The Effect of Temporal Structure Cues on Predictive Motion in the Blocking Paradigm

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Abstract

The task of determining when an occluded moving object will reach a certain target position is called a predictive motion task. Currently, the mechanism by which temporal structure influences predictive motion tasks in occlusion paradigms remains unclear. Experiment 1 employed a continuous experiment to investigate the effect of temporal structure on predictive motion, with results showing that compared to conditions with different temporal structures, identical temporal structures could significantly improve participants' task performance; Experiment 2 used a flicker experiment to isolate the effect of visual speed on predictive motion, with results showing that identical temporal structures could also improve participants' task performance; Experiment 3 investigated the effect of temporal structure on predictive motion under interference conditions through a random experiment, with results showing that identical temporal structures also increased the accuracy of participants' judgments. This study demonstrates that in predictive motion tasks, identical temporal structure is a key factor in improving individual task performance, and its effect exhibits stability within the visual modality.

Full Text

The Impact of Time Structure Cues on Prediction Motion in the Interruption Paradigm

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Abstract

The task of judging when an occluded moving object will arrive at a target location is known as a prediction motion task. Currently, the mechanism by which temporal structure influences prediction motion tasks within the interruption paradigm remains unclear. Experiment 1 employed a continuous procedure to investigate the effect of temporal structure on prediction motion, revealing that identical temporal structures significantly improved participant performance compared to non-identical structures. Experiment 2 utilized a flicker procedure to isolate the influence of visual velocity, demonstrating that identical temporal structures still enhanced performance. Experiment 3 employed a random presentation procedure to examine the stability of temporal structure effects under interference conditions, showing that identical temporal structures also increased judgment accuracy. These findings indicate that temporal structure congruence is a critical factor for enhancing individual performance in prediction motion tasks, and that this effect demonstrates stability within the visual modality.

Keywords: prediction motion, rhythm, temporal structure, interruption paradigm

Introduction

In daily life, people frequently need to accurately estimate when a moving object will reach a particular location to guide future actions (Teichmann et al., 2021), such as catching a ball, crossing a street, or braking to avoid obstacles. The task of judging when a moving object will arrive at a target location is termed a visual motion inference task. In laboratory settings, researchers typically employ the prediction motion paradigm to investigate the processing mechanisms underlying visual motion inference. In this paradigm, participants must judge when an occluded moving stimulus will reach a target location and then execute a keypress response (Makin, 2018).

How do humans process moving objects that become occluded? Initially, researchers used tau theory (Guo et al., 2000; Lee, 1976; Lee et al., 1983) to explain processing mechanisms in prediction motion tasks. Tau theory proposes that the ratio (τ) between the visual angle subtended by a moving stimulus on the retina and the rate of change of this angle can be used to infer the remaining time until the stimulus arrives. For instance, when a stimulus moves toward an observer, the remaining time can be calculated using $\tau = 2\ \ / \mathrm{d}(2\ )/\mathrm{d}(\mathrm{t})$, where   represents the visual angle and d(2)/d(t) represents its rate of change. However, this theory only applies to situations involving relative motion directly toward the observer' s eyes, substantially limiting its applicability since most naturalistic movements requiring responses are not directly collinear with the observer' s gaze. Consequently, an increasing number of researchers now employ cognitive strategies to explain prediction motion processing (Baurès et al., 2021; Law et al., 1993).

Cognitive strategies posit that individuals construct a mental representation of an object' s motion based on its kinematic information to simulate its movement patterns and predict future positions (Watamaniuk & McKee, 1995). For example, Makin and Poliakoff (2011) found that participants' velocity representations of visible motion stimuli determined their performance in prediction motion tasks. Liu and Huang (1991) demonstrated that distance, velocity, and acceleration significantly affected task performance, with shorter occlusion distances, faster velocities, and accelerating motion all improving accuracy. According to cognitive strategy models, as the visible distance traveled by a stimulus increases, individuals' representations of its visual velocity become increasingly accurate, leading to improved performance. However, research has found that when visible and occluded distances are equal, participants exhibit smaller response biases and better performance (Baurès, Balestra, et al., 2018), suggesting that temporal variables may play an important role in prediction motion tasks —a phenomenon that cognitive strategies struggle to explain adequately.

Time, as a crucial attribute of moving objects, has long remained underexplored in prediction motion research. Broadly defined, temporal structure (T) refers to the distribution pattern of information along the temporal dimension. In cognitive psychology, the classification of temporal structures is essential for explaining their role in motion tasks (Spencer et al., 2003; Zelaznik et al., 2002). One classification is based on the regularity of stimulus presentation timing, commonly employed in laboratory settings using auditory or visual stimuli presented at fixed frequencies. This structure provides stable temporal expectancy cues that facilitate rhythmic perception and response regulation in motion tasks (Hove et al., 2010). Another classification is based on the regularity of stimulus transformation patterns, such as periodic modulation of a physical attribute, whose cyclical nature enables individuals to predict subsequent changes and plan actions accordingly, demonstrating the predictive quality of temporal structure (Hove et al., 2013). Previous research has shown that both presentation-based and transformation-based temporal structures share three fundamental characteristics: rhythmicity, hierarchical organization, and predictability (Hu et al., 2019), and that individuals can leverage these features to facilitate object recognition (Miller et al., 2013), perceptual organization (Alais & Blake, 1998), unconscious processing (Bauer et al., 2009), and attentional allocation (Jones & Boltz, 1989). Although syntactic-based temporal structures exist in other contexts (e.g., natural language and music), they fall outside the scope of the present motion task research and will not be discussed further.

In the prediction motion domain, researchers have proposed an operational definition of temporal structure based on stimulus motion patterns: the ratio of movement time in visible versus occluded portions (Chang & Jazayeri, 2018; Qin et al., 2022). Temporal structure congruence ($T = 1.0$) occurs when movement time in the visible phase equals that in the occluded phase, whereas incongruence ($T \neq 1.0$) occurs when these durations differ. Previous studies demonstrate that temporal structure significantly affects prediction motion performance (Qin et al., 2022), with identical temporal structures ($T = 1.0$) yielding superior performance compared to non-identical structures (T ≠ 1.0). The similarity between temporal structure congruence in prediction motion tasks and isochronous interval segmentation in time estimation tasks suggests shared processing mechanisms. Research on time estimation shows that isochronous interval segmentation improves temporal judgment performance (Jazayeri & Shadlen, 2010), and prediction motion studies similarly find that identical temporal structures enhance performance (Qin et al., 2022). However, important distinctions exist: time estimation research focuses broadly on how different interval segmentation methods affect performance, whereas the present concept of temporal structure congruence is task-specific, examining the proportional relationship between visible and occluded movement durations in prediction motion contexts.

Prediction motion tasks employ two common paradigms: occlusion and interruption. In the occlusion paradigm, participants judge when an occluded moving stimulus will reach a target location and press a key accordingly. In the interruption paradigm, participants determine whether a stimulus reappearing at the target location arrived earlier or later than expected. While the occlusion paradigm is straightforward and requires fewer trials—making it the predominant method for investigating temporal structure effects (e.g., Baurès, Balestra, et al., 2018; Qin et al., 2024)—research suggests that participants might exploit the changing angle between stimulus motion direction and gaze direction to estimate arrival time, potentially confounding the effects of temporal structure. The interruption paradigm offers a unique advantage: the interval between occlusion and target appearance varies dynamically, making it difficult for participants to use gaze-motion angle changes, thereby eliminating this confound. This design overcomes occlusion paradigm limitations and enables more precise examination of temporal structure effects.

Therefore, the present study employs the interruption paradigm to investigate temporal structure effects on prediction motion tasks. Since no previous research has used this paradigm to explore temporal structure in prediction motion, Experiment 1 first implemented a classic interruption task where a stimulus moved from start to target, became occluded at an interception point, and later reappeared at the target location, with participants judging whether arrival was early or late. However, classic interruption paradigms cannot eliminate visual velocity interference. Consequently, Experiment 2 removed visual velocity cues to isolate temporal structure effects. Experiment 3 employed a random presentation procedure to examine the stability of temporal structure effects under interference conditions. Collectively, this research systematically investigates temporal structure effects on prediction motion using the interruption paradigm, with two innovative contributions: (1) Conceptually, time as a fundamental attribute of moving objects has received limited direct attention in prediction motion research. This study focuses on temporal structure' s role, enriching theoretical perspectives. (2) Methodologically, the interruption paradigm' s dynamic occlusion-to-appearance intervals avoid gaze-motion angle confounds, enabling more precise temporal structure examination. Theoretically, this research extends cognitive strategy models, which propose that individuals construct motion representations from kinematic information but inadequately address temporal factors. By verifying temporal structure’ s impact on judgment accuracy and sensitivity, we expand the temporal dimension of cognitive strategy models, laying empirical groundwork for a unified spatiotemporal integration framework. Additionally, this work broadens temporal structure applications in cognitive psychology, extending beyond object recognition and perceptual organization to prediction motion tasks, thereby deepening understanding of temporal structure mechanisms across cognitive domains.

Experiment 1: Continuous Procedure

Participants

Sample size was calculated using G*Power 3.1. Based on previous research with a medium effect size of f = 0.30, a sample of 20 participants would achieve 80% statistical power at $\alpha = 0.05$ for detecting temporal structure effects. To account for potential attrition, 25 university students were recruited (11 male, 14 female; aged 19–22 years). All participants had normal or corrected-to-normal vision, were right-handed, and had no prior experience with similar experiments. The study was approved by Shaanxi Normal University’ s Human Subjects Research Ethics Committee. Participants provided informed consent and received compensation after completing the experiment. Two participants were excluded for overall accuracy below 70% and single-condition accuracy below 60%, leaving a final sample of 23 participants.

Experimental Task

In this continuous procedure, a blue square moved from a starting point toward a target location on the right side of the screen. Upon reaching an interception point, the square became occluded, and after a delay, reappeared at the target location (see Figure 1 [Figure 1: see original paper], left panel). Participants judged whether the square arrived earlier or later than expected, pressing corresponding keys. The occluded segment remained constant at 8° of visual angle, while visible segments measured 4°, 8°, and 12°. The square’ s velocity remained constant across trials, yielding temporal structure ratios (visible time to occluded time) of 0.5, 1.0, and 1.5.

Procedure

The experiment was programmed in PsychoPy 3.0 and employed a single-factor, three-level (T: 0.5, 1.0, 1.5) within-subjects design. The T = 1.0 condition represented temporal structure congruence, while T = 0.5 and T = 1.5 represented incongruence. Each trial began with a black background displaying the start point, interception point, and target location (vertical line on the right). After a random delay of 0.2–0.5 s, the blue square moved uniformly from the start point toward the target. Upon reaching the interception point, it became occluded. After an occlusion interval, the square reappeared at the target location.

Participants judged whether arrival was early or late, pressing "F" for early and "J" for late.

In the three temporal structure conditions, pre-interception distances were 4°, 8°, and 12°, while post-interception distance remained fixed at 8°. The square' s velocity was constant at 5.33°/s, resulting in visible-phase durations of 0.75, 1.5, and 2.25 s, and an occluded-phase duration of 1.5 s (theoretical arrival time). This yielded the three temporal structures of 0.5, 1.0, and 1.5. However, during the experiment, the square actually appeared at the target at 0.8, 1.1, 1.2, 1.45, 1.55, 1.8, 1.9, and 2.2 s after entering occlusion. The first four times represented early arrival, while the latter four represented late arrival, with deviations from theoretical arrival time of -0.7, -0.4, -0.3, -0.05, 0.05, 0.3, 0.4, and 0.7 s. All eight occlusion durations were included across the three temporal structures, creating 24 experimental conditions, each repeated 20 times for a total of 480 trials. Participants completed 24 practice trials (one per condition) before the formal experiment, which lasted approximately 80 minutes.

Data Analysis

For each participant and temporal structure condition, we calculated the percentage of "late" responses (J key) and fitted logistic functions using R (Linares & López-Moliner, 2016) to derive two key measures: the point of subjective equality (PSE) and just noticeable difference (JND). PSE represents the x-axis value corresponding to 50% on the fitted curve. A PSE of 0 indicates responses match theoretical values, with greater distances from 0 indicating larger biases. Positive PSE values reflect a tendency to respond early (underestimating arrival time), while negative values reflect a tendency to respond late (overestimating arrival time). However, PSE alone cannot indicate judgment accuracy, so we used absolute PSE (aPSE) values to represent estimation accuracy, with smaller values indicating greater precision. JND was calculated as half the difference between the x-values corresponding to 75% and 25% on the fitted curve (semi-interquartile difference), reflecting sensitivity to temporal structure differences, with smaller values indicating higher sensitivity. For repeated-measures ANOVA, Mauchly' s test assessed sphericity; when violated, Greenhouse-Geisser corrections were applied.

Results

Figure 2 [Figure 2: see original paper]A presents PSE values from Experiment 1. A one-way repeated-measures ANOVA revealed significant differences across temporal structure conditions, $F(2,44) = 27.64$, $p < 0.001$, $p^2 = 0.557$. Post-hoc tests showed PSE at $T = 0.5$ was significantly greater than at $T = 1.0$ ($p < 0.001$) and $T = 1.5$ ($p < 0.001$), and PSE differed significantly between $T = 1.0$ and $T = 1.5$ ($p = 0.002$), indicating significant differences in response bias across conditions.

A one-way repeated-measures ANOVA on aPSE values (Figure 3 [Figure 3: see original paper]A) revealed significant performance differences across temporal structures, F(2,44) = 6.38, p = 0.010, $p^2 = 0.225$. Post-hoc tests showed aPSE at T = 1.0 was significantly smaller than at T = 0.5 (p = 0.002) and T = 1.5 (p = 0.001), indicating superior performance under temporal structure congruence. No significant difference emerged between T = 0.5 and T = 1.5 (p = 0.348), suggesting equivalent performance across incongruent conditions.

Analysis of JND values (Figure 3B) also revealed significant differences, F(2,44) = 5.33, p = 0.015, $p^2 = 0.195$. Post-hoc tests showed JND at T = 1.0 was significantly smaller than at T = 0.5 (p = 0.007) and T = 1.5 (p = 0.017), indicating greater sensitivity to temporal structure congruence. No significant difference appeared between T = 0.5 and T = 1.5 (p = 0.363), suggesting comparable sensitivity across incongruent conditions.

Discussion

Experiment 1 demonstrated that temporal structure cues significantly affect prediction motion performance. PSE analysis revealed that at T = 0.5, participants tended to respond early (underestimating arrival time) compared to T = 1.0 and T = 1.5, while at T = 1.5 they tended to respond late (overestimating arrival time) relative to T = 1.0. These results show that temporal structure influences response bias, with congruent structures providing clear, stable external timing cues that reduce estimation uncertainty and minimize bias. At T = 0.5, participants may have over-relied on representations formed during the visible phase, neglecting the potentially longer occlusion duration and thus underestimating total movement time; the opposite pattern occurred at T = 1.5, leading to overestimation.

aPSE analysis revealed that temporal structure congruence significantly improved performance compared to incongruence, consistent with previous findings (Qin et al., 2024). JND analysis further showed that sensitivity was significantly higher under congruent conditions, indicating that reliable task cues enable better discrimination of temporal intervals. These results demonstrate that temporal structure congruence enhances performance, likely because when stimuli move with fixed frequency or equal interval durations, individuals can use rhythmic properties for estimation. In the present experiment, the congruent condition created rhythmicity by equating visible and occluded movement durations. This rhythmicity modulates attentional resource distribution through expectancy generation, directing attention to specific time points (Hu et al., 2019). Research shows that people detect stimuli appearing at expected beat positions more effectively. Thus, in the congruent condition, participants likely used the stimulus’ s rhythmic properties, distributing attentional resources to the anticipated arrival moment based on pre-occlusion timing. When temporal structures were incongruent, this reliable cue was unavailable, resulting in poorer performance.

These findings indicate that temporal structure significantly influences prediction motion. However, Barnes (2008) found that in visual tracking tasks, individuals store stimulus velocity in working memory and use this representation to continue tracking during occlusion. Similarly, occlusion paradigm studies show that working memory velocity representations guide gaze until the stimulus reaches the target (Makin & Poliakoff, 2011). Chang and Jazayeri (2018) also found that visible pre-occlusion motion enables integration of both temporal structure and visual velocity information to enhance performance. Since Experiment 1' s results may have been confounded by visual velocity, Experiment 2 employed a flicker paradigm to mask visible motion trajectories and isolate temporal structure effects.

Experiment 2: Flicker Procedure

Participants

Twenty-nine undergraduate students were recruited (13 male, 16 female; aged 19–21 years). All were right-handed with normal or corrected vision and no prior experience with similar experiments. Participants received compensation after completing the study. Three participants were excluded for overall accuracy below 70% and single-condition accuracy below 60%, leaving a final sample of 26 participants.

Experimental Task, Design, and Procedure

The flicker experiment resembled Experiment 1, except that the blue square was also masked during its movement from start point to interception point (Figure 1 [Figure 1: see original paper], right panel). This manipulation eliminated visual velocity cues to isolate temporal structure effects.

The procedure was as follows: After pressing the spacebar, the stimulus appeared at the start point for 0.1 s, then became masked. Upon reaching the interception point, it reappeared for 0.1 s before continuing toward the target. After a delay, the square appeared at the target location, and participants judged whether arrival was early or late, pressing corresponding keys. The experimental design, procedure, and data analysis mirrored Experiment 1. The primary aim was to eliminate visual velocity interference and examine temporal structure effects in the interruption paradigm.

Results

PSE values from Experiment 2 are shown in Figure 2B. A one-way repeated-measures ANOVA revealed no significant differences in PSE across temporal structure conditions, F(2,50) = 1.13, p = 0.333, indicating comparable response biases.

However, aPSE analysis (Figure 4 [Figure 4: see original paper]A) revealed significant differences across conditions, F(2,50) = 3.90, p = 0.027, p^2 = 0.135. Post-hoc tests showed aPSE at T = 1.0 was significantly smaller than at T =

0.5 (p = 0.035) and T = 1.5 (p = 0.012), indicating superior performance under temporal structure congruence. No significant difference emerged between T = 0.5 and T = 1.5 (p = 0.628).

JND analysis (Figure 4B) also revealed significant differences, F(2,50) = 4.87, p = 0.019, $p^2 = 0.163$. Post-hoc tests showed JND at T = 1.0 was significantly smaller than at T = 0.5 (p = 0.017) and T = 1.5 (p = 0.019), indicating greater sensitivity to congruent temporal structures. No significant difference appeared between T = 0.5 and T = 1.5 (p = 0.281).

Discussion

To eliminate visual velocity effects, Experiment 2 examined temporal structure cues using a flicker paradigm. PSE analysis revealed no consistent response bias across temporal structures. Previous research indicates that participants tend to underestimate arrival time in fast conditions and overestimate it in slow conditions, suggesting that response bias may be influenced by visual velocity. Without visual velocity cues, temporal structure became the primary basis for judgment, potentially requiring greater cognitive resources and resulting in unstable bias patterns. Compared to the intuitive velocity-time relationship in Experiment 1, isolated temporal structure information in Experiment 2 may have prevented rapid, accurate bias formation, making responses more variable and obscuring potential temporal structure effects on response tendency.

aPSE analysis showed that performance was significantly better under temporal structure congruence than incongruence. JND results similarly demonstrated greater sensitivity to congruent structures even without visual velocity cues, consistent with Experiment 1. With visual velocity eliminated, temporal structure served as the primary judgment basis. When temporal structures were congruent, participants could still utilize rhythmic properties for estimation, yielding both higher accuracy and greater sensitivity. These findings further suggest that temporal structure is a primary determinant of estimation accuracy and sensitivity in prediction motion tasks.

Experiment 2 isolated visual velocity to examine temporal structure effects. While PSE results differed from Experiment 1, aPSE and JND findings were consistent, suggesting that response bias may reflect interactive effects of visual velocity and temporal structure, whereas accuracy and sensitivity are primarily influenced by temporal structure. Experiment 3 investigated the stability of temporal structure effects.

Experiment 3: Random Procedure

Participants

Twenty-six undergraduate students were recruited (10 male, 16 female; aged 19–22 years). All were right-handed with normal or corrected vision and no prior experience with similar experiments. Participants received compensation after completing the study. One participant was excluded for overall accuracy below 70% and single-condition accuracy below 60%, leaving a final sample of 25 participants.

Experimental Task, Design, and Procedure

The random experiment resembled Experiment 2, except that before reaching the interception point, the blue square flickered at random positions. This manipulation interfered with stable temporal structure formation based on start-to-interception timing (Qin et al., 2023). For T = 0.5, the stimulus flickered once between start and interception; for T = 1.0, it flickered three times; for T = 1.5, it flickered five times.

The procedure was as follows: After pressing the spacebar, the stimulus appeared at the start point and moved uniformly toward the interception point, flickering randomly one, three, or five times depending on condition. Upon reaching the interception point, it reappeared briefly before continuing toward the target. After a delay, the square appeared at the target location, and participants judged early or late arrival. The experimental design, procedure, and data analysis mirrored Experiment 1. This experiment examined whether temporal structure congruence still improved performance under interference, thereby assessing stability.

Results

PSE values from Experiment 3 are shown in Figure 2C. A one-way repeated-measures ANOVA revealed significant differences across temporal structures, $F(2,48) = 4.06$, $p = 0.039$, $p^2 = 0.145$. Post-hoc tests showed PSE at T = 0.5 was significantly greater than at T = 1.0 ($p = 0.025$) and T = 1.5 ($p = 0.040$), with no significant difference between T = 1.0 and T = 1.5 ($p = 0.335$), indicating significant response bias differences.

aPSE analysis (Figure 5 [Figure 5: see original paper]A) revealed significant differences, $F(2,48) = 9.21$, $p < 0.001$, $p^2 = 0.277$. Post-hoc tests showed aPSE at T = 1.0 was significantly smaller than at T = 0.5 ($p < 0.001$) and T = 1.5 ($p = 0.019$), indicating superior performance under temporal structure congruence. No significant difference emerged between T = 0.5 and T = 1.5 ($p = 0.094$).

JND analysis (Figure 5B) revealed marginally significant differences, $F(2,48) = 3.45$, $p = 0.055$, $p^2 = 0.126$. Post-hoc tests showed JND at T = 1.0 was significantly smaller than at T = 0.5 ($p = 0.006$), but not significantly different from T = 1.5 ($p = 0.084$). No significant difference appeared between T = 0.5 and T = 1.5 ($p = 0.951$), indicating comparable sensitivity across incongruent conditions.

Discussion

To examine stability, Experiment 3 investigated temporal structure effects under interference. PSE analysis showed that at T = 0.5, participants tended to respond early compared to T = 1.0 and T = 1.5, while no significant bias emerged between T = 1.0 and T = 1.5. Random interference caused imbalanced cognitive resource allocation, with attention captured by unpredictable flicker locations and requiring frequent attentional shifts. This reduced resources available for temporal structure processing, increasing response variability. Under T = 1.0 and T = 1.5 conditions, participants may have reallocated cognitive resources to compensate for interference, rendering PSE differences non-significant. In contrast, the short interval at T = 0.5 relied heavily on rapid temporal expectancy updating, which random interference disrupted, producing significant PSE bias.

aPSE analysis confirmed that performance remained superior under temporal structure congruence, consistent with previous experiments. According to temporal structure’ s hierarchical characteristics, basic units can repeat to create rhythms or nest within larger-scale units (Hu et al., 2019). In this experiment, random flicker positions between start and interception created smaller temporal structure units that could not provide effective task cues. Participants likely needed to inhibit these units and rely on larger-scale temporal structure. When temporal structures were congruent, participants could use the start-to-interception interval to generate expectancy and focus attention on the occlusion-to-target interval, whereas incongruent structures failed to provide reliable cues, resulting in poorer performance. However, the non-significant JND difference between T = 1.0 and T = .5 ($p = 0.084$) may reflect insufficient statistical power due to sample size. Although interference reduced performance, rhythmic properties under congruent conditions still enabled relatively accurate judgments. The comprehensive analysis showed no significant accuracy difference between random and flicker experiments, suggesting that within the visual modality, interference did not substantially affect judgment accuracy. We infer that temporal structure effects on prediction motion demonstrate stability in the visual channel.

Previous research shows that distracting stimuli typically impair prediction motion performance. For example, Lyon and Waag (1995) found that distractors moving in the same or opposite direction reduced performance, and Baurès, Maquestiaux, et al. (2018) showed that concurrent working memory tasks affected estimation. However, most studies used dual-task paradigms requiring resource division between tasks, preventing examination of temporal structure stability under full attentional focus. Unlike dual-task interference, random interference disrupts stimulus presentation patterns, allowing observation of performance changes when temporal structure is perturbed within the primary task itself (Qin et al., 2023). This approach reveals temporal structure characteristics and coping strategies when facing unstable temporal patterns. Overall, these findings demonstrate that temporal structure effects in prediction motion are stable, complementing the three fundamental characteristics of temporal structure.

The three experiments also revealed inconsistent effects of temporal structure on response bias across procedures. Experiment 1 showed significant bias differences across temporal structures, Experiment 2 showed stable bias when visual velocity was isolated, and Experiment 3 demonstrated that interference still affected bias, albeit differently. These results collectively indicate that temporal structure' s influence on response bias is complex, warranting further investigation into how temporal structure affects bias across different task contexts.

Comprehensive Analysis

To reduce error and further examine temporal structure effects, we combined data from Experiments 1, 2, and 3 in a mixed-design analysis with 3 (procedure: continuous, flicker, random) × 3 (temporal structure: 0.5, 1.0, 1.5) factors, with procedure as a between-subjects factor and temporal structure as a within-subjects factor.

PSE analysis (Figure 6 [Figure 6: see original paper]A) revealed significant main effects of temporal structure, F(1.41,100.27) = 5.63, p = 0.040, $p^2 = 0.073$, and procedure, F(2,71) = 8.46, $p < 0.001$, $p^2 = 0.192$, with a significant interaction, F(4,142) = 4.65, p = 0.001, $p^2 = 0.116$. Simple effects analysis showed that at T = 0.5, PSE in the random procedure was significantly greater than in the flicker procedure (p = 0.005). At T = 1.0, PSE in the random procedure was significantly greater than in both continuous (p = 0.002) and flicker (p = 0.001) procedures. At T = 1.5, PSE in the continuous procedure was significantly smaller than in both flicker (p = 0.008) and random (p = 0.023) procedures. These results demonstrate significant PSE differences across temporal structures and procedures.

aPSE analysis (Figure 6B) revealed significant main effects of temporal structure, F(2,71) = 16.42, $p < 0.001$, $p^2 = 0.188$, and procedure, F(2,72) = 6.76, p = 0.002, $p^2 = 0.160$, but no significant interaction, F(4,142) = 0.50, p = 0.712. Post-hoc tests showed aPSE at T = 1.0 was significantly smaller than at T = 0.5 ($p < 0.001$) and T = 1.5 ($p < 0.001$), with no significant difference between T = 0.5 and T = 1.5 (p = 0.224). For procedure, aPSE in the continuous procedure was significantly smaller than in the random procedure (p = 0.001), but not significantly different from the flicker procedure (p = 0.090), with no significant difference between flicker and random procedures (p = 0.404).

JND analysis (Figure 6C) revealed a significant main effect of temporal structure, F(2,71) = 13.28, $p < 0.001$, $p^2 = 0.158$, but no significant effect of procedure, F(2,71) = 1.20, p = 0.308, and no significant interaction, F(4,142) = 0.26, p = 0.902. Post-hoc tests showed JND at T = 1.0 was significantly smaller than at T = 0.5 ($p < 0.001$) and T = 1.5 ($p < 0.001$), with no significant difference between T = 0.5 and T = 1.5 (p = 0.800).

General Discussion

This study examined temporal structure effects on prediction motion tasks across different procedures using the interruption paradigm. Experiment 1 demonstrated that temporal structure congruence significantly improved estimation accuracy. However, these results may have been confounded by visual velocity, prompting Experiment 2 to isolate this factor. Results confirmed that temporal structure congruence enhanced accuracy even without visual velocity cues. Building on these findings, Experiment 3 investigated stability under interference conditions, showing that congruent temporal structures still improved accuracy despite distractions, demonstrating stability within the visual modality. These experiments support the hypothesis that temporal structure influences prediction motion performance in the interruption paradigm.

Research indicates that temporal structure affects judgment accuracy in prediction motion tasks. Tresilian (1995) proposed a timing strategy where individuals predict arrival time based on retinal image change rates during visible motion, then count down during occlusion (Bennett et al., 2010). This strategy suggests passive use of temporal information after occlusion (Chang & Jazayeri, 2018). However, our findings show that under congruent temporal structures, participants exhibited not only higher accuracy but also greater sensitivity, indicating active utilization of temporal structure cues rather than passive reception (Qin et al., 2024).

We propose that under temporal structure congruence, individuals use rhythmic properties for estimation. Research shows that fixed-frequency or isochronous stimuli enable rhythm-based estimation (Herrmann, 2001). Jones et al. (2006) found that isochronous auditory rhythms increased sensitivity to subsequent stimuli, and Miller et al. (2013) demonstrated that visual rhythms improved target detection performance. These findings suggest enhanced detection for stimuli appearing at expected beat positions. In prediction motion tasks, temporal structure congruence creates rhythmicity by equating visible and occluded durations. This rhythmicity modulates attentional resource distribution through expectancy generation (Jones et al., 2002), directing attention to specific time points. When stimuli appear before the rhythm-based expectancy point, participants judge them as early; when after, as late. Incongruent structures lack this cue, resulting in poorer performance. Alternatively, temporal structure congruence may activate endogenous temporal orienting (Qin et al., 2024)—the active use of predictive cues to focus attention on future time points (Cotti et al., 2011; Coull & Nobre, 2008). Temporal orienting studies show that predictive cues improve both accuracy and response speed (Correa et al., 2004). In prediction motion tasks, congruent structures provide more effective predictive cues than incongruent structures, potentially triggering endogenous temporal orienting. Neuroimaging research suggests that rhythmic processing activates basal ganglia (Grahn & Brett, 2007), supplementary motor area (Chen et al., 2008), premotor cortex (Bengtsson et al., 2009), and cerebellum (O' Reilly et al., 2008), while endogenous temporal orienting activates right dorsolateral prefrontal cortex (Pfeuty et al., 2003) and left inferior parietal cortex (Cotti et al., 2011). Future research could combine the interruption paradigm with neuroimaging to test these hypotheses.

Experiment 2 isolated visual velocity interference, demonstrating that temporal structure congruence still improved accuracy. This confirms temporal structure' s role in prediction motion tasks. When temporal structures were congruent, participants could still use rhythmic properties for estimation, yielding superior performance (Chang & Jazayeri, 2018). However, the comprehensive analysis showed no significant accuracy difference between Experiments 1 and 2. Eliminating visual velocity cues increased perceptual ambiguity, which may have enhanced temporal structure processing. Cognitive resource theory suggests that increased task difficulty prompts allocation of limited resources to more critical, reliable information (Gepshtein & Banks, 2003), processing it more elaborately. This may explain why visual velocity presence did not significantly affect accuracy.

Experiment 3 examined stability using random interference. According to temporal structure' s hierarchical nature, random flicker positions between start and interception created smaller structural units (Hu et al., 2019) that could not provide effective cues and may have interfered with temporal structure processing. When using temporal structure for estimation, participants needed to inhibit these units and rely on larger-scale structure. Although random interference consumed attentional resources, rhythmic processing appears to be relatively automatic (Capizzi et al., 2012), with performance unaffected by attentional control (Sanabria & Correa, 2013). Right prefrontal damage does not eliminate rhythm-based estimation (Triviño et al., 2011), and TMS suppression of dorsolateral prefrontal cortex does not impair rhythm utilization (Correa et al., 2014). Therefore, despite random interference disrupting stimulus regularity and consuming attentional resources, rhythmic properties under congruent conditions still enabled relatively accurate judgments. The comprehensive analysis also showed no significant accuracy difference between random and flicker procedures, suggesting that within the visual modality, interference did not substantially affect judgment accuracy. We infer that temporal structure effects on prediction motion demonstrate stability in the visual channel.

Previous research shows that distracting stimuli typically impair prediction motion performance. Lyon and Waag (1995) found that same- or opposite-direction moving distractors reduced performance, and Baurès, Maquestiaux, et al. (2018) showed that concurrent working memory tasks affected estimation. Most studies used dual-task paradigms requiring resource division, preventing examination of temporal structure stability under focused attention. Unlike dual-task interference, random interference disrupts stimulus presentation patterns, allowing observation of performance changes when temporal structure is perturbed within the primary task itself (Qin et al., 2023). This approach reveals temporal structure characteristics and coping strategies when facing unstable temporal patterns. Overall, our findings demonstrate that temporal structure effects in prediction motion are stable, complementing the three fundamental characteristics of temporal structure.

The three experiments also revealed inconsistent effects of temporal structure on response bias. Experiment 1 showed significant bias differences across temporal structures, Experiment 2 showed stable bias when visual velocity was isolated, and Experiment 3 demonstrated that interference still affected bias, albeit differently. These results collectively indicate that temporal structure' s influence on response bias is complex, warranting further investigation into how temporal structure affects bias across different task contexts.

This study systematically validated temporal structure effects on prediction motion tasks using the interruption paradigm. Results show that temporal structure congruence improves performance, and that this effect demonstrates stability within the visual modality.

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