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Frequency- and Phase-Dependent Effects of Auditory Entrainment on Attentional Blink

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Abbreviations

AB: attentional blink
RSVP: rapid serial visual presentation
T1: first target
T2: second target
T2|T1: T2 given T1 correct
ANOVA: analysis of variance

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Abstract

Attentional blink (AB) is the impaired detection of a second target (T2) after a first target has been identified. In this paper, we investigated the functional roles of alpha and theta oscillations on AB by determining how much preceding rhythmic auditory stimulation affected the performance of AB. Healthy young adults participated in the experiment online. We found that when two targets were embedded in rapid serial visual presentation (RSVP) of distractors at 10 Hz (i.e., alpha frequency), the magnitude of AB increased with auditory stimuli. The increase was limited to the case when the frequency and phase of auditory stimuli matched the following RSVP stream. On the contrary, when only two targets were presented without a distractor, auditory stimuli at theta, not alpha, increased the AB magnitude. These results indicate that neural oscillations at two different frequencies, namely, alpha and theta, are involved in attentional blink.

Keywords

Attentional blink, Entrainment, Oscillations, Alpha, Theta

Introduction

Despite continuous changes in the visual world, the human brain has severe constraints in allocating attentional resources in time. Researchers have investigated this limitation in temporal attention using attentional blink (AB) tasks (Dux & Marois, 2009; Raymond et al., 1992). In a typical AB task, participants must identify two targets among distractors in a rapid serial visual presentation (RSVP) stream at the rate of 100 ms/item (corresponding to 10-Hz presentation frequency). Critically, the temporal lag between the first (T1) and the second (T2) targets was varied to assess the time course of attentional allocation. While participants had little difficulty reporting the T1, their ability to detect T2 was considerably impaired with T1 to T2 lag of about 300 ms.

Recent researchers have argued that this rhythmic stimulus presentation (i.e., RSVP) used in the AB paradigm entrains the ongoing alpha oscillation in the brain, which can result in deficits in detecting the second target on AB tasks (Hanslmayr et al., 2011; Jason & Kranczioch, 2011; Klimesch, 2012; Shapiro & Hanslmayr, 2014). For example, Martin et al. (2011) introduced an arrhythmic RSVP stream in an AB task by randomly changing the stimulus-onset asynchrony. They found that such arrhythmic streams reduced the AB magnitude relative to the canonical rhythmic presentation, concluding that preventing alpha entrainment was one of the key factors to attenuate the AB. Consistent with this, Shapiro et al. (2017) set the presentation frequency of RSVP stream to 6.26 Hz (theta), 10.3 Hz (alpha), 16.0 Hz (beta), or 36.0 Hz (gamma) and found that the AB magnitude was larger for alpha and beta than for the other frequencies. Zauner et al. (2012) recorded electroencephalogram (EEG) responses during the AB task and found significant alpha phase locking for AB trials but not for no-AB trials. Overall, alpha entrainment is a critical factor for the AB phenomenon.

Given the above findings that alpha entrainment can affect AB performance, it is reasonable to hypothesize that presenting sensory stimuli at the alpha band, which can entrain ongoing alpha oscillations, enhances the effects of AB. Ronconi et al. (2016), however, reported the opposite effects: 10-Hz auditory stimulation before the RSVP streams rather reduced the AB magnitude. They provided 2 s of auditory stimulation at 10 Hz before the RSVP streams and found that the T2|T1 accuracy (T2 accuracy given T1 was correct) at lag 3 under rhythmic condition was higher than it was when arrhythmic or no sounds were presented. One possible explanation of this discrepancy could be that such a short duration of auditory streams (2 s) is insufficient to entrain endogenous alpha rhythms given that the strength of the external stimulation is one of the factors for entraining neural populations (Thut et al., 2011). Therefore, the results of Ronconi et al. (2016) need to be reevaluated using a more intense stimulation.

This study aimed to investigate the relationships between alpha and theta oscillations and AB. We first reinvestigated how pre-RSVP auditory rhythmic stimulation modulates AB performance by modifying the paradigm of Ronconi et al. (2016). To enhance the effect of auditory entrainment, we extended the duration of stimulation from 2 to 5 s; we then examined the frequency- and phase-dependent effects of auditory entrainment on AB performance. Specifically, we manipulated the frequency of auditory stimulation (4 vs. 10 Hz) and the phase match between auditory and RSVP streams (in-phase vs. out-of-phase). We further investigated whether this alpha entrainment would have similar effects on a so-called skeletal or minimalist AB task (Duncan et al., 1994; McLaughlin et al., 2001) where only the two targets are presented in succession. According to alpha entrainment accounts of AB, frequency- and phase-matched auditory stimulation with RSVP streams produce the largest AB.

Experiment 1

With Experiment 1, we aimed to reinvestigate the effect of pre-RSVP auditory rhythmic stimuli on AB performance. The participants performed an AB task where two targets were embedded in RSVP streams (RSVP AB) immediately after the presentation of auditory stimulation either with a constant interstimulus interval (ISI; 10 Hz or rhythmic condition), with jittered ISI (arrhythmic condition), or with no sound (baseline condition). We compared the magnitudes of the AB effects among these three conditions. The experiment was conducted online.

Method

Participants

We attempted to double Ronconi et al.'s (2016) sample size of 23 to ensure robust statistical analysis. A total of 55 subjects were recruited *via* Sona Systems, a web-based recruitment system, for monetary compensation of 1,000 Japanese yen, approximately 10 US dollars. We could not acquire the data for two participants due to Internet difficulties, and we eliminated another two participants who used a monitor with a refresh rate of 50 Hz because the stimulus presentation durations had been optimized for refresh rates of 60 Hz. We also removed six participants because their performance on T2 detection was below the chance level. In total, we had available data on 45 participants for the statistical analyses. The participants were aged between 20 and 28 years (*M* = 22.3, *SD* = 1.77, 18 females); all but four were right-hand dominant, and all reported normal visual and auditory acuities. The study was approved by the local ethics committee of the National Institute of Information and Communications Technology.

Stimuli and apparatus

Stimuli were presented *via* Pavlovia.org based on PsychoPy (v2020.1; Peirce et al., 2019). After consent was explained on the initial screen of the survey, a blank screen was presented for 5 s during which the refresh rate of each participant's monitor was computed. We then calculated the logical pixel density (pixel/mm) of the participants' monitors using a card task and obtained their viewing distance with a blind spot task (Li et al., 2020). The blind spot task had three practice trials (repeated if needed), followed by five experimental trials, and we used these parameters to determine the visual angles of the stimuli.

The audio stimuli were generated and presented as .wav files by Praat (v 6.1.37; Boersma, 2001). The sounds were presented through headphones or earphones, which we asked the participants to wear. Prior to the task practices, we measured the participants' comfortable loudness levels by asking them to adjust their computers' volumes while they were presented 500-Hz sounds of 20-ms duration at an ISI of 1,000 ms.

All stimuli were presented on a black background. T1 and T2 were randomly selected from all letters of the alphabet, excluding I, M, O, Q, and W, without duplication. Numerals as distractors, excluding 0 and 1, were arranged with the restriction that the same numerals did not appear in succession in each trial. All stimuli were presented in white, except for T1, which was red, and Arial font was used for both targets and distractors (3.8° × 2.9°).

Design and procedure

We attempted to make the search and probe displays similar to Ronconi et al. (2016), as presented in Figure 1A. A white fixation cross (2° × 2°) was presented in the center of the screen for 5,000 ms, during which three possible auditory entrainment conditions were presented. In the rhythmic condition, 500-Hz sounds for 20 ms were presented 50 times at a constant ISI of 80 ms, resulting in a 10-Hz auditory stream, and the onset of the first sound was synchronized with the onset of the fixation cross. In the arrhythmic condition, 500-Hz sounds for 20 ms were presented 50 times at staggered ISIs that were randomly sampled from 10 to 130 ms in steps of 10 ms (the mean ISI was 80 ms). In the baseline condition, no auditory stimuli were presented.

After the entrainment period, the RSVP stream was presented, each of which contained 15 items (2 targets and 13 distractors). In the rhythmic condition, the onset of stimulus presentation was synchronized with the auditory stream presented immediately before it. Each visual item was presented for 100 ms with no ISI. Two target letters (T1 and T2) were presented for 67 ms, each of which was masked with a hash mark (#) for 33 ms. T1 appeared as either the fourth, fifth, or sixth item in the RSVP stream, whereas T2 was presented at lag 1, 3, or 8 relative to T1 with equal frequency. At the end of the RSVP stream, the participants were asked to report T1 and T2 by pressing a key. They were instructed to respond as accurately as possible with no time pressure, and they received feedback on whether they had pressed the correct keys for each target at the end of each trial for 800 ms. The ISIs were jittered (700, 800, or 900 ms).

The main experiment consisted of six blocks of 33 trials (198 trials in total). There were 180 T2-present trials (3 entrainment conditions × 3 lag × 20 repetitions) and 18 T2-absent catch trials. Trials were randomly intermixed. The experiment was preceded by 48 practice trials.

Statistical analysis

We calculated the T1 and T2 detection accuracies for each entrainment and lag condition. For the T2 detection accuracy, we included only T1-correct trials in the analyses because our research focuses on the T2 processing after the successful T1 identification. We conducted a repeated-measures analysis of variance (ANOVA) with factors of entrainment (rhythmic, arrhythmic, and baseline) × lag (lag 1, 3, and 8) for both the T1 and T2|T1 accuracies.

Results

For T1 accuracy (Figure 2A), there were significant main effects of entrainment and lag (F (2, 88) = 12.15, p < .001, η_p^2 = .22; F (2, 88) = 109.48, p < .001, η_p^2 = .71). In addition, we found significant interaction between entrainment and lag (F (4, 176) = 4.19, p = .029, η_p^2 = .09). We further found that in the lag 1 condition, the accuracy in the arrhythmic condition was significantly lower than that in the baseline condition (t (44) = 3.43, p = .004); we observed a marginal difference between the baseline and rhythmic conditions (t (44) = 2.00, p = .052). We also found a significantly higher accuracy in the rhythmic condition under lag 3 than under both the baseline and arrhythmic conditions (t

(44) = 3.90, *p* = .001; *t* (44) = 3.88, *p* = .001). Under lag 8, the accuracy was marginally significantly higher in the arrhythmic condition than in both the baseline and rhythmic conditions (*t* (44) = 2.46, *p* = .054; *t* (44) = 2.21, *p* = .054). We observed no difference between rhythmic and baseline conditions (*t* (44) = 0.16, *p* = .871).

Subsequently, we calculated the T2 accuracy given correct T1 (T2|T1) (Figure 2B). There were significant main effects of entrainment and lag (*F* (2, 88) = 13.08, *p* < .001, η_p^2 = .23; *F* (2, 88) = 166.99, *p* < .001, η_p^2 = .79). Importantly, we observed a significant interaction (*F* (4, 176) = 12.23, *p* < .001, η_p^2 = .22). Further analysis of the simple main effect revealed that in the lag 1 condition, the accuracy in the rhythmic condition was significantly higher than that in both baseline and arrhythmic conditions (*t* (44) = 4.41, *p* <. 001; *t* (44) = 4.97, *p* < .001). In the lag 3 condition, the baseline accuracy was significantly higher than that in both rhythmic and arrhythmic conditions (*t* (44) = 2.31, *p* =. 026; *t* (44) = 2.89, *p* = .018). In addition, no significant difference was observed in accuracy between the rhythmic and arrhythmic conditions (*t* (44) = 1.11, *p* = .273). In the lag 8 condition, the accuracy in the arrhythmic condition was lower than the baseline accuracy (*t* (44) = 4.78, *p* < .001), and the accuracy was still lower in the rhythmic condition (*t* (44) = 3.03, *p* = .004).

To examine the differences between the entrainment conditions, we computed the AB magnitude by subtracting the T2|T1 accuracy at lag 3 from that at lag 8 (Figure 3); this measure is frequently used to quantify the size of AB (e.g., Colzato et al., 2008). It should be noted that quantifying the AB using the lag 3 performance alone could have underestimated the AB (MacLean & Arnell, 2012). One-way ANOVA revealed significant differences in AB magnitude among conditions (*F* (2, 88) = 13.78, *p* < .001, η_p^2 = .24). Critically, *post hoc* comparisons showed significantly greater AB magnitude in the rhythmic condition than in the arrhythmic and baseline conditions (*t* (44) = 4.45, *p* < .001; *t* (44) = 4.33, *p* < .001). We observed no difference between the arrhythmic and baseline conditions (*t* (44) = 0.44, *p* = .664).

Discussion

The results of Experiment 1 indicated that presenting pre-RSVP 10-Hz auditory stimulation considerably increased AB magnitude; this is consistent with the findings of several previous studies that alpha entrainment increases the AB magnitude (e.g., Zauner et al., 2012). Our findings support the finding that entraining alpha oscillations by RSVP streams, which auditory stimulation can enhance, affects AB. Ronconi et al. (2016), in contrast, found that rhythmic auditory streams at 10 Hz cause *improvements* in AB. We believe that their shorter entrainment period of 2 s was not adequate for entraining endogenous alpha oscillations.

Experiment 2

With Experiment 2, we investigated whether impairment in T2 detection depends on the frequency and phase of auditory stimuli. By using sounds with different frequencies (4 vs. 10 Hz) and manipulating the phase relationship between auditory and RSVP streams (in-phase vs. out-of-phase), we assessed whether the increased AB magnitude that we observed in Experiment 1 was specific to the frequency- and phase-matched auditory stimulation. If the rhythmic sound itself influenced AB regardless of its frequency, the AB magnitude would be modulated even when at 4-Hz auditory stimulation. In addition, if the phase relationship between auditory and RSVP streams mattered, the AB magnitude would differ between in-phase and out-of-phase conditions. This experiment was also conducted online.

Method

Participants

A total of 55 different subjects were recruited *via* Sona Systems for monetary compensation of 1,000 Japanese yen, approximately 10 US dollars. We could not obtain the data for one participant due to Internet difficulties, and we removed another two participants who used a monitor with a refresh rate of 50 or 140 Hz because the stimulus presentation durations were optimized for a screen with a refresh rate of 60 Hz. We also removed eight participants because their performances on T2 detection were below the chance level. In total, we included 44 participants in the analyses who were aged between 20 and 31 years (*M* = 22.6, *SD* = 2.51, 21 females). All but four were right-hand dominant, and all reported normal visual and auditory acuities. The study was approved by the local ethics committee of the National Institute of Information and Communications Technology.

Stimuli and apparatus

The apparatus and the stimulus were the same as those in Experiment 1.

Design and procedure

The design and procedure were the same as those in Experiment 1, except that there were four auditory entrainment conditions. In the 10-Hz (in-phase) condition, 50 500-Hz sounds (20-ms duration) were presented at a constant ISI of 80 ms (the same as the rhythmic condition in Experiment 1). In the 10-Hz (out-of-phase) condition, auditory stimuli were presented as in the 10-Hz (in-phase) condition; however, immediately after the last 80-ms ISI, an additional 50-ms ISI was inserted. This half-cycle interval produced an antiphase relationship between auditory and RSVP streams. In the 4-Hz condition, 20 500-Hz sounds (20-ms duration) were presented at a constant ISI of 230 ms. In the baseline condition, no auditory stimuli were presented. The main experiment consisted of six blocks of 43 trials for a total of 258 trials (240 T2-present trials [4 entrainment conditions × 3 lag × 20 repetitions] and 18 T2-absent catch trials). Trials were randomly intermixed, and the experiment was preceded by 48 practice trials.

Statistical analysis

We calculated the T1 and T2 detection accuracies for each entrainment and lag condition. To calculate the T2 accuracy, we only included T1-correct trials in the analyses. We conducted repeated-measures ANOVA with factors of entrainment (10-Hz (in-phase), 10-Hz (out-of-phase), 4-Hz and baseline) × lag (lag 1, 3, and 8) for both the T1 and T2|T1 accuracies.

Results

For T1 accuracy (Figure 4A), there were significant main effects of entrainment and lag (*F* (3, 129) = 7.42, *p* < .001, η_p^2 = .15; *F* (2, 88) = 60.90, *p* < .001, η_p^2 = .59) as well as significant interaction between entrainment and lag (*F* (6, 258) = 6.59, *p* < .001, η_p^2 = .13). In a further analysis of the simple main effects, under lag 1, accuracy at 10-Hz out-of-phase was significantly higher than that in the other conditions (*p*s < .007). Moreover, we found that in the lag 3 condition, the accuracy at 10 Hz in-phase was significantly higher than that at 4 Hz (*t* (43) = 3.82, *p* = .003). We observed no significant simple main effect under lag 8 (*F* (3, 129) = 1.06, *p* = .371, η_p^2 = .02).

We then calculated the T2 accuracy given correct T1 (T2|T1) (Figure 4B), and there were significant main effects of entrainment and lag (*F* (3, 129) = 11.01, *p* < .001, η_p^2 = .20; *F* (2, 86) = 197.81, *p* < .001, η_p^2 = .82). Importantly, we observed the significant interaction (*F* (6, 258) = 13.09, *p* < .001, η_p^2 = .23). Further analysis of the simple main effect revealed that in the lag 1 condition, the accuracy in the 10-Hz (in-phase) condition was significantly higher than that in both the 4-Hz and baseline conditions (*t* (43) = 4.20, *p* <. 001; *t* (43) = 3.30, *p* = .006); the accuracy in the 10-Hz (out-of-phase) condition was also significantly higher than that in both the 4-Hz and baseline conditions (*t* (43) = 5.04, *p* <. 001; *t* (43) = 4.40, *p* < .001). In the lag 3 condition, the accuracy in the 10-Hz (in-phase) condition was significantly lower than that in the baseline condition (*t* (43) = 2.56, *p* =. 043), and the accuracy in the 10-Hz (out-of-phase) condition was significantly lower than that in both the 4-Hz and baseline conditions (*t* (43) = 3.14, *p* =. 009; *t* (43) = 4.15, *p* < .001). In the lag 8 condition, the accuracy in the 10-Hz (in-phase) condition was higher than that in the other three conditions (*p*s < .021), and the baseline accuracy was higher than that in the 10-Hz (out-of-phase) condition (*t* (43) = 3.56, *p* =. 003).

To examine the differences in the AB performance between entrainment conditions, we further computed the AB magnitude by subtracting the T2|T1 accuracy on lag 3 from the T2|T1 accuracy at lag 8 for each entrainment condition (Figure 5). One-way ANOVA revealed significant differences in AB magnitude among conditions (*F* (3, 129) = 8.71, *p* < .001, η_p^2 = .17). Critically, *post hoc* comparisons revealed that the magnitude of the AB in the 10-Hz (in-phase) condition was significantly larger than that in the other three conditions (*p*s < .001). No difference among the 10-Hz (out-of-phase), 4-Hz, and baseline conditions was observed (*p*s > .705).

Discussion

In Experiment 2, we replicated the findings in Experiment 1 that rhythmic auditory stimulation at 10 Hz increased AB magnitude. Furthermore, we did not observe enhanced AB magnitude under 4 Hz, indicating that the rhythmic sound itself had little effect on AB performance. Critically, 10-Hz sounds with phase mismatch produced no change in AB magnitude from the baseline condition, suggesting that both the phase and frequency are key to enhance AB magnitude.

Experiment 3

We next assessed whether the observed 10-Hz auditory entrainment effect depended on the task settings. Experiment 3 presented auditory stimulation (4 vs. 10 Hz) before the skeletal AB task where only two targets appeared (Duncan et al., 1994; McLaughlin et al., 2001). If the alpha sound itself influenced AB regardless of the task settings, the AB magnitude would be modulated under 10-Hz auditory stimulation even under the skeletal AB task. The experiment was conducted online.

Method

Participants

A total of 47 subjects were recruited *via* Sona Systems for monetary compensation of 1,000 Japanese yen, approximately 10 US dollars. We set this sample size to be similar to those in Experiments 1 and 2 given the research budget at hand; for Experiment 3, 11 of the subjects had participated in Experiment 1, and 4 had participated in Experiment 2. We removed three participants because their T2 detection performance was below the chance level to ultimately include 44 participants in the analyses. The Experiment 3 participants were aged between 20 and 31 years (*M* = 22.5, *SD* = 2.15, 23 females); all but five were right-hand dominant, and all reported normal visual and auditory acuities. The study was approved by the local ethics committee of the National Institute of Information and Communications Technology.

Stimuli and apparatus

The apparatus and the stimuli were the same as those in Experiments 1 and 2.

Design and procedure

Figure 1B illustrates a trial sequence. The design and procedure were the same as those in Experiment 1, except that we presented no distractor: Only two target letters (T1 and T2) were presented in succession for 50 ms, each of which were masked with a # for 50 ms. T2 was presented 100, 300, or 800 ms after T1 with equal frequency.

There were three entrainment conditions: 10-Hz, 4-Hz, and baseline conditions. The main experiment consisted of six blocks of 30 trials (180 trials in total: 3 entrainment conditions × 3 lag × 20 repetitions). Trials were randomly intermixed. The experiment was preceded by 48 practice trials.

Statistical analysis

We calculated the T1 and T2 detection accuracies for each entrainment and lag condition. To calculate the T2 detection accuracy, we only included T1-correct trials in the analyses. We conducted repeated-measures ANOVA with factors of entrainment (10 Hz, 4 Hz and baseline) × lag (lag 1, 3, and 8) for both the T1 and T2|T1 accuracies.

Results

For T1 accuracy (Figure 6A), there were significant main effects of entrainment and lag (F (2, 86) = 12.85, p < .001, η_p^2 = .23; F (2, 86) = 77.60, p < .001, η_p^2 = .64) as well as significant interaction between entrainment and lag (F (4, 172) = 7.70, p < .001, η_p^2 = .15). Further analysis of the simple main effects revealed that under lag 1, the accuracy was significantly higher at 10 Hz than under the other conditions (*p*s < .009). Moreover, we found that under lag 3, the accuracy was significantly higher in the 4-Hz condition than in the other conditions (*p*s < .001). In the lag 8 condition, we observed no significant simple main effect (F (2, 86) = 1.50, p = .229, η_p^2 = .03).

Subsequently, we calculated the T2 accuracy given correct T1 (T2|T1) (Figure 6B). There were significant main effects of entrainment and lag (F (2, 86) = 25.94, p < .001, η_p^2 = .37; F (2, 86) = 47.93, p < .001, η_p^2 = .53), and importantly, we observed a significant interaction (F (4, 172) = 4.13, p = .003, η_p^2 = .09). Further analysis of the simple main effect revealed significantly higher accuracy in the 10-Hz condition than in both the baseline and 4-Hz conditions under lag 1 (t (43) = 3.77, p <. 001; t (43) = 3.40, p < .001) and lag 8 (t (43) = 7.89, p <. 001; t (43) = 6.81, p < .001). In the lag 3 condition, the accuracy under 4 Hz was lower than that at the baseline condition (t (43) = 4.36, p < .001), followed by that under 10 Hz (t (43) = 2.55, p = .014). We found no U-shaped pattern of accuracy over lag for skeletal AB, which is consistent with the results of McLaughlin et al. (2001) using similar stimuli. This is possibly because lag 1 sparing, or better detection of T2 immediately after T1, is an epiphenomenon of the failure to adequately mask T1 (Martin & Shapiro, 2008).

To examine differences in AB performance between the entrainment conditions, we further computed the AB magnitude by subtracting the T2|T1 accuracy at lag 3 from the T2|T1 accuracy at lag 8 for each entrainment condition (Figure 7). One-way ANOVA revealed significant differences in the AB magnitude among conditions (F (2, 86) = 9.84, p < .001, η_p^2 = .19). Critically, *post hoc* comparisons showed that the AB magnitude under 4 Hz was significantly larger than that under the baseline and 10-Hz conditions (t (43) = 4.13, p < .001; t (43) = 3.99, p < .001). We observed no difference between 4-Hz and baseline conditions (t (43) = 0.55, p = .585).

Discussion

In contrast to Experiments 1 and 2, the rhythmic auditory stimulation at 10 Hz did not affect the AB magnitude in the skeletal AB task; rather, the auditory stimulation at 4 Hz increased the AB magnitude, suggesting that enhanced AB magnitude due to alpha entrainment is limited to the classic AB task where two targets are embedded in the RSVP streams.

General Discussion

The goal of the present study was to investigate how alpha and theta auditory stimulations affect AB performance. Experiment 1 showed that in an RSVP AB task, rhythmic auditory streams at 10 Hz enhanced AB magnitude compared with the baseline condition without sound or arrhythmic sound condition. Experiment 2 replicated and extended the finding of Experiment 1 in that the enhanced AB magnitude was limited to when auditory stimuli were frequency- and phase-matched with the RSVP streams. Experiment 3 further provided the boundary conditions of alpha entrainment of AB, showing that the 10-Hz auditory stimulation did not modulate the AB magnitude in the skeletal AB task. These results indicate that alpha oscillation entrainment by RSVP streams was strengthened with phase-matched pre-RSVP auditory stimulation, which enhanced the AB magnitude. These findings are consistent with previous findings that the failure to detect T2 was associated with alpha oscillations (Martin et al., 2011; Shapiro et al., 2017; Zauner et al., 2012). Together, our results strongly support the recent finding that the AB is mediated by alpha oscillations (Hanslmayr et al., 2011; Klimesch, 2012; Shapiro & Hanslmayr, 2014).

Auditory entrainment at 10 Hz increased AB magnitude

Researchers have proposed that AB occurs because of capacity limitations in consolidating T1 perceptual representations, by which the processing of the subsequent T2 at lag 3 is impaired (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998). We here argue that alpha entrainment makes T1 consolidation inefficient, thereby increasing the likelihood that T2 will be missed. Because one of the roles of alpha oscillations is to suppress visual processing (Clayton et al., 2018; Mazaheri & Jensen, 2010), ongoing alpha oscillations entrained by auditory stimulation at 10 Hz could have inhibited visual processing. Consistent with this view, higher pre-stimulus alpha power led to longer P3 latency, suggesting that the inhibitory neural state suppresses post-stimulus memory processing (Min & Herrmann, 2007), and the pre-T1 alpha-band power was larger in AB trials than in no-AB trials (Kranczioch et al., 2007). Thus, we assumed that inefficient T1 processing driven by the inhibition caused by alpha entrainment delayed allocation of attention to T2, which extended AB. For phase-mismatched 10 Hz auditory stimulation condition, we suggest that the entrained alpha oscillation would be canceled out during the RSVP flow. Further experiments measuring oscillations and T1 evoked neural responses will be required to ground this account.

Although our results are in agreement with the recent claim that entrained alpha oscillations increase AB magnitude, Ronconi et al. (2016) reported the opposite effect of auditory entrainment on AB; those authors demonstrated that the 10-Hz auditory stimulation reduced AB magnitude. One possible explanation of the discrepancy is that alpha entrainment was stronger in our study than in Ronconi et al.'s because we extended the entrainment period from 2 to 5 s, thereby increasing the number of pulses for neural entrainment (Thut et al., 2011). To test this hypothesis, we conducted an additional experiment in which we manipulated the duration of 10-Hz auditory stimulation (2 s vs. 5 s) in the RSVP AB task (see Supplemental methods and Figure S1). As shown in Figure S2, we observed larger AB at 5 s than at 2 s, and these results are fully consistent with our idea that the duration of auditory stimulation is a key factor in its effects on AB. Therefore, auditory streams of short durations might be insufficient to entrain endogenous alpha rhythms (Thut et al., 2011). Although this is speculative, it is plausible that the shorter auditory streams used in the previous study could have disturbed the participants' attention, which could have reduced the AB effect (Olivers & Nieuwenhuis, 2005). Unlike Ronconi et al. (2016), however, we found no difference in the AB magnitude between 2-s and baseline conditions, which might be due to differences in experimental setting (offline vs. online experiment).

Increased pre-stimulus alpha power has been associated with enhanced AB effects in some studies (Kranczioch et al., 2007; Keil & Heim, 2009) but with decreased effects in others (Janson et al., 2014; MacLean & Arnell, 2011; Petro & Keil, 2015; Yuan et al., 2021). Here, the idea of attentional state and its effect on the AB magnitude would resolve this observed disagreement. MacLean and Arnell (2011) interpreted increased pre-stimulus alpha power resulting in AB reduction as indicating anticipatory attentional overinvestment: less attentional investment prior to the AB task, as indexed by alpha power increase, may be associated with smaller AB magnitude. This idea is consistent with the finding of AB reduction with concurrent mental activities (Olivers & Nieuwenhuis, 2005). Unlike these studies, our modulation of alpha power by auditory stimulation will not change attentional state: the entrainments were presented on a trial-by-trial basis, which canceled out attentional fluctuations over experiments. Increased alpha power associated with enhanced AB effects (Kranczioch et al., 2007; Keil & Heim, 2009) might also reflect mechanisms other than attentional state. In any case, cognitive factors such as attentional investment should be considered to clarify the effects of alpha power on AB.

Although we found effects of auditory stimulation on AB, they were smaller than the effects of lag in the RSVP stream; this could have been because participants paid less attention to the auditory streams than to the RSVP stimulus. Lakatos et al. (2008) presented monkeys with both visual and auditory streams that were out of phase and found that the phase of ongoing delta oscillations in visual areas synchronized with the attended stream; thus, task-related visual streams had larger impacts on neural activities than did task-unrelated auditory streams. Based on this assumption, it can be hypothesized that the larger effect of 10-Hz entrainment on AB could be observed by simply prolonging the visual streams that precede the target presentation. Although Ronconi et al. (2016) found that visual entrainment prior to RSVP streams had no modulatory effect on AB performance, the lack of effect could have been because of the short duration of entrainment on the visual stimuli, as we discussed for auditory stimuli. Future researchers can explore whether the entrainment effects on AB are specific to auditory entrainment by controlling attention levels.

Effects of auditory entrainment at 10 Hz on T2|T1 accuracy lags 1 and 8

We found that 10-Hz auditory entrainment decreased accuracy at lag 3 but increased accuracy at lag 1 (as in Shapiro et al., 2017), even though the two lags correspond to the same phase of the auditory alpha stimulation. This is likely because T2 detection at lag 1 and T2 detection at lag 3 are considered to be based on different mechanisms (Livesey & Harris, 2011). As discussed earlier, typical AB occurs for T2 at lag 3 because attentional resources are dedicated to T1 processing. In contrast, the easy detection of T2 at lag 1, known as lag-1 sparing (Raymond et al., 1992), occurs because the first and second targets tend to fall within the same attentional window (Jefferies & Di Lollo, 2009; Jefferies et al., 2019). The better performance of T2|T1 accuracy at lag 1 by 10-Hz auditory entrainment suggests that increased alpha power might make it easier to process T1 and T2 within a single attentional window. However, although this is interesting, we avoid a further consideration thereof because, as Shapiro et al. (2017) noted, scholars have attributed differences in lag-1 sparing between conditions to a wide range of causes (e.g., Visser et al., 1999). Further experiments are required to elucidate the mechanisms that underlie enhanced lag-1 sparing.

Unexpectedly, we observed that 10-Hz auditory stimulation increased T2|T1 accuracy at lag 8; the data, although speculative, should provide some hints about auditory entrainment effects in AB. Although our focus was AB magnitude (amplitude of AB effects), blink recovery (width of AB effects), which represents how long T1 processing impairs T2|T1 accuracy, is another aspect of AB (Cousineau et al., 2006). Research has shown that successfully suppressing distractors correlated with faster AB recovery (Slagter & Georpgopoulou, 2013). We speculate that the inhibitory state driven by alpha entrainment leads to more efficient suppression that speeds up AB recovery over baseline; this faster AB recovery would lead to the improved T2|T1 accuracy at lag 8. Future work is necessary using longer lags (>1,000 ms) as a baseline condition to investigate the more precise time course of effects of auditory stimulation. Notably, we also found weak albeit significant differences in T1 accuracy among entrainment conditions, which could have originated from T1-T2 trade-offs; namely, T1 and T2 representation could compete for attentional resources (e.g., Potter et al, 2002): in other words, the more the resources allocated to T1 are, the fewer the resources available for T2 are and vice versa.

Effects of auditory entrainment at 10 Hz on T1 detection

If entrained alpha inhibited visual processing in general, T1 detection should have deteriorated as well; however, we did not observe the same in our experiments. T1 was less susceptible to 10-Hz auditory entrainment for several reasons. First, T1 was relatively easy to detect because T1 has higher saliency than T2 and distractors (different color: Experiments 1 and 2). In fact, phase of ongoing EEG oscillations has been reported to influence the detection of a near-threshold visual stimulus (Busch et al., 2009; Mathewson et al., 2009, 2010; van Dijk et al., 2008). Second, the timing of the T1 presentation was predictable to some extent because T1 always appeared as the 4th–6th item in RSVP. This sort of predictable temporal sequence will induce long-range synchronization of beta band across cortical areas (Gross et al., 2004), which research has shown serves to prepare for temporal events (Meijer et al., 2016). For these reasons, there was little difference in the T1 accuracy among the entrainment conditions.

Another interesting finding is that the T1 detection accuracy was lower in the in-phase than in the antiphase condition, especially at lag 1 (Figure 4A). Spaak et al. (2014) compared the detection accuracy of a near-threshold target after 10 Hz of visual entrainment between the in-phase and antiphase delays and found lower accuracy in the in-phase than in the out-of-phase. Similarly, Mathewson et al. (2009) recorded EEG during a detection task and found an antiphase relationship of alpha oscillations between detected and undetected trials. Our findings agree well with these findings of phase-dependent visual sensitivity.

Double dissociation between auditory frequency and attentional blink task types

Here, we employed not only the conventional RSVP AB task but also the skeletal AB task that presents only two targets without distractors. Although performance on the two tasks is known to be correlated (.66; McLaughlin et al., 2001), we found clear double dissociation between the two tasks; namely, the AB magnitude for RSVP AB task was increased by auditory stimulation of 10 Hz but not 4 Hz, whereas the AB magnitude in the skeletal AB task was increased by 4 Hz but not by 10 Hz. This double dissociation between the auditory stream frequency and AB type suggests the influence of two distinct neurocognitive mechanisms in visual processing: spontaneous occipital alpha rhythm for determining visual sensitivity and frontoparietal theta in multi-item attention (Fiebelkorn & Kastner, 2019; VanRullen, 2016). We speculate that these two neural oscillatory mechanisms underlie AB as well.

Functional differences in alpha and theta oscillations in cognitive control can explain the observed double dissociation between auditory stimulation frequency and AB type. Gratton (2018) hypothesized that alpha oscillations are associated with maintaining active representations to protect them from interference whereas theta oscillations are associated with updating representation for shifting attention to incoming stimuli. For the RSVP AB task (Experiments 1 and 2), T1 representations should be protected from distractors, which might make alpha oscillations more dominant, leading to greater effect on AB performance. In contrast, for the skeletal AB task (Experiment 3), where no distractor was presented, neural representations must be switched after the exploration of T1, which might make theta oscillations more dominant and have greater effect on AB. Given these proposals, we argue that two different frequencies modulated the two different AB task types.

Limitations and future directions

Although neural entrainment can adequately explain our results, it is still not clear whether auditory streams truly entrain endogenous alpha oscillations. Empirical studies have shown that auditory input can reset activities in the visual cortex in a cross-sensory fashion and modulate visual performance (Fiebelkorn et al., 2011, 2013). Researchers have further shown auditory stimuli resetting the alpha rhythms in the visual cortex and modulating visual perception (Romei et al., 2012; Sauseng, 2012), indicating some cross-modal neural entrainment (Bauer et al., 2020). Bauer et al. (2021) also demonstrated that auditory stimulation at 3 Hz was indeed accompanied by rhythmic modulation of neural activity over visual areas. Future researchers should measure neural activity during and after the auditory stimulation at the alpha frequency that we used here.

Researchers have shown that AB occurs with RSVP streams at multiple frequencies such as alpha, beta, and theta (Shapiro et al., 2017). Whether AB induced by non-alpha-band RSVP streams is modulated by rhythmic stimulation at the alpha or the RSVP-congruent frequency is an interesting issue. We speculate that alpha entrainment will not modulate AB at other RSVP frequencies (e.g., beta) because the effect of auditory stimuli at alpha is phase specific (Experiment 2) and stimulus-sequence specific (i.e., lack of effect for skeletal AB, Experiment 3). However, this is merely speculation, and it would be valuable to test whether the AB induced by, for example, beta-band RSVP streams would be modulated by alpha-band or beta-band auditory stimulation.

Conclusion

In conclusion, AB magnitude was increased when phase-matched 10-Hz auditory stimuli were applied in an RSVP AB task. Entraining endogenous alpha oscillations by 10-Hz sound drives inhibitory state, resulting in deteriorated T2|T1 accuracy in the most attention-demanding condition (i.e., lag 3). It also speeds up AB recovery, rather improving T2|T1 accuracy at lag 8. Furthermore, when only two targets were presented without a distractor, AB magnitude was increased by auditory stimuli at 4 Hz, not 10 Hz. Our findings demonstrate that two different brain oscillations, theta and alpha, underlie AB processes depending on the existence of distractors.

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Author Contributions

T.K. developed the study concept. All authors contributed to the study design. T.K. performed experiments and analyzed data, and K.A., S.S., and T.K. designed experiments, defined and validated data analysis methods, and wrote the paper. All authors approved the final version of the manuscript for submission.

Data Availability Statement

None of the experiments reported in this article was formally preregistered. All raw data are included in the Supplemental Online Material associated with this article at [URL].

Conflict of Interest Statement

We report no potential conflicts of interest.

Figure Legends

Figure 1. Schematic illustration of the experimental trials. (A) Dual-target RSVP attentional blink (AB) task used in Experiments 1 and 2. The participants had to report the two target letters (T1 in red and T2 in white) in rapid serial visual presentation streams of distractor numbers presented in white (100 ms/item, corresponding to 10 Hz). (B) Skeletal AB task used in Experiment 3; only two targets appeared, and both were masked. Prior to the presentation of each AB task, auditory streams of 5,000 ms were presented to the participants (see the Methods section for detail).

Figure 2. Mean accuracy for the (A) first target (T1) and (B) second target (T2|T1) in Experiment 1. Error bars represent standard errors.

Figure 3. Mean attentional blink (AB) magnitude in Experiment 1. The AB magnitude is defined as the second target (T2) accuracy at lag 8 minus T2 accuracy at lag 3, conditional on correctly reporting the first target (T1). Each dot represents the mean AB magnitude per participant.

Figure 4. Mean accuracy for the (A) first target (T1) and (B) second target (T2|T1) in Experiment 2. Error bars represent standard errors.

Figure 5. Mean attentional blink (AB) magnitude in Experiment 2. AB magnitude is defined as the second target (T2) accuracy at lag 8 minus T2 accuracy at lag 3, conditional on correctly reporting the first target (T1). Each dot represents the mean AB magnitude per participant.

Figure 6. Mean accuracy rates for the (A) first target (T1) and (B) second target (T2|T1) in Experiment 3. Error bars represent standard errors.

Figure 7. Mean attentional blink (AB) magnitude in Experiment 3. AB magnitude is defined as second target (T2) accuracy at lag 8 minus T2 accuracy at lag 3, conditional on correctly reporting the first target (T1). Each dot represents the mean AB magnitude per participant.

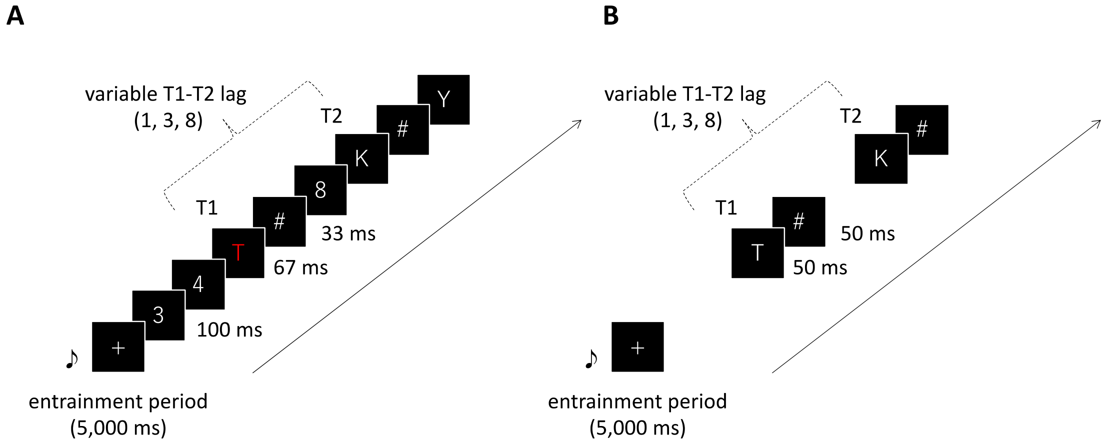
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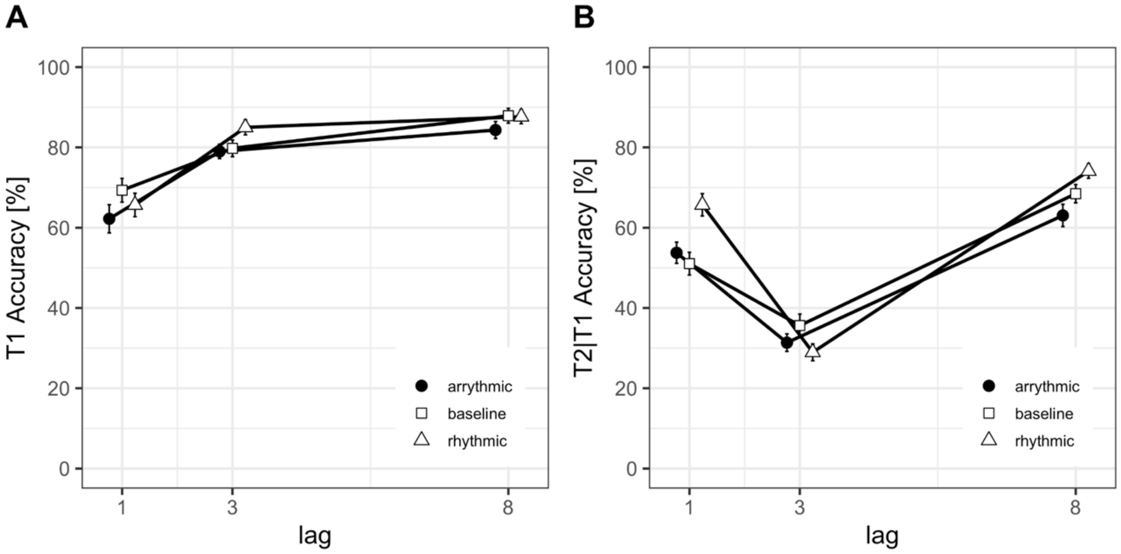
Figure 1.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T1 Accuracy [%]
T2|T1 Accuracy [%]
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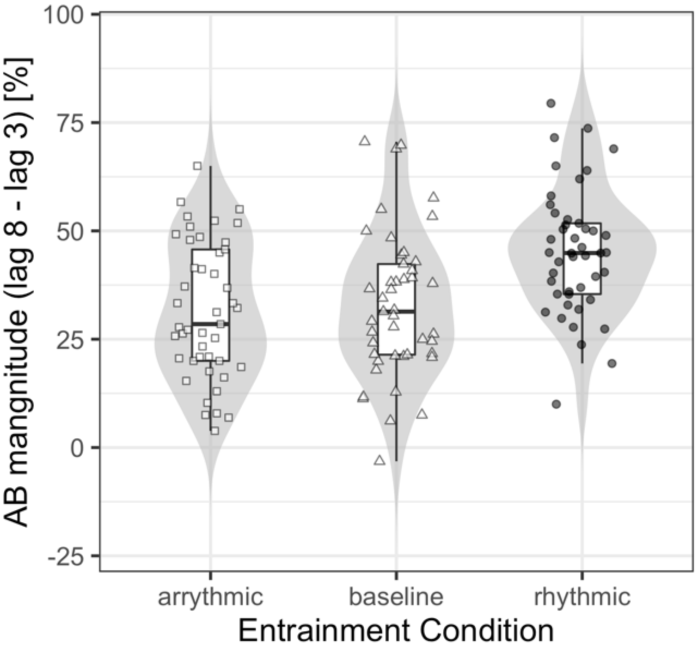
Figure 2.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rhythmic
Entrainment Condition

Figure 3.

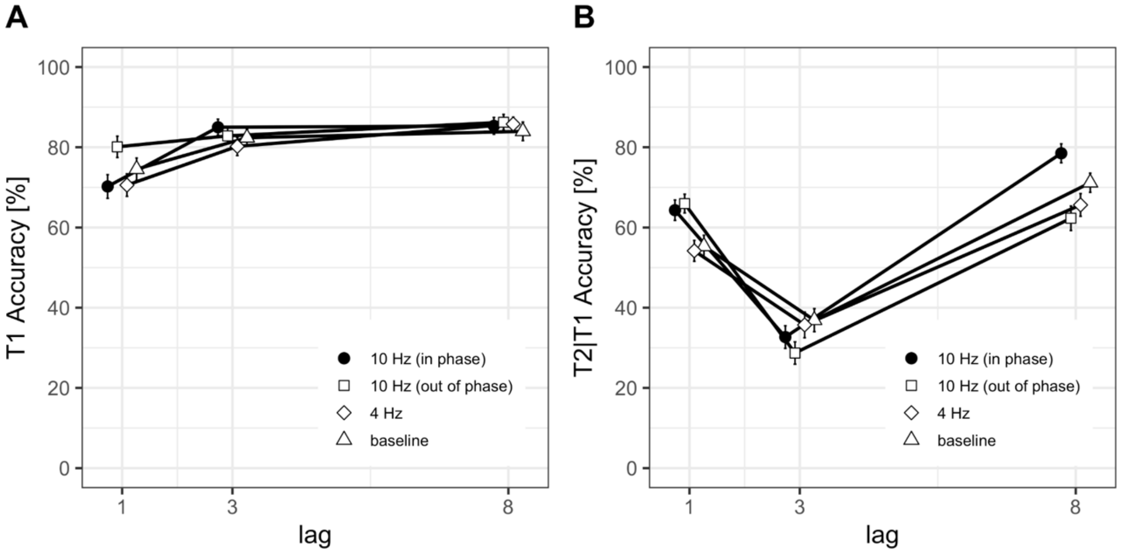

A
B
T1 Accuracy [%]
T2|T1 Accuracy [%]
0
20
40
60
80
100
1
3
8
lag
● 10 Hz (in phase)
□ 10 Hz (out of phase)
◇ 4 Hz
△ baseline

Figure 4.

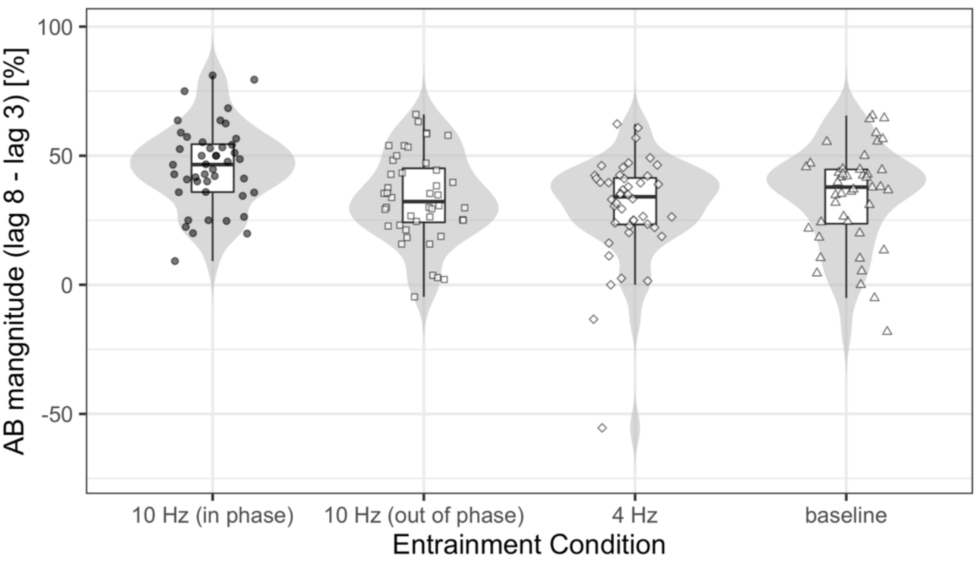


Figure 5.

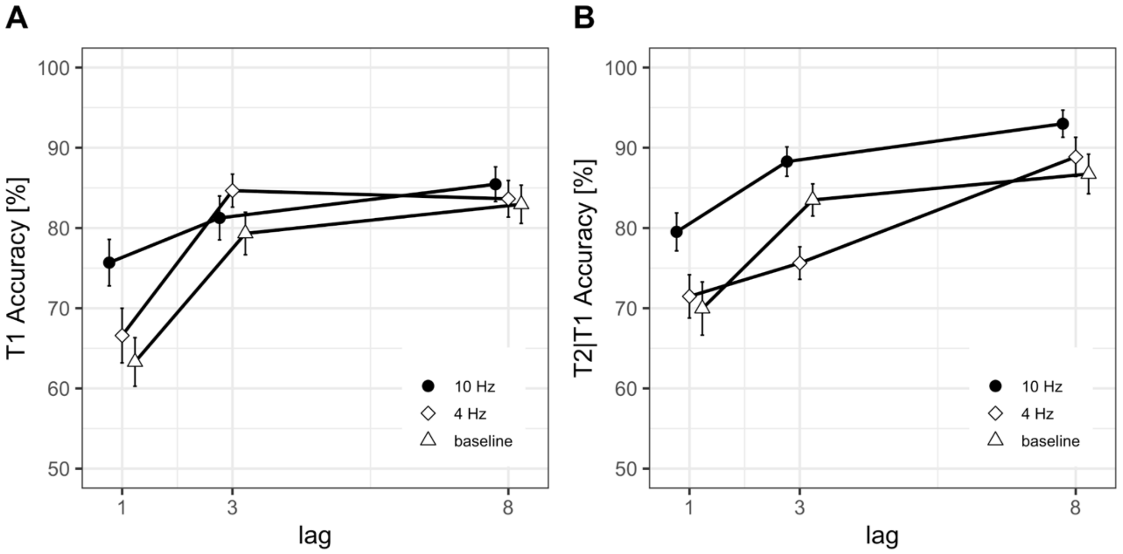


Figure 6.

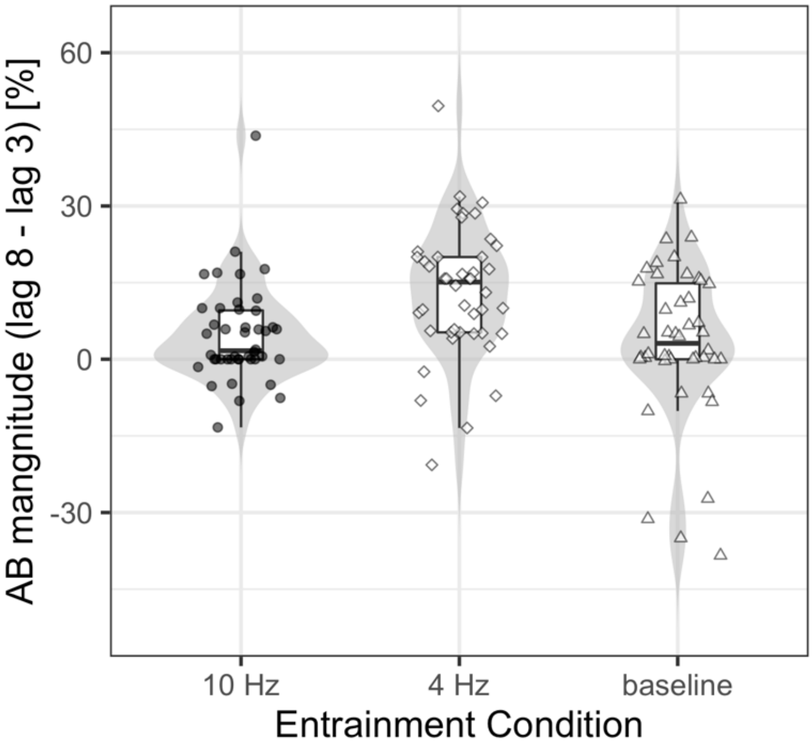

AB mangnitude (lag 8 - lag 3) [%]
60
30
0
-30
10 Hz
4 Hz
baseline
Entrainment Condition

Figure 7.

Supplementary material

Supplementary Methods

Additional experiment

Participants

A total of 56 subjects were recruited via Sona Systems for monetary compensation of 1,000 Japanese yen, approximately 10 US dollars. Of the subjects, 11 had participated in Experiment 1, 3 had participated in Experiment 2, and 18 had participated in Experiment 3. We removed two participants who used a monitor with a refresh rate of 75 Hz and 100 Hz because the stimulus presentation durations had been optimized for refresh rates of 60 Hz. We also removed three participants because their performance on T2 detection was below the chance level. In total, we had available data on 51 participants for the statistical analyses. The participants were aged between 20 and 29 years (*M* = 23.0, *SD* = 2.13, 28 females); all but one was right-hand dominant, and all reported normal visual and auditory acuities. The study was approved by the local ethics committee of the National Institute of Information and Communications Technology.

Stimuli and apparatus

The apparatus and the stimulus were the same as those in Experiment 1.

Design and procedure

The design and procedure were the same as those in Experiment 1 except that the duration of auditory stimulation was manipulated (2 s vs. 5 s) and the entrainment conditions were blocked. In the 2-s condition, 20 500-Hz sounds (20-ms duration) were presented at an interstimulus interval (ISI) of 80 ms. In the 5-s condition, 50 500-Hz sounds (20-ms duration) were presented at an ISI of 80 ms (the same as the rhythmic condition in Experiment 1 and the 10-Hz (in-phase) condition in Experiment 2). In the baseline condition, no auditory stimuli were presented. Half of the baseline trials were 2 s, and half were 5 s. Both 2-s and 5-s trials were blocked (90 T2-present trials and 9 T2-absent catch trials/block, total = 198 trials), and their order was counterbalanced across participants. The experiment was preceded by 48 practice trials where 2-s and 5-s trials were randomly intermixed.

Statistical analysis

We calculated the T1 and T2 detection accuracies for each entrainment and lag condition. To calculate the T2 detection accuracy, we only included T1-correct trials in the analyses. We conducted repeated-measures analysis of variance with factors of entrainment (10-Hz (2 s), 10-Hz (5 s), and baseline) × lag (lag 1, 3, and 8) for both the T1 and T2|T1 accuracies.

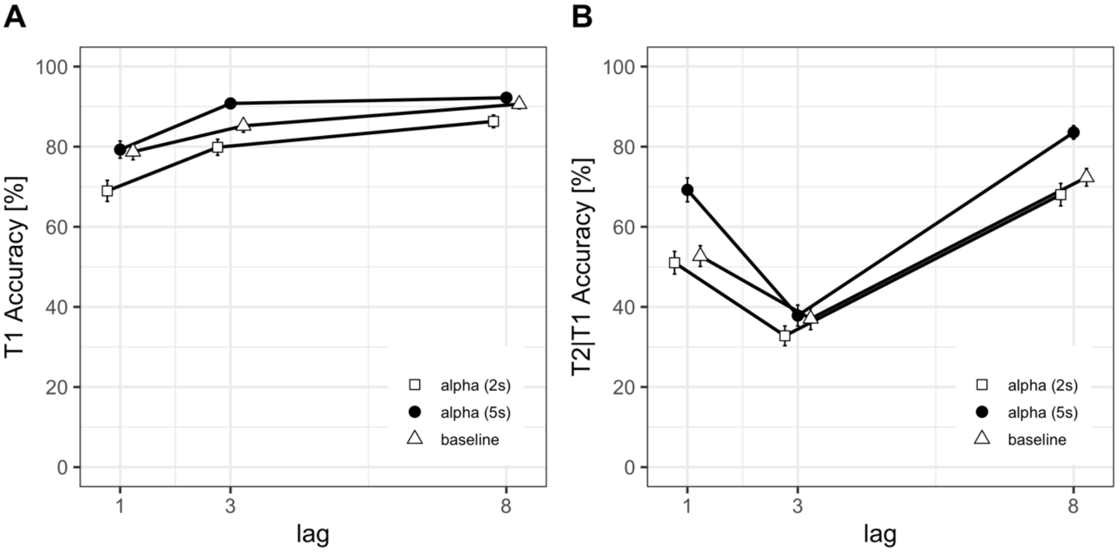


Figure S1. Mean accuracy for the (A) first target (T1) and (B) second target (T2|T1) in the additional experiment. Error bars represent standard errors. For T1 accuracy (Figure S1a), there were significant main effects of entrainment and lag (*F* (2, 100) = 31.16, *p* < .001, η_p^2 = .38; *F* (2, 100) = 63.46, *p* < .001, η_p^2 = .56) as well as significant interaction between entrainment and lag (*F* (4, 200) = 3.85, *p* = .005, η_p^2 = .07). In a further analysis of the simple main effects, under lag 1, the accuracy in the 5-s condition was significantly higher than that in the 2-s condition (*t* (50) = 4.76, *p* <. 001); the accuracy in the baseline condition was also significantly higher than that in 2-s condition (*t* (50) = 4.79, *p* < .001). We further found that in the lag 3 condition, the accuracy in the 5-s condition was significantly higher than that in both the 2-s and baseline conditions (*t* (50) = 5.72, *p* <. 001; *t* (50) = 3.64, *p* = .006); the accuracy in the baseline condition was also significantly higher than that in the 2-s condition (*t* (50) = 3.44, *p* =. 001). We then calculated the T2 accuracy given correct T1 (T2|T1) (Figure S1B); there were significant main effects of entrainment and lag (*F* (2, 100) = 31.86, *p* < .001, η_p^2 = .39; *F* (2, 100) = 140.30, *p* < .001, η_p^2 = .74). Importantly, we observed a significant interaction (*F* (4, 200) = 8.62, *p* < .001, η_p^2 = .15). Further analysis of the simple main effect revealed that in the lag 1 condition, the accuracy in the 5-s condition was significantly higher than that in both the 2-s and baseline conditions (*t* (50) = 6.35, *p* <. 001; *t* (50) = 7.09, *p* < .001). In the lag 8 condition, the accuracy in the 5-s condition was significantly higher than that in both the 2-s and the baseline conditions (*t* (50) = 7.02, *p* <. 001; *t* (50) = 6.44, *p* <. 001), and the accuracy in the 2-s condition was significantly lower than that in the baseline condition (*t* (50) = 2.30, *p* =. 025). We observed no simple main effect off entrainment condition at lag 3 (*F* (2, 100) = 2.13, *p* = .125, η_p^2 = .04).

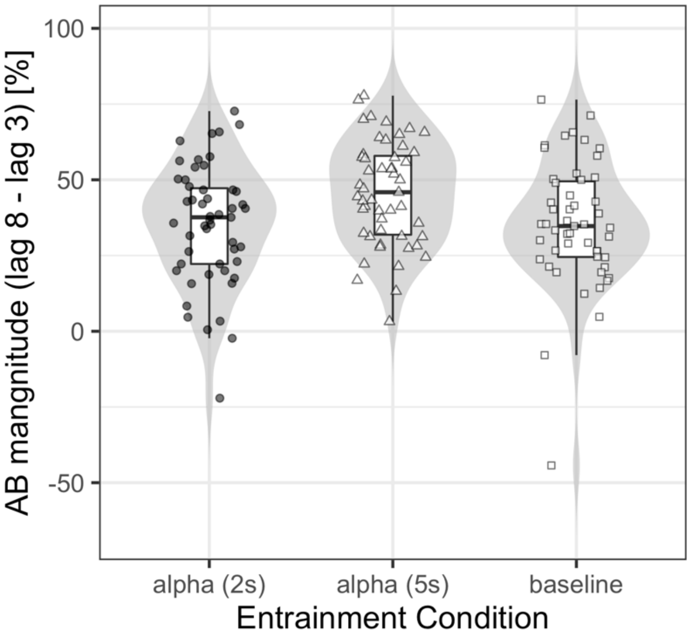
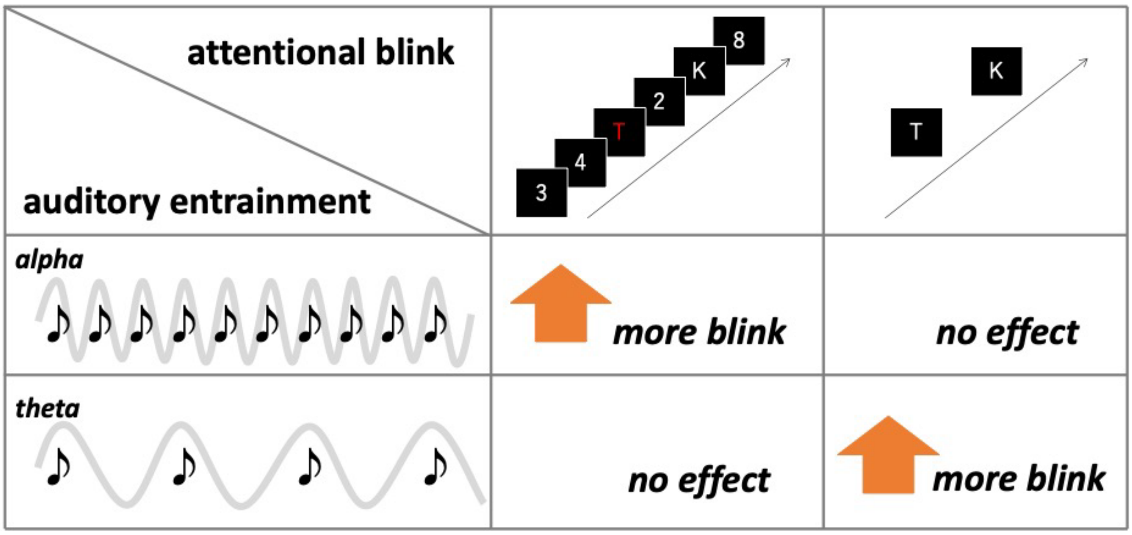


Figure S2. Mean attentional blink (AB) magnitude in the additional experiment. AB magnitude is defined as T2 accuracy at lag 8 minus T2 accuracy at lag 3, conditional on correctly reporting T1. Each dot represents mean AB magnitude per participant. One-way analysis of variance revealed significant differences in AB magnitude among conditions (*F* (2, 100) = 10.16, *p* < .001, η_p^2 = .17). Critically, *post hoc* comparisons showed that AB magnitude at 5 s was significantly larger than that at baseline and 2 s (*t* (50) = 3.94, *p* < .001; *t* (50) = 3.54, *p* < .001). We observed no difference between 2 s and baseline conditions (*t* (50) = 0.03, *p* = .978).



Graphical Abstract Text

Attentional blink (AB) shows the temporal constraints of attention. We here studied how much preceding rhythmic auditory stimulation affected the performance of AB. Auditory stimuli at the alpha frequency increased the AB magnitude in the conventional AB paradigm with distractors, while auditory stimuli at the theta, not alpha, increased the AB magnitude in the AB paradigm without distractors. These results suggest that two different brain oscillations, theta and alpha, underlie AB processes depending on the existence of distractors.