Distinct Sequential Effects in Space and Time: Repulsion in Direction Judgments and Attraction in Time Reproduction

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Abstract

Our current perception and decision-making are continuously shaped by recent experiences, a phenomenon known as sequential dependence. While it is well-documented in spatial perception and has been recently explored in time perception, their functional similarities across space and time remain elusive, particularly in relation to tasks and working memory loads. To address these questions, we designed a unified experimental paradigm, employing coherent motion stimulus, for both spatial direction and time reproduction tasks. Experiment 1 involved a pre-cue setting where participants were informed about the task before the stimulus presentation, while Experiment 2 used a post-cue setting, informing participants of the task after the stimulus presentation. Our findings reveal a consistent attraction bias in time reproduction and a dominant repulsion in spatial direction estimation. Notably, the temporal attraction was more pronounced when the preceding task was also time-related, compared to a direction task. In contrast, the direction repulsion in spatial tasks remained unaffected by the nature of the preceding task. Additionally, both attraction and repulsion biases were intensified by the post-cue compared to the pre-cue. These findings underscore distinct sequential effects in spatial and temporal tasks, suggesting that while sensory processing and adaptation primarily shape spatial repulsion biases, temporal attraction biases are more influenced by working memory load at the post-perceptual processing.

Keywords: sequential effect, repulsion, attraction, working memory

Introduction

Our brain estimates magnitudes of stimuli not merely from noisy sensory inputs, but also from the recent past, resulting in sequential or serial dependence and central tendency bias (Cicchini et al., 2018; Cross, 1973; J. Fischer & Whitney, 2014; Glasauer & Shi, 2022; Holland & Lockhead, 1968; Jesteadt et al., 1977). Sequential effects can lead to either attractive or repulsive biases. Attraction occurs when consecutive stimuli are perceived as more similar than they actually are, while repulsion occurs when the current percept is biased away from the preceding stimulus. Both sequential attraction and repulsion have been extensively explored in spatial perception (Bae & Luck, 2020; Barbosa & Compte, 2020; J. Fischer & Whitney, 2014; Pascucci et al., 2023). In contrast, similar research on time perception is less developed (Glasauer & Shi, 2022; Wehrman et al., 2018; Wiener et al., 2014). Studies concurrently addressing sequential dependence in both spatial and temporal perception are particularly rare. This study, thus, addresses this gap, investigating sequential effects in both dimensions using a unified stimulus.

There is ongoing debate regarding the underlying mechanisms of sequential effects. One view suggests that sequential attraction helps maintain perceptual stability and temporal continuity by integrating past and current information to filter out abrupt noises, serving as a perceptual mechanism (Cicchini et al., 2017; Fornaciai & Park, 2018; Glasauer & Shi, 2022; Liberman et al., 2016). The evidence comes from the fact that this bias can even emerge in the absence of a decision process when participants are not required to report the target feature in the previous trial (Czoschke et al., 2019).

An alternative perspective links sequential effects to decision-related post-perceptual factors (Bae & Luck, 2020; Ceylan et al., 2021; Ceylan & Pascucci, 2023; Pascucci et al., 2019). Take, for example, a study involving either orientation or color judgments with a post-cue (Bae & Luck, 2020), sequential dependence emerged only when both the preceding and current trials were the orientation task, diminishing when tasks differed. This underlines the necessity of task-related responses from previous trials, not just the encoding of the prior stimulus. Here, working memory involves in combining preceding stimuli with current sensory inputs for decision-making and motor planning (Bae & Luck, 2020; Bliss et al., 2017; Kiyonaga, Scimeca, et al., 2017). A recent fMRI study on duration reproduction further demonstrates that consecutive responses play a key role in sequential dependence (Cheng et al., 2023), showing that

consecutive responses enhanced sequential dependence. Crucially, in these consecutive response trials, sequential dependence negatively correlated with hippocampus activities (Cheng et al., 2023). Their finding highlights the crucial role of memory in sequential dependence, aligning with previous studies that link sequential effects to memory retention (Bliss et al., 2017) and short-term memory maintenance (de Azevedo Neto & Bartels, 2021).

It is important to note that research exploring the impact of tasks and working memory on sequential dependence has primarily focused on a single modality, be it spatial or temporal perception. These studies often employ high memory loads, achieved either through post-cue paradigms (Bae & Luck, 2020; Cheng et al., 2023) or extended retention intervals (Bliss et al., 2017). Given that working memory is often shared between tasks within the same modality (e.g., orientation and color), its influence on sequential bias might be specific to that modality. The question of whether working memory on sequential bias is a modality-independent phenomenon, applicable across both space and time, remains an open issue.

To address this, our study employed the post-cue paradigm that prior research used (Bae & Luck, 2020; Cheng et al., 2023) and extended it to include a pre-cue paradigm to vary memory loads. Participants reproduced either the direction (space task) or duration (time task) of a coherent motion display, the task depending on a cue shown either before (pre-cue, Experiment 1) or after (post-cue, Experiment 2) stimulus presentation. We hypothesized that the pre-cue task, relative to the post-cue task, by removing the need to remember an alternative task, would lessen the memory load. If memory load is crucial in both spatial and temporal tasks, stronger sequential dependence should occur in the post-cue than in the pre-cue task. Furthermore, if spatial and temporal memories function separately, a preceding trial of a different task does not interfere with the current trial, resulting in minimal impact on the current trial response, regardless of whether it's the spatial or temporal task. Conversely, if spatial and temporal memories have differential roles in the direction and duration tasks (e.g., if the spatial task is predominantly influenced by early perceptual processing rather than post-perceptual memory mixing), we may expect distinct patterns in two tasks when comparing the pre-cue to the post-cue tasks.

To foreshadow the results, in two experiments (each N=23), using the pre-cue and post-cue paradigms, we found the post-cue, relative to the pre-cue, intensified sequential effects. For timing tasks, strong attraction was only found to depend on the task of the preceding trial.

The same task enhanced the attraction bias. In contrast, we observed repulsion biases for mild inter-trial orientation differences, regardless of the preceding task. These findings highlight distinct processing mechanisms for assimilation in timing and repulsion in direction, both reinforced by working memory.

Experiment 1

Method

Participant

Twenty-three volunteers participated in Experiment 1 (14 females, 9 males; age ranged from 21 to 38, mean ± SD: 26.83 ± 4.18 years). All participants were right-handed and had normal or corrected-to-normal visual acuity and color vision. Previous research (Bae & Luck, 2020; Cheng et al., 2023; J. Fischer & Whitney, 2014) has shown large effect sizes for the serial dependence effect (Cohen's d > 0.75). With an effect size of 0.75 and a power of 80%, we obtained a minimum of 19 participants according to G*Power (Faul et al., 2007). On the safe side, we increased the sample size to 23. Prior to the experiment, participants gave written informed consent and received compensation of 9 Euro/hour for their involvement. The study was approved by the ethics committees of the Psychology Department at LMU Munich.

Stimuli and procedure

We used PsychoPy3 (Peirce et al., 2019) to control stimulus presentation and data collection. Participants were seated on a chair in a soundproof, dimly lit cabin, resting their head on a chin rest, keeping a viewing distance of 60 cm from a 21-inch CRT monitor (refresh rate at 85 Hz), which presented stimuli on a light grey display background (luminance of 39.3 cd/m^2).

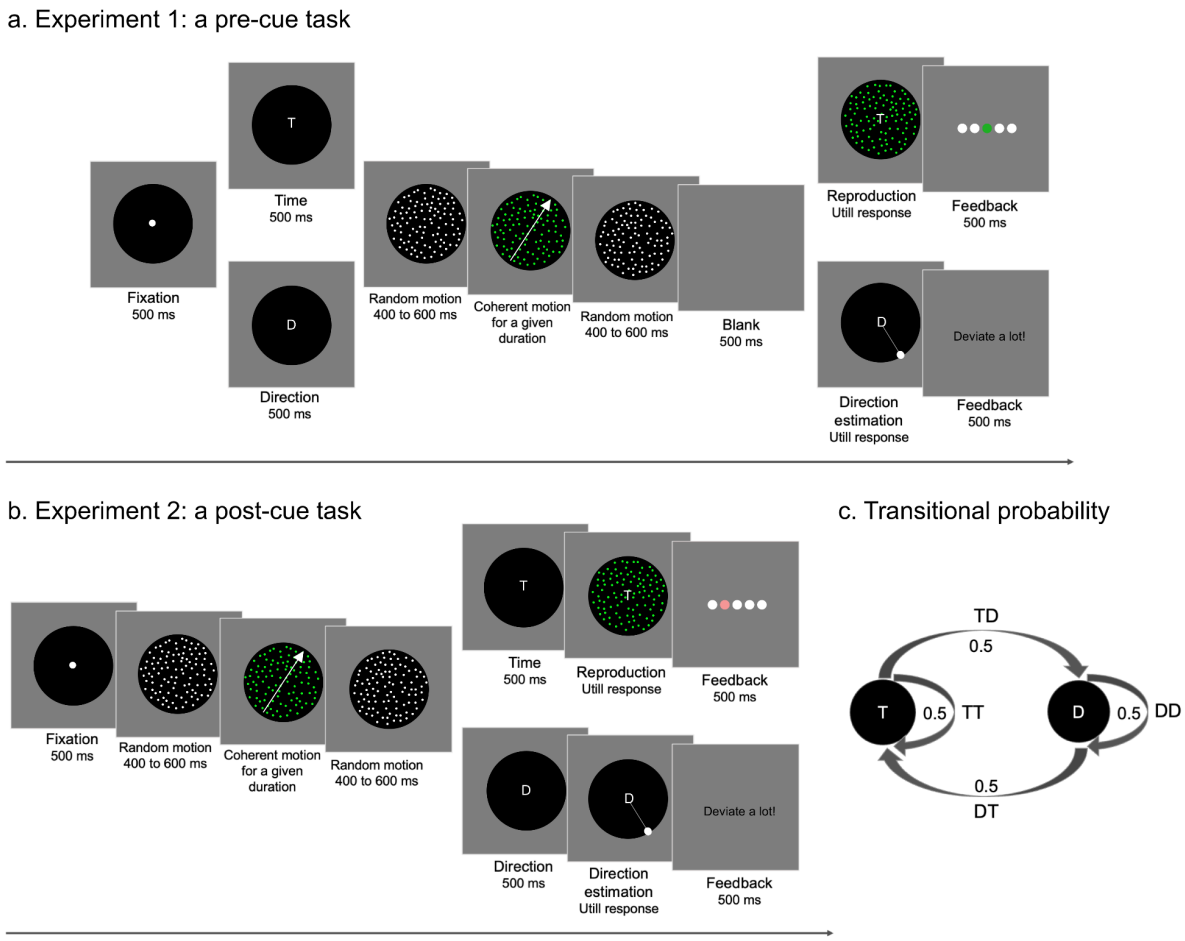

Figure 1. Schematic illustration of the study. (**a**) Procedure of Experiment 1 (the pre-cue task). Each trial began with a fixation dot, followed by a pre-cue letter indicating whether participants should report the direction ("D") or duration ("T") of motion. The encoding phase began with a random dot kinematogram (RDK). When the white random-walked dots turned green, they moved in a specific direction for a given duration (indicated by the illustrative white arrow, not shown in the experiment). Then, they reverted to the random-walked white dots motion. The coherent motion was the target stimulus that participants had to remember either its direction or duration according to the cue. The reproduction phase began after 500 ms of a blank screen. For the duration task, a green RDK display appeared and participants had to click the left mouse to terminate it when the duration matched to the coherent movement perceived during the encoding phase. For the direction task, a display with an adjustable line point appeared and participants adjusted its orientation using a mouse, finalizing the direction report by pressing the space key. After their response, a 500-ms feedback display showed their accuracy; (**b**) Procedure of Experiment 2 (the post-cue task). It included the same encoding phase as in Experiment 1, but without a pre-cue. After the encoding phase, a post-cue displays for 500 ms, prompting participants for either duration or direction reproduction.

The rest procedure was the same as in Experiment 1. (**c**) The inter-trial transitional probability (from trial *n-1* to trial *n*) between the duration and direction tasks. This transitional structure guarantees equal transitional probability of "Direction to Time (DT)", "Time to Time (TT)", "Direction to Direction (DD)", and "Time to Direction (TD)" trials.

Figure 1 illustrates the study setup. We employed a pre-cue for duration and motion direction reproduction task in Experiment 1. Each trial began with a fixation dot (subtended 0.5°; luminance of 85.7 cd/m^2) for 500 ms, indicating the beginning of the trial and prompting participants to focus their attention. A pre-cue with a letter ("D" or "T", visual angle of 0.8° × 1.0°, luminance of 85.7 cd/m^2) appeared in the display center for 500 ms, indicating whether participants should report the direction (the letter "D") or duration (the letter "T") of the coherent motion. The reproduction task consisted of an encoding phase and a reproduction phase. Immediately after the cue display, the encoding phase started with a random dot kinematogram (RDK) display for 400 to 600 ms. The RDK consisted of 100 randomly generated white dots (each dot diameter of 0.2°; luminance of 85.7 cd/m^2) within a dark disk (subtended 17.8°, luminance of 16.5 cd/m^2) at the center of the screen. Those random dots randomly walked at a speed of 1°/s. Subsequently, the white dots turned green (luminance of 45.8 cd/m^2) and moved coherently (100%) with a speed of 6°/s in one direction (randomly selected from 11.25° to 348.75°, in steps of 22.5°) for a randomly sampled duration (0.8, 1.0, 1.2, 1.4, or 1.6 s). When a dot moved out the dark disk, a new dot was randomly regenerated within the disk, keeping 100 dots all the time for the RDK presentation. This coherent motion was the encoding target. According to the pre-cue letter, participants were instructed to remember the direction or duration of the coherent motion for their reproduction task. Then, the dots reverted to random-walked white dot movements for 400 to 600 ms. The RDK displays served as masks before and after the target.

Following the encoding phase, there was a 500 ms blank interval before the participants' response. For the duration task, a letter 'T' appeared in the center of the screen along with random-walked green dots (100 dots, each dot diameter of 0.2°; luminance of 45.8 cd/m^2; velocity of 1 °/s). We used a random-walked motion instead of a coherent motion to minimize inter-trial bias caused by the motion from the reproduction phase, given that we were interested in the sequential effects of the motion from the encoding phase. Participants had to terminate the

presentation by clicking the left mouse when they perceived the duration to match the duration of the green dots' coherent motion from the encoding phase. After their response, feedback was given for 500 ms using a horizontally arranged display of five disks (each subtended 1.8°). The accuracy of the response was indicated by one colored disk, from the left to the right indicating the relative error below -30%, between [-30%,-5%], (-5%, 5%), [5%, 30%] and greater than 30%, respectively. The middle circle appeared in green, representing high accuracy. The middle left and middle right circles are displayed in light red, indicating some deviation from the actual interval. The utmost left and right circles were shown in dark red, indicating a large reproduction error. If it was a direction task, a line pointer with a superimposed letter D appeared. The line started from the center, pointing to a random direction. Participants adjusted the pointer by moving the mouse and confirmed the final orientation by pressing the space key. If the final estimated direction deviated more than 60° from the true direction, a feedback display with the message "Direction deviated a lot!" appeared at the center of the display for 500 ms. Otherwise, a blank display appeared for 500 ms. The next trial began after one second intertrial interval.

Before the formal experiment, participants received 16 practice trials to familiarize themselves with the task. The formal experiment consisted of 480 trials, randomly shuffled with half for duration reproduction and half for direction reproduction. The inter-trial transitional probability (from trial *n-1* to trial *n*) between the duration and direction trials ensured an equal probability of "Direction to Time (DT)", "Time to Time (TT)", "Direction to Direction (DD)", and "Time to Direction (TD)" trials. Participants could take a short break after each block of 30 trials.

Data analysis

We excluded the first trial of each block, resulting in 16 omitted trials. Outliers due to accidental button presses or inattention were also excluded, specifically those with reproduction errors exceeding three standard deviations from the mean error for duration report trials and response errors larger than 45° for direction report trials, before proceeding with further analyses. These outliers were rare, constituting only 0.38% of duration reproduction trials (ranging individually from 0 to 6 outlier trials) and 0.24% of direction report trials (ranging individually from 0 to 13 outlier trials). Next, we categorized the remaining trials into four categories based on the inter-trial transition (from trial *n-1* to trial *n*): Direction to Time (DT), Time to Time (TT), Direction to Direction (DD), and Time to Direction (TD). To investigate the

influence of prior tasks on the sequential effects of current estimates, we conducted separate analyses for duration reproduction and direction reproduction trials.

Duration reproduction trials. We focused on two conditions: the "Time to Time (TT)" representing the prior task-related condition, and the "Direction to Time (DT)" representing the prior task-unrelated condition. Previous research has shown that subjective timing, on an open scale, is susceptible to both the central tendency bias and the sequential bias (Glasauer & Shi, 2022; Holland & Lockhead, 1968). The central tendency bias leads to an overestimation of shorter durations and an underestimation of longer durations, while the sequential bias indicates that duration estimations are influenced by preceding durations.

To calculate the central tendency effect, we employed linear regression to approximate the relationship between the current reproduction error ($Error_n$) and the current duration (T_n) (Cicchini et al., 2012; Jazayeri & Shadlen, 2010; Shi et al., 2013).

$$Error_n = a \cdot T_n + b, \tag{1}$$

where the absolute slope of the linear fit ($|a|$) reflects the central tendency effect. A slope of 0 indicates no central tendency and 1 represents a strong central tendency.

The conventional measures of the serial dependence effect, which correlates the current response error to the difference between the previous and the current stimuli (Bliss et al., 2017; Cicchini et al., 2018; e.g., J. Fischer & Whitney, 2014; Kiyonaga, Manassi, et al., 2017), are not sufficient to separate sequential dependence from the central tendency bias (for more details, see Glasauer & Shi, 2022). Thus, we employed linear regression to the previous trial (Holland & Lockhead, 1968; Jesteadt et al., 1977) to analyze the sequential effect. This involved examining the correlation between the current error and the previous duration (T_{n-1}):

$$Error_n = c \cdot T_{n-1} + d, \tag{2}$$

where the slope of the linear fit (c) indicates the sequential bias (e.g., Glasauer & Shi, 2022; Jesteadt et al., 1977). A positive slope indicates that the current estimation is attracted towards the previous duration (also referred to as the "assimilation"), while a negative slope indicates that the current time estimation is repulsed from the previous duration. Additionally, as a sanity check and for further verification, we also computed the sequential effect using similar regressions for the durations presented in future trials (n+1).

Direction reproduction trials. We focused on two conditions: the "Direction to Direction (DD)" representing the prior task-related condition, and the "Time to Direction (TD)" representing the prior task-unrelated condition. The direction of motion was randomly selected from a circular distribution, featuring 16 equally spaced angles (from 11.25° to 348.75°, in steps of 22.5°), which effectively neutralized any central tendency. Consequently, we focused solely on the sequential effect and skipped the central tendency analysis. The response error was calculated as the difference between the reported direction and the true motion direction for the current trial (i.e., estimate - direction). Negative errors indicated a counter-clockwise deviation from the true direction, while positive errors suggested a clockwise deviation. Additionally, the direction difference was also calculated between the current trial and the previous trial (the previous direction - the current direction), following the same method used in previous research (e.g., J. Fischer & Whitney, 2014). Trials with a direction difference of 0° or ± 180° were excluded, as response errors relative to these direction differences are undefined. Following previous research (Moon et al., 2022) highlighting a significant role of non-directional orientation in the coding of visual motion direction, we reduced the direction difference range from [-180 to 180°] to [-90 to 90°] accordingly. To better reflect the repulsion and attractive biases, we converted the response errors from clockwise or counterclockwise directions to the repulsion (negative) and attractive (positive) biases by collapsing the direction differences to the positive range [0, 90.0°]. This analysis is akin to previous studies (Bae & Luck, 2020).

Prior research has shown that small orientation differences (within 45°) led to a significant attractive bias, while large orientation differences (greater than 45°) resulted in a repulsive bias (Bae & Luck, 2019; Bliss et al., 2017; Fritsche et al., 2017; Fritsche & de Lange, 2019b; Samaha et al., 2019). For example, attraction was observed when the orientation difference was around 17°, and repulsion was found for orientations more than 60° apart (Fritsche et al., 2017). We hypothesized that the reported orientation for the current trial would be repelled by the orientation in the previous trial, particularly when orientations differed markedly. Thus, we calculated the average response errors for mild-orientation-difference trials (45.0° and 67.5°) and compared them to zero for each condition (the prior task being direction reproduction or duration reproduction for the current direction reproduction trials).

Additionally, to deepen our analysis, we computed the sequential effect in direction estimation, separated for the "short" and "long" stimulus presentation. Durations of 0.8 and 1.0

seconds were categorized as “short”, while durations of 1.4 and 1.6 seconds were deemed “long”. We excluded the intermediate duration of 1.2 seconds in this analysis. We then analyzed whether the sequential effects in direction estimation were modulated by the durations (short vs. long) of the target stimulus.

The statistical significance of the central tendency effect and the sequential effect was assessed individually using analysis of variances (ANOVAs) and one-sample *t*-tests against a null hypothesis of zero effect, and paired *t*-tests were run for within-subject between-condition comparisons.

Results and discussion

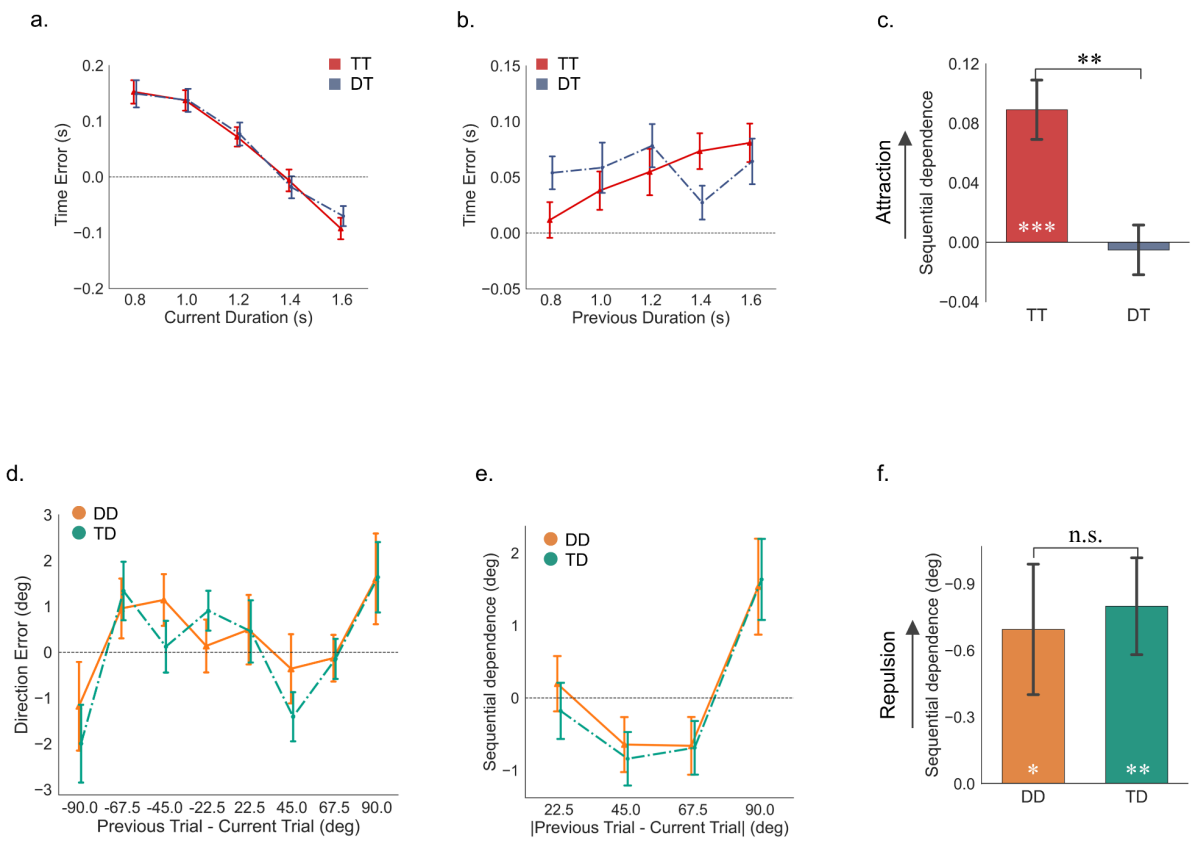

Figure 2. Results of Experiment 1. (**a**), (**b**), and (**c**) were the results of duration reproduction trials. (**a**) Central tendency effect. Mean reproduction errors on the current sample duration, plotted separately for trials preceded by time report (TT) and direction report (DT). (**b**) Sequential effect. Mean reproduction errors on the previous duration, plotted separately for TT and DT conditions. (**c**) The mean slope of the linear fit. (**d**), (**e**), and (**f**) were the results of direction reproduction trials. (**d**) Mean response errors on the

orientation difference of [-90°, 90°], plotted separately for trials preceded by direction report (DD) and time report (TD). The angular difference was realigned to represent the relative motion orientation (plus 180° for the opposite direction) of the previous trial. (**e**) Mean errors on the absolute orientation difference of [0°, 90°], plotted separately for DD and TD conditions. The sign of the response error was coded so that positive values indicate that the current-trial direction report was biased toward the direction of the previous trial, and negative values indicate that the current-trial direction report was biased away from the direction of the previous trial. Maximum repulsion occurred at 45° and 67.5° orientation differences. (**f**) Mean errors averaged across 45.0° and 67.5°, were plotted separately for DD and TD conditions. Error bars represent ± SEM. *** denotes $p < .001$,** $p < .01$,* $p < .05$, and n.s. non-significant.

Duration reproduction trials Overall, the mean reproduction errors (and associated standard errors, SEs) for prior duration trials (task-related: TT) and prior direction trials (task-unrelated: DT) were 51 ± 14 ms and 57 ± 15 ms, respectively. There was no significant difference between the two conditions ($t_{(22)}$ = -0.647, p = .524, d = -0.090). To examine the precision of duration reproduction for two kinds of preceding task (time vs. direction), we calculated the standard deviation of reproduction between TT and DT conditions, and it didn't show any significant difference between the two conditions ($t_{(22)}$ = 0.142, p = .888, d = 0.012). Regarding the central tendency effect (Eq. 1), it was evident in both the prior task-related TT and prior task-unrelated DT conditions. The mean central tendency indices (and associated SEs) were 0.317 ± 0.037 ($t_{(22)}$ = 8.605, p <.001, d = 1.794) and 0.297 ± 0.039 ($t_{(22)}$ = 7.565, p <.001, d = 1.577) for the TT and DT conditions, respectively. However, there was no difference between the conditions ($t_{(22)}$ = 1.364, p = .186, d = 0.109, BF_{10} = 0.479), as illustrated in Figure 2a.

To quantify the sequential effect, we plotted the reproduction errors on the previous durations separately for the TT and DT conditions (as shown in Figure 2b). The reproduction error increased with increasing prior duration, showing a longer prior duration attracted bias to a positive direction, manifesting an attractive sequential effect. This effect was quantified using the slope of linear regression (Eq. 2), which showed that the average slope was larger for the prior task-related TT condition (8.9% ± 2.0%) than that for the task-unrelated DT condition (-0.5% ± 1.7%), with paired t-test $t_{(22)}$ = 3.813, p = .001, d = 1.064. The slope was only significantly positive for the TT condition ($t_{(22)}$ = 4.457, p < .001, d = 0.929), but not for the DT condition ($t_{(22)}$ = -0.304, p = .764, d = 0.063). To ensure the validity of the findings and avoid statistical artifacts

(Cicchini et al., 2014), we also tested the sequential effect on the durations presented in future trials (*n+1*) and found no effects (*ps* > .417).

Direction estimation trials The mean response errors were plotted against the orientation difference between the previous and the current trials (ranging from -90° to 90°, a positive value representing the difference in the clockwise direction), separated for the prior task-related (DD) and task-unrelated (TD) conditions (Figure 2d). We first examined the precision of response, and the standard deviation of direction reproduction between DD and TD conditions didn't show any significant difference between the two conditions ($t_{(22)}$ = 0.967, p = .344, d = 0.061). Additionally, the direction errors were translated into the repulsion (negative) and attractive (positive) sequential effect and replotted as a function of the absolute orientation difference for each condition (illustrated in Figure 2e). By visual inspection, the maximum repulsion effect is likely located between 45.0° and 67.5°, with a large difference between preceding trial types. Indeed, the average repulsive biases across the orientation differences of 45.0° and 67.5° were -0.695° ± 0.294° and -0.799° ± 0.218° for the DD and TD conditions, showing no difference between the two, $t_{(22)}$ = 0.283, p =.78, d = 0.084, BF_{10} = 0.227 (Figure 2f), and both were significantly negative (DD: $t_{(22)}$ = 2.367, p =.027, d = 0.494; TD: $t_{(22)}$ = 3.665, p =.001, d = 0.764).

We further explored whether target durations modulated the repulsion effect. With the short stimulus exposure (< 1.2 s), the average repulsive biases were -0.248° ± 0.522° and -0.596° ± 0.424° for the DD and TD conditions, respectively, across orientation differences of 45.0° and 67.5°. For long stimulus exposure, these biases were -0.686° ± 0.353° and -0.879° ± 0.288°. An ANOVA examining these biases, considering Stimulus Exposure and Prior Task, revealed no significant main effects for Prior Task ($F_{(1,22)}$ = 0.280, p = .602, η_p^2 = 0.005), Stimulus Duration ($F_{(1,22)}$ = 1.326, p = .262, η_p^2 = 0.009), or their interaction ($F_{(1,22)}$ = 0.045, p = .834, η_p^2 = 0.000). These results suggest that the repulsion effect across the orientation differences of 45.0° and 67.5° was not affected by the variation in stimulus durations.

When the orientation difference was large at 90°, both (DD: 1.537° ± 0.663°, $t_{(22)}$ = 2.320, p =.030, d = 0.484; TD: 1.638° ± 0.599°, $t_{(22)}$ = 2.927, p =.008, d = 0.610) were significantly assimilated toward the previous direction with a comparable magnitude ($t_{(22)}$ = -0.100, p =.921, d = -0.034, BF_{10} = 0.220). Furthermore, this assimilation effect at 90° was unaffected by the

variation of stimulus durations. The ANOVA on the reproduction biases, considering factors of Stimulus Duration and Prior Task failed to reveal any significance (Fs < .345, ps > .564, $\eta_p^2 s$ < .005), indicating the assimilation bias was unaffected by the variations of stimulus exposure.

Thus, Experiment 1 revealed an attractive bias in duration reproduction, only when the prior task was also time-related, suggesting that assimilation in temporal perception requires reproduction to the same dimension in the previous trial. In contrast, the direction task yielded comparable biases that remained unaffected by the prior task type and stimulus exposure. When the difference between two consecutive orientations was large (e.g., 45.0° and 67.5°), a repulsion bias was observed, whereas for orientation differences (90°), an attractive bias emerged.

Experiment 2

In Experiment 1, we employed a pre-cue paradigm in which participants were aware of the response dimension in advance, and the unattended dimension did not require active working memory maintenance during encoding. This setup might have led to a diminished encoding of the unattended feature dimension, leading to the lack of sequential dependence. To address this, in Experiment 2, we adopted a post-cue paradigm where both response dimensions, duration and direction, had to be memorized during the encoding phase, and a post-cue revealed which dimension was relevant for the response.

Methods

Participant

Twenty-three participants were recruited in Experiment 2 (13 females, 10 males; age 19 - 40, mean ± SD: 27.78 ± 5.31 years). All participants provided their written informed consent prior to the experiment and received 9 Euro/hour for their participation. The study was approved by the ethics committees of the Psychology Department at LMU Munich.

Stimuli and procedure

Experiment 2 used the post-cue paradigm, which was essentially the same as in Experiment 1, with one key difference: the task cue display (500 ms) was shown after the encoding phase (see Figure 1 b). In order to perform the tasks properly, participants had to

remember both direction and duration in the encoding phase and then report one of them according to the post-cue.

Data analysis

The data analysis for Experiment 2 followed essentially the same approach as that of Experiment 1. The first trial of each block was excluded. The outliers, using the same criteria as in Experiment 1, were rare in Experiment 2, on average only 0.40% of the duration reproduction trials (ranging individually from 0 to 4 outlier trials) and 0.96% of the direction reproduction trials (ranging individually from 0 to 37 outlier trials). The remaining trials were grouped into four categories based on the inter-trial task changes: Direction to Time (DT), Time to Time (TT), Direction to Direction (DD), and Time to Direction (TD). We analyzed the sequential effects in duration reproduction trials (including prior task-related: TT and prior task-unrelated: DT conditions) and direction reproduction trials (including prior task-related: DD and prior task-unrelated: TD conditions) separately.

The same statistical analysis as in Experiment 1 was employed in Experiment 2. To examine the effects across experiments, we performed a two-way mixed-design ANOVA on the dependent variables of interest, which included the central tendency effect and sequential effect for duration reproduction trials, and sequential effect for direction reproduction trials. The prior task (task-related response vs. task-unrelated response) was included as a within-subject factor, and the experiment (pre-cueing vs. post-cueing) was included as a between-subject factor. In instances where post hoc analyses were required, additional tests were carried out.

Results and discussion

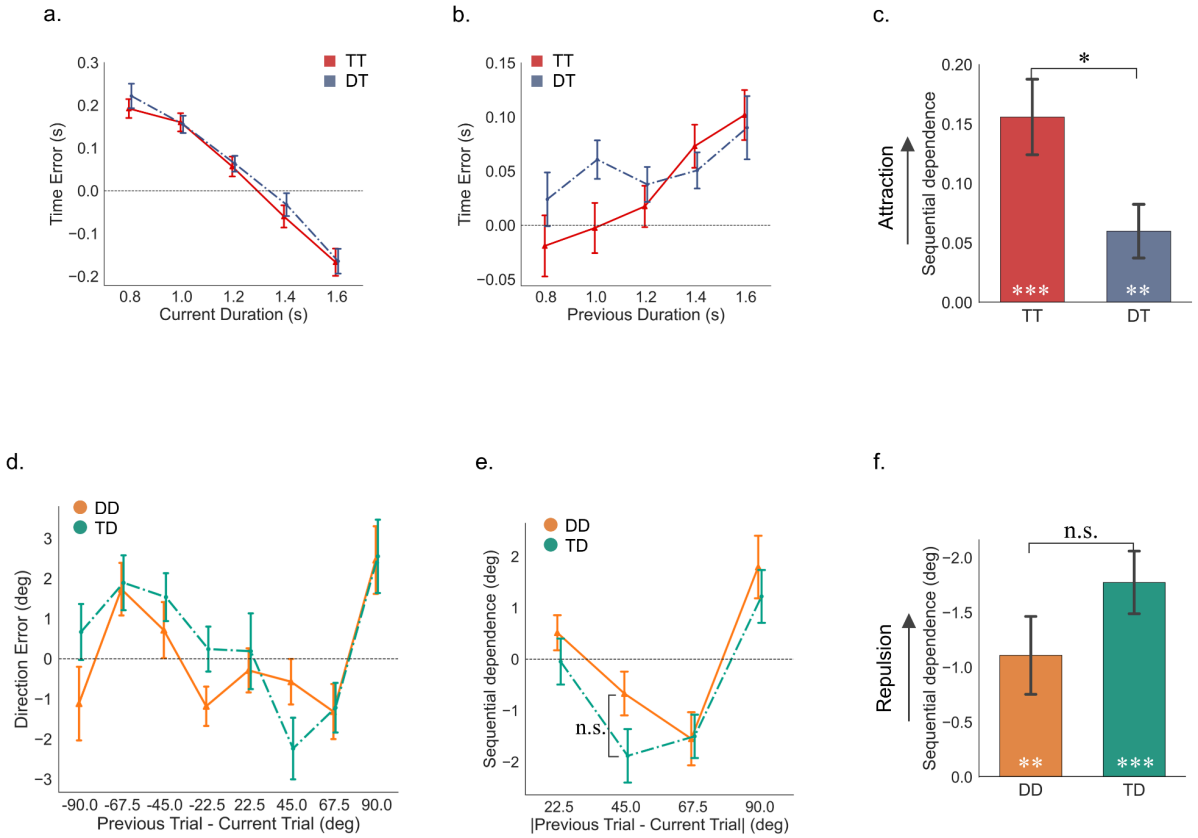

Figure 3. Results of Experiment 2. (**a**), (**b**), and (**c**) were the results of duration reproduction trials. (**a**) Central tendency effect. Mean reproduction errors on the current sample duration, plotted separately for trials preceded by time report (TT) and direction report (DT). (**b**) Sequential effect. Mean reproduction errors on the previous duration, plotted separately for TT and DT conditions. (**c**) The slope of the linear fit. (**d**), (**e**), and (**f**) were the results of direction reproduction trials. (**d**) Mean response errors on the orientation difference of [-90°, 90°], plotted separately for trials preceded by direction report (DD) and time report (TD). The angular difference was realigned to represent the relative motion orientation (plus 180° for the opposite direction), rather than the motion direction, of the previous trial. (**e**) Mean errors on the absolute orientation difference of [0°, 90°], plotted separately for DD and TD conditions. The sign of the response error was coded so that positive values indicate that the current-trial direction report was biased toward the direction of the previous trial, and negative values indicate that the current-trial direction report was biased away from the direction of the previous trial. The difference between the DD and TD conditions for the 45° orientation difference didn't reach significance, for the large separation was due to one participant who had large response errors in this type. Maximum repulsion occurred at 45° and 67.5° orientation differences. (**f**) Mean errors averaged across 45.0° and 67.5°, were plotted separately for

DD and TD conditions. Error bars represent ± SEM. ***p < .001,**p < .01,*p < .05, n.s denotes no significant effect.

Duration reproduction trials The average reproduction errors and their associated SEs for trials with prior duration reproduction (task-related: TT) and trials with prior direction reproduction (task-unrelated: DT) were 34 ± 18 ms and 51 ± 16 ms, respectively. The difference between the two conditions was not significant, ($t_{(22)}$ = -1.755, p = .093, d = -0.208, BF_{10} = 0.818). The standard deviation of duration reproduction between TT and DT conditions didn't show any significant difference between the two conditions ($t_{(22)}$ = 0.316, p = .755, d = 0.020). Both conditions exhibited significant central tendency biases: 0.471 ± 0.057 and 0.486 ± 0.058 for the TT and DT conditions, respectively (ts$_{(22)}$ > 8.3, ps <.001, ds > 1.7). There was no significant difference between them ($t_{(22)}$ = -0.581, p = .580, BF_{10} = 0.255, Figure 3a).

The sequential effects for each condition were illustrated in Figure 3b, with mean slopes of 15.6% ± 3.2% and 6.0% ± 2.3% for the task-related (TT) and task-unrelated (DT) conditions, respectively (Figure 3c). Both slopes were significantly higher than zero (ts$_{(22)}$ > 2.6, ps < .02, ds > 0.55), indicating a significant attractive bias in both conditions. Moreover, a paired t-test showed that the assimilation was significantly larger in the TT than in the DT condition ($t_{(22)}$ = 2.513, p = .020, d = 0.728). Tests of the sequential effect on future trial durations ($n+1$) ruled out any statistical artifacts (ps > .769).

Direction estimation trials Figure 3d depicted the response errors against the orientation difference from -90° to 90° for prior direction reproduction and duration reproduction trials separately. The standard deviation of direction reproduction between prior direction report and duration report trials didn't show any significant difference between the two conditions ($t_{(22)}$ = 1.091, p = .287, d = 0.103). The direction errors were translated into the repulsion (negative) and attractive (positive) sequential effect and replotted in Figure 3e. Repulsion biases occurred at orientation differences of 45.0° and 67.5°. The averaged repulsion biases from the two orientation differences were significant for both task-related (DD) and task-unrelated (TD) conditions (DD: -1.110° ± 0.355°; TD: -1.775° ± 0.286°, ts$_{(22)}$ > 3.127, ps < .005, ds > 0.65), but did not differ from each other ($t_{(22)}$ = 1.918, p =0.068, d = 0.431, BF_{10} = 1.038). A further ANOVA on the reproduction biases, considering factors of Stimulus Duration and Prior Task

failed to reveal any significance (Fs < .2.84, ps > .106, $\eta_p^2 s$ < .017), indicating the repulsion bias was unaffected by the variations of stimulus exposure.

We also observed an attractive bias for both TD and DD conditions at an orientation difference of 90° (DD: 1.796° ± 0.610° and TD: 1.224° ± 0.514°, $ts_{(22)}$ > 2.38, p < .026, d > 0.49), and they were comparable ($t_{(22)}$ = 0.937, p =.359, d = 0.211, BF_{10} = 0.324). A further ANOVA on the reproduction biases, considering factors of Stimulus Duration and Prior Task failed to reveal any significance (Fs < .438, ps > .51, $\eta_p^2 s$ < .003), indicating the assimilation bias was unaffected by the variations of stimulus exposure.

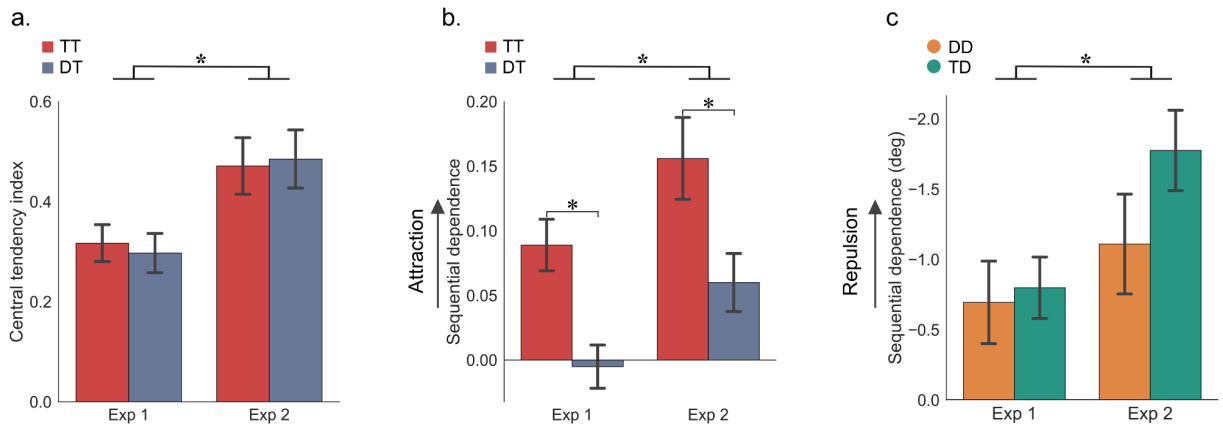

Figure 4. ANOVA results between experiments (pre-cueing vs. post-cueing) and prior tasks (task-related vs. task-unrelated). (**a**) Central tendency effect for duration reproduction trials. (**b**) Attractive sequential effect for duration reproduction trials. (**c**) Repulsive sequential effect for direction reproduction trials. Error bars represent ± SEM. *p < .05.

Omnibus analysis

To gain a better understanding of the differences between the pre-cue and post-cue paradigms in terms of central tendency and sequential effects, we further conducted an omnibus analysis across both experiments.

For the duration reproduction trials, an ANOVA on the central tendency index with factors of Experiment and Prior Task revealed a significant main effect of Experiment ($F_{(1,44)}$ =

6.448, p = .015, η_p^2 = 0.128), indicating a larger central tendency in the post-cueing experiment (Figure 4a). However, neither the main factor of Prior Task ($F_{(1,44)}$ = 0.047, p = .830, η_p^2 = 0.001, BF_{10} = 0.163) nor their interaction ($F_{(1,44)}$ = 1.397, p = .244, η_p^2 = 0.031) was significant. By contrast, a separate two-way ANOVA on the sequential effect with the same two factors revealed both main factors were significant: Experiment, $F_{(1,44)}$ = 7.541, p = .009, η_p^2 = 0.146; Prior Task, $F_{(1,44)}$ = 17.465, p < .001, η_p^2 = 0.284. The results showed that the attraction was significantly larger with the preceding same rather than the different task. Additionally, the attraction was amplified with the post-cue compared to the pre-cue. However, there was no significant interaction ($F_{(1,44)}$ = 0.002, p = .966, η_p^2 < 0.001).

Next, we applied an ANOVA on the standard deviation of responses (i.e., precision) with factors of Experiment (Exp. 1: pre-cueing vs. Exp. 2: post-cueing) and Task (duration reproduction vs. direction report), which revealed that neither Task ($F_{(1,44)}$ = 0.104, p = .748, η_p^2 = 0.002), nor Experiment ($F_{(1,44)}$ = 1.522, p = .224, η_p^2 = 0.033), nor their interaction ($F_{(1,44)}$ = 0.014, p = .905, η_p^2 = 0.000) was significant. The results suggest that the task difficulties for the two tasks and experiments were comparable.

For the direction reproduction, a separate two-way mixed ANOVA on the repulsion effect (averaged across 45.0° and 67.5°) revealed a significant main effect of Experiment ($F_{(1,44)}$ = 4.542, p = .039, η_p^2 = 0.146). The repulsion effect was significantly enhanced with the post-cue relative to the pre-cue. Neither Prior Task ($F_{(1,44)}$ = 2.309, p = .136, η_p^2 = 0.050, BF_{10} = 0.463) nor the interaction ($F_{(1,44)}$ = 1.227, p = .274, η_p^2 = 0.027) was significant.

In summary, comparison across experiments revealed that the post-cue enhanced the central tendency and sequential biases, suggesting that the sequential attractive bias in time reproduction is influenced by working memory and post-perceptual processing, consistent with prior research (Bliss et al., 2017). In contrast to duration reproduction, direction reproduction was unaffected by the preceding task in both experiments. We consistently observed a sequential

repulsion for orientation differences of 45.0° and 67.5°, along with an attraction for an orientation difference of 90°. Although the sequential effect was enhanced by the post cue, possibly through the interaction of memory retention, the prior task did not differentiate the sequential effect in general. If any, it was weak (p = .068), with the post-cue paradigm, and diminished with the pre-cue paradigm. The finding contrasts with the results of Bae and Luck (2020), who reported differential effects of prior tasks with the post-cue paradigm. The discrepancy may arise from the fact that their experimental setup involved two spatial tasks (color and direction) that might interact with each other in working memory, while we employed time and space tasks.

General Discussion

The present study investigated how task changes influence our ability to estimate direction and timing. We used both pre-cue and post-cue paradigms to examine these influences and their underlying mechanisms. Intriguingly, in both experiments, we observed only sequential attraction in timing tasks, but both repulsion and attraction effects in direction tasks. Importantly, the sequential attraction was reliable for the duration reproduction task when the preceding trial involved the same task. However, this attraction in duration reproduction was significantly reduced in the post-cue setting - and vanished in the pre-cue setting - when the preceding trial involved a direction task. Meanwhile, the nature of the preceding task had no effect on sequential repulsion or attraction in direction reproduction, regardless of the cue type. Nonetheless, the post-cue setting enhanced both attraction and repulsion effects. Our findings thus highlight distinct sequential biases for timing and spatial tasks, suggesting separate underlying processes for temporal and spatial sequential effects.

Both attraction and repulsion effects are documented in previous studies on static orientation judgments. For example, when stimuli such as Gabor orientations or gratings are used, small orientation differences between trials (under 20°) typically yield attraction biases, while larger differences elicit repulsion biases (Alais et al., 2017; Bliss et al., 2017; Ceylan & Pascucci, 2023; Fritsche et al., 2017; Fritsche & de Lange, 2019a). Contrastingly, studies using coherent motion predominantly report a repulsion effect (e.g., Bae & Luck, 2020), aligning with our findings. Motion processing involves the representation of both motion direction and

orientation (Alais et al., 2017; Moon et al., 2022). In the case of brief or mostly random motion presentation, the orientation signal of the motion may become more dominant, resulting in attraction effects similar to those observed in static orientation studies (J. Fischer & Whitney, 2014; Manassi et al., 2018). In contrast, long exposure to a coherent motion signal (e.g., here 800 to 1600 ms) can induce motion adaptation, resulting in repulsive motion aftereffects (Alais et al., 2005; Anstis et al., 1998). These effects tend to overshadow any attraction biases that might occur with small cross-trial differences. Furthermore, in our study, the repulsion effect remained unaffected by stimulus duration, likely due to the relatively long stimulus exposure times we employed compared to previous research (e.g., 200 or 500 ms (Bae & Luck, 2020; C. Fischer et al., 2020)). Interestingly, we observed an attraction effect at a 90° orthogonal difference, which might also be interpreted as a repulsion to the opposite motion direction.

It is worth noting that unlike the study by Bae and Luck (2020), which involved two spatial tasks, our study, using one spatial and one timing task, did not show any differential impacts of the preceding task, even when the task was known in advance, as in the pre-cue task. This indicates that repulsive biases in motion direction judgments might be attributed to long-lasting visual sensory adaptation, with minimal influence from task-specific attentional orienting. This aligns with the typical pattern of sensory adaptation, where negative biases dominate when previous stimuli are either unattended or irrelevant to the task, or when visual stimuli have a long duration and high contrast, or a reference (Manassi et al., 2018; Pascucci et al., 2019; Pascucci & Plomp, 2021; Su et al., 2023). Although earlier studies have suggested that motion adaptation could be a result of low-level perceptual processing, our findings imply that maintaining both tasks in working memory (as shown in the post-cue task) can enhance the repulsion bias. This suggests a potential involvement of high-level working memory interference, particularly the active discarding of irrelevant information, could be pivotal. Recent research supports this, showing that items removed from working memory as no longer relevant in the current trial exert a repulsion effect on the subsequent trial (Shan & Postle, 2022). Moreover, empirical findings suggest that disengaging attention from an item might also involve a mechanism of removing information from working memory (Lewis-Peacock et al., 2018).

Conversely, we observed a sole assimilation effect in timing tasks. What accounts for the observed distinct patterns in sequential biases between timing and spatial tasks? Time perception, unlike spatial perception, lacks dedicated sensory systems (Wittmann & Paulus, 2008). The brain

constructs time perception by integrating the current sensory estimation with recent history and the prior knowledge of the stimuli to enhance processing efficiency. This integration leads to an assimilation effect in time perception. For spatial perception, Fischer et al. (2014) argued that the assimilation effect may stem from a "continuity field", where the brain smooths out noises by averaging the past and the current information, promoting sensory stability and continuity. For time perception, Glasauer and Shi (2022) showed that individual beliefs of temporal continuity can impact the magnitudes of the sequential bias. Those with a high belief in temporal continuity yielded strong attraction effects. Recent studies also propose that the attraction bias involves post-perceptual processes that link sensory representation to responses (Ceylan et al., 2021; Fritsche & de Lange, 2019b; Glasauer & Shi, 2022; Kim et al., 2020; Kim & Alais, 2021; Suárez-Pinilla et al., 2018). In line with this, the assimilation effect was more pronounced in duration reproduction following the same timing task, rather than the motion direction task.

Moreover, time perception relies on a memory system for monitoring the passage of time and temporal decisions (Gibbon & Church, 1990; Shi et al., 2013), and it is susceptible to manipulation through working memory tasks, such as pre-cue and post-cue tasks. As a result, buffering two tasks in working memory using the post-cue paradigm amplified the attraction effect in duration reproduction. This suggests that the attractive sequential effect may involve active recall of memory traces (Bliss et al., 2017; Ceylan & Pascucci, 2023; Fornaciai & Park, 2020; Fritsche & de Lange, 2019a; Ranieri et al., 2022). The lingering memory trace from a preceding stimulus in working memory likely contributes to sequential biases, as the brain employs recent experiences to shape our perception of the sensory environment in the present moment.

In summary, our study dissected sequential biases in space and time using a unified setting that tested both spatial motion direction and time reproduction. We uncovered distinct sequential biases: time blends through assimilation, while direction skews via dominant repulsion, with time particularly influenced by the preceding task. Our findings highlight that sensory processing and adaptation are key in shaping sequential biases in coherent motion direction, while working memory and post-perceptual processes have a greater effect on the bias in time reproduction. Moreover, increasing the working memory load intensified both the attraction in timing and repulsion in direction tasks. The distinct pattern of sequential biases

between time and space potentially links to the dual roles of working memory in retrieving and discarding information, which presents an exciting avenue for further research.

Conflict of Interest

All the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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. All data and code will be made available in online repositories upon acceptance.

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