Rhythmic Sampling of Visual Attention: Insights from Temporal Reset and Spatial Cueing Paradigms

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Abstract. Recent research indicates that human visual attention is rhythmic as opposed to continuous, with the level of perceptual sensitivity varying in phase with inherent brain oscillations. The current review summarises behavioural and neurophysiological evidence on two prevailing paradigms, the reset-event dense-sampling paradigm and the spatial-cuing paradigm, which explore attentional sampling. The reset-event paradigm aligns with persistent attentional oscillations by temporally precise visual resets and integrates fine-temporal profiles of sensitivity to detections, demonstrating the theta and alpha band periodicities by indicating the alternations between visual representations. Conversely, the spatial-cuing paradigm studies spatial variations in rhythmic changes of attention to spatial locations following predictive or nonpredictive cues with a hierarchy of slower theta rhythms that aligned faster alpha-band sensory sampling of spatial variations. Collectively, these paradigms yield convergent evidence that the information is sampled rhythmically within time and space, which is regulated by oscillatory neural processes within the frontoparietal and occipital circuits. Nevertheless, each method has its own distinct methodological limitations. The reset-event designs are prone to stimulus-induced confounding, and cueing tasks sacrifice temporal specificity for an ecologically valid design. Combining the strengths of two designs, future studies are suggested to use hybrid paradigms that incorporate both time and space sampling to isolate intrinsic and entrained rhythmic aspects of attention. This synthesis identifies rhythmic attentional sampling as the fundamental principle of perceptual selection, connecting behavioural dynamics to oscillatory brain activities.

Keywords: Rhythmic attention, attentional sampling, reset-event paradigm, spatial-cueing paradigm, theta–alpha oscillations.

1. Introduction

Attention has been viewed as a continuous process that selectively enhances relevant sensory information while suppressing distractors. Nevertheless, it has been discovered in current decades of research that attention varies rhythmically over time through sampling experiments on continuous time stream and spatial locations [1-4]. Findings of this kind of research indicate that perceptual sensitivity and information uptake are inherent but dependent on intrinsic neural oscillations, especially the theta (4-8 Hz) oscillations and alpha (8-12 Hz) oscillations, with more demonstrating that the theta rhythm is active in the visual system.

1.1. Rhythmic Nature of Visual System

One vivid presentation of the rhythmic aspects of visual perception is the continuous wagon-wheel illusion (c-WWI) [5-7]. Whenever a spoke wheel turns on a steady light, sometimes people watching it may think it is moving backwards or moving at rest, this is called temporal aliasing. Unlike its movie equivalent, which is caused by the discrete frame rate of a camera, the c-WWI is observed under natural viewing conditions, suggesting that the visual system itself can periodically sample motion information rather than continuously. This illusion has been associated with psychophysiological and electrophysiological activity as an inherent oscillatory process in the brain, especially the alpha band (10-13 Hz), suggesting that perception is not a continuum, but a discrete series of time slices. This effect has consequently inspired increasing research on attentional sampling of visual representations, examining how variations in neural excitability and the configuration of attentional focus influence the temporal organisation of visual information processing.

1.2. Rationale for Comparing Paradigms

Research on attentional sampling has developed through multiple psychophysical paradigms, offering complementary insights into how attention fluctuates over time under varying task demands. Variation in task demands, measurement precision, and temporal resolution has led to the emergence of several dominant designs, the reset-event paradigm [8] and the spatial-cuing paradigm [9]. While both investigate rhythmic fluctuations of attention, their conceptual pivot differs. The reset-event design aims to synchronise internal oscillations to a defined temporal anchor, whereas spatial-cuing tasks examine endogenous reorienting of attention across space and time. These differences reflect broader theoretical debates concerning whether attentional rhythms are primarily intrinsic neural dynamics or externally entrained processes [1, 5].

While focusing on single paradigm risks, it overgeneralises conclusions about the nature of attentional rhythmicity. For instance, reset-based studies often prioritise temporal precision but may underrepresent spatial flexibility, whereas spatial-cuing tasks capture ecological attentional shifts but are less suited to fine temporal modelling. Moreover, inconsistencies in reported sampling frequencies, ranging from alpha-band (~10 Hz) in sustained attention to theta-band (~4-7 Hz) in divided attention, suggest that paradigm-specific constraints may shape observed outcomes and may also reflect adaptive modulation of attentional load across task contexts [4, 10]. Therefore, comparing paradigms is essential for disentangling methodological artefacts from theoretical differences. The present review aims to synthesise findings across these approaches, identify convergent evidence for rhythmic attentional control, evaluate paradigm-specific limitations, and propose integrative future directions that bridge the temporal and spatial dimensions of attentional sampling.

2. First Paradigm

2.1. Temporal Cueing/Continuous Performance Tasks

One of the most prevailing ways to study rhythmic attention is the reset-event dense-sampling paradigm, which offers unsurpassed estimations of time compared to standard cueing experiments, and that makes it possible to measure the sensitivity of attention continuously over a continuous time stream. Within such paradigms, a brief salient visual reset event has been employed to synchronise the phase of local attentional oscillations, after which target detection performance is sampled across a finely spaced series of temporal intervals. Four representative studies, Landau and Fries , Landau et al. , Re, Karvat, and Landau , and Re, Kusnir, and Landau , illustrate the design and evolution of this approach.

In their work, Landau and Fries developed a behavioural paradigm in which participants fixated centrally while monitoring two drifting gratings, one presented in each visual hemifield. The participants were asked to observe a short 33-millisecond contrast decrement (target) of either of the gratings. There was a flash of four white dots (33 milliseconds) at the position of one of the gratings. This happened randomly within 1.25 to 2.5 seconds following the onset of the stimulus and was a nonpredictive reset stimulus. The purpose of this flash was a nonpredictive reset event, which was aimed at realigning a current attentional oscillation. Targets were then presented at 105 stimulus-onset asynchronies (SOAs) relative to the flash, spanning −750 to +1000 milliseconds in 16.7 millisecond increments. Each trial produced one data point in a dense sampling of detection performance across time, from which an accuracy time course (ATC) was constructed by averaging performance across thousands of trials. In a subsequent neurophysiological experiment, Landau et al. also used a dual-grating configuration, but avoided any explicit reset event. Participants again monitored both gratings for unpredictable contrast decrements while magnetoencephalography (MEG) recorded ongoing neural activity. By doing so, the authors were able to examine endogenous fluctuations in neural phase preceding the target, rather than those aligned by an external stimulus. This adaptation preserved the dual-object attentional demand of the original paradigm but allowed for the investigation of spontaneous oscillatory dynamics. Re, Karvat, and Landau extended the reset-event paradigm to test whether rhythmic attentional sampling occurs even before binocular fusion, suggesting that such rhythmic processes may operate at monocular stages and reflect early sensory-level mechanisms.

Finally, Re, Kusnir and Landau conceptualised the above findings by establishing the reset-event paradigm as a generic method to examine rhythmic attention. This paper described a canonical series of steps followed by such experiments: temporal accurate reset event, intensive sampling of behavioural or neural reactions, and spectral analysis to determine rhythmic variation. It also explained the application of such a methodology to various levels of the visual hierarchy, such as spatial, ocular and feature-based attention.

2.2. Dependent Variables

The main dependent variables across these studies measured a change in perceptual sensitivity or neural activities across time after a reset or relative to the target onset. Detection accuracy was an index of temporal attentional sensitivity in behavioural experiments [4, 11], assessed as a function of the target-to-reset SOA. This resulted in an accuracy time course (ATC) of fine-grained temporal changes in detection probability. The spectral analysis was followed by Fourier spectral analysis techniques that identified the periodicity in the ATC, especially in the theta (4-7 Hz) or alpha (8-12 Hz) bands. This analysis was further improved by Re et al. , which modelled the aperiodic 1/f component of behavioural time series in order to guarantee that peaks of a phenomenon were linked with periodic modulation instead of slow trends or noise.

Furthermore, several studies have also observed relationships between phases of competing representations. In Landau and Fries , oscillations in detection accuracy at the two spatial locations were found to be anti-phased, whereas Re et al. reported anti-phased oscillations between the two eyes. These phase relationships were taken as evidence for serial, alternating sampling by attention.

2.3. Paradigm-Based Revelation of Attentional Rhythmicity

By demonstrating that perceptual performance varies periodically in time after a temporally aligned reset, the reset-event paradigm reveals rhythmic attention. If attention samples sensory input rhythmically, resetting its phase should cause these oscillations to align across trials. Researchers are able to reconstruct a continuous time course of attentional sensitivity by densely sampling performance at numerous SOAs. This time course's notable periodic components show that attention functions cyclically as opposed to continuously.

According to Landau and Fries , behavioural performance showed anti-phase relationships between the left and right hemifields and oscillated at about 4 Hz after the flash. This pattern, which was in line with a sequential sampling model, showed that attention alternated rhythmically between two spatial locations at theta frequency. Landau et al. extended the result further, showing that in the absence of a reset event, the theta-phase of persisting LGA was a predictor of detection probability. This finding demonstrated that attentional sampling is an intrinsic, ongoing, and naturally occurring nervous system oscillation that is not triggered by outside influences. Re, Karvat, and Landau further demonstrated that attentional sampling can occur as early as the monocular level of processing. In contrast to monocular channel resets, which resulted in 4 Hz oscillations that were anti-phased between the two eyes, binocular channel resets caused detection to oscillate around 8 Hz, which is consistent with concentrated attention on a single object. These results imply that the sampling frequency is determined by the number of concurrently competing representations, with divided attention corresponding to theta rhythms and single-object attention to alpha rhythms.

2.4. Strengths and Limitations

The main benefit of this paradigm is that it can measure time with sub-second accuracy, which makes it possible to create detailed statistical maps of how attentional sensitivity changes over time. Detecting sampling targets in 10 to 20 millisecond intervals enables the reconstruction of attentional dynamics at sub-second resolution. The paradigm is also non-invasive and very flexible, making it good for both behavioural experiments and neuroimaging techniques like EEG and MEG. This lets researchers look at rhythmic attentional processes from different angles. Additionally, the incorporation of a reset event establishes a distinct temporal reference, synchronising the attentional phase across trials and facilitating significant spectral averaging. Its logic has demonstrated domain-general applicability, encompassing spatial attention, ocular competition, and potentially feature-based competition, indicating a unifying mechanism.

Despite its utility, the paradigm also faces important limitations. The most significant issue is that the reset event, usually a brief visual flash, might disrupt target processing by masking or temporarily suppressing sensory input, which could confuse rhythmic effects with stimulus-driven artefacts. Furthermore, hemispheric and dominance asymmetries have been noted, exemplified by more pronounced effects for right-field or right-eye resets, potentially indicating sensory biases rather than attentional rhythms. Finding rhythmicity with spectral analysis is also methodologically sensitive because detrending methods and window parameters can change the apparent frequency peaks. Additionally, although MEG and EEG studies yield converging evidence, these metrics remain correlational and cannot conclusively identify causal neural generators. Subsequent research utilising brain stimulation methodologies, including TMS or tACS, may elucidate the causal neural mechanisms associated with rhythmic attentional sampling. Finally, the paradigm's ecological validity is limited, as it employs repetitive, low-load visual tasks far removed from natural attentional behaviour, and its reliance on long, high-trial-count sessions introduces participant fatigue.

3. Second Paradigm

3.1. Spatial Sampling / Spatial Attention Tasks

Spatial pre-cueing paradigms have also been used to study rhythmic sampling of attention. These paradigms focus on how attention moves between different locations over time, rather than how it resets itself. In this design, a cue temporarily directs spatial attention to a specific location, followed by target or probe stimuli presented at varying time intervals to uncover potential periodic variations in perceptual sensitivity or behavioural performance. Although each study adopted this general framework, the precise timing structure, cue type, and analytic focus differed in ways that shaped their sensitivity to rhythmic attentional processes.

Song et al. used an exogenous, uninformative peripheral pre-cueing paradigm that has since become a reference for behavioural experiments of attentional oscillations. Participants fixated on the centre as two peripheral placeholder boxes were presented to the left and right of the fixation cross. A brief peripheral cue (a luminance change at one box) appeared for 50 ms but did not predict the target location with only 50% validity. Following the cue, a target stimulus, a circle or square, was presented at one of the two locations after a variable stimulus-onset asynchrony (SOA) ranging from 200 to 1100 ms. Crucially, the SOA was manipulated in very fine increments of 20 ms, allowing for dense temporal sampling of behavioural responses. Participants performed a rapid shape-discrimination task on the target. With around 880 trials for each participant and reaction times (RTs) z-scored and detrended, the resulting RT time series based on the cue-target interval offered a high-resolution metric from which rhythmic fluctuations could be derived. The eye position of a subset of participants was observed to ensure fixation stability.

Senoussi et al. employed an endogenous spatial attention paradigm designed to differentiate between rhythmic reorientation of attention and localised sensory sampling. Participants focused on a central fixation cross while an arrow cue in the middle showed where the next visual grating stimulus was most likely to appear, in one of two lower quadrants, with 75% validity. After a fixed 350 ms cue–stimulus interval, two oriented gratings were shown for a short time to see how attention affects the processing of visual inputs that are happening at the same time. Following a short delay, a central response cue indicated which grating's orientation participants should report. Importantly, at different times after the stimulus ended, the authors showed short probe stimuli, called Landolt squares, at both places. The authors calculated an estimate of attentional allocation over time at each spatial position by combining the joint probabilities of correct and incorrect probe identifications across locations. This "attention read-out" was taken at different time delays, which made it possible to continuously build up the attentional time course. Each observer completed about 1,872 trials, which made it possible to get stable spectral estimates of how attention changes over time.

3.2. Dependent Variables

All studies relied on time-resolved behavioural indices of attentional efficiency to capture dynamic fluctuations of attention. However, these measures may conflate perceptual and decisional processes, and they varied in their specific dependent measures and analytical approaches. Song et al. examined reaction time (RT) in relation to cue validity and stimulus onset asynchrony (SOA). After normalising and detrending to eliminate slow expectancy effects, the authors calculated the power spectrum of the RT time course and analysed the phase relationships between valid and invalid locations. They also conducted cross-frequency coupling analyses to examine how slow (3–5 Hz) and fast (8–20 Hz) changes in performance interacted. In comparison, Senoussi et al. used a more direct probabilistic measure of attentional allocation derived from probe report accuracy. For each probe latency, they calculated the proportion of attention allocated to the cued and uncued locations based on probabilities of correct and incorrect probe responses. This measure produced a continuous time series of attention probabilities at each location, enabling Fourier transforms to discern dominant oscillatory frequencies. The accuracy of orientation discrimination in the grating task functioned as a supplementary metric for perceptual performance.

3.3. Paradigm-Based Evidence for Rhythmic Attentional Dynamics

In Song et al. , rhythmicity was derived from systematic oscillations in reaction times as a function of the cue–target interval. Spectral analysis of the RT time courses demonstrated substantial power within the 8–20 Hz range, indicating an alpha-to-beta-band rhythmic variation in behavioural performance that corresponds to periodic modulation of attentional engagement. Also, the phase of these faster oscillations switched between the cued and uncued locations. This suggests that attention samples multiple spatial positions in a rhythmic way instead of staying focused on one. The alternation was itself modulated by a slower 3–5 Hz theta rhythm, suggesting a cross-frequency hierarchy in which theta cycles coordinate faster perceptual sampling cycles. The presence of such rhythmicity, observed after the cue reset and independent of slow expectancy effects, provided robust evidence that attentional allocation varies cyclically over time. Whereas Senoussi et al. extended this experiment rationale by reconstructing the attentional time course directly from probe-based measurements. They found that during the reorienting period, when the cue was invalid and attention had to shift to the opposite location, the estimated probability of attending to each location oscillated at approximately 4 Hz, corresponding to the theta frequency range. In contrast, within each individual location, alpha-band (~11 Hz) fluctuations were observed, consistent with local sensory sampling cycles. These findings supported a hierarchical model in which global attentional exploration (shifting between locations) is governed by a slower theta rhythm, while local sensory processing within a selected region follows faster alpha cycles, suggesting that slower global shifts may modulate faster local sensory sampling rhythms.

3.4. Strengths and Limitations

Together, these paradigms demonstrate how precisely timed spatial cueing tasks can expose the rhythmic organisation of attention. The strength of Song et al.'s paradigm lies in its dense SOA sampling (20-ms resolution), which offers fine frequency resolution and strong statistical power for detecting oscillatory evidence. The inclusion of both valid and invalid cueing conditions further facilitates the examination of inter-hemifield phase relationships. However, as the dependent measure was reaction time, the rhythmic effects could reflect not only perceptual sampling but also fluctuations in decision or motor processes. Moreover, the use of an uninformative exogenous cue limits its generalisation to voluntary attentional control.

Senoussi et al.’s paradigm addressed some of these concerns by directly estimating attentional allocation at each location, thereby reducing reliance on RTs and enabling the separation of reorienting and local sampling rhythms. The task offered a more cognitive, endogenous manipulation of attention with strict gaze control. Nevertheless, its analytical method relies on model-based estimation of attention probabilities obtained from joint response statistics, which assumes independence across trials and may therefore oversimplify the continuous and dynamic nature of attentional fluctuations. The unequal number of valid and invalid trials also requires careful subsampling to prevent spectral bias, and the dual demands of orientation and probe identification tasks may introduce additional cognitive load.

4. Conclusion

The reviewed paradigms, the reset-event and spatial-cuing approaches, offer complementary perspectives on the temporal dynamics of attention. Both paradigms demonstrate that attention functions in rhythmic cycles rather than through continuous engagement, providing complementary temporal and spatial insights into the unfolding of attentional dynamics. Together, they provide convergent behavioural and neurophysiological evidence that attentional sampling reflects a fundamental mechanism coordinating perceptual selection across the visual hierarchy.

4.1. Converging Evidence for Rhythmic Attentional Control

Both paradigms support the view that attention fluctuates rhythmically, often within the theta-to-alpha frequency range (4–8 Hz). The reset-event paradigm captures its periodicity by a salient event that resets ongoing oscillations followed by fine-grained temporal sampling of detection performance [3, 4, 8, 11]. In contrast, the spatial-cuing paradigm detects similar rhythmic modulations during the reorientation of attention between cued and uncued stimuli [10, 12]. Across both methods, performance oscillations corresponding to fluctuations in neural excitability are successfully observed in EEG, MEG, and intracranial recordings, restating the link between behavioural rhythms and low-frequency neural oscillations in frontoparietal and occipital hierarchies. These convergences indicate that attentional sampling is not task-specific, but a general organising principle of selective processing adopted by the human brain.

4.2. Paradigm-specific Insights

The reset-event paradigm excels in separating intrinsic rhythmic dynamics by using dense temporal sampling following a controlled reset. This design allows high temporal resolution and direct mapping of behavioural oscillations, making it particularly powerful for inferring frequency-specific attentional cycles. Furthermore, the observation that sampling frequency halves when attention is distributed across multiple competing stimuli, 8 Hz for single object focus and 4 Hz for two objects, offers strong evidence that rhythmic sampling serves as a mechanism to resolve neuronal competition. Such competition is consistent with biased competition theory, in which neural populations representing different stimuli alternate in activation due to limited shared resources along the visual hierarchy. The paradigm thus places attentional sampling as an emergent trait of hierarchical cortical dynamics rather than as a purely top-down control process.

Conversely, the spatial-cuing paradigm emphasises the dynamic deployment of attention across space by adding a time gap between the cue and target and testing detection performance at different times. Its ecological robustness lies in modelling naturalistic attentional shifts, where attention periodically disengages and reorients. The paradigm also directly links behavioural sampling to neural oscillations in frontal eye fields and parietal cortex, consistent with electrophysiological findings that theta-phase activity modulates visual sensitivity and gamma power in these regions. Unlike the reset-event design, which assumes internal rhythmicity, the spatial-cuing approach highlights how external cues entrain attentional oscillations and synchronise them with task-relevant events.

4.3. Methodological and Interpretational Challenges

Despite their complementary strengths, both paradigms face methodological challenges that compromise their interpretations. In the reset-event paradigm, the reliance on an external event to synchronise attention raises questions about whether the observed rhythms are naturally intrinsic or partially stimulus-driven. Additionally, there is still question about whether statistical methods can find rhythmicity in behavioural time courses, since aperiodic noise or the way trials are set up can make frequency peaks appear. Recent improvements like surrogate-based null models and phase-consistency analyses have made reliability stronger, but there is still no agreement on the best methods.

The spatial-cuing paradigm, by contrast, trades temporal precision for ecological validity. Because attentional reorienting inherently involves multiple overlapping processes, expectancy, motor preparation, and perceptual gating, it can be difficult to distinguish whether rhythmic fluctuations reflect true attentional sampling or extensive sensorimotor cycles. Additionally, behavioural oscillations in cueing tasks frequently exhibit variations in frequency based on spatial distance, task complexity, or target quantity, thereby limiting cross-study comparisons.

4.4. Future Directions

Future research should aim to bridge these paradigms by combining temporal precision from reset-event designs with the spatial dynamics of cueing tasks. Hybrid paradigms could use spatially distributed reset events or continuous tracking tasks to reveal how intrinsic attentional rhythms adapt to environmental demands. Simultaneous EEG or MEG recording would also help determine whether behavioural rhythms arise from intrinsic phase resets, external entrainment, or both. Additionally, cross-modal extensions, such as auditory–visual cueing, could test whether rhythmic sampling is a domain-general cognitive mechanism. Finally, computational models that combine biased competition and oscillatory phase coding could show how rhythmic attention deals with perceptual competition over time and space.

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