

Task relevance strengthens the sequential dependence in time reproduction but not in time discrimination

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Abstract

Our recent experiences shape our perception, a concept known as sequential bias. While extensively studied in the visual domain, this phenomenon remains largely uncharted in time perception. The present study examined how task relevance and task types influence temporal sequential biases. Employing a dual-feature random dot kinematogram (RDK) - duration and direction - we asked participants to encode both features in each trial and report one based on a post-cue. The preceding duration-report trials were regarded as task-relevant responses, while the previous direction-report trials were considered task-irrelevant responses. Additionally, we used the time discrimination task in Experiment 1 and the duration reproduction task in Experiment 2. Both experiments revealed a significant sequential bias: durations were perceived as longer following longer previous durations, and vice versa. Moreover, we found a decisional carryover effect in both tasks. Intriguingly, in the discrimination task (Experiment 1), the sequential effect showed no significant variation whether following timing or direction tasks. Conversely, in the reproduction task (Experiment 2), the sequential effect was more marked following the same timing task than the direction task. These findings indicate that the sequential bias in time perception is likely modulated by working memory processes that link sensory representation and task-specific decision-making.

Introduction

The world around us is relatively stable and predictable over short periods, our experiences are thus useful to guide decisions because the past and the present often correlate. Large amounts of research using visual stimuli, including orientation, color, and motion direction (Bae & Luck, 2020; Barbosa & Compte, 2020; Fischer & Whitney, 2014) have demonstrated that our current perception is influenced by recent events. Fewer research focuses on time perception, and our understanding remains limited. Time perception is inherently subjective and susceptible to various factors, including attention, memory, sensory modality, psychophysical task, and temporal context (Lapid et al., 2008; Penney et al., 2000; Shi et al., 2013; Wittmann, 2009; Treisman & Williams, 1984). For instance, the subjective duration can be biased toward recent history (Burr et al., 2009; Jazayeri & Shadlen, 2010; Nakajima et al., 1992), leading to an underestimation of long durations and an overestimation of short durations, known as the central tendency effect (Glasauer & Shi, 2021; Hollingworth, 1910). The other phenomenon in time perception that is frequently studied is the sequential effect, which is different from the central tendency effect, for it refers to the influence of recent past stimuli on the perception of the current stimuli, rather than a tendency to the average or mean value of a set of stimuli. Only a handful of recent studies have explored trial-to-trial sequential effects on timing (Glasauer & Shi, 2022; Togoli et al., 2021; Wehrman et al., 2020; Wiener et al., 2014), and the

mechanism underlying temporal sequential effects remains unclear based on the relatively limited research evidence.

The sequential effect, seen as carryover effects, can be categorized into sensory carryover and decisional carryover. Sensory carryover reflects how past stimuli influence current perception, often under the broader term “serial dependence” (Fischer & Whitney, 2014). This influence manifests as assimilation or repulsion biases: assimilation makes successive stimuli seem more alike than they are, while repulsion biases the current percept away from the preceding one. Decisional carryover, on the other hand, is shaped by prior responses. Mechanisms underlying sequential dependence remain debatable. Some studies primarily focus on the preceding sensory input (Cicchini et al., 2017; Fornaciai & Park, 2018; Togoli et al., 2021), while others attribute the sequential bias mainly to prior responses (Feigin et al., 2021; Wehrman et al., 2020; Wiener et al., 2014). For instance, research has identified behavioral or neural signatures of serial dependence effects without a response (Czoschke et al., 2019; Fornaciai & Park, 2018) or with a ‘flipped’ response (Cicchini et al., 2017), suggesting that the serial dependence is a perceptual mechanism independent of task-related responses (Liberman et al., 2016). In contrast, recent studies found that sequential bias strongly depends on the prior response (Feigin et al., 2021). For instance, serial dependence for motion direction is only observed when the preceding trials involved the same direction-report response rather than a different task response (Bae & Luck, 2020), underscoring the significance of post-perceptual, response-related factors (Pascucci et al., 2019; Ranieri et al., 2022; Suárez-Pinilla et al., 2018). Furthermore, (Wiener et al., 2014) showed that participants tended to repeat their previous trial’s decision, highlighting a decisional carry-over effect.

Many studies on the sequential effect have focused on scenarios involving a single type of stimulus. Typically, participants report a single target feature in most trials, but sometimes no response is required (Czoschke et al., 2019; Fischer & Whitney, 2014). These studies showed serial dependence even without a response in prior trials, suggesting that a task-relevant response isn’t essential for sequential effects. However, focusing on a single feature might blur the lines between perceiving and reporting it. The frequent need to report a target feature might prime participants to prepare responses, even when responses are not needed, potentially skewing the observed sequential dependence.

Recently, (Bae & Luck, 2020) introduced two task-relevant features, requiring participants to engage with them attentively - color and motion direction - during the presentation (encoding) and perform either color or motion adjustment tasks according to post cues. This approach is ecologically consistent with real-world scenarios where we often encounter and remember multiple objects and features simultaneously. Their results showed that sequential dependence on motion direction was mainly evident when the preceding and the current tasks were the same direction adjustments but diminished when tasks changed. Their finding highlights the role of task relevance in sequential effects: both features were attentively encoded, but only the reported one impacts sequential effects (Bae & Luck, 2020; Li et al., 2023; Suárez-Pinilla et al., 2018).

Researchers often employ reproduction or forced-choice tasks to assess sequential effects (Pascucci et al., 2023). In reproduction tasks, participants replicate the perceived attribute of a stimulus. On the other hand, the forced-choice task involves binary responses, requiring participants to judge the perceived stimulus if it is shorter (larger, clockwise) or longer (smaller, anticlockwise) relative to a standard reference. The influence of task-relevant responses on sequential bias does not consistently align with each other using different tasks. For example, reproduction tasks have shown serial dependence linked to prior choices and post-perceptual decisions (Bae & Luck, 2020), while others demonstrated that serial dependence can occur even without explicit responses in a forced-choice numerosity task (Fornaciai & Park, 2018). This discrepancy in evidence raises questions about the consistency of sequential dependence effects across different measurements.

To date, how tasks influence sequential effects has not been systematically investigated. The reproduction and force-choice tasks may use working memory differently. Reproduction may require continuous comparison of the adjusting stimulus to the reference from memory, while the force-choice task only compares the sensory input to the reference once. If force-choice tasks employ other strategies, such as response criteria (Lages & Treisman, 1998), the impact of task relevance might be minimal.

On this ground, the current study examined how previous task-relevant responses affect temporal sequential effects, exploring if these effects vary with different tasks, specifically the time discrimination and reproduction tasks. We employed the Random Dot Kinematogram (RDK), incorporating two features: motion direction and timing, in a post-cue setup. Participants had to remember its duration and direction, reporting one according to post cues. This post-cueing paradigm required attentive engagement with both features in each trial.

Our primary focus is the sequential effects on duration estimates across trials. We consider trials where participants previously reported duration as task-relevant and those reporting direction as task-irrelevant. To understand how the task type influences carry-over effects in time perception, we employed a time discrimination task in Experiment 1, where participants judged whether the perceived duration was shorter or longer than a standard 1-second reference. In Experiment 2, participants performed a time reproduction task, requiring them to reproduce the perceived duration. We analyzed sequential effects on timing-report trials based on whether the previous trial involved reporting the direction (task-irrelevant) or the time (task-relevant).

Experiment 1

Method

Participant

Twenty-six volunteers participated in Experiment 1 (14 females and 12 males, ranging in age from 18 to 26 years, with a mean of 20.8 years and a standard deviation of 2.17 years). All participants were right-handed, with normal or corrected-to-normal color vision. We excluded two participants for their large response variability (see the section “Data Analysis”) and reported the results from the rest 24 participants. We chose the sample size by referencing prior studies (Bae & Luck, 2020; Fischer & Whitney, 2014), which often identify significant effects (Cohen’s $d > 0.753$). Participants signed the informed consent form before the experiment commenced and received compensation at a rate of 9 Euros/hour compensation. The study was approved by the ethics committees of the Psychology Department at LMU Munich.

Stimuli and procedure

We used PsychoPy (Peirce et al., 2019) to manage stimuli presentation and to collect data. Participants were seated approximately 60 cm from the screen in a soundproof, dimly lit cabin. The stimuli were presented on a 24-inch DELL monitor (refresh rate 60 Hz) against a light grey background (39.3 cd/m^2).

As outlined in Figure 1, each trial began with a fixation dot for half a second (0.5° in diameter with a brightness of 85.7 cd/m^2), which cued the start of the trial and drew participants’ attention. Next came the encoding phase, wherein a random dot kinematogram (RDK) featuring 15 white dots (each dot diameter of 0.4° ; the luminance of 85.7 cd/m^2) against a dark disc (17.8° , 16.5 cd/m^2) appeared at the center of the screen. Initially, the dots within the RDK moved randomly for 400 to 600 ms, without any pattern (at a speed of $1^\circ/\text{s}$ and a coherence level of 0%). Subsequently, these dots turned green (45.8 cd/m^2) and began moving together (at 100% coherence) at a speed of $6^\circ/\text{s}$ in a predetermined direction (randomly selected from 11.25° to 348.75° , in steps of 22.5°) for a randomly chosen length of $[0.4, 0.6, 0.8, 1.2, 1.4, 1.6] \text{ s}$. When a dot exited the dark disc boundary, another dot appeared randomly inside to maintain a constant count of fifteen. These green, coherently moving dots served as the target, which participants were asked to memorize regarding their movement direction and duration. After this, the dots returned to their initial random motion

for another 400 to 600 ms. The alternating white dot displays served as visual masks to present any residual visual effects from the previous trial.

Following the encoding phase, a post cue - either the letter ‘D’ ($0.8^\circ \times 1.0^\circ$, 85.7 cd/m^2) for the direction task or ‘T’ for the time task - appeared at the center of the display for half a second, prompting participants to report either the direction or duration. Participants could respond at their own pace. For the duration discrimination task, a display showing the left and the right arrows (“< or >”) prompted participants to assess if the duration of the coherent motion was shorter or longer than one second. They made this two-alternative forced choice (2AFC) judgment by pressing the left arrow for “shorter than one second” or the right arrow for “longer than one second”.

In the direction task, a line segment started from the center with an overlaid ‘D’, pointing to a random direction. Participants rotated this line to match the observed motion’s direction using the left (counter-clockwise) and right (clockwise) arrow keys. A continuous readjustment updated the pointer’s direction, and they finalized their choice by pressing the spacebar. If their estimated direction deviated by more than 60° , a warning message “Direction deviated a lot!” would flash on-screen for half a second. The next trial began after a one-second intertrial interval.

To prepare participants for the main experiment, a practice session with 24 practice trials exposed them to a standard one-second stimulus, represented by yellow dots moving horizontally (at a speed of $6^\circ/\text{s}$; coherence of 100%). Following a 500 ms blank interval, a comparison stimulus with a duration randomly chosen of [0.4, 0.6, 0.8, 1.2, 1.4, 1.6] s was presented. The comparison stimulus was the same RDK display used in the main experiment. Participants had to judge which one was longer. After the response, they received feedback on their accuracy. The formal experiment consisted of 480 trials, randomly shuffled, and split evenly between duration and direction tasks. The inter-trial transitional probability (from trial $n-1$ to trial n) between the duration and direction trials ensured an equal probability of all inter-trial combinations. Participants could take a short break after each block of 30 trials.

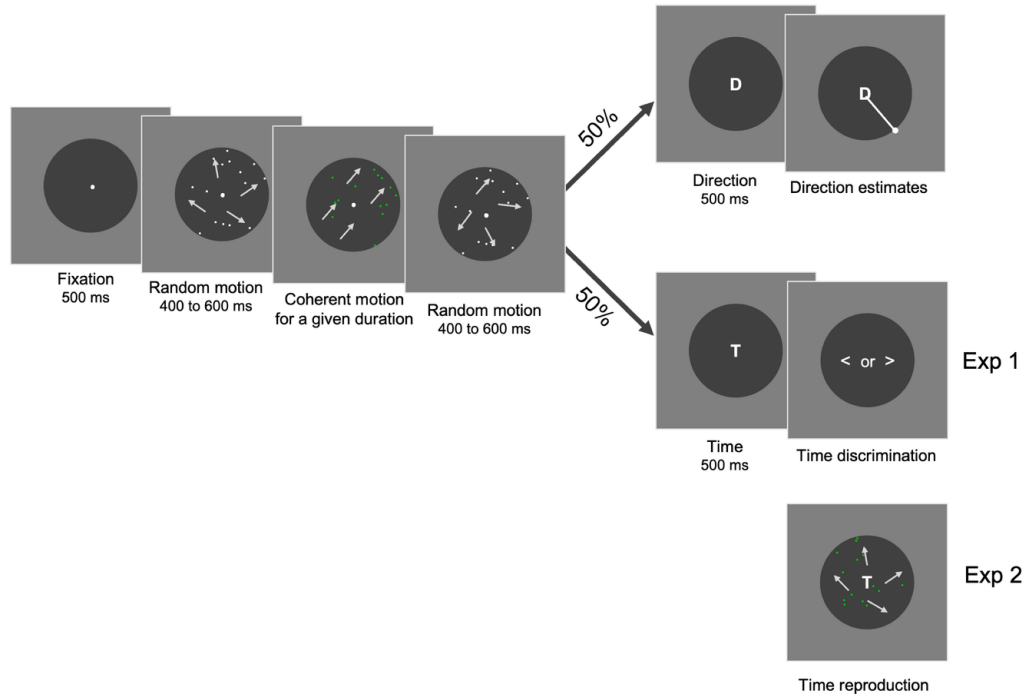


Figure 1: Schematic illustration of the experimental procedure. A trial started with a fixation dot, followed by a white random dot kinematogram. After 400 ms to 600 ms, they turned green and moved together in one direction for a given duration; then the display shifted back to the white random dot kinematogram. Next, a cue appeared for half a second, either the letter ‘D’ for the direction task or the letter ‘T’ for the timing task. For the direction task, participants adjusted a line pointer with arrow keys and confirmed their report by pressing the spacebar. Experiments 1 and 2 differed in the timing task. In Experiment 1, it was a discrimination task, with a prompt display (“< or >”), while in Experiment 2, the letter ‘T’ stayed on till the completion of the reproduction task.

Data analysis

As our study focused on how previous trials influence duration judgments in timing tasks, we categorized trials based on the duration (less than or more than 1 second) and type (Time or Direction) of the previous trial, creating four categories: “Short/Direction”, “Long/Direction”, “Short/Time”, and “Long/Time”. We further classified consecutive Time-Time trials according to the preceding timing trials’ responses as “Short Response” or “Long Response.” Excluding the first trial of each block, we analyzed responses using a psychometric function, a cumulative Gaussian function, including an initial 5% lapse rate for attention errors (Wichmann & Hill, 2001). We then determined each participant’s Points of Subjective Equality (PSE) to identify biases in duration perception and computed the just-noticeable difference (JND) and Weber fraction (WF = JND/PSE) for precision. Participants with a WF greater than one were excluded. Lastly, we used repeated measures ANOVAs and *t*-tests to determine the significance of our findings.

Results and discussion

Trials were categorized into four groups based on prior task (Time or Direction) and duration (Short or Long), as shown in Figure 2A's psychometric curves. A distinct difference was visible between curves for the preceding 'Short' vs. 'Long' conditions while preceding 'Time' and 'Direction' tasks had similar curves. PSEs (with standard errors) were 770 ± 48 , 833 ± 51 , 775 ± 49 , and 820 ± 54 ms for Time/Long, Time/Short, Direction/Long, and Direction/Short, respectively (Figure 2B). A two-way repeated measures ANOVA revealed a significant effect of Prior Duration, $F_{(1,23)} = 6.083$, $p = .022$, $\eta_p^2 = 0.013$. However, there was no significant main effect of task relevance ($\eta_p^2 = 0.012$, but not of Prior Task ($F_{(1,23)} = 0.045$, $p = .833$, $\eta_p^2 = 0.000$) nor an interaction between the two factors ($\eta_p^2 < 0.001$) or their interaction ($F_{(1,23)} = 0.138$, $p = .714$, $\eta_p^2 = 0.000$) < 0.001). These findings indicate that prior duration impacts current duration judgment, with shorter prior durations leading to shorter perceived current durations and vice versa, indicating an assimilation bias. The type of prior task (time or direction), however, had little effect.

Further analysis on the impact of preceding responses revealed a decisional carry-over effect. Figures 2C and 2D show psychometric curves according to prior responses, with a leftward shift for "Long" prior responses, indicating a tendency to judge current durations as longer following "Long" report. The PSE was significantly lower after "Long" responses (741 ± 44 ms) than "Short" (901 ± 51 ms), $t_{(23)} = 3.795$, $p = .001$, $d = 0.684$.

These findings indicate that duration judgments are influenced by both previous durations and decisions, manifesting as both an assimilation effect and a decisional carry-over effect. Interestingly, the type of preceding task (Time or Duration) did not significantly impact these biases, suggesting that the task relevance may not be involved in the sequential effect underlying duration discrimination tasks. It is important to note, however, that in the discrimination task, decisions are binary, involving simple judgments as either "shorter" or "longer" than one second. This raises the question of whether these findings from Experiment 1 are applicable to tasks with continuous variables, such as reproduction tasks. Therefore, Experiment 2 employed a time reproduction task, asking participants to replicate the duration of a given stimulus.

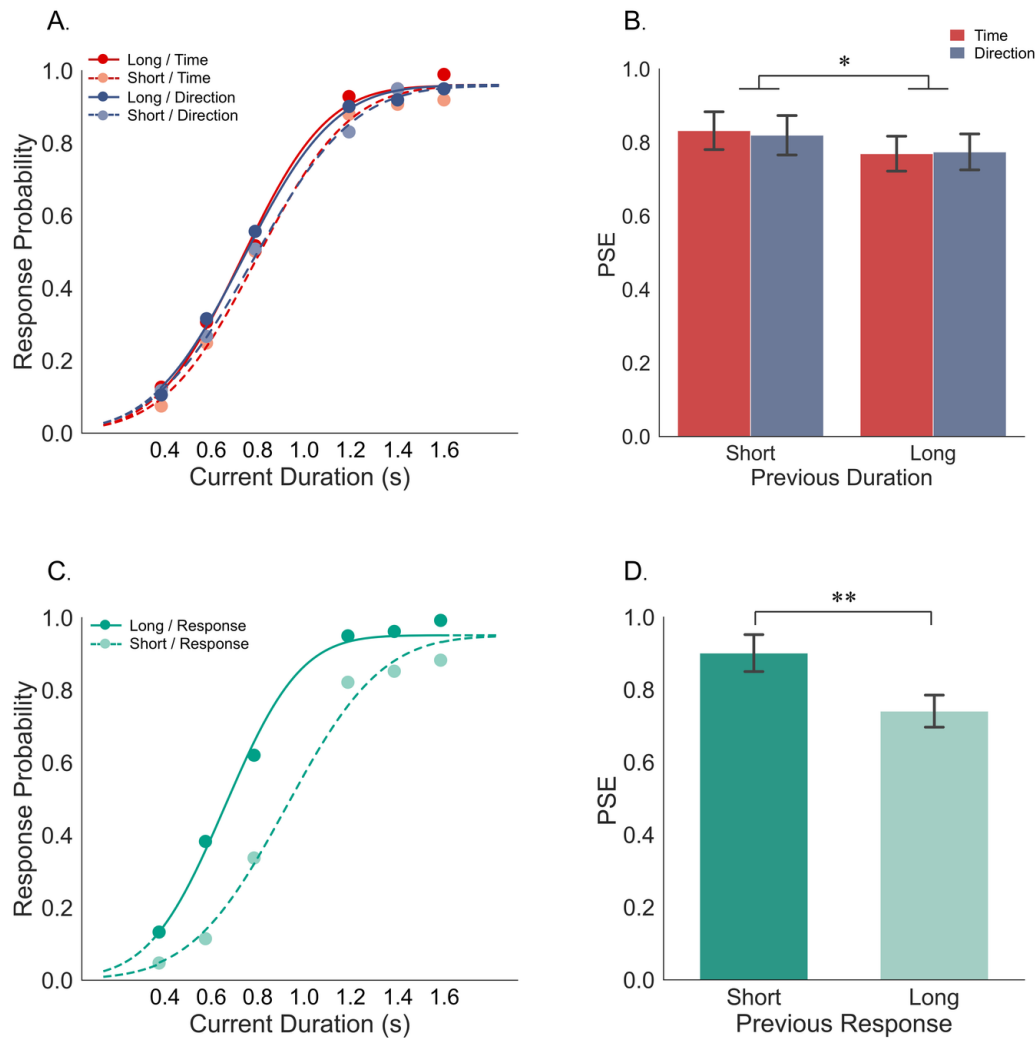


Figure 2: Results of Experiment 1. **(A)**. Response probabilities of “Longer than 1 second” on the comparison duration (0.4, 0.6, 0.8, 1.2, 1.4, and 1.6 s) separately for previous task types (Time or Direction) when the prior duration was either short (including 0.4, 0.6, and 0.8 s) or long (including 1.2, 1.4, and 1.6 s). The lines show the best-fitting psychometric function. **(B)**. Points of subjective equality (PSE) values were plotted for previous time discrimination and direction adjustment trials when the previous duration was short or long. **(C)**. Response probabilities of “Longer than 1 second” on the comparison duration when participants made “Short Response” or “Long Response” in the previous time discrimination trials. The lines show the best-fitting psychometric function. **(D)**. Corresponding PSE values for prior “Short Response” and “Long Response”. Error bars represent $\pm$ SEM. ** $p < .01$, * $p < .05$.

Experiment 2

Method

Participant

Twenty-four participants were recruited in Experiment 2 (13 females; age 18 - 27, mean $\pm$ SD: 20.75 ± 2.45 years), all right-handed, with normal or corrected-to-normal vision and color vision. Before the experiment, participants provided written informed consent and received 9 Euros/hour compensation.

Stimuli and procedure

Experiment 2 closely followed the design of Experiment 1, with some changes for the timing task. This time, participants had to reproduce the duration of the target stimuli, randomly selected from 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 s (see Figure 1). After the post-cue display, participants initiated the task at their own pace by pressing and holding the down arrow key, releasing it when they felt the elapsed duration matched the target duration. Immediately after pressing the down arrow key, a display showing static green random dots (15 dots, each dot diameter of 0.4° ; the luminance of 45.8 cd/m^2) turned into a random motion display (velocity of $6^\circ/\text{s}$) to minimize inter-trial bias. The key holding duration was recorded as the reproduced duration. If their reproduction error exceeded 30%, they received feedback: “Too short” for relative errors below -30% and “Too long” for errors above 30%. The procedure for the direction adjustment task remained the same as in Experiment 1.

Data analysis

Response errors in duration reproduction trials were calculated as the difference between the reproduced and actual durations. We excluded the first trial of each block and filtered out trials where errors exceeded three standard deviations from the participant’s mean error, accounting for accidental presses or attention lapses. These outliers constituted only 0.39% of trials. The remaining trials were categorized into two conditions based on the prior task (Time or Direction).

Previous research has demonstrated that subjective timing is susceptible to contextual factors, such as the “central tendency effect”, leading to underestimating long durations and overestimating short durations (Burr et al., 2009; Jazayeri & Shadlen, 2010; Nakajima et al., 1992), and the sequential effect, where reproductions are influenced by preceding durations (Glasauer & Shi, 2022; Dyjas et al., 2012). We modeled these effects using multiple linear regressions, with current (T_n) and previous (T_{n-1}) durations as predictors:

$$\text{Error}_n = a * T_n + b * T_{n-1} + c.$$

The model’s slope (a) for the current duration indicates the central tendency effect. Following the convention adopted in the literature (Cicchini et al., 2012; Jazayeri & Shadlen, 2010; Shi et al., 2013), we used the positive value ($|a|$) as the central tendency index, with 0 indicating no central tendency. The slope (b) for the previous duration reflects the sequential bias (Glasauer & Shi, 2022; Cicchini et al., 2014), and a positive slope indicates that the current estimation is attracted towards the previous duration, denoted as the “assimilation”, while a negative slope indicates that the current time estimation is repelled from the previous duration.

Furthermore, we categorized reproduced durations as “Longer” or “Shorter” than 1.2 s (omitting 1.2 s) and analyzed sequential effects based on prior stimuli and responses, such that we can compare sequential effects between Experiments 1 and 2.

Additionally, to visualize the variability of the sequential effect between experiments, we computed a sequential effect index as the difference in PSEs between groups with prior short and prior long durations for each prior task condition. To assess the decisional carry-over effect between experiments, we calculated

a decisional carry-over effect index as the difference in PSEs between prior short and prior long reports separately for each experiment.

Results and discussion

The overall mean response error (with SE) for the duration reproduction trials was significantly positive (97 ± 25 ms, $t_{(23)} = 3.911$, $p = .001$, $d = 0.798$), indicating a general overestimation. The mean reproduction error for the prior Time task was 113 ± 24 ms, significantly larger than the mean error for the prior Direction task (78 ± 27 ms), $t_{(23)} = 3.393$, $p = .003$, $d = 0.278$.

Central tendency effect. Both the preceding Time and Direction conditions exhibited significant central tendency biases, with participants tending to overestimate short durations and underestimate long durations. The mean central tendency index was 0.318 ± 0.048 ($t_{(23)} = 6.654$, $p < .001$, $d = 1.358$) for the Time condition and 0.354 ± 0.048 ($t_{(23)} = 7.329$, $p < .001$, $d = 1.496$) for the Direction condition. They were comparable ($t_{(23)} = 1.503$, $p = .147$, $d = 0.154$), as depicted in Figure 3A. This suggests that the task relevance did not influence the central tendency effect. The lack of difference can be attributed to the same distribution and range of durations tested in both tasks, resulting in a stable prior representation of durations across conditions. This finding aligns with previous research that mixing durations leads to generalized prior representation across different conditions (Roach et al., 2017).

Serial dependence effect. Figure 3B depicts that reproduction errors increased with longer prior durations, indicating a positive assimilation effect. We quantified this effect using the mean slope b from linear regressions (Eq. 1), resulting in slopes of 0.077 for prior Time and 0.031 for prior Direction tasks, as shown in Figure 3C. Both slopes were significantly greater than zero (Time: $t_{(23)} = 4.370$, $p < .001$, $d = 0.892$; Direction: $t_{(23)} = 2.921$, $p = .008$, $d = 0.596$), confirming a sequential effect in both conditions. Interestingly, the sequential effect was significantly larger in the prior Time relative to the Direction condition ($t_{(23)} = 2.368$, $p = .027$, $d = 0.652$). To rule out statistical artifacts (Cicchini et al., 2014), we also analyzed reproduction errors against durations in future trials, which showed no significance ($ps > .460$). These findings provide clear evidence that, at least in the case of the time reproduction task, task-relevant response in the preceding trials enhanced the sequential effect.

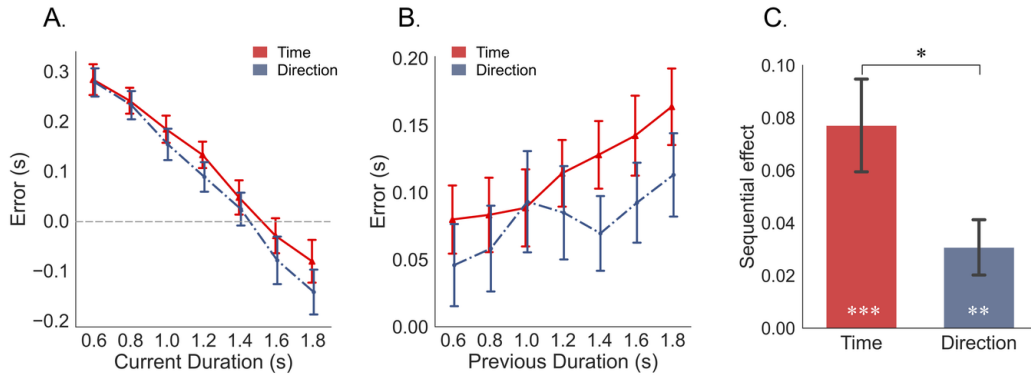


Figure 3: Results of Experiment 2. (A). Central tendency effect. Mean reproduction errors were plotted on the current sample duration, separately for trials preceded by time reproduction and direction adjustment tasks. (B). Sequential dependence. Mean reproduction errors were plotted on the previous duration, separately for trials preceded by time reproduction and direction adjustment tasks. (C). Index of sequential effect. The slope of the linear regression of the reproduction errors on the previous duration, plotted separately for trials preceded by time reproduction and direction adjustment tasks. Error bars represent $\pm$ SEM. ** $p < .01$, * $p < .05$.

To compare the findings between Experiments 1 and 2, we categorized reproduced duration as “Short” or “Long” relative to 1.2 s. Figure 4A presents psychometric curves that reveal an assimilation bias toward previous durations only in the prior Time condition. In the prior Time condition, the PSE for prior long and short intervals were 987 ± 59 ms and 1111 ± 52 ms, respectively. In the prior Direction condition, these values were 1124 ± 52 ms and 1114 ± 61 ms, respectively (Figure 4B). A two-way repeated measures ANOVA revealed a main effect of the previous Duration, $F_{(1,23)} = 5.407$, $p = .029$, $\eta_p^2 = 0.011$, and a main effect of the prior Task, $F_{(1,23)} = 6.150$, $p = .021$, $\eta_p^2 = 0.017$, and a significant interaction effect between these factors ($F_{(1,23)} = 5.479$, $p = .028$, $\eta_p^2 = 0.015$). Further analysis revealed a significant assimilation effect in the task-relevant (Time) condition ($t_{(23)} = 3.465$, $p = .004$, $BF_{10} = 18.385$) but not in the task-irrelevant (Direction) condition ($t_{(23)} = 0.239$, $p = 1$, $BF_{10} = 0.22$).

Additionally, to assess the decisional carry-over effect, we grouped trials based on the preceding reports (“Short Response” or “Long Response”). Figure 4C displays psychometric curves for each group, revealing a distinct difference based on prior responses. As indicated in Figure 4D, the PSE values for the prior “Long Response” was 934 ± 45 ms, significantly shorter than the prior “Short Response” (1166 ± 55 ms), revealing a significant decisional carry-over effect ($t_{(23)} = 3.457$, $p = .002$, $d = 0.939$).

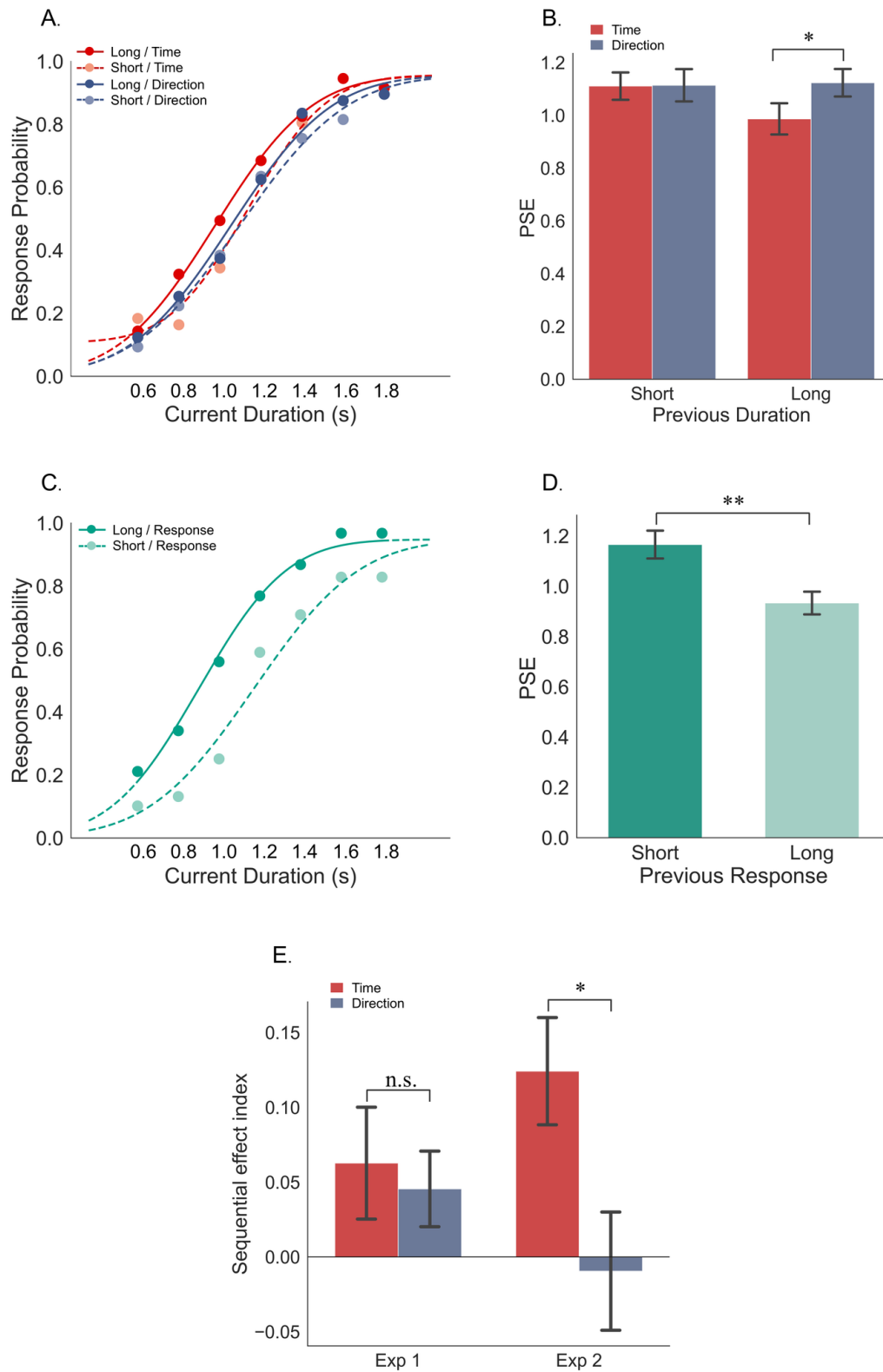


Figure 4: (A), (B), (C) and (D) are psychometric function plots of Experiment 2. (E) displays the sequential effect index between Experiment 1 and Experiment 2. (A). Response probabilities of “Longer than 1.2 second” on the comparison duration (0.6, 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8 s) separately for previous time reproduction and direction adjustment tasks when the prior duration was either short (including 0.6, 0.8, and 1.0 s) or long (including 1.4, 1.6, and 1.8 s). The lines show the best-fitting psychometric function. (B). Points of subjective equality (PSE) values were plotted for previous time reproduction and direction adjustment tasks when the previous duration was short or long. (C). Response probabilities of “Longer than 1.2 second” on the comparison duration when participants made “Short Response” or “Long Response” in the previous time reproduction trials. The lines show the best-fitting psychometric function. (D). Corresponding

We further conducted an omnibus analysis to compare the sequential effects across the timing discrimination (Experiment 1) and the time reproduction (Experiment 2) tasks. An ANOVA on the sequential effect index, considering factors of Experiment and Task Relevance, revealed a significant main effect of Task Relevance ($F_{(1,46)} = 4.206$, $p = .046$, $\eta_p^2 = 0.084$), indicating a more pronounced sequential dependence in trials with consecutive timing tasks. However, neither the main effect of Experiment ($F_{(1,46)} = 0.010$, $p = .922$, $\eta_p^2 = 0.000$) nor the interaction effect ($F_{(1,46)} = 2.505$, $p = .120$, $\eta_p^2 = 0.052$) was significant (Figure 4E). Further paired t -tests for the difference of sequential effect between task relevance (Time vs. Direction) failed to reveal any significant difference in Experiment 1 ($t_{(23)} = 0.371$, $p = .714$, $d = 0.110$), but a significant difference in Experiment 2 ($t_{(23)} = 2.341$, $p = .028$, $d = 0.723$). For the decisional carry-over effect, a separate t -test on the sequential effect index did not show a significant difference between Experiments 1 and 2 ($t_{(23)} = 0.911$, $p = .367$, $d = 0.263$).

Overall, both time discrimination and reproduction tasks demonstrated consistent assimilation toward prior durations, indicating a robust sequential effect in time perception. The comparative analysis revealed that task relevance enhanced sequential biases in the time reproduction task, but not in the time discrimination task. This suggests that the measurement type modulates the mechanism of sequential effect. The difference might stem from the interaction of the timing task with memory retrieval of the encoded duration, with the time reproduction task requiring continuous attention and memory comparison during reproduction.

General Discussion

The present study explored the impact of task relevance on sequential effects in time perception, using discrimination and reproduction tasks, extending upon previous research that predominantly explored sequential dependence in non-temporal domains (Fischer & Whitney, 2014). Across both timing tasks, we observed a consistent assimilation effect: participants perceived current durations as longer following long previous stimuli and shorter following short ones. Interestingly, while the assimilation effect in the discrimination task was unaffected by task relevance, it was more pronounced in the time reproduction task following the same time task, highlighting the importance of task relevance in sequential dependence during time reproduction. Furthermore, we observed significant decisional carry-over effects in both tasks, where participants were more likely to repeat their responses, with no significant difference between the two types of tasks, consistent with previous studies on duration judgments (Brown et al., 2005; Wehrman et al., 2018; Wehrman et al., 2020; Wiener et al., 2014). This tendency for participants to repeat their prior choice, especially under response uncertainty, aligns with the notion of motoric repetition, where participants tend to repeat their previous motor response when uncertain about the test stimulus (Akaishi et al., 2014).

Recent past time intervals, being more accessible in memory, can influence the perception of current intervals. The brain forms time perception by integrating noisy sensory inputs with recent past stimuli (sequential effect) and the general knowledge of the stimuli (central tendency effect) to enhance processing efficiency, leading to an assimilation effect of prior stimuli in time perception. (Fischer & Whitney, 2014) suggested that the assimilation effect could be due to a “continuity field”, where the brain smooths out noises by averaging the past information and the current input to promote sensory stability and continuity.

In the current study, the notable sequential effect was evident in both duration discrimination and reproduction tasks, indicating its general applicability across various tasks. However, comparing sequential effects between discrimination and reproduction tasks, we found distinct patterns in how task relevance affects sequential effects. This difference between the two tasks is unlikely attributable to task-specific estimations. As we converted reproductions from Experiment 2 to binary “Short” vs. “Long” categories, similar to the task used in Experiment 1, the difference remained evident (see Figure 4E).

One explanation could be the difference in memory processes between the reproduction and discrimination

tasks. In the reproduction task, participants actively maintain the encoded duration in working memory through the reproduction phase, as it is used as a reference for stopping the reproduction. This active maintenance in timing trials differs from direction trials (recognizing direction may not be needed for the entire presentation), leading to unequal carryover effects between reproduction-reproduction and direction-reproduction trials. The active memory trace of the target duration during reproduction may thus bias the encoding of the subsequent trial, similar to findings in spatial memory tasks where the increased memory retention interval between the stimulus and response enhances sequential dependence (Bliss et al., 2017). In contrast, the binary discrimination task only requires participants to monitor the target duration until it matches a reference duration (1 second). If the target duration finishes before the reference, a response is made; if it surpasses the reference, a response is made without waiting for the entire duration. This means fully encoding the target duration is unnecessary for the discrimination task, leading to a smaller sequential effect and making the preceding task-irrelevant. This observation aligns with previous research suggesting that in discrimination tasks, the information retained is related to a pre-established criterion value (Lages & Treisman, 1998). In this context, participants create internal or external criteria and compare incoming sensory input with this response criterion, likely showing less dependence on the working memory and post-perceptual processes (Bausenhardt et al., 2014; Dyjas et al., 2012; Lages & Treisman, 1998).

Our findings highlight that the nature of the task plays a crucial role in shaping sequential dependence in time perception. Time perception is distinct from visual perception, not being tied to a specific sensory process and more susceptible to contextual distortions from mental states, emotions, or selective attention (Shi et al., 2013; Wittmann, 2009). However, the varied impact of different tasks on working memory usage, as observed in our study, could be a universal phenomenon. Therefore, the distinct sequential effects by task relevance we noted in time perception might also be relevant to other perceptual domains, presenting an intriguing avenue for future research.

In conclusion, our research revealed assimilation effects in time perception and highlighted the distinctive role of task relevance on sequential effects in both time discrimination and reproduction tasks. While the assimilation effect in the time discrimination task was unaffected by task relevance, it was notably stronger in the time reproduction task following the same duration task. These results indicate that the sequential bias in time perception are likely modulated by working memory processes that link sensory representation and decisional templates, resulting in a more pronounced sequential bias when the prior tasks involve relevant time reproduction tasks. Our findings thus imply that a reassessment of the existing evidence for sequential dependence, considering its potential association with the specific nature of the task, may be beneficial.

Declaration of competing interest

The authors declare no competing interests.

Data and code availability statement

The data and analysis code that support the findings of this study will be made available from the author, Si Cheng (chengsi123456@gmail.com), upon reasonable request.

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References

Serial dependence in vision: Merely encoding the previous-trial target is not enough.. (2020). *Psychon Bull Rev*, 27, 293–300.

- Build-up of serial dependence in color working memory.. (2020). *Sci Rep*, 10, 10959.
- Serial dependence in visual perception.. (2014). *Nat Neurosci*, 17, 738–743.
- On estimating the difference limen in duration discrimination tasks: a comparison of the 2AFC and the reminder task.. (2008). *Percept Psychophys*, 70, 291–305.
- Differential effects of auditory and visual signals on clock speed and temporal memory.. (2000). *J Exp Psychol Hum Percept Perform*, 26, 1770–1787.
- Bayesian optimization of time perception.. (2013). *Trends Cogn Sci*, 17, 556–564.
- The inner experience of time.. (2009). *Philos Trans R Soc Lond B Biol Sci*, 364, 1955–1967.
- A theory of criterion setting with an application to sequential dependencies.. (1984). *Psychological Review*, 91(1), 68–111. <https://doi.org/10.1037/0033-295x.91.1.68>
- Auditory dominance over vision in the perception of interval duration.. (2009). *Exp Brain Res*, 198, 49–57.
- Temporal context calibrates interval timing.. (2010). *Nat Neurosci*, 13, 1020–1026.
- Time-shrinking: a discontinuity in the perception of auditory temporal patterns.. (1992). *Percept Psychophys*, 51, 504–507.
- The origin of Vierordt’s law: The experimental protocol matters.. (2021). *Psych J*, 10, 732–741.
- The Central Tendency of Judgment. (1910). *The Journal of Philosophy Psychology and Scientific Methods*, 7(17), 461. <https://doi.org/10.2307/2012819>
- Individual beliefs about temporal continuity explain variation of perceptual biases.. (2022). *Sci Rep*, 12, 10746.
- Serial dependence in time and numerosity perception is dimension-specific.. (2021). *J Vis*, 21, 6.
- Decisional carryover effects in interval timing: Evidence of a generalized response bias.. (2020). *Atten Percept Psychophys*, 82, 2147–2164.
- Continuous carryover of temporal context dissociates response bias from perceptual influence for duration.. (2014). *PLoS One*, 9, e100803.
- Serial dependencies act directly on perception.. (2017). *J Vis*, 17, 6.
- Attractive Serial Dependence in the Absence of an Explicit Task.. (2018). *Psychol Sci*, 29, 437–446.
- Perceptual decisions are biased toward relevant prior choices.. (2021). *Sci Rep*, 11, 648.
- Two types of serial dependence in visual working memory.. (2019). *Br J Psychol*, 110, 256–267.
- Serial dependence promotes object stability during occlusion.. (2016). *J Vis*, 16, 16.
- Laws of concatenated perception: Vision goes for novelty, decisions for perseverance.. (2019). *PLoS Biol*, 17, e3000144.
- Evidence of Serial Dependence from Decoding of Visual Evoked Potentials.. (2022). *J Neurosci*, 42, 8817–8825.
- Serial dependence in the perception of visual variance.. (2018). *J Vis*, 18, 4.
- Modality-specific sensory and decisional carryover effects in duration perception.. (2023). *BMC Biol*, 21, 48.
- Serial dependence in visual perception: A review.. (2023). *J Vis*, 23, 9.
- Spatial frequency discrimination: Visual long-term memory or criterion setting?. (1998). *Vision Research*, 38(4), 557–572. [https://doi.org/10.1016/s0042-6989\(97\)88333-2](https://doi.org/10.1016/s0042-6989(97)88333-2)

- PsychoPy2: Experiments in behavior made easy.. (2019). *Behav Res Methods*, 51, 195–203.
- The psychometric function: II. Bootstrap-based confidence intervals and sampling.. (2001). *Percept Psychophys*, 63, 1314–1329.
- Trial-by-trial updating of an internal reference in discrimination tasks: evidence from effects of stimulus order and trial sequence.. (2012). *Atten Percept Psychophys*, 74, 1819–1841.
- Optimal encoding of interval timing in expert percussionists.. (2012). *J Neurosci*, 32, 1056–1060.
- Compressive mapping of number to space reflects dynamic encoding mechanisms, not static logarithmic transform.. (2014). *Proc Natl Acad Sci U S A*, 111, 7867–7872.
- Generalization of prior information for rapid Bayesian time estimation.. (2017). *Proc Natl Acad Sci U S A*, 114, 412–417.
- Identification and bisection of temporal durations and tone frequencies: common models for temporal and nontemporal stimuli.. (2005). *J Exp Psychol Hum Percept Perform*, 31, 919–938.
- Short-term effects on temporal judgement: Sequential drivers of interval bisection and reproduction.. (2018). *Acta Psychol (Amst)*, 185, 87–95.
- Autonomous mechanism of internal choice estimate underlies decision inertia.. (2014). *Neuron*, 81, 195–206.
- Serial dependence is absent at the time of perception but increases in visual working memory.. (2017). *Sci Rep*, 7, 14739.
- Temporal reproductions are influenced by an internal reference: explaining the Vierordt effect.. (2014). *Acta Psychol (Amst)*, 147, 60–67.