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Seeing through space and time: Comparing the effects of exogenous spatial and rhythmic temporal attention on visual awareness

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ABSTRACT

Unlike spatial attention, the role of rhythmic temporal attention in visual awareness remains less explored. To address this issue, we investigated how rhythmic temporal attention operates with exogenous spatial attention during detection of near-threshold Gabor patch targets. Targets appeared after a series of placeholders flickering either regularly or irregularly in the left or right visual field. Each target was equally likely to occur at the same location as the rhythmic stream (spatially attended trial) or the opposite location (unattended trial). Participants first made a detection response, followed by a localization judgment. Target visibility was calibrated to 50% in Experiment 1 and 75% in Experiment 2. At 50% visibility, spatial attention induced a more conservative response criterion for unattended compared to attended trials. Unexpectedly, irregular rhythms enhanced perceptual sensitivity relative to regular rhythms. At 75% visibility, rhythms had no effect on perceptual sensitivity, whereas spatial attention improved perceptual sensitivity, sped responses, and maintained a more conservative response pattern for unattended trials. In follow-up experiments with fully visible (100%) targets, responses were faster after regular rhythms, but only when the localization response was removed, suggesting that rhythmic temporal sequences primarily facilitated response preparation under simplified task demands. Overall, these results call for caution in attributing a direct role of rhythmic temporal attention to visual awareness, at least under the current rhythmic sequences and in the presence of spatial uncertainty, while confirming a key role for exogenous spatial attention in enhancing conscious perception.

1. Introduction

Imagine you are driving and your phone is right next to you. As you stop at a red light, a notification pops up and you glance at the screen for a split second. Have you ever wondered why sometimes you are aware of part of the message, maybe just the sender's name, while other times you have no awareness of it at all? Which factors help explain variations in awareness of visual stimuli in the environment?

Previous studies highlighted the role of spatial attention as a selection mechanism that determines whether visual information reaches consciousness (e.g., Carrasco & Barbot, 2019; Chica et al., 2011; Vernet et al., 2019). Spatially predictive peripheral cues that attract attention to a specific location can help maintain attention at that position, enhancing perceptual sensitivity (d') to detect near-threshold stimuli. Attentional modulations elicited by exogenous spatial cues are typically more effective than those produced by purely endogenous cues (Chica et al., 2011). By contrast, the role of other forms of attention, such as temporal attention, and their interaction with spatial attention in conscious perception has been less explored. Although spatial and temporal attention are often studied separately, prioritizing locations in space and moments in time are both crucial for perception (see Capizzi et al., 2023).

Like spatial attention, temporal attention can be deployed endogenously, through symbolic cues, or exogenously, through regular rhythmic sequences (see Capizzi & Correa, 2018; Nobre & van Ede, 2018; Seibold et al., 2023, for reviews). A seminal study on the latter (Jones et al., 2002) demonstrated enhanced accuracy for auditory targets presented in-phase, rather than out-of-phase, with a preceding regular rhythm. As formalized in the *Dynamic Attending Theory* (Jones, 1976; Large & Jones, 1999), these benefits have been attributed to the

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proposal that temporal attention oscillates between moments of engagement and disengagement, such that the synchronization of internal oscillations with external rhythms facilitates the processing of events that align with the rhythm compared to misaligned ones. Common rhythmic manipulations include comparing in-phase versus out-of-phase targets within a regular sequence (e.g., Jones, 2015; Sanabria et al., 2011), as in the original study by Jones et al. (2002), or comparing regular versus irregular sequences with fixed target timing (e.g., Attout et al., 2024; Capizzi et al., 2026; Cutanda et al., 2015).

In most tasks manipulating rhythmic temporal attention, target stimuli are typically presented at a supra-threshold level. When targets are presented near-threshold, rhythmic sequences have been shown to enhance sensitivity to targets that align in-phase with the preceding rhythm (Mathewson et al., 2010). In such a study, rhythms were presented at a single spatial location, thereby eliminating spatial uncertainty. A follow-up study by Kizuk and Mathewson (2017) introduced a spatiotemporal task in which a symbolic cue predicted the upcoming target location with 70% validity. Between the cue and the target, a series of bilateral visual stimuli served as entrainers. Following the last entrainer, a backward masked target (with target luminance set to 60% detection performance for each participant via a staircasing procedure) appeared on either the attended or unattended side of space, either in synchrony with the rhythm or out of synchrony. The results showed that rhythmic temporal attention improved accuracy (i.e., proportion of correct detections) for in-phase versus out-of-phase targets only in the spatially unattended condition; no significant differences were observed in the attended condition. In these two studies, rhythmic stimuli were presented at an alpha frequency of approximately 12 Hz. This choice was motivated by the well-established role of alpha rhythms in entraining spatial attention (Klimesch et al., 2007; Pascucci et al., 2025). In this context, rhythmic stimulation was thus used as a means to entrain spatial attention rather than as an independent temporal cue.

In the present study, we aimed to further investigate whether and how rhythmic temporal and spatial attention modulate visual awareness. To this end, we presented rhythms at a slower frequency (∼2.5 Hz), as rhythms within this timeframe (1–3 Hz range) have been shown to enhance behavioral performance either in isolation (Cutanda et al., 2015; de la Rosa et al., 2012; Rohenkohl et al., 2012) or in combination with spatial attention (Attout et al., 2024; Charras et al., 2023; Jones, 2015). Moreover, unlike previous studies, we manipulated the regularity of the rhythm (regular vs. irregular), rather than the timing of target appearance (in-phase vs. out-of-phase), to avoid the confounding effect of temporal expectation that arises simply from the passage of time at the late out-of-phase moment. Indeed, when the timing of target appearance is manipulated, rhythmic benefits are typically limited to the comparison between in-phase and early out-of-phase targets, whereas no difference is often observed between in-phase and late out-of-phase targets (Barne et al., 2022; Jones, 2015; Román-Caballero et al., 2024). This pattern occurs because, when the target fails to appear at the expected moment, the probability of its appearance increases as time progresses, a phenomenon known as the ́foreperiod effect ́ (Coull, 2009; Niemi & Näätänen, 1981; Visalli et al., 2023). To avoid this confound, we assessed rhythmic benefits by comparing regular and irregular sequences, rather than using only a regular rhythm with varying target onset timings.

In brief, participants were presented with a series of placeholders flickering at either a regular or irregular pace on the left or right side of the visual field. Following this sequence, a Gabor patch appeared with equal probability at the same location as the rhythm (spatially attended trial) or at the opposite location (unattended trial). By manipulating target visibility (50%), we examined whether the combination of rhythmic temporal and exogenous spatial attention modulates visual awareness. Based on previous studies, we hypothesized increased sensitivity to targets appearing at attended compared to unattended locations (Chica et al., 2011; Vernet et al., 2019) and following regular rather than irregular rhythms (Mathewson et al., 2010). Regarding the interaction between temporal and spatial attention, our study took a more explorative approach, as it remains debated whether these two forms of attention operate independently or interactively to optimize performance. According to a recent review (Capizzi et al., 2023), interactive effects are expected when the task imposes high perceptual demands, whereas independent effects are more likely under lower task demands. However, these conclusions have been mainly drawn from studies involving supra-threshold targets or other types of attentional manipulations (e.g., endogenous spatial attention; Charras et al., 2023; Jones, 2015; Kizuk and Mathewson, 2017). Therefore, further investigation is warranted to clarify these interactive patterns under different task conditions.

2. Experiment 1

In Experiment 1, we investigated the effects of rhythmic temporal and exogenous spatial attention on the perception of near-threshold targets. Participants viewed a lateralized placeholder that flickered either regularly or irregularly. A Gabor patch target subsequently appeared at the same location as the flickering placeholder (attended location) or at the opposite (unattended) location. Both spatial and temporal attention were set at 50%.

2.1. Method

2.1.1. Participants

Sample size was determined a priori based on a re-analysis of a previous study by Chica et al. (2011; Experiment 4), which reported an effect size (η_p^2) of 0.42 for the main effect of exogenous spatial attention on conscious perception. The required sample size for a repeated-measures ANOVA (within-participants) was calculated using the G*Power 3.1.9.4 software (Faul et al., 2007), indicating that 26 participants would provide a power of 0.95 with an alpha level of 0.05. Although the calculation was based on the effects of spatial attention, the resulting sample size is larger than those used in previous studies combining rhythmic temporal and spatial attention (e.g., $N = 18$, Kizuk & Mathewson, 2017; $N = 16$, Jones, 2015; see also Mathewson et al., 2010, $N = 16$, for a study on rhythmic temporal attention). To account for potential data loss, 34 students from the University of Granada (Spain) participated in the experiment.

Three participants were excluded from data analysis due to excessive eye movements (>30%), and one additional participant for excessive anticipatory responses before target onset (>10%), leaving a final sample of 30 participants (mean age = 23.43 years, mean range = 18–35 years, 15 females). Four participants self-reported as being left-handed.

Participants in this and subsequent experiments received 10 euros/hour for their participation. All participants had normal or corrected-to-normal vision and reported no history of neurological or psychiatric disorders. All of them provided written informed consent before the experiment, which was approved by the Ethics Committee of the University of Granada (reference number: 1862/CEIH/2020) and conducted in accordance with the guidelines of the Declaration of Helsinki.

2.1.2. Apparatus and stimuli

E-Prime software was used for stimulus presentation and data collection (Schneider, Eschman, & Zuccolotto, 2002). Stimuli were presented on a Benq T903 LCD monitor (19″, 1280 x 1024 resolutions) configured to operate at 60 Hz. The eye-tracking system was the Eyelink 1000 (SR Research; Mississauga, Canada), with a temporal resolution of 1000 Hz and a spatial resolution of 0.25°. All the stimuli were presented against a grey background (RGB color: 192, 192, 192; luminance 5.3 NITS cd/m^2 on x10 scale).

Stimuli consisted of a black fixation cross (0.5° x 0.5° visual angle from a distance of approximately 57 cm) displayed at the center of the screen and two grey rectangles serving as placeholders (RGB: 128, 128, 128; size 3.3° x 2.7°, border thickness 0.2°), located 6.5° to the left and right of the fixation cross. The target stimulus was a Gabor patch with a diameter of 1.5°, tilted 5° to the right or 5° to the left. A total of 200 Gabor patches was generated using Matlab (The MathWorks, Inc., Natick, Massachusetts, United States), with 4 cycles or degrees of spatial frequency per degree of visual angle. The Gabor patches had a maximum Michelson contrast of 0.92 and a minimum contrast of 0.02. The contrast levels of the 200 Gabor patches were equidistant, with 0.0045 Michelson contrast points between levels. The Gabor contrast was adjusted before the experimental session using a staircase procedure to ensure that each participant detected the presence of the Gabor in approximately 50% of the trials (see the Procedure section).

Two arrow-like symbols (≪<≪ or ≫>≫; 1.2° x 0.5°), filled with grey color and displayed 2.6° above and below the fixation cross, appeared at the end of each trial to prompt the localization response.

2.1.3. Procedure

Fig. 1 illustrates the timing and sequence of events forming a trial. Each trial began with a fixation cross displayed for a random duration between 1000 and 1500 ms, which remained visible throughout the entire trial. Participants were instructed to maintain central fixation for the duration of the trial. Subsequently, two placeholders, one on the left and one on the right side of the fixation cross, appeared for 50 ms. Next, either the left or right placeholder began to flicker while the other one remained steady. The flickering effect was created by presenting five additional screens (50 ms each) in which both placeholders were visible and separating them with an inter-stimulus interval (ISI) during which only one placeholder was present. The ISI duration was either fixed at 400 ms (i.e., 2.5 Hz, regular rhythm) or randomly selected from 100, 250, 400, 550, or 700 ms (irregular rhythm). Thus, regular and irregular sequences had the same total duration, differing only in the rhythm pace at which the placeholders flickered. For both regular and irregular rhythms, the last ISI preceding the target (i.e., the foreperiod) was always 800 ms. The foreperiod duration was set to be exactly double the regular ISI, as this proportion has been shown to be particularly effective for engaging temporal attention guided by rhythmic sequences (e.g., Charras et al., 2023; Cutanda et al., 2015; de la Rosa et al., 2012; Lange, 2010). After the foreperiod, both placeholders were shown, and the target appeared inside either the left or right placeholder for 33 ms. When the target appeared inside the flickering placeholder, the trial was classified as *spatially attended*; when it appeared inside the steady placeholder, it was classified as *spatially unattended*. Attended and unattended trials occurred with equal probability (50% each). Participants were informed that the flickering of the placeholders was non-predictive of target location.

If participants detected the target, they had to press the numeric "1″ key on the computer keyboard with the index finger of their right hand as fast as possible. This response measured reaction time (RT) to the onset of the Gabor. A maximum of 2000 ms from target onset was allowed for the response. If participants did not detect the Gabor, they were instructed to withhold any response. After the 2000 ms interval elapsed, two arrow-like stimuli pointing either to the left (≪<≪) or to the right (≫>≫) appeared above and below the fixation cross. Participants indicated whether they had seen the Gabor inside the left or right placeholder by pressing the "d" key (e.g., associated with the upper arrow) or the "c" key (e.g., associated with the lower arrow) on the computer keyboard with the middle and index fingers of their left hand, respectively. In case participants did not detect the Gabor, they had to press the spacebar with their left thumb. To prevent participants from anticipating the response based on the location of the Gabor, the arrow-

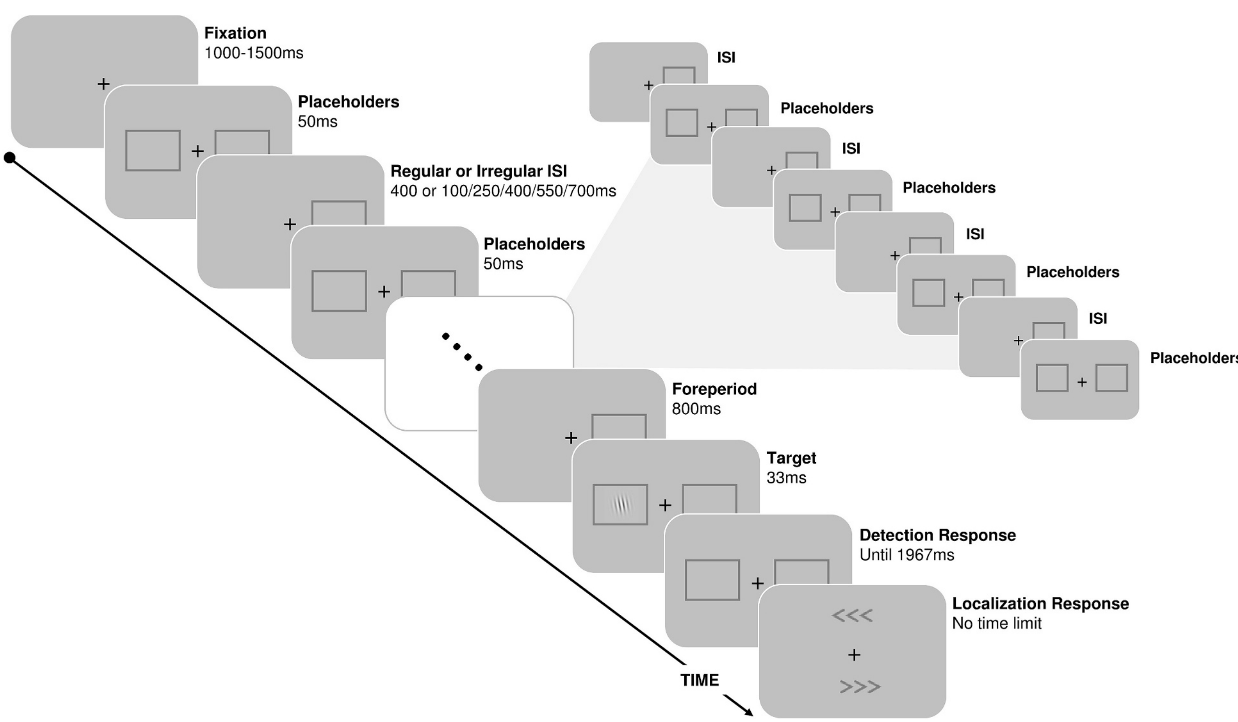

Fig. 1. Schematic representation of a spatially attended trial. After a fixation cross, two placeholders briefly appeared on the left and right side of the screen. Then, with equal probability, either the left (as shown) or the right placeholder began to flicker, creating a rhythmic sequence. The white rectangle with the inset on the right illustrates the sequence of events generating the rhythm: the alternation between screens displaying both placeholders and those displaying only one placeholder produced a flickering effect. The inter-stimulus interval (ISI) between screens could be either regular or irregular. The target was a Gabor patch appearing within the flickering placeholder (*spatially attended trial,* as shown) or within the steady placeholder (*unattended trial*, not shown). Gabor visibility was individually titrated using a staircase procedure (50% in Experiment 1, 75% in Experiment 2), whereas in Experiments 3 and 3b-control Gabor patches were fully visible. Participants were instructed to respond to the onset of the Gabor in a first detection task and to report the side of its appearance in a subsequent localization task (using the arrow-like stimuli). Please refer to the main text for further details. Video examples of each trial type from Experiment 3 (with a fully visible Gabor) are provided as online supplementary material on OSF (https://osf.io/75dns).

like stimuli were randomly associated with either the upper or lower position on a trial-by-trial basis. There was no time limit for responding to the location of the Gabor.

The task consisted of eight experimental blocks for a total of 320 trials. Each block included 40 trials comprising 16 *regular rhythmic trials* (8 *attended* and 8 *unattended*; 40%), 16 *irregular rhythmic trials* (8 *attended* and 8 *unattended*; 40%), and 8 *catch-trials* (i.e., trials without target presentation; 20%). Before the experimental blocks, participants underwent a calibration phase that also served as a practice session. In the calibration phase, the timing and stimuli were the same as those used in the experimental trials.

All participants began the experiment practicing with a supra-threshold Gabor (Michelson Contrast = 0.4). After completing 20 trials (consisting of 4 trials for each condition: attended regular, unattended regular, attended irregular, unattended irregular, and catch trials), the ability to accurately detect the Gabor was calculated. If the detection rate was higher than 63%, the contrast level used in the subsequent 20 trials was lowered by one level. The new contrast level was calculated by subtracting 0.0045 from the previous contrast level. Conversely, if the detection rate was lower than 37%, the contrast level for the next 20 trials was increased by adding 0.0045 to the previous contrast level. The calibration continued until the detection rate fell between 37% and 63% for two consecutive blocks of trials. Once the calibration phase was completed, participants proceeded to the experimental blocks. Short breaks between blocks were allowed throughout the experiment.

Before each experimental block, the eye-tracking apparatus was calibrated by presenting 5 points at different locations on the screen, which participants were required to fixate on. Following the calibration phase, the dots were presented again in a validation phase, which was considered valid only if the distance between the mean fixation obtained during calibration and the mean fixation obtained during validation was less than 0.7°. Visual dominance was assessed with the hole-in-the-card test (Lopes-Ferreira et al., 2013). The total duration of the experiment was approximately 1.30 to 2 h.

2.1.4. Data analysis

The dependent variables were the RT for the detection response, the hit rate (number of target stimuli correctly identified when the Gabor was present), and the false alarm rate (number of targets incorrectly identified when the Gabor was absent). Using the hit and false alarm rates, A' and B'' indices were calculated as two commonly used non-parametric indices that provide measures of perceptual sensitivity and response bias in perceptual tasks (Stanislaw & Todorov, 1999).

$$A' = 0.5 + \frac{(Hits - FAs)*(1 + Hits - FAs)}{4*Hits*(1 - FAs)}$$

$$B'' = \frac{Hits*(1 - Hits) - FAs*(1 - FAs)}{Hits*(1 - Hits) + FAs*(1 - FAs)}$$

A' reflects the ability to discriminate between signal and noise. Values close to 0.5 indicate difficulty in distinguishing signal from noise, while a value of 1 indicates perfect discrimination. B'' reflects participants' decision-making criteria in responding to the presence or absence of the target. The B'' index ranges from −1 (indicating an extremely liberal response criterion) to 1 (indicating a conservative response criterion), with a value of 0 indicating no bias in responding.

For all analyses, trials in which participants broke fixation (5.81%) or responded prematurely before target onset (0.066% of the remaining trials) were excluded. For the RT analysis, we considered only trials in which the target was present, correctly detected in the initial detection response, and accurately reported as "seen" in the subsequent Gabor localization task. Because target visibility was individually titrated to 50% in this experiment, a substantial proportion of target-present trials did not meet these accuracy criteria, and only 35.6% of all experimental trials were retained for the RT analysis. Within this dataset, trials with RTs falling more than ±2.5 SD from their individual mean in each condition were considered outliers and removed (2.92% of trials; Berger & Kiefer, 2021; see also Attout et al., 2024; Capizzi et al., 2026; Chica et al., 2011, for similar trimming procedures). Due to these exclusion criteria, a limited and variable number of trials was available for the omnibus RT analysis for some of the participants (see Supplementary Table 1). Therefore, we conducted separate *t*-tests to examine the effects of Rhythm (irregular, regular) and Spatial attention (attended, unattended). Cohen's dz was used as a measure of effect size (Cohen, 1977). In the analysis of spatial attention, even after collapsing data across irregular and regular trials, five participants still had to be excluded (final $N = 25$) due to an insufficient number of observations (maximum 11 and minimum 0 trials; see Supplementary Table 1).

In contrast to the RT analysis, the analyses of A' and B'' indices were based on the complete dataset ($N = 30$) and conducted using separate repeated-measures ANOVAs, with Rhythm and Spatial attention as within-participant factors. Partial Eta Squared (η_p^2) was used as a measure of effect size. In addition to frequentist statistics, we conducted Bayesian repeated-measures ANOVAs in JASP (version 0.16.1; JASP Team, 2022) using the default random-intercepts-only specification to obtain inclusion Bayes factors (BFs). Inclusion BFs quantify the evidence for including a specific main effect or interaction in the model. A BF > 100 is regarded as extreme evidence for the experimental hypothesis; 30–100, very strong evidence; 10–30, strong evidence; 3–10, moderate evidence; 1–3, weak evidence, and 1 inconclusive evidence for the experimental or the null hypothesis. Conversely, a BF < 1 indicates evidence against inclusion, with smaller values reflecting stronger evidence against inclusion (Wagenmakers et al., 2018). Inclusion BFs were obtained through Bayesian model averaging (across matched models).

2.1.5. Results

For the RT analysis, the *t*-test for the rhythm condition showed no significant difference between irregular (M = 693.161 ms, SD = 167.5) and regular trials (M = 699.761, SD = 190.67), $t_{(29)} = -0.69$, $p = 0.5$, Cohen's dz = −0.12. Likewise, there was no significant difference between spatially attended (M = 713.306, SD = 209.57) and unattended trials (709.517, SD = 178.18), $t_{(24)} = 0.19$, $p = 0.85$., Cohen's dz = 0.04).

Full descriptive data for A' and B'' values are reported in the Supplementary Tables 2 and 3. Participants correctly perceived 51.37% of the presented Gabors, with false alarms occurring in 6.85% of trials.

The ANOVA on the A' index showed a significant main effect of Rhythm ($F_{(1,29)} = 20.35$, $p < 0.001$, $\eta_p^2 = 0.41$, inclusion BF = 0.778), indicating greater perceptual sensitivity for irregular compared to regular rhythms (Fig. 2, left). Neither the main effect of Spatial attention nor the Rhythm by Spatial attention interaction were statistically significant ($F_{(1,29)} = 0.42$, $p = 0.52$, $\eta_p^2 = 0.01$, inclusion BF = 0.335, and $F_{(1,29)} = 3.19$, $p = 0.08$, $\eta_p^2 = 0.010$, inclusion BF = 0.338, respectively).

The ANOVA on the B'' index yielded a significant main effect of Spatial attention ($F_{(1,29)} = 20.52$, $p \leq 0.001$, $\eta_p^2 = 0.41$, inclusion BF = 1.031e + 6), with more conservative responses on unattended than attended trials (Fig. 2, right). There were no significant main effects of Rhythm and no significant Rhythm by Spatial attention interaction ($F_{(1,29)} = 0.54$, $p = 0.47$, $\eta_p^2 = 0.02$, inclusion BF = 0.215, and $F_{(1,29)} = 2.15$, $p = 0.15$, $\eta_p^2 = 0.07$, inclusion BF = 0.426, respectively).

3. Discussion

Experiment 1 investigated the relationship between exogenous spatial attention and rhythmic temporal attention in visual awareness of near-threshold targets. While no significant effects were found in the RT analysis, spatial and temporal attention affected perceptual sensitivity and response criterion in distinct ways. Exogenous spatial attention influenced the response criterion, leading to more conservative responses on unattended compared to attended trials, without affecting

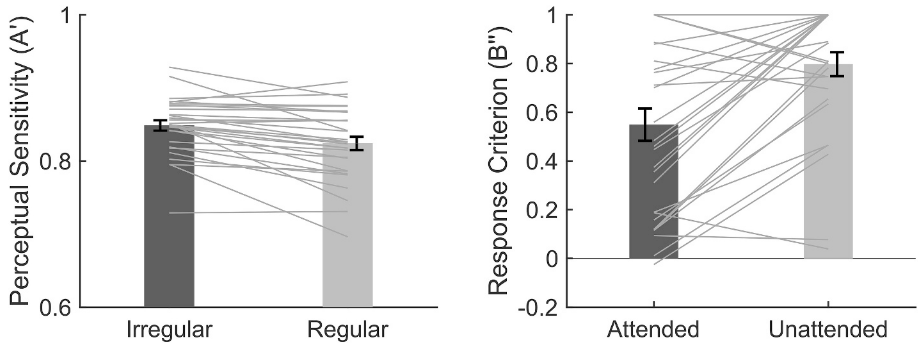

Fig. 2. Results of Experiment 1. The left panel shows the mean perceptual sensitivity (A') for the irregular and regular rhythmic conditions, while the right panel shows the mean response criterion (B'') for the spatially attended and unattended conditions. Individual lines represent participants, and error bars indicate standard errors of the mean.

perceptual sensitivity. In contrast, rhythmic temporal attention modulated perceptual sensitivity but had no effect on the response criterion. However, contrary to our predictions, perceptual sensitivity was higher for targets following irregular rather than regular rhythms. No significant interactions between spatial and temporal attention were observed in perceptual sensitivity and response criterion measures.

The finding of a more conservative response criterion in unattended compared to attended trials replicates previous studies, indicating that participants are less likely to report unattended stimuli (Chica et al., 2011). Interestingly, this bias was not accompanied by a change in perceptual sensitivity, as indexed by similar A' values in both unattended and attended trials. This latter result contrasts with previous evidence showing that exogenous spatial attention can affect perceptual sensitivity, albeit such benefits have been mainly observed with higher stimulus visibility (75%; Chica et al., 2011) or under different cueing conditions (e.g., Herreros et al., 2017).

For rhythmic temporal attention, we expected shorter RTs on regular compared to irregular trials, in line with previous studies using similar rhythmic sequences (e.g., Attout et al., 2024; Charras et al., 2023; Cutanda et al., 2015). A plausible explanation for the absence of this effect is that response preparation might have been discouraged by the task design itself, which required a subsequent localization response (''Where did the target appear?''). Given that target visibility was titrated to 50%, participants may have favored an accuracy-based approach over a response preparation strategy, remaining equally (un) prepared for both regular and irregular trials.

A more surprising finding was the higher perceptual sensitivity for irregular compared to regular rhythms. Because regular rhythms are assumed to entrain attention and enhance perceptual processing (Jones et al., 2002), one would typically expect greater perceptual sensitivity under regular than irregular conditions. One possible explanation for this unexpected result is that the irregular context may have increased alertness, which has been associated with better perceptual sensitivity (e.g., Cobos et al., 2019; Kusnir et al., 2011). Another possibility is that this effect was spurious, especially given the limited support from the Bayesian analysis, which provided inconclusive evidence for including the main effect of rhythm in the model, despite the significant frequentist results.

To further investigate the unexpected rhythm-related findings on perceptual sensitivity, and to examine the influence of exogenous spatial attention under conditions of higher stimulus visibility, we increased the visibility of the Gabor patches to 75% in Experiment 2. Apart from this modification, all other aspects of the experimental design remained the same as in Experiment 1.

4. Experiment 2

Experiment 2 aimed to test whether the perceptual benefits of irregular rhythms observed in Experiment 1 would replicate, as well as to further explore the role of exogenous spatial attention in conscious perception using more visible Gabor patches (75% visibility).

4.1. Method

4.1.1. Participants

Thirty-three participants took part in Experiment 2. Three participants were excluded due to excessive eye movements (>30%), leaving a final sample of 30 participants (mean age = 20.45 years, mean range = 18–27 years, 27 females). Two participants self-reported as being left-handed. None of them had participated in the previous experiment.

4.1.2. Apparatus, stimuli and procedure

Everything was the same as in Experiment 1, except that Gabor visibility was titrated to achieve a 75% detection rate. More specifically, detection rate was titrated between 62.5% and 87.5% across two consecutive blocks of trials during the titration phase.

4.1.3. Data analysis and results

Trials in which participants broke fixation (6.28%) or responded prematurely before target onset (0.022% of the remaining trials) were excluded. For the RT analysis, the same criteria as in the previous experiment were applied. Specifically, only trials in which the target was present and participants provided responses for both the initial detection task and the subsequent Gabor localization task were retained (51.6% of all experimental trials). Within this dataset, trials with RTs more than ±2.5 SD from each participant's mean in each condition were considered outliers and removed (2.99% of trials). Two participants had too few observations (<10 trials in some conditions) and were therefore excluded from the RT analysis (see Supplementary Table 4). Data from the remaining participants ($N = 28$) were entered into a repeated-measures ANOVA with Rhythm and Spatial attention as within-participant factors.

Full descriptive data for RTs are reported in Supplementary Table 5. The RT analysis showed a significant main effect of Spatial attention ($F_{(1,27)} = 16.95$, $p < 0.001$, $\eta_p^2 = 0.39$, inclusion BF = 176637.194), indicating shorter RTs for attended compared to unattended trials (Fig. 3, left). Neither the main effect of Rhythm nor the Rhythm by Spatial attention interaction were statistically significant ($F_{(1,27)} = 1.36$, $p = 0.25$, $\eta_p^2 = 0.05$, inclusion BF = 0.264, and $F_{(1,27)} = 0.54$, $p = 0.47$, $\eta_p^2 = 0.020$, inclusion BF = 0.297, respectively).

The analyses of A' and B'' indices (Supplementary Tables 6 and 7) were based on the complete dataset ($N = 30$). Participants perceived 70.51% of the presented Gabors. False alarms were committed in 2.79% of trials.

As concerns A', the ANOVA showed a significant main effect of Spatial attention ($F_{(1,29)} = 59.16$, $p < 0.001$, $\eta_p^2 = 0.67$, inclusion BF = 1.602e + 13), with higher perceptual sensitivity for attended compared to unattended trials (Fig. 3, right). Neither the main effect of Rhythm nor

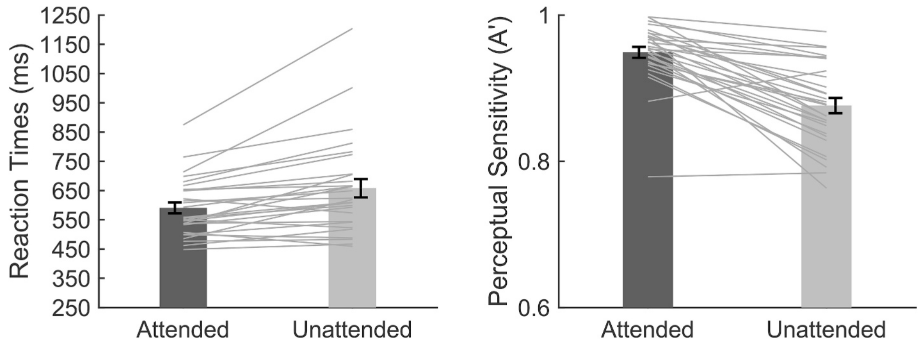

Fig. 3. Results of Experiment 2. The left panel shows the mean reaction times in milliseconds (ms), while the right panel shows the mean perceptual sensitivity (A'), for the spatially attended and unattended conditions. Individual lines represent participants, and error bars indicate standard errors of the mean.

the Rhythm by Spatial attention interaction were statistically significant ($F_{(1,29)} = 0.97$, $p = 0.33$, $\eta_p^2 = 0.03$, inclusion BF = 0.267, and $F_{(1,29)} = 3.43$, $p = 0.07$, $\eta_p^2 = 0.11$, inclusion BF = 0.612, respectively).

Regarding the B'' index, there was a significant main effect of Spatial attention ($F_{(1,29)} = 10.96$, $p = 0.002$, $\eta_p^2 = 0.27$, inclusion BF = 1350.048), indicating more conservative responses on unattended compared to attended trials. Although the main effect of Rhythm was not significant ($F_{(1,29)} = 0.40$, $p = 0.53$, $\eta_p^2 = 0.01$, inclusion BF = 0.212), the Rhythm x Spatial attention interaction was statistically significant ($F_{(1,29)} = 5.99$, $p = 0.02$, $\eta_p^2 = 0.17$, inclusion BF = 0.847). This interaction was driven by a more conservative response criterion for unattended compared to attended trials in the irregular condition ($t = -4.051$, Bonferroni-corrected $p = 0.001$), as compared to the regular condition ($t = -1.891$, $p = 0.39$; Fig. 4).

5. Discussion

Compared to Experiment 1, Experiment 2 used more visible Gabor patches (75% visibility), while all other aspects remained the same.

Regarding the spatial manipulation, exogenous attention to the attended location resulted in shorter RTs, higher perceptual sensitivity, and a more liberal response criterion. In contrast, rhythmic temporal attention did not significantly modulate participants' RTs or perceptual sensitivity, except for an interaction with spatial attention in the response criterion measure. This interaction was driven by a larger and significant difference between attended and unattended trials (with more conservative responses in unattended trials) observed only in the irregular rhythm condition, but not in the regular one. Notably, the inclusion Bayesian factor of 0.847 indicates inconclusive evidence for this interaction, which should therefore be interpreted with caution.

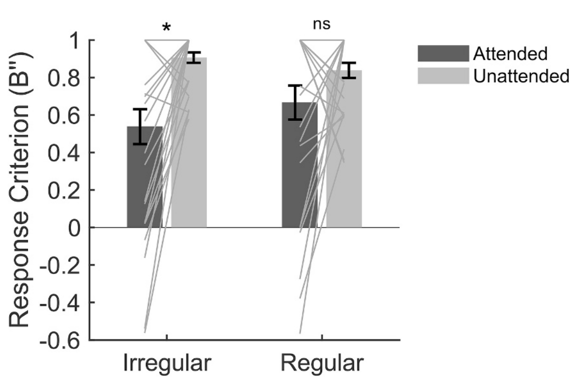

Fig. 4. Interaction effects in Experiment 2. Mean response criterion (B'') as a function of rhythmic condition (irregular, regular) and spatial attention (attended, unattended). Individual lines represent participants, and error bars indicate standard errors of the mean. The asterisk denotes a significant effect, whereas "ns" indicates a non-significant effect.

While the results for exogenous spatial attention align well with previous studies showing that spatial attention can enhance conscious perception under similar target visibility conditions (Chica et al., 2011), the rhythm-related findings failed to replicate the results from Experiment 1. This pattern may suggest that irregular rhythms are effective only under more perceptually demanding conditions (50% visibility), or, alternatively, that the initial finding was spurious. Supporting the latter hypothesis, the Bayesian analysis provided moderate evidence against including the effect of rhythm.

Given the absence of a significant rhythm effect on RTs in both Experiments 1 and 2, it is also possible that our regular rhythmic sequences simply failed to influence performance, whether at the perceptual or the motor level. Although previous studies using the same sequences have already shown a behavioral advantage for the detection of suprathreshold targets (Attout et al., 2024; Charras et al., 2023), we conducted another test in Experiment 3 using fully visible Gabor patches.

6. Experiment 3

The aim of Experiment 3 was to explore the effects of rhythmic temporal attention on response preparation using fully visible Gabor patches.

6.1. Method

6.1.1. Participants

Thirty-nine participants initially took part in Experiment 3. Of these, one dataset was excluded due to a technical malfunction of the eye-tracking system, and nine participants were excluded because they systematically responded in the first detection response regardless of Gabor presence (mean response rate of 0.95 on catch trials), indicating a clear misunderstanding of the task instructions.[1] These datasets were removed prior to further analysis. Seven additional participants were subsequently tested to compensate for this data loss. Of the remaining 36 tested participants, one was excluded for failing to respond to the Gabor, and four were excluded for excessive eye movements (>30%). This resulted in a final sample of 31 participants (mean age = 24.21 years, age range: 19–37 years, 18 females, 5 left-handed according to self-report).

6.1.2. Apparatus, stimuli and procedure

Everything was the same as in Experiment 2, except that we used a

[1] Because in this experiment, even for fully visible Gabors, participants had to first make a speeded detection response and then a localization response (or press the spacebar if they did not detect the Gabor), these excluded participants appeared to confuse the two steps. They almost always pressed either the spacebar or the '1′ key on the initial detection response, regardless of Gabor presence, and then pressed the spacebar again on the second response.

fixed Gabor contrast that was fully visible.

6.1.3. Data analysis and results

As expected with supra-threshold targets, participants correctly reported 99% of the presented Gabors. They responded on 6.10% of catch trials. The analysis focused on RTs only (see Supplementary Table 8). Trials in which participants broke fixation (5.93%) or responded prematurely before target onset (0.032% of the remaining trials) were excluded. To maintain consistency with Experiments 1 and 2, only trials in which the target was present and participants provided responses for both the initial detection task and the subsequent Gabor localization task were retained (73.44% of all experimental trials). Moreover, trials with RTs more than ± 2.5 SD from each participant's mean in each condition were considered outliers and removed from the analysis (2.79% of the remaining trials).

The ANOVA showed a significant main effect of Spatial attention ($F_{(1,30)} = 4.41$, $p = 0.04$, $\eta_p^2 = 0.13$, inclusion BF = 2.460), indicating shorter RTs for unattended compared to attended trials (Fig. 5, left). Neither the main effect of Rhythm nor the Rhythm by Spatial attention interaction were statistically significant ($F_{(1,30)} = 1.42$, $p = 0.24$, $\eta_p^2 = 0.05$, inclusion BF = 0.313, and $F_{(1,30)} = 3.03$, $p = 0.09$, $\eta_p^2 = 0.09$, inclusion BF = 0.729, respectively).

7. Discussion

Experiment 3 aimed to explore the effects of rhythmic temporal attention on motor performance. As in the previous experiments, participants first made a speeded response to the Gabor and then reported its location. The only difference from the previous experiments was that the Gabor was fully visible. Regarding spatial attention, RTs were slightly shorter for unattended compared to attended trials, consistent with the Inhibition of Return (IOR) phenomenon (Klein, 2000; Lupiáñez et al., 2006). In exogenous spatial attention tasks, it is common to observe a reversal of validity effects at longer cue-target intervals, with faster responses to unattended locations. The absence of IOR in the more demanding visibility conditions of Experiments 1 and 2 is consistent with previous findings showing that IOR is more robust in simple detection tasks (Chica et al., 2006; Martín-Arévalo et al., 2013, 2020), while it tends to diminish or disappear as task demands increase (e.g., discrimination tasks; Castel et al., 2005; Martín-Arévalo et al., 2013) or in the presence of distractors (Martín-Arévalo et al., 2020). Of note, however, the Bayesian analysis provided only weak support for including the effect of Spatial attention in the model (see also below for further discussion).

Regarding the rhythmic manipulation, contrary to our expectations, we again observed no significant effect of rhythms on RTs. Although Experiment 3 was designed as a simple RT task, participants were still required to provide an accuracy-based response after their initial detection response. We speculated that this additional task may have influenced response preparation. To test this possibility, we conducted Experiment 3b-control with a smaller sample, in which participants performed only the initial RT task, omitting the subsequent localization task.

8. Experiment 3b-control

Everything was the same as in Experiment 3, except that participants performed only the initial speeded detection task (pressing the "1″ key when the Gabor was present) and were not required to perform the subsequent localization task.

8.1. Method

8.1.1. Participants

Twenty-two participants took part in this control experiment. None of them had participated in the previous experiments. Data from one participant were excluded due to a high proportion of missed responses (>30%), resulting in a final sample of 21 participants (mean age = 23.48 years, age range: 18–32 years, 15 females, one left-handed according to self-report).

8.1.2. Data analysis and results

Participants responded to 1.12% of catch trials. Trials in which participants broke fixation (10.6%), responded prematurely before target onset (0.22% of the remaining trials), or failed to respond (1.91% of the remaining trials) were excluded. Additionally, trials with RTs more than ± 2.5 SD from each participant's mean in each condition were considered outliers and removed (2.23% of the remaining trials). Descriptive data are reported in Supplementary Table 9.

The ANOVA on the mean RT showed a significant main effect of Rhythm ($F_{(1,20)} = 9.19$, $p = 0.007$, $\eta_p^2 = 0.32$, inclusion BF = 8.275), indicating shorter RTs for regular compared to irregular sequences (see Fig. 5, right). Neither the main effect of Spatial attention nor the Rhythm by Spatial attention interaction were statistically significant ($F_{(1,20)} = 1.76$, $p = 0.2$, $\eta_p^2 = 0.08$, inclusion BF = 0.685, and $F_{(1,20)} = 0.12$, $p = 0.74$, $\eta_p^2 = 0.006$, inclusion BF = 0.322, respectively).

9. Discussion

Results from Experiment 3b-control showed slightly shorter RTs for regular compared to irregular rhythms when the localization task was omitted. Under simplified task conditions, these findings replicate previous studies using similar rhythmic sequences, confirming that our manipulation effectively facilitated RT performance, although the advantage was numerically modest (Fig. 5, right; see also Charras et al., 2023). To further evaluate spatial and temporal effects with increased statistical power, we combined data from both Experiments 3 and 3b-control in a single ANOVA (see Supplementary Table 10). Given that

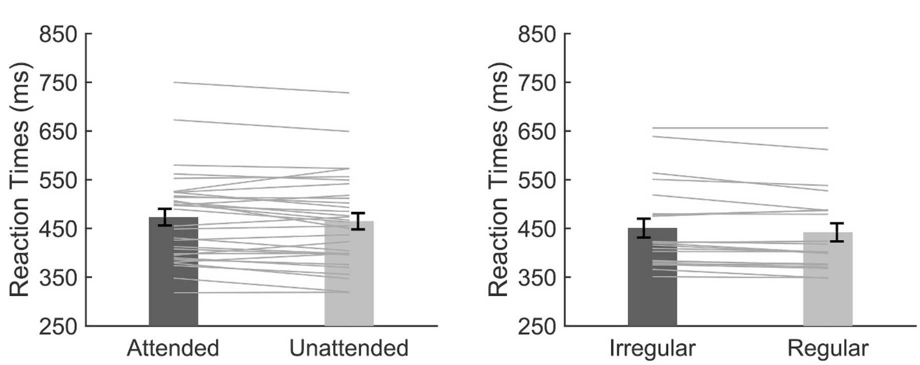

Fig. 5. Results of Experiment 3 and 3b-control. The left panel shows the mean reaction times in milliseconds (ms) for the spatially attended and unattended conditions in Experiment 3, while the right panel shows the mean reaction times for the irregular and regular rhythmic conditions in Experiment 3b-control. Individual lines represent participants, and error bars indicate standard errors of the mean.

Experiment 3b was designed as a methodological control that closely matched Experiment 3 in task structure, pooling the data allowed us to obtain more precise estimates of the effects of interest.

Results showed a significant main effect of Rhythm ($F_{(1,50)} = 7.41$, $p = 0.009$, $\eta_p^2 = 0.13$, inclusion BF = 2.195), with shorter RTs for regular compared to irregular sequences, and a significant main effect of Spatial attention ($F_{(1,50)} = 5.32$, $p = 0.02$, $\eta_p^2 = 0.010$, inclusion BF = 6.248), with shorter RTs for unattended compared to attended trials. The interaction between the two factors was not statistically significant ($F_{(1,50)} = 2.17$, $p = 0.15$, $\eta_p^2 = 0.04$, inclusion BF = 0.553). Neither the main effect of Experiment nor any interaction involving this factor reached statistical significance (all $ps > 0.1$, all inclusion BFs < 1).

Overall, the combined analysis of Experiment 3 and 3b-control confirmed significant main effects of Rhythm and IOR, with no significant interaction between them.

10. General discussion

A major debate in consciousness research centers on whether attention is a necessary prerequisite for conscious perception (Koch & Tsuchiya, 2007; Lamme, 2003). While this issue has been primarily framed in the context of spatial attention (Chica & Bartolomeo, 2012), much less is known about the role of temporal attention. In the present study, we investigated this issue by adapting the classic spatial orienting task (Posner, 1980; see Chica et al., 2014); a lateralized placeholder flickered either regularly or irregularly, but this flickering was uninformative with respect to both the target location (50% validity) and timing (neither regular nor irregular sequences predicted the onset) of a subsequent near-threshold target. In summary, our results align with previous findings showing that exogenous spatial attention can enhance awareness of near-threshold stimuli under conditions of 75% target visibility (Experiment 2). By contrast, rhythmic temporal attention had no significant and replicable effect on conscious perception. If anything, in Experiment 1 (50% visibility), irregular rather than regular rhythms enhanced perceptual sensitivity. Below, we provide a detailed discussion of these findings.

Unlike endogenous spatial attention, which appears to be most effective when stimuli are difficult to perceive (Botta et al., 2017), exogenous spatial attention in our study enhanced perceptual sensitivity when targets were more visible (75% visibility) rather than less visible (50% visibility). In the higher-visibility condition, participants' sensitivity was greater for attended compared to unattended locations. Importantly, this benefit cannot be attributed to overt shifts of spatial attention, as voluntary eye movements toward the attended location were controlled for with eye-tracking. The increase in perceptual sensitivity was accompanied by shorter RTs for detecting Gabor patches on attended trials (i.e., validity effects), as well as a stricter response criterion, with participants adopting more conservative responses when stimuli were unattended. These findings align with Chica et al. (2011), who dissociated between endogenous and exogenous spatial attention in conscious perception (see also Vernet et al., 2019). Unlike endogenous attention, exogenous orienting appears to play a crucial role in conscious perception. Electrophysiological evidence supports this claim, showing that attentional engagement by a peripheral spatial cue, as indexed by the early P1 component, correlates with conscious reports of near-threshold targets (Chica et al., 2010; see also Chica et al., 2012). Together, these results suggest that exogenous spatial attention is a key modulator of conscious perception. Beyond perceptual sensitivity, spatial attention also affected response criterion, with participants adopting a more conservative criterion for unattended compared to attended trials, a pattern largely consistent with previous findings (Chica et al., 2011; Spagna et al., 2023; but see Rahnev et al., 2011).

A final result regarding spatial attention was the presence of Inhibition of Return (IOR) in Experiment 3, which used fully visible Gabor patches. In this case, participants were slightly faster on unattended than on attended trials. Although not the main focus of the study, this finding supports the idea that spatial validity effects, commonly observed in more demanding detection or discrimination tasks, can reverse to IOR in simpler tasks, such as detection of supra-threshold targets (Klein, 2000; Lupiáñez et al., 2006). Indeed, although in Experiment 2 participants performed a detection task, discriminating signal from noise at near-threshold levels was still challenging. This probably explains why validity effects, rather than IOR, were observed. Notably, although the IOR effect did not emerge in Experiment 3b-control, a combined analysis across both experiments confirmed its reliability with supra-threshold targets, indicating that the null result observed in the control experiment was likely attributable to limited statistical power.

Overall, our results support the role of exogenous spatial attention in conscious perception and extend them using a different cueing manipulation, namely the repetition of a series of stimuli rather than the abrupt onset of a salient peripheral cue. They also suggest that a more visible context (75% visibility) is optimal for fully capturing the effects of exogenous spatial attention on conscious perception, which might suggest that the effect of exogenous attention under these perceptual conditions might be related to response gain mechanisms (Herrmann et al., 2010).

In contrast to spatial attention, rhythmic temporal attention did not enhance visual awareness. In Experiment 1, perceptual sensitivity was higher for irregular than for regular rhythms. This unexpected result contrasts with Mathewson et al. (2010), who found that near-threshold targets presented in-phase with a preceding rhythm were detected with greater sensitivity than out-of-phase targets. A key difference is that, in their study, all stimuli were presented at fixation, eliminating spatial uncertainty. A follow-up study (Kizuk & Mathewson, 2017), combining bilateral rhythms with an endogenous spatial manipulation, further showed that rhythmic modulation of target detection was stronger in the unattended spatial condition. Direct comparison with the present findings is difficult, however, as the studies differed in several critical aspects, including the use of endogenous versus exogenous spatial cues, bilateral versus unilateral rhythmic stimulation, and task demands (simple detection versus combined detection and localization). In the present study, rhythmic temporal and exogenous spatial attention did not interact to influence perceptual sensitivity; instead, only a significant main effect of rhythm emerged in Experiment 1.

The finding that irregular rhythms improved conscious perception more than regular ones remains puzzling. As noted above, one possible explanation is that irregular temporal sequences may have enhanced alertness, which has been associated with greater conscious access (e.g., Cobos et al., 2019; Kusnir et al., 2011). For example, Kusnir et al. (2011) reported that alerting tones presented before the onset of a near-threshold target increased both perceptual sensitivity and response criterion, suggesting that the alerting network can boost activity in fronto-parietal systems supporting the top-down amplification required for consciousness (Dehaene et al., 2006). Our speculation that irregular rhythms were more alerting than regular ones could fit this framework. However, this should be treated with caution, as Kusnir et al. (2011) employed stimuli with 75% visibility, whereas in our study irregular rhythms improved perceptual sensitivity only at the lowest visibility level (50%), not the highest (75%). In addition, the Bayesian analysis (conducted with a random-intercepts-only implementation) provided inconclusive evidence for including the main effect of rhythm in the model. Taken together, these results suggest that, at least under our experimental conditions, rhythmic temporal attention did not enhance conscious perception as expected, with no observed benefit of regular rhythms over irregular ones.

Another unexpected finding was the absence of a significant main effect of rhythm on response preparation across Experiments 1–3. Prior studies using similar rhythmic sequences (Attout et al., 2024; Charras et al., 2023; Cutanda et al., 2015) have shown that regular rhythms elicit faster responses than irregular rhythms in simple detection tasks. The main difference in our study was the inclusion of a subsequent localization task, which may have induced participants to prioritize accuracy over response preparation, even in Experiment 3 with supra-threshold targets. Supporting this interpretation, Experiment 3b-control, in which only the detection response was required, showed slightly faster RTs for regular compared to irregular rhythms. Reconciling these results with prior literature is challenging due to several methodological differences. Nevertheless, null effects of rhythmic temporal attention on behavior are increasingly reported, specifically regarding the proposed "entrainment" benefit of regular rhythms, commonly measured as faster or more accurate responses to in-phase versus out-of-phase targets (e.g., Bauer et al., 2015; Elbaz & Yeshurun, 2020; Jones, 2015; Lin et al., 2022; Román-Caballero et al., 2024).

Recent evidence further indicates that regular rhythms do not always confer behavioral advantages over irregular rhythms, even when target timing is fixed. For example, de Graaf and Duecker (2022) used a design closely resembling ours, combining rhythmic stimulation with spatial attention. In their study, participants were exposed to rhythmic versus arrhythmic alpha-frequency visual flashes in one hemifield and responded to visual targets presented ipsilaterally or contralaterally, with or without distractors. They found no significant effect of rhythm on RTs or on its interaction with spatial attention. In contrast, the spatial congruence between the unilateral rhythm and the subsequent visual target modulated RTs, but only in the presence of contralateral distractors. Given the similarities with our paradigm (unilateral rhythmic stimulation and spatial manipulations), these findings further underscore the fragility of rhythm effects on RTs under specific task conditions. Notably, while de Graaf and Duecker (2022) used rhythms within the alpha frequency range to entrain spatial attention, we employed a much slower sequence and still observed no clear behavioral effect of rhythm, except in the simplest detection-only condition. In both studies, however, the rhythmic sequence length was fixed, and the target always appeared after a predictable number of repetitions. This lack of temporal uncertainty may have reduced participants' reliance on regular rhythms to anticipate target onset, particularly in the presence of distractors or a subsequent localization task. Of note, even when the effect of rhythm reached significance in the simplest Experiment 3b-control, the difference between regular and irregular rhythms was modest (see also Charras et al., 2023). Overall, these findings warrant further investigation to delineate the boundary conditions under which rhythmic temporal attention facilitates, or fails to enhance, behavioral performance and/or visual awareness. Possible follow-up studies could include the use of different rhythmic sequences spanning from faster to slower rates (e.g., Sanabria et al., 2011), varying the number of repetitions to avoid habituation to the rhythms (e.g., Attout et al., 2024), or comparing in-phase versus out-of-phase targets (e.g., Kizuk & Mathewson, 2017).

A final point deserves discussion. Across all experiments, rhythmic temporal and spatial attention interacted only in the analysis of the response criterion index in Experiment 2. This interaction was driven by a larger, significant difference between attended and unattended trials (with more conservative responses in unattended trials) that emerged in the irregular rhythm condition. One possible interpretation is that participants adopted a more conservative response strategy in irregular contexts, whereas regular rhythms may have mitigated this difference. However, given that the Bayesian analysis yielded inconclusive evidence for this interaction, any explanation remains speculative.

Overall, our results suggest that rhythmic temporal and exogenous spatial attention operate largely independently. Whether spatial and temporal attention interact or function independently remains, however, a topic of ongoing debate (e.g., Rohenkohl et al., 2014; Tal-Perry & Yuval-Greenberg, 2022; Weinbach et al., 2015). A key modulating factor appears to be the type of attentional manipulation (endogenous versus exogenous) as well as task demands, such as perceptual difficulty (see Capizzi et al., 2023, for a review). Charras et al. (2023) also showed that the way in which spatial and temporal information is conveyed, through independent versus integrated cues, may influence whether the two types of attention exert additive or interactive effects, respectively. In the present study, both spatial and temporal information were conveyed by the same unilateral cue, suggesting that the two might have competed for shared resources rather than combining synergistically, a possibility that deserves systematic examination in future research.

To conclude, our findings call for caution regarding the role of rhythmic temporal attention in visual awareness, while corroborating the pivotal influence of exogenous spatial attention. Since space and time are fundamental dimensions of perception, further research integrating both factors is needed to elucidate whether and how spatial and temporal attention jointly shape visual awareness.

Ethical approval

This work was approved by the Ethics Committee of the University of Granada (reference number: 1862/CEIH/2020).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT-5 in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Mariagrazia Capizzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pom Charras:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Ana B. Chica:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2026.104040.

Data availability

Raw and processed data are fully available at https://osf.io/75dns. The study was not preregistered.

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