency patterns in perception across conditions, we calculated the instantaneous alpha frequency (IAF) for different percepts. In the F2 condition, the IAF was significantly higher in 2-flash than 1-flash trials during both the prestimulus period (p = 0.02) and poststimulus period (p = 4.00×10^{-3}; Figure 2A). In contrast, no significant difference was found in the F2B1 condition (Figure 2B), suggesting distinct roles of prestimulus IAF in predicting perceptual outcomes in unimodal and cross-modal conditions. We also examined how prestimulus alpha phase influences perceptual outcomes using the phase opposition sum (POS). The results showed a significant prestimulus alpha phase difference between 1-flash and 2-flash trials in the F2B1 (p = 3.03×10^{-3}, cluster-based correction; Figure 2D), but not in the F2 (Figure 2C), indicating a prevailing phase modulation effect on perceptual outcomes during audiovisual processing.

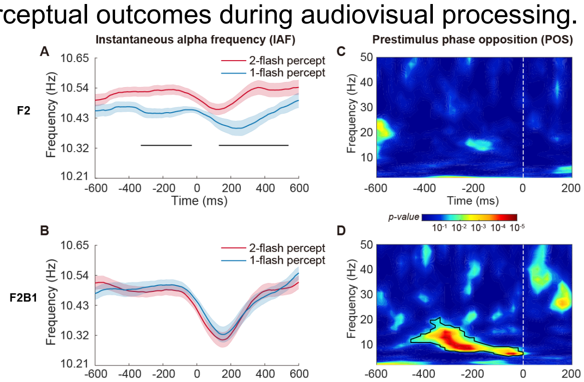

Figure 2. (A and B) IAFs over time for different perceptual outcomes in F2 and F2B1. (C and D) Time–frequency representation of p-values for prestimulus alpha phase differences between 1-flash and 2-flash trials, computed as the proportion of surrogate phase-opposition values exceeding the empirically observed values in the F2 and F2B1 conditions.

To explain these findings, we introduced a phase-resetting model for examining perceptual processing (Figure 3A). Based on the perceptual cycles framework (VanRullen, 2016b), both frequency and phase play fundamental roles in shaping perceptual outcomes. Frequency governs the temporal resolution of the visual system—higher frequencies favor the perception of two distinct flashes, while lower frequencies tend to amalgamate them into a single event (Figure 3B, *upper panel*). The oscillatory phase represents brain states fluctuating between high and low cortical excitability (Engel et al., 2001; Lakatos et al., 2007), influencing perceptual processing intensity (Figure 3B, *lower panel*). Our model differentiates percepts by assessing whether two flash stimuli fall within a single cycle, with the phase of the second flash determining perceptual clarity. Good phases near the peak enhance processing efficiency, resulting in clearer perceptions of 1-flash and 2-flash percepts. Conversely, bad phases near the trough lead to less efficient processing and increased perceptual ambiguity. The model successfully replicated key behavioral and neural findings, showing that phase resetting can disrupt the timing and synchronization of oscillations, potentially shifting their speed (details see Xu et al., 2025).

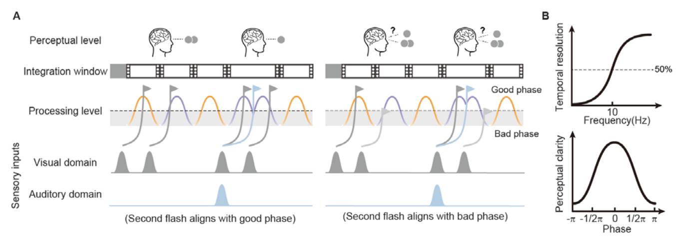

Figure 3. Hypothesized phase-resetting model of perceptual processing.

Discussion

Our study integrates behavioral, neurophysiological, and computational evidence to highlight the complex interplay between auditory and visual modalities in shaping temporal perception, specifically examining the impact on the temporal window of integration. The findings indicate that the introduction of auditory stimuli extends the temporal window of integration, with a notable influence on alpha oscillations. We propose that this effect is driven by auditory input-induced phase resetting in visual areas, which extends the duration of the alpha cycle. Consequently, this elongation strengthens the dominant predictive role of the alpha phase while simultaneously reducing the influence of alpha frequency in multisensory processing. In combination with previous studies investigating similar paradigms, our current findings lend further support to the perceptual cycle theory and offer a novel interpretation for the divergent outcomes observed in previous research on frequency and phase.

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