Motion duration is overestimated behind an occluder in action and perception tasks

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Abstract

Motion estimation behind an occluder is a common task in situations like crossing the street or passing another car. People tend to overestimate the duration of an object's motion when it gets occluded for subsecond motion durations. Here, we explored (1) whether this bias depended on the type of interceptive action: discrete keypress vs. continuous reach and (2) whether it was present in a perception task without an interceptive action. We used a prediction-motion task and presented a bar moving across the screen with a constant velocity that later became occluded. In the action task, participants stopped the occluded bar when they thought the bar reached the goal position via keypress or reach. They were more likely to stop the bar after it passed the goal position regardless of the action type, suggesting that the duration of occluded motion was overestimated (or its speed was underestimated). In the perception task, where participants judged whether a tone was presented before or after the bar reached the goal position, a similar bias was observed. In both tasks, the bias was near constant across motion durations and directions and grew over trials. We speculate that this robust bias may be due to a temporal illusion, Bayesian slow-motion prior, or the processing of the visible-occluded boundary crossing. Understanding its exact mechanism, the conditions on which it depends, and the relative roles of speed and time perception requires further research.

Keywords: occluded motion, motion estimation, speed perception, time perception

Introduction

Extrapolating a moving object's trajectory when it becomes occluded is a common task for the visuomotor system. For instance, while navigating through traffic, we need to keep track of moving objects such as cars, bikes, and pedestrians as they momentarily become occluded and adjust our course of action accordingly. In the motion perception literature, this ability has been studied by measuring time-to-contact judgments using the prediction-motion task (e.g., DeLucia & Liddell, 1998; Schiff and Oldak 1990; Tresilian, 1995). The prediction-motion task involves estimating the time of contact between an initially visible moving object that becomes occluded and a goal position within the occluded region. Thus, observers need to extrapolate the spatiotemporal trajectory of the object to successfully predict its future position. Modeling work has shown that observers combine speed, distance, and time information to derive accurate estimates (Chang & Jazayeri, 2018). Performance can be modulated by stimulus properties and task parameters such as movement duration, speed, and direction, the size and perceived mass of the moving object, the extent of the occlusion, as well as contextual cues (for reviews, see Battaglini & Ghiani, 2021; Bosco et al., 2015).

While performance may vary under different conditions, some consistent biases have been reported. For example, people tend to underestimate the movement duration (or overestimate the speed) of an occluded moving object if the object is approaching the observer, which likely reflects cautious, collision-avoidance judgment strategies (e.g. Schiff & Detwiler, 1979; Schiff & Oldak, 1990). Interestingly, however, people tend to overestimate the movement duration (or underestimate the speed) of an occluded object if it is moving along a parallel plane to the observer (e.g. Agostino, et al., 2022; Battaglini & Mioni, 2019; Bennett et al., 2010; Chen et al., 2020; Reynolds, 1968; Sokolov & Pavlova, 2003; Vicovaro et al., 2019; Yakimoff et al., 1993). For instance, when tasked with intercepting a moving object at a specified location behind an occluder, on average, people stop the object after it passes the specified location.

Such duration overestimation is typically observed for occluded motion durations around or less than a second. Nevertheless, evidence exists that duration overestimation bias can be observed for suprasecond occlusion durations (e.g. Battaglini & Mioni, 2019; Sokolov & Pavlova, 2003) while the opposite can be true where duration underestimation can be observed for subsecond occlusion durations (e.g. Benguigui et al., 2004; Bennett et al., 2010; Peterken et al., 1991). A closer look at these studies reveals that a duration overestimation bias is generally observed for conditions with higher motion speeds (e.g. >10 deg/s) and shorter motion durations (e.g. <1s or around 1s).

Here, we explored the role of interceptive action type (discrete vs. continuous) and the nature of the task (action vs. perception) in the abovementioned duration overestimation bias for occluded motion in two experiments. We used a prediction-motion task where we presented a bar that moved across the screen with a constant velocity. The moving bar was visible during the first half of the movement duration and disappeared behind an occluder in the second half (see **Fig. 1A**). We varied the motion duration and direction across trials. Participants estimated the moment when the bar reached the goal position behind the occluder.

First, we examined whether the type of interceptive action affected the occlusion bias. Previous studies have used discrete responses where participants pressed a key to intercept the moving object at a specified position behind an occluder (e.g. Chen et al., 2020; Sokolov & Pavlova, 2003; Yakimoff, et al., 1993). In Experiment 1, we contrasted the performance using an interceptive discrete action (keypress) with a continuous action where participants made reaching movements to touch the screen to intercept the moving object (see **Fig. 1C**, action task). We reasoned that continuous movements might alleviate the occlusion bias given the findings that concurrent continuous movements can improve time perception (for a recent review, see De Kock et al., 2021). For example, it has been shown that participants who made concurrent hand movements compared with those who kept their hand still during a temporal bisection task or the encoding phase of a temporal reproduction task were less variable in their responses (Wiener et al., 2019). This pattern may be explained by a Bayesian cue combination, a proposed mechanism by which the brain combines noisy information from different modalities in a near-optimal fashion (Alais & Burr, 2019). In the case of time perception, movements may provide more precise temporal information compared with the sensory stimuli carrying temporal information (De Kock et al, 2021; Wiener et al., 2019), leading to a combined estimate that is biased toward the more reliable information source and more precise than either of the estimates alone. Thus, we may observe better motion extrapolation performance either marked by attenuated bias and/or improved precision when the interceptive action allows for continuous movements in the case of reaching.

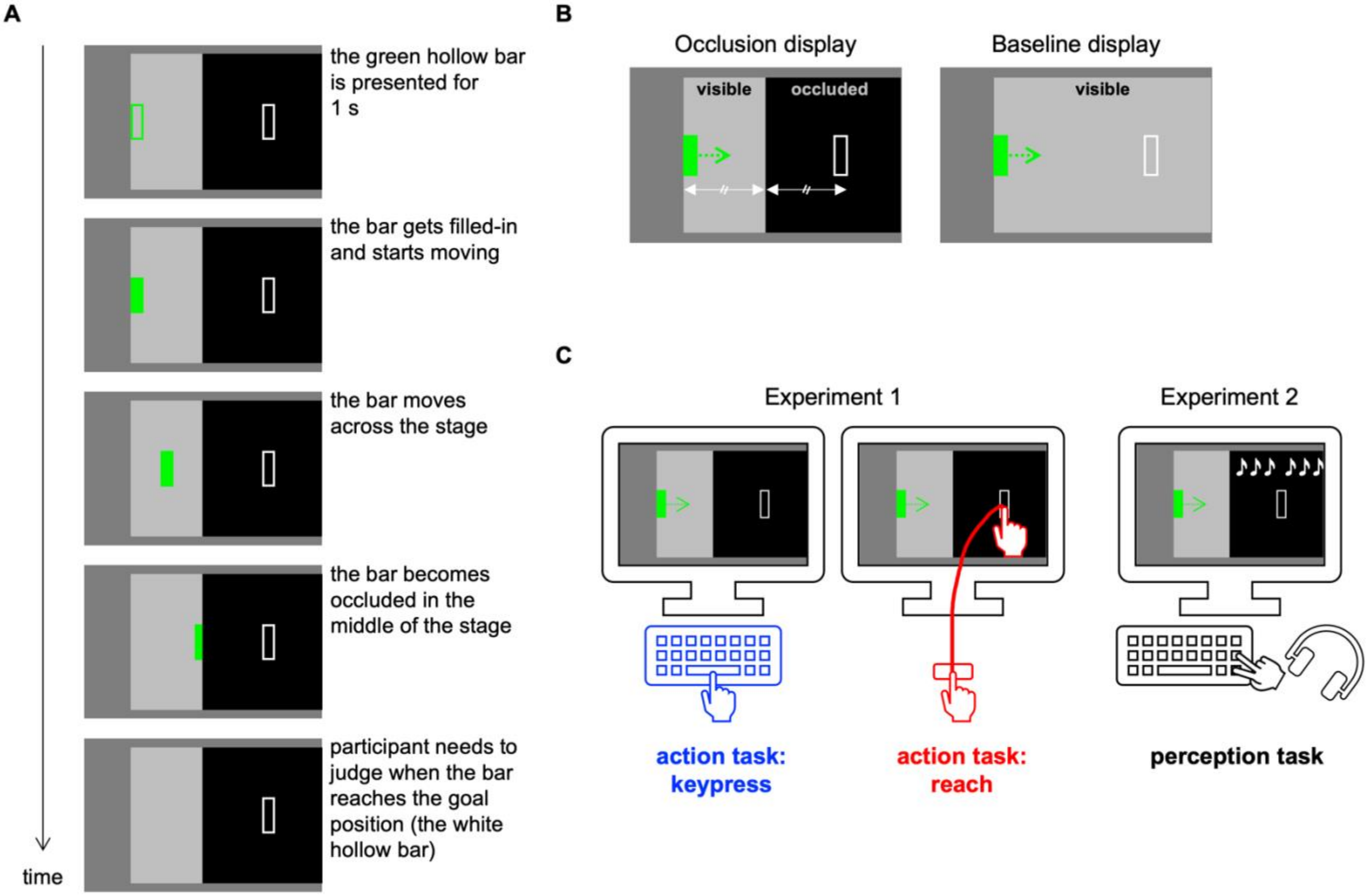

Figure 1. A) Sequence of events in a given trial is shown. **B)** Displays used in the occlusion and baseline conditions in both experiments are shown. **C)** The action tasks, which involved intercepting the moving bar via keypress or reach, and the perception task, which involved judging whether a tone was presented before or after the moment of contact, are shown.

Second, we examined whether this bias was present in a perception task that did not require an interceptive action. Manual interception in prediction-motion tasks requires successfully updating predictions of the object's location based on available sensory information and the existing knowledge about the environment and controlling movement according to those predictions to intercept the object at the right place and the right time (for reviews, see Bosco et al., 2015; Brenner & Smeets, 2018). Having to coordinate perception and action, or the extra step of movement control might have an impact on motion estimation performance. In particular, while movement preparation and/or execution can improve time perception, it can also bias it (for a review, see, De Kock et al, 2021; Merchant & Yarrow, 2016). Such effects include saccadic chronostasis (e.g. Morrone et al., 2005; Yarrow et al., 2001) or manual chronostasis (Yarrow & Rothwell, 2003) characterized by the duration of the object of an eye or hand movement being overestimated, temporal binding between action-triggering event and the triggered action (Yabe & Goodale, 2015) or between action-triggered event and triggering action (Wenke & Haggard, 2009), and action preparation slowing down perceived time (Hagura et al., 2012). These findings may be unsurprising considering the close link between action and timing in many everyday movements and the commonality between the neuroanatomical, neurophysiological, and neurochemical systems associated with action and timing (for a review, see Merchant et al., 2013).

Thus, in Experiment 2, we explored whether the occlusion-driven duration overestimation bias was due to temporally precise actions. If it is the case, when measuring motion extrapolation performance using a perceptual judgment task, we should expect the bias to attenuate or disappear. To that end, we employed a perceptual task where participants judged the onset of a tone that was presented at various moments around when the object reached the goal position (see **Fig. 1C**, perception task) using the method of constant stimuli. We then used participants' responses to determine a point of subjective equality (PSE) at which the tone seemed simultaneous with the object reaching the goal position.

Experiment 1: Motion estimation for discrete (keypress) and continuous (reach) action

In Experiment 1, motivated by recent studies showing that continuous movements can improve time perception (for a recent review, see De Kock et al., 2021), we examined whether the type of the interceptive action, discrete or continuous, had an effect on the duration overestimation bias observed in occluded motion estimation (see **Fig. 1C**, action tasks).

Methods

Participants. Twenty-five Brown University undergraduate students were recruited to participate in the study. All were right-handed and had normal or corrected-to-normal vision. Participants received partial course credit for their participation, which lasted approximately one hour. We excluded one participant because they could not complete the baseline session due to computer issues. Thus, our sample included 24 participants (16 females) between the ages of 18 and 21 years (M = 18.96 years, SD = 0.75). The protocol was approved by the Institutional Review Board at Brown University. Participants gave informed consent and were treated according to the guidelines of the Institutional Review Board.

The sample size required to observe a significant effect for the occlusion bias in a paradigm incorporating discrete and continuous responses was determined based on our preliminary study with N = 24 participants (see Supplementary Materials for preliminary study details). A robust occlusion bias (using a paired samples t-test comparing occlusion block vs. baseline block performance) was found with an effect size of *d* = 0.78 for keypress responses and *d* = 0.81 for reach responses. Using G*Power 3.1 (Faul et al., 2007) with an α of .05 and power of .95, a minimum sample size of 23 was determined (based on *d* = 0.80). To have an even number of participants for task order counterbalancing, we included 24.

Stimuli and procedure. Stimuli were presented using a computer running MATLAB (Version 2015b; Mathworks) and Psychtoolbox (Version 3.0.14; Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Stimuli were projected from behind a Plexiglas display that was arranged upright on a table perpendicular to the observer's line of vision, facing the seated observer at approximately 50cm. We used a ViewSonic DLP PJD6221 projector with a refresh rate of 60 Hz and a resolution of 1024x768.

Visual stimuli were presented against a mid-gray background (48° by 37° visual angle). For the occlusion trials, each trial began with the presentation of a rectangle stage consisting of a light-gray region (12.5° by 25°) and a black region (24° by 25°), in the center of the screen. While the black region extended until the edge of the screen, the critical visible and occluded movement distances were equal (12.5° by 25°, see white arrows in **Fig. 1B**). On the far edge of the light-gray region, a green hollow bar was presented (1° by 5°), indicating the starting position. Within the black region, a white hollow bar was presented, indicating the goal position (see **Fig. 1A**). This display was presented for 1000ms. Then the green bar became filled and moved across the stage with constant velocity in a linear fashion This was done using real motion where the stimulus position was updated every frame (with a 60Hz refresh rate). The speed of the bar was determined such that the bar moved in equal steps from the starting position to the goal position (distance of 25°) in either 1000, 1200, 1400, or 1600ms across trials (i.e. motion duration). Thus, these values corresponded to motion speeds of 25, 20.83, 17.86, or 15.63 degrees per second, respectively. The bar could move rightward (as shown in example frames in **Fig. 1**), or leftward where the display configuration was flipped horizontally. The bar was visible on the light-gray region and disappeared when it crossed into the black region and did not reappear (see **Fig 1B, left**). The bar continued to move until the participant stopped the bar by pressing the spacebar in the keypress block or reaching and touching the goal position in the reach block. For the baseline trials, the configuration was the same as occlusion trials except that the stage only consisted of the visible light-gray section (see **Fig 1B, right**).

On keypress trials, participants were instructed to press the spacebar using their right hand when they thought the bar reached the goal position. On reach trials, participants were instructed to reach and touch the goal position when they thought the bar reached the goal position, using their right hand. We recorded the three-dimensional finger position at a rate of approximately 60Hz using an electromagnetic position and orientation recording system (Liberty, Polhemus). We secured a motion-tracking marker with a Velcro strap near the tip of the participant's right index finger. Participants rested their index finger on a Styrofoam block placed 27cm away from the screen along the z-dimension (i.e., the distance between the participant and the display screen). Participants were instructed to keep their finger in the starting position until the bar started moving and to touch the goal position when they thought the bar reached the goal position. To calibrate the hand-tracking system at the beginning of each session, participants were asked to sequentially touch nine equally spaced points on the screen.

Participants completed two occlusion blocks, keypress-occlusion and reach-occlusion, followed by two baseline blocks, keypress-baseline and reach-baseline. Participants completed 144 trials in each occlusion block and 56 trials in each baseline block. Before each occlusion block, participants completed 16 practice trials which were excluded from analyses. Participants received feedback on practice trials such that the location of the stopped bar was revealed. They did not receive feedback on the main trials. The order of response type was counterbalanced.

Data analysis. Data were analyzed using Matlab (Version 2021b) and R (Version R 3.4.3). We measured response time (RT) as the time between the bar's movement onset and when the participant stopped the bar (either via keypress or reach). We removed RT outliers per participant using the ±1.5 InterQuartile Range (IQR) rule on RTs corrected for motion duration (RT minus motion duration for a given trial). After outlier removal, we subtracted mean RT on baseline trials from mean RT on occlusion trials to calculate the amount of mean *occlusion bias* per condition per participant.

We then conducted a 3x2x2 repeated measures analysis of variance (ANOVA) on occlusion bias with factors Motion Duration (1000, 1200, 1400, 1600ms), Motion Direction

(Leftward vs. Rightward) and Response Type (Keypress vs. Reach). We also conducted a one-way repeated measures ANOVA on occlusion bias with the factor Trial Bin (four equal-sized trial bins) to test the time-on-task effect. When dealing with factors with three or more levels (i.e. Motion Duration and Trial Bin), we applied The Greenhouse–Geisser correction for lack of sphericity when necessary. We followed up significant ANOVA effects with paired samples t-tests using Bonferroni's correction for multiple comparisons when appropriate or planned contrast tests. We also examined the relationship between occlusion bias measured for keypress and reach responses using Pearson's correlation.

Lastly, to measure the variability of responses, we calculated the Coefficient of Variation (CV) as the standard deviation of RT divided by the mean RT. CVs were calculated per motion duration, per participant for the occlusion block. We then compared the CVs in the keypress and reach conditions using a paired samples t-test.

Results

In **Fig. 2A**, we present RTs as a function of motion duration, separately for occlusion blocks (solid lines) and baseline blocks where the moving bar was always visible (dashed lines), and separately for keypress (blue lines) and reach (red lines) responses. We collapsed across motion directions. The baseline RTs are near the identity line indicating the ideal response (gray dotted line). As expected and similar to the baseline condition, the RTs in the occlusion blocks (connected by solid lines) increased as motion duration increased indicating

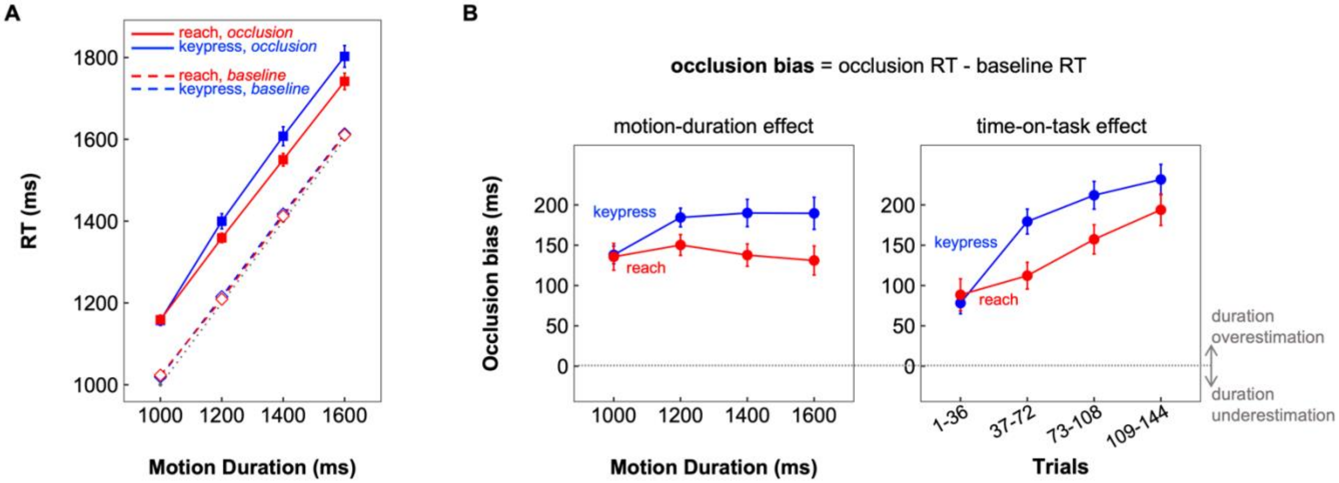

Figure 2. Results from Experiment 1 are summarized. **A)** RT as a function of motion duration is shown separately for occlusion and baseline conditions and keypress and reach responses. Gray dotted line represents ideal response. **B)** Occlusion bias (Occlusion RT minus baseline RT) as a function of motion duration separated by response type is shown on the left. Occlusion bias as a function of binned trials separated by response type is shown on the right. The error bars represent ±1 standard error of the mean, adjusted for within-participants comparisons (Morey, 2008).

that participants successfully took into account the visible motion's duration and/or speed when estimating the occluded motion duration. The occlusion RTs are elevated for both response types. This indicates that participants tended to intercept the moving bar later than they should in both keypress and reach conditions, i.e. they overestimated the occluded motion duration. Notably, the error in the occlusion block relative to the baseline block (solid lines being higher than dashed lines) appeared to be constant across motion durations.

To visualize this effect more clearly, in **Fig. 2B left panel**, we plot the occlusion bias (occlusion RT minus baseline RT) as a function of motion duration and response type, collapsing across motion directions. All values are above zero, indicating that for all conditions, there is a robust duration overestimation bias when the object gets occluded (occlusion vs. baseline: $t(23) = 7.36$, $p < .0001$, $d = 1.50$).

The ANOVA on occlusion bias with factors motion duration, motion direction, and response type revealed a non-significant effect of duration ($F(1.47, 33.81) = 3.49$, $p = .055$, $\eta_p^2 = 0.13$). In particular, we did not find evidence that the occlusion bias increased as motion duration increased (Linear Contrast: $F(1, 23) = 1.34$, $p > .19$, $\eta_p^2 = 0.07$), meaning that there was no evidence that occlusion bias scaled with motion durations sampled here.

The effect of motion duration was qualified by an interaction with response type ($F(2.07, 47.61) = 5.16$, $p = .009$, $\eta_p^2 = 0.18$). For keypress, the occlusion bias on 1000ms condition was smaller than 1200ms ($p = .004$) and 1400 ($p = .014$), and numerically smaller than 1600 ($p = .057$) which did not reach significance. For reach, there were no differences between motion durations. This interaction can also be interpreted as the difference between keypress and reach depending on motion duration; reach had numerically smaller bias than keypress on longer motion durations that did not reach significance ($p = .07$ at 1400ms; $p = .09$ at 1600ms) while there were no differences for shorter ones ($p > .9$ at 1000ms; $p > .1$ at 1200ms).

The effect of motion direction did not reach significance ($F(1, 23) = 4.08$, $p = .055$, $\eta_p^2 = 0.15$). There was a small interaction effect between motion direction and response type ($F(1, 23) = 4.51$, $p = .045$, $\eta_p^2 = 0.16$). The direction effect in which the occlusion bias was greater for leftward than rightward movement direction was significant for reach ($p = .021$), but not for keypress ($p > .08$). None of the other effects were significant (all *p*s > .1).

Previously, Chen et al. (2020) reported that the duration overestimation bias tended to increase as participants completed more trials. We also explored our data for such time-on-task effects. In **Fig. 2B right panel**, we plot the occlusion bias as a function of trial bins to visualize the time-on-task effect. We binned 36 consecutive trials, separately for the keypress block and reach block. Similar to Experiment 1, for both keypress and reach blocks, occlusion bias increased as the trial count increased. This observation was supported by a significant effect of bin on occlusion bias ($F(1.53, 35.19) = 41.18$, $p < .0001$, $\eta_p^2 = 0.64$) and a significant linear contrast ($F(1, 23) = 54.92$, $p < .0001$, $\eta_p^2 = 0.70$). This increase in occlusion bias over trials may be pointing to an accumulation of error due to fatigue and/or lack of visual feedback (e.g., Smeets et al., 2006).

When examining the relationship between keypress and reach occlusion bias, collapsing across motion durations and directions, we found a significant positive correlation, $r(22) = .55$, $p = .005$ (**Fig. 3**). In other words, participants who showed a greater occlusion bias with keypress responses also showed a greater occlusion bias with reach responses, further indicating that there is a response-modality independent aspect of the bias. **Figure 3** also demonstrates the consistency of the duration overestimation across participants such that 21 out of 24 participants overestimated the occluded motion duration in keypress (data points to the right of the blue dotted line) and reach (data points above the red dotted line) blocks.

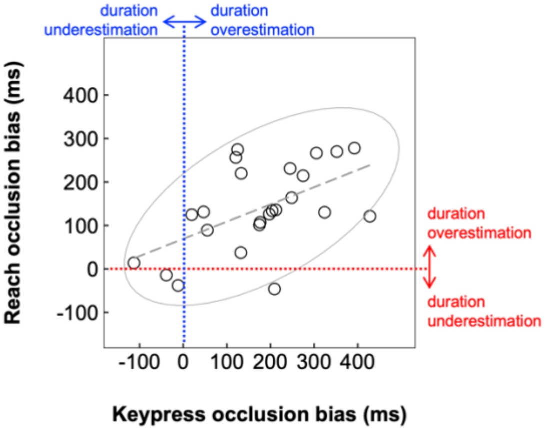

Figure 3. The positive correlation between occlusion bias observed in keypress and reach blocks is illustrated. Each data point reflects a single participant's occlusion bias in keypress and reach blocks, collapsing across motion duration and directions. Note that 21 out of 24 participants in both conditions show a duration overestimation bias (values above 0 in either direction). 95%-confidence ellipse and linear regression line are shown in gray.

Lastly, we compared the CVs, calculated as the standard deviation of RT divided by the mean RT per participant per motion duration, in keypress and reach responses to see whether discrete and continuous responses differed in variability. CVs in keypress ($M = 0.09$, $SE = 0.002$) and reach ($M = 0.09$, $SE = 0.003$), trials were not different ($t(23) = 0.48$, $p > .6$, $d = 0.098$), suggesting that response variability in discrete keypress and continuous reach responses were not different.

Overall these results are in line with the previous reports of a duration overestimation (speed underestimation) bias for occluded motion. These results are also consistent with our preliminary experiment which had a slight difference in the visual display (see **Supplementary Materials**). Furthermore, our use of baseline condition reassures that the bias is present over and above any response delay. As for the hypothesized differences between discrete vs. continuous movements, occlusion bias was mostly similar across keypress and reach although we observed a small advantage for reach for the longer motion durations where the bias was numerically smaller but did not reach statistical significance. The response variability in keypress and reach was comparable. This pattern of results indicates that the occlusion-driven duration overestimation bias, previously shown using discrete interceptive action, is also present with continuous interceptive action.

Experiment 2: Motion estimation for perception

In Experiment 2, motivated by a vast number of studies establishing a close link between action and time perception (for reviews, see, Coull & Droit-Volet, 2018; De Kock et al, 2021; Merchant & Yarrow, 2016), we examined whether the duration overestimation bias was present in a perception task that did not involve interceptive action (see **Fig. 1C**, perception task).

Methods

Participants. Twenty-six Brown University undergraduate students were recruited to participate in the study. All were right-handed and had normal or corrected-to-normal vision. Participants received partial course credit for their participation, which lasted approximately one hour. We excluded two participants because they were clear outliers given their performance (based on their average PSE). Thus, our sample included 24 participants (17 females) between the ages of 18 and 21 years (M = 19.5 years, SD = 1.14). The protocol was approved by the Institutional Review Board at Brown University. Participants gave informed consent and were treated according to the guidelines of the Institutional Review Board. Note that we aimed to have the same number of participants as Experiment 1.

Stimuli and procedure. Visual stimuli and display setup details were identical to Experiment 2. Additionally, we presented a pure tone (a 60 dB, 500 Hz, and 50 ms tone with 5-ms rise and fall times) from headphones at one of six critical moments. The tone could be presented at the -30%, -20%, -10%, +10% +20%, or +30% mark, relative to the moment of contact. For instance, for the 1000ms duration trials, the tone could be presented at the 700, 800, or 900ms mark (early tones) or 1100, 1200, or 1300ms mark (late tones). Participants were asked to indicate whether the tone occurred before or after the moment of contact using the up or down arrow keys on a keyboard, respectively. No feedback was given. Participants completed 480 trials in the occlusion block followed by 240 trials in the baseline block. Before the occlusion block, participants completed 8 practice trials which were excluded from the analyses.

Data analysis. We calculated the proportion of “beep occurred after” responses as a function of relative beep timing (±30%, ±20%, ±10%) per participant, separately for occlusion and baseline blocks. We then fitted a logit link function using MATLAB’s glmfit function. For each participant, we calculated the point of subjective equality (PSE), the y=50% point on the fitted curve. We subtracted the PSE on baseline trials from the PSE on occlusion trials to calculate the amount of mean *occlusion bias* per participant. We calculated the occlusion bias (the PSE difference) separately for all motion durations and motion directions.

We conducted a one-way repeated measures ANOVA to test the effect of motion duration and a paired samples t-test to test the effects of motion direction on occlusion bias separately. Note that we tested each effect independently because doing a factorial ANOVA with both effects would entail fitting the data using very few trials (i.e., we would need to fit a curve using 10 trials per minimum condition cell, per relative beep timing). We also conducted a one-way repeated measures ANOVA on occlusion bias with factor Trial Bin (eight 60-trial bins) to test the time-on-task effect. We chose 60 as the bin size as it struck a good balance between having bin sizes that are close to the previous experiments and having enough trials per relative beep timing when fitting the data.

Results

In **Figure 4** we present the proportion of “beep occurred after” responses as a function of relative beep timing, separately for occlusion and baseline blocks. The psychometric curves depict the fits to the group-average data for visualization purposes. The ideal response would have a PSE of zero. We observed that both the baseline and occlusion PSEs were greater than zero. This indicates that, under both conditions, for the beep to be perceived as being simultaneous with the moment of contact, the beep needed to occur later than the actual moment of contact. The baseline PSE being greater than zero is likely

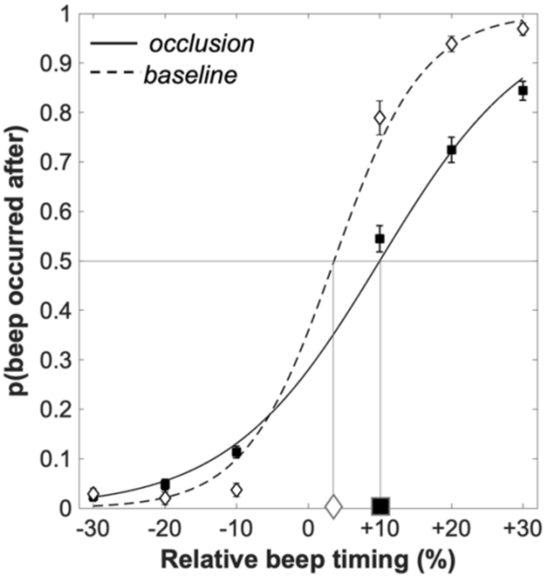

Figure 4. Group-mean performance on the baseline block (empty diamonds) and occlusion block (filled squares) are shown. Psychometric curves represent the fits to the group-average data, separately for baseline block (dashed curve) and occlusion block (solid curve). Points marked with an empty diamond and filled square roughly indicate the mean PSE for baseline and occlusion locks, respectively. The error bars represent ±1 standard error of the mean, adjusted for within-participants comparisons (Morey, 2008).

explained by differences in the speed of sensory processing of auditory and visual signals. In particular, the first later tone (Relative beep timing: +10%) is miscategorized as an earlier tone in ~20% of the trials, likely due to auditory signals being processed faster than visual signals (Fain, 2003; King, 2005), which then pulls the baseline PSE to the right. Importantly, the PSE observed in the occlusion block was greater than the PSE observed in the baseline block. This indicates that, on average, participants estimated the moment of contact to occur later in the occlusion block than baseline block. This pattern of findings is in line with Experiment 1.

In **Fig. 5**, we present the PSE findings in the same way we presented the RT findings in Experiment 1 in Fig 2. In **Fig. 5A**, we present PSE (in milliseconds) as a function of motion duration, separately for occlusion (solid line) and baseline blocks (dashed line). Similar to Experiment 1, the baseline PSEs are close to the identity line (dotted line).

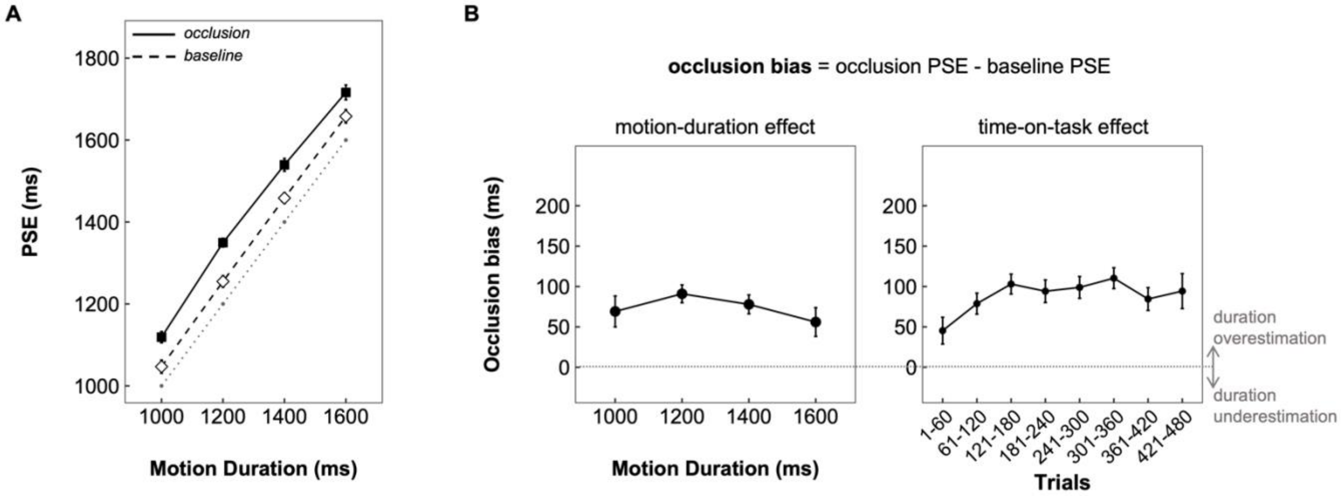

Figure 5. Results from Experiment 2 are summarized. **A)** PSE (ms) as a function of motion duration is shown separately for occlusion and baseline blocks. Gray dotted line represents ideal response. **B)** Occlusion bias (occlusion PSE minus baseline PSE) as a function of motion duration is shown on the left. Occlusion bias as a function of binned trials (averaged over 60 trials) is shown on the right. The error bars represent ±1 standard error of the mean, adjusted for within-participants comparisons (Morey, 2008).

As expected and similar to Experiment 1, the PSEs in the occlusion block increased as motion duration increased indicating that participants successfully considered the visible motion's duration and/or speed when judging the timing of the tone with respect to the moment of contact. The PSEs in the occlusion block were elevated compared to the baseline block and this error (the solid line is considerably higher than the dashed line) appeared to be roughly constant across motion durations.

To visualize this effect more clearly, in **Fig. 5B left panel**, we plot the occlusion bias (occlusion PSE minus baseline PSE) as a function of motion duration, collapsing across motion directions. Similar to Experiment 1, there is a robust occlusion bias such that the motion duration is overestimated (or motion speed is underestimated) when the moving object is occluded (occlusion vs. baseline: $t(23) = 4.17$, $p < .001$, $d = 0.85$). Similar to Experiment 1, the duration overestimation bias was consistent across participants with 20 out of 24 participants showing a positive PSE difference between occlusion and baseline block.

Further tests (separately conducted) revealed non-significant effects of motion duration $F(2.22, 51.06) = 0.34$, $p = .74$, $\eta_p^2 = 0.015$) and motion direction ($t(23) = .84$, $p = .41$, $d = 0.17$), suggesting that occlusion bias does not depend on motion duration or direction.

In **Fig. 5B right panel**, we plot the occlusion bias as a function of trial bins to visualize the time-on-task effect. We grouped trials into 8 bins of 60 consecutive trials. The one-way ANOVA revealed that the bin effect did not reach significance ($F(7, 161) = 1.79$, $p = .09$, $\eta_p^2 = 0.07$). When we limited the analysis to the first three bins, which closely overlap with the bins from Experiment 1 in terms of the number of trials, the bin effect became significant $F(1.68, 38.64) = 4.57$, $p = .02$, $\eta_p^2 = 0.17$). This indicates that, similar to the action task, the bias tends to accumulate as participants complete more trials, likely due to fatigue and lack of feedback. Since we had more trials in the perception than action task, we could see the point where the bias plateaus (after 180 trials into the experiment).

Overall, the results show that a tendency to overestimate the motion duration of an occluded moving object is not only present when the task involves precisely timed interceptive action but also when it involves a perceptual estimation that does not require timed action.

Exploratory between-experiment comparison: Action vs. Perception

Next, we explored whether the magnitude of occlusion bias was different when the task required an interceptive action. Thus, we directly compared participants' performance in the action task, keypress and reach combined (Exp. 1), and in the perception task (Exp. 2).

We quantified the occlusion bias as the difference in error in the occlusion block and baseline block. While we observed a reliable occlusion bias in the same direction in action and perception tasks, the amount of occlusion bias was greater in the action task than the perception task (**Fig. 6**, white bars), *t*(46) = 2.53, *p* = .015, *d* = 0.73). We plotted individual participant data in **Figure 6** to further demonstrate the distribution of occlusion bias.

The difference in occlusion bias across the two tasks was due to greater errors in the baseline block in the perception than action task (**Fig. 6** gray bars; perception > action), *t*(46) = 3.53, *p* < .001, *d* = 1.02) combined with a non-significant difference in errors in the occlusion block trending in the opposite direction (**Fig. 6**, black bars; action > perception), *t*(46) = 1.36, *p* = .18, *d* = 0.39).

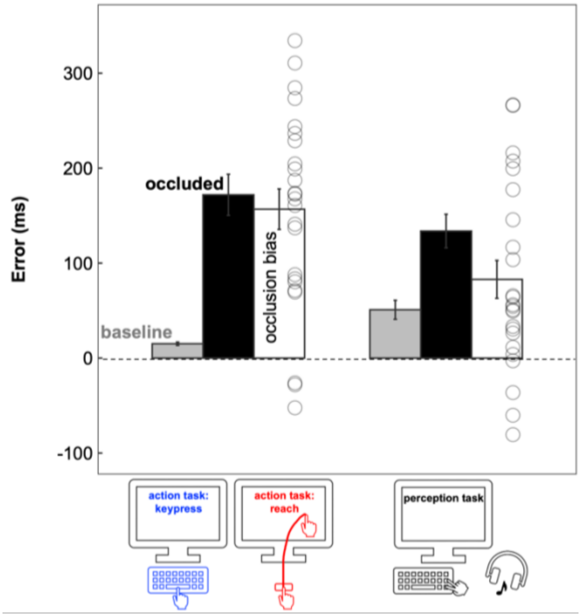

Figure 6. Error in occlusion block (black bars), baseline block (gray bars) and the difference between occlusion and baseline blocks (occlusion bias, white bars) are shown for action (left bars) and perception (right bars) experiments. The open circles overlayed on the group-average bars represent individual participant datapoints for occlusion bias in action tasks (average of reach and keypress) and perception task. The error bars represent ±1 standard error of the mean (not adjusted for within-participant comparison).

Overall, this pattern of results indicate that duration overestimation bias is observed both in action and perception tasks. The occlusion bias measured as a difference score (occlusion-block error minus baseline-block error) was smaller in perception than action task due to a clear difference in baseline errors. Elevated errors in the baseline block for the perception task are likely due to our use of an audiovisual task and the processing speed differences for visual and auditory signals. In particular, auditory transduction in the ear is faster than visual transduction in the eye and neural transmission times are also shorter in the auditory than visual system (Fain, 2003; King, 2005), which could lead to temporal order reversals when judging the onset of visual and auditory events occurring close in time. Future experiments using a visual perception task (as opposed to audiovisual) could further explore the potential action vs. perception difference in occluded motion estimation performance.

Nevertheless, a non-significant numeric difference exists in the same direction in the occlusion-block errors (**Fig. 6**, black bars) as the occlusion bias (**Fig. 6**, white bars) across action and perception tasks. It is important to note that in the action task, there was no timeout, and thus participants did not have an upper limit of when to intercept the moving object. In the perception task, participants were informed that the tone would be presented earlier or later with respect to the moment of contact without the exact timing details. It may be argued that the later tones used in the perception task could have acted as a temporal cue for the upper limit of when the bar could reach the goal position. This temporal cue could be expected to lead to better estimates of the moment of contact (e.g. Chang & Jazayeri, 2018) or smaller duration overestimation in our case. This possible confound could be alleviated in future experiments by introducing a timeout in an action task that corresponds to the latest comparison stimuli in a perception task, or by simply including more delayed comparison stimuli in a perception task so as not to artificially restrict participants' estimates in the occlusion blocks.

General Discussion

Here, we observed a robust tendency to overestimate the motion duration of an object when it becomes occluded. This bias has been previously reported using a discrete interceptive task; here we extend it to include a continuous (reaching) interceptive action task and also to a perceptual judgment task. The occlusion-driven duration overestimation, or speed underestimation, bias was similarly present when the task involved either type of interceptive action, keypress or reach, or judging the timing of an auditory event during the occlusion period. The occlusion bias did not scale with motion durations (1000, 1200, 1400, and 1600ms), i.e. was constant, and did not depend on motion direction (leftward or rightward). The bias also increased as participants completed more trials. In both tasks, we contrasted occlusion performance with baseline performance where the moving object was visible. This ensured that the occlusion bias observed here was not merely due to response delay.

In exploring the occlusion bias, we first used an interceptive action task and contrasted discrete (keypress) and continuous (reach) responses in Experiment 1. We reasoned that continuous reaching could lead to better performance given that it allows for concurrent movements during the timed durations, both during the visible and occluded movement portions. Participants could adopt motor strategies that may be beneficial given the previous findings showing that concurrent movements can improve precision (De Kock et al, 2021). While we did not find any effect of action type on precision (no difference in CV), we observed a slight advantage of reach over keypress such that the duration overestimation bias was reduced (better accuracy) on reach trials. This effect did not reach significance and was restricted to longer durations; however, it is still worth noting as it is in line with a recent study showing a similar trend comparing performance between ocular and ocular-manual tracking in a prediction-motion task (Zheng & Maraj, 2018).

It is also important to note that we did not impose any strategy for reach or keypress responses with the assumption that participants' intuitive cognitive and motor strategies may help optimize performance. The only restriction was that in the reach block participants had to rest their reach finger at the starting position on the table until the bar started moving. Consequently, participants employed various strategies as they noted in their responses to the post-experiment survey and as reflected in their reach trajectories (see **Supplementary Materials** for more details). Some commonly reported strategies on reach trials included following the bar with the finger (during visible and/or occluded portion) or matching the speed of the finger moving toward the goal position to the bar's speed, both of which involve concurrent movement that we presumed could improve estimations. They also reported moving the finger close to the goal position as soon as the bar started moving and waiting there, which involves less concurrent movements. Other strategies reported in both reach and keypress blocks included following the bar with eyes and/or head, counting seconds, beats, or rhythms, moving the non-responding hand or tapping, mental imagery, or even imagining a sound to mark the time. Participants also reported trying out multiple strategies within a block. The presence of movement cues in both reach and keypress blocks and the participants' use of various strategies with various degrees of movement cues within and across blocks may explain the lack of robust differences between the discrete and continuous movement conditions. Indeed, earlier work has shown that allowing eye movements as opposed to fixation can benefit motion estimation performance at speeds that are conducive to smooth pursuit eye movements (Bennett et al., 2010; Peterken et al., 1991; Spering et al. 2011; van Donkelaar & Lee, 1994) and that eye movements are integral for accurately forming predictions about moving objects and preparing interceptive manual actions (for a review, see Fooken et al. 2021). Nonetheless, the fact that we observed an occlusion bias in both conditions while participants used various strategies, speaks to the overall robustness of the bias.

Next, we explored whether the occlusion bias was specific to tasks involving interceptive action or it could extend to a perception task. When participants needed to judge the onset of a tone with respect to the occluded moving object, they still showed a similar duration overestimation bias. This indicates that the reported bias does not solely reflect motor error. Further, the occlusion bias measured in the perception task was smaller than in the action task. This was mostly due to unequal baseline (visible motion) performance in perception and action tasks, where error in baseline was greater in the direction of duration overestimation in the perception task. This is likely an audiovisual effect and may be alleviated in a purely visual perception task. Nevertheless, even the un-baselined occlusion bias was numerically smaller in the perception task, hinting at a perception advantage in occluded motion estimation. Another difference between the action and perception tasks was that in the perception task, the auditory stimuli could have served as a temporal cue and thus enabled participants to form more accurate estimates. Previous research has in fact shown that observers integrate temporal information and rely on temporal cues to improve their estimates of occluded motion (e.g. Chang and Jazayeri, 2018).

What could be at the root of this robust occlusion bias that we observed in multiple experiments with different tasks? We considered several alternatives, including the previously reported temporal illusions, a Bayesian slow-motion prior, or the visible-occluded boundary crossing creating a lag in estimations.

First, we consider the possibility that the bias observed here is related to previously reported temporal illusions. In a temporal reproduction task, participants are presented with a standard interval (e.g. a visual stimulus is presented for a given duration) and tasked with reproducing the learned standard interval (e.g. press the spacebar to start and stop the presentation of a visual stimulus to match the standard stimulus' duration). Sampled durations typically range from a few hundred milliseconds to a few seconds. Numerous studies have shown that stimulus features can affect temporal reproduction performance. Longer reproduction times are observed when the standard interval consists of high-intensity stimuli, such as brighter visual stimuli or louder auditory stimuli, while the produced interval consists of low-intensity stimuli such as dimmer visual stimuli, quieter auditory stimuli (e.g., Indraccolo et al., 2016). This indicates that high-intensity stimuli are associated with expanded perceived time relative to low-intensity stimuli. Further, among dynamic stimuli, faster speeds or higher temporal frequencies are associated with expanded perceived time relative to slower speeds or lower temporal frequencies (e.g. Kanai et al., 2006). Attention to time or attention to timed stimuli also expands perceived time (e.g. Tse et al., 2004). These temporal illusions altogether may be explained by the “coding efficiency” idea where perceived time is positively related to the amount of energy used to represent stimuli (Eagleman & Pariyadath, 2009), or “processing principle” whereby perceived time is positively related to the perceptual vividness or the allocation of processing resources (Matthews & Meck, 2016).

Our tasks, especially the interceptive action tasks, resemble a temporal reproduction task where the standard interval is the visible portion and the produced interval is the occluded portion. Our main result can therefore be interpreted as a tendency to have longer reproduction times. For instance, on a 1000ms motion duration trial, where the standard interval was 500ms, the produced interval (elapsed time between the disappearance of the bar behind the occlusion and participant’s response to stop the bar) was around 600ms. Notably, there were apparent differences between the standard interval and the produced interval, including the intensity of the stimuli marking these intervals (gray vs. black regions), dynamic stimuli observed within these intervals (moving object vs. no object), and potential differences in the amount of attention to stimuli or to time when processing the visible and occluded regions. Therefore, some or all of the abovementioned temporal illusions could be at the root of the occlusion bias observed here. While having dynamic vs. static input is inherent to the task as one needs to have visible and occluded motion portions, the possible effects of stimulus intensity and attention can be further explored by swapping the colors of the visible and occlusion regions and employing a dual-task paradigm, respectively. Although the stimuli intensity difference in the current paradigm could be contributing to the occlusion bias, it is unlikely to fully explain it given that intensity-driven temporal reproduction differences are smaller than the reported effects here (e.g. Indraccolo et al., 2016) and the existing reports of a similar bias for occluded motion with a lighter occlusion section (Agostino et al., 2022).

Second, we consider the possibility that the observed duration overestimation (or speed underestimation) bias reflects a Bayesian prior favoring slow velocity. In particular, modeling work has shown that visual motion perception is consistent with a Bayesian model with the assumptions that initial measurements are noisy and that slower motions are more probable than faster motions (Weiss et al., 2002; Stocker & Simoncelli, 2006). This model can account for a variety of motion illusions including the cases when low-contrast stimuli (less reliable initial measurement) are perceived to move slower than high-contrast stimuli (more reliable) when speed is matched (e.g. Stone & Thompson, 1992; Thompson, 1982), which is also reported in occluded motion perception (Battaglini et al. 2013), 3D motion perception (Welchman et al., 2008), perception of moving sounds (Senna et al., 2015) or even in driving behavior under low-visibility conditions (Snowden et al., 1998). In our case, one can assume that occluded motion is less reliable than visible motion and thus more influenced by a prior preference for slower speeds.

One may expect the effect driven by these proposed mechanisms, the temporal illusions and the Bayesian slow-motion prior, to be duration and/or speed relative. However, we did not find evidence that the occlusion bias scaled with the sampled durations or speeds. It was roughly constant for total movement durations of 1000, 1200, 1400, or 1600ms (or occluded motion durations half of those: 500, 600, 700, or 800ms). This could be a range-specific finding as suggested by other reports of constant errors specific to occluded motion speeds and durations similar to those used here (e.g., Chen et al., 2020; Sokolov and Pavlova, 2003).

Although Weber's law holds for many timing tasks in which timing error is proportional to the estimated duration, similar cases of duration-invariant constant errors have been reported. One instance of this that may be particularly relevant to our findings is a constant error observed in a temporal reproduction task with filled intervals (marked by a single continuous stimulus) and empty intervals (marked by two discrete onset and offset stimuli). In particular, Craig (1973) presented the critical interval as two filled intervals separated by an empty variable interval (e.g. two 1s tone bursts separated by a given interval). Then, he asked participants to adjust the empty interval to be equal to the filled intervals. In other words, participants learned the filled intervals and reproduced them as empty intervals. He found that filled intervals ranging between 200 to 1200ms were overproduced as empty intervals by a constant amount, for auditory, visual, and vibrotactile stimuli. He suggested that this was due to the processing of the offset of a stimulus requiring a perceptual timing process that adds a lag in estimations. Grondin (1993) proposed a related idea, the internal-marker hypothesis, positing that the internal onset and offset signals differ between filled and empty intervals. For the filled interval, the beginning of the interval and sensory trace of the ending of the interval provide internal onset and offset signals, respectively. For the empty interval, the sensory trace of the ending of the first marker and the beginning of the second marker may provide the internal onset and offset signal, making it perceived shorter than the filled one. A similar mechanism may be at play in the current study.

Thus, in addition to temporal illusions and Bayesian slow-motion prior, as a third mechanism we consider the possibility that the moment that the bar goes behind the occluder, i.e. the visible-occluded boundary crossing (see the 4th frame in **Fig. 1A**), requires additional processing and therefore adds a delay to the estimated time-of-contact. This could be due to the processing of the offset of the stimulus or the sensory trace being converted to an offset signal, the visual system interpreting the crossing of the boundary as a collision event or change of motion plane, etc. Nevertheless, it is unclear why such an effect would be restricted to certain durations. More studies are needed to determine the possible contributions of the abovementioned mechanisms and others to occluded motion estimation and the motion durations or speeds for which they follow or deviate from Weber's law.

In conclusion, we extend the earlier findings and report a robust duration overestimation bias in occluded motion perception. We observed a similar bias in an action task requiring a discrete or continuous response as well as in a perception task requiring temporal order judgment. The bias was observed for all sampled motion durations and directions in a near-constant manner and also tended to accumulate throughout the experiment. This bias may be related to previously reported temporal illusions, explained by a Bayesian slow-motion prior, and/or the processing of the visible-occluded boundary crossing. Understanding the exact mechanism, the conditions on which the bias depends, and the relative roles of speed and time perception requires further research.

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Supplementary Materials

Preliminary Experiment: Motion estimation for action (with a square stage)

Here, we present the methods and results of a preliminary experiment that is a slight deviation from Experiment 1 (action experiment) of the main text. The visual display in the preliminary experiment shown here closely follows the design of the experiment from Chen et al., 2020, where the background color changes at the boundary of the goal position (the mid-gray window that surrounds the square stage).

Methods

Participants. Twenty-four Brown University undergraduate students were recruited to participate in the study. All were right-handed and had normal or corrected-to-normal vision. Participants received partial course credit for their participation, which lasted approximately one hour. Our sample included all 24 participants (14 women, 10 men) between the ages of 18 and 22 years (M = 18.92 years, SD = 1.06). The protocol was approved by the Institutional Review Board at Brown University. Participants gave informed consent and were treated according to the guidelines of the Institutional Review Board.

Stimuli and procedure. Stimuli were presented using a computer running MATLAB (Version 2015b; Mathworks) and Psychtoolbox (Version 3.0.14; Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Stimuli were projected from behind a Plexiglas display that was arranged upright on a table perpendicular to the observer's line of vision, facing the seated observer at approximately 50cm. We used a ViewSonic DLP PJD6221 projector with a refresh rate of 60 Hz and a resolution of 1024x768.

Visual stimuli were presented against a mid-gray background (48° by 37° visual angle). For the occlusion trials, each trial began with the presentation of a rectangle stage (25° by 25°) consisting of a light-gray region (12.5° by 25°) and a black region (12.5° by 25°), in the center of the screen. On the far edge of the light-gray region, a green hollow bar was presented (1° by 5°), indicating the starting position. On the far edge of the black region, a white hollow bar was presented, indicating the goal position (see **Fig. S1A**). This display was presented for 1000ms. Then the green bar became filled and moved across the stage with constant velocity in a linear fashion. This was done using real motion where the stimulus position was updated every frame (with a 60Hz refresh rate). The speed of the bar was determined such that the bar moved in equal steps from the starting position to the goal position (25°) in 1000, 1200, 1400, or 1600ms across trials. Thus, these values corresponded to movement speeds of 25, 20.83, 17.86, or 15.63 degrees per second, respectively. The bar could move rightward (as shown in example frames in **Fig. S1**), or leftward where the display configuration was flipped horizontally. The bar was visible on the light-gray region and disappeared when it crossed into the black region and did not reappear (see **Fig S1B, top left**). The bar continued to move until the participant stopped the bar by pressing the spacebar in the keypress block or reaching and touching the goal position in the reach block. For the baseline trials, the configuration was the same as occlusion trials except that the stage only consisted of the visible light-gray section (see **Fig S1B, bottom left**).

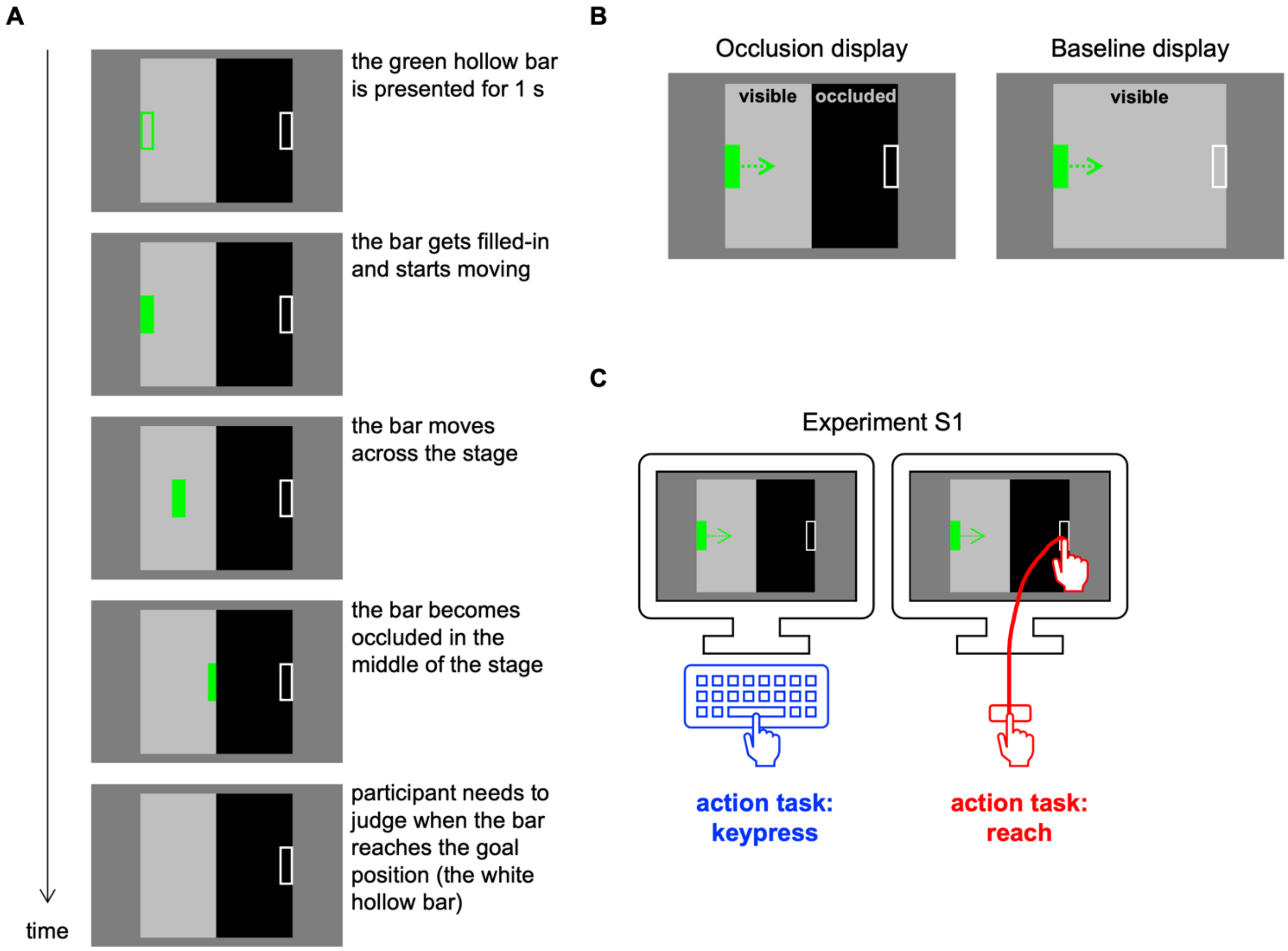

Figure S1. A) Sequence of events in a given trial is shown. **B)** Displays used in the occlusion and baseline conditions are shown. **C)** Discrete (keypress) and continuous (reach) action tasks are shown.

On keypress trials, participants were instructed to press the spacebar using their right hand when they thought the bar reached the goal position. On reach trials, participants were instructed to reach and touch the goal position when they thought the bar reached the goal position. We recorded the three-dimensional finger position at a rate of approximately 60Hz using an electromagnetic position and orientation recording system (Liberty, Polhemus). We secured a motion-tracking marker with a Velcro strap near the tip of the participant's right index finger. Participants rested their index finger on a Styrofoam block placed 27 cm away from the screen along the z-dimension (i.e., the distance between the participant and the display screen). Participants were instructed to keep their finger in the starting position until the bar started moving and to touch the goal position when they thought the bar reached the goal position. To calibrate the hand-tracking system at the beginning of each session, participants were asked to sequentially touch nine equally spaced points on the screen.

Participants completed two occlusion blocks, keypress-occlusion and reach-occlusion, followed by two baseline blocks, keypress-baseline and reach-baseline. Participants completed 160 trials in each occlusion block and 64 trials in each baseline block. Before each occlusion block, participants completed 16 practice trials which were excluded from analyses. Participants received feedback on practice trials such that the location of the stopped bar was revealed after their response. They did not receive feedback on the main trials. The order of response type was counterbalanced. Participants used their right hand to respond in all blocks.

Data analysis. We measured RT as the time between the bar's movement onset and when the participant stopped the bar (either via keypress or reach). We removed RT outliers per participant using the ±1.5 InterQuartile Range (IQR) rule on RTs corrected for motion duration (RT minus motion duration for a given trial). After outlier removal, we subtracted mean RT on baseline trials from mean RT on occlusion trials to calculate the amount of mean *occlusion bias* per condition per participant.

We then conducted a 3x2x2 repeated measures analysis of variance (ANOVA) on occlusion bias with factors Motion Duration (1000, 1200, 1400, 1600ms), Motion Direction (Leftward vs. Rightward), and Response Type (Keypress vs. Reach). We also conducted a one-way repeated measures ANOVA on occlusion bias with the factor Trial Bin (four equal-sized trial bins) to test the time-on-task effect. When necessary, we applied The Greenhouse–Geisser correction for lack of sphericity. We followed up significant ANOVA effects with paired samples t-tests with Bonferroni's correction for multiple comparisons when appropriate or planned contrast tests. We also examined the relationship between occlusion bias measured for keypress and reach responses using Pearson's correlation.

Lastly, to measure the variability of responses, we calculated the Coefficient of Variation (CV) as the standard deviation of RT divided by the mean RT separately for keypress and reach. CVs were calculated separately for each motion duration per participant. We then compared the CV in keypress and reach conditions.

Results and Discussion

In **Fig. S2A**, we present RTs as a function of motion duration, separately for occlusion and baseline blocks (dashed and solid lines), and separately for keypress and reach responses (blue and red lines). While the baseline RTs are near the identity line indicating the ideal response (gray dotted line), the occlusion RTs are elevated for all motion durations and both response types.

As expected, similar to the baseline condition (connected by dashed lines), the RTs in the occluded condition (connected by solid lines) increased as motion duration increased indicating that participants successfully considered the visible motion's duration and/or speed when estimating the occluded motion duration. Notably, the error observed in the occlusion block relative to the baseline block (solid lines being higher than dashed lines) appeared to be constant across motion durations.

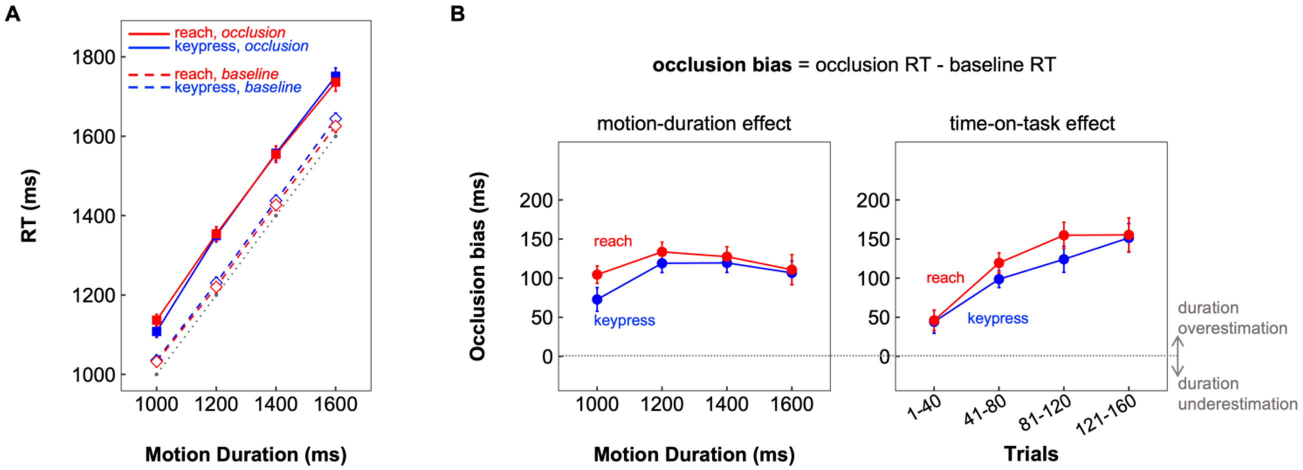

Figure S2. Data from the preliminary experiment are summarized. **A)** RT as a function of motion duration is shown separately for occlusion and baseline conditions and keypress and reach responses. **B)** Occlusion bias (occlusion RT minus baseline RT) as a function of motion duration separated by response type is shown on the left. Occlusion bias as a function of binned trials separated by response type is shown on the right. The error bars represent ±1 standard error of the mean, adjusted for within-participants comparisons (Morey, 2008).

To visualize this effect more clearly, in **Fig. S2B left panel**, we plot the occlusion bias (occlusion RT minus baseline RT) as a function of motion duration and response type, collapsing across motion directions. All values are above zero, indicating that for all conditions, motion duration is overestimated (or motion speed is underestimated) when the moving object is occluded (occlusion vs. baseline: $t(23) = 4.16$, $p = .0004$, $d = 0.85$).

Further, the ANOVA on occlusion bias with factors motion duration, motion direction, and response type revealed a significant main effect of motion duration ($F(1.5, 34.5) = 5.42$, $p = .015$, $\eta_p^2 = 0.19$), which was due to the occlusion bias on 1000ms condition being smaller than 1200ms ($p = .008$) and marginally smaller than 1400ms condition ($p = .057$). None of the other pairwise comparisons were significant (all ps > .2). Critically, we did not find evidence that the occlusion bias increased as motion duration increased (Linear Contrast: $F(1, 23) = 1.36$, $p > .2$, $\eta_p^2 = 0.06$).

The rest of the effects were non-significant, including the effect of motion direction $F(1, 23) = 2.77$, $p > .1$, $\eta_p^2 = 0.11$), response type ($F(1, 23) = 0.48$, $p > .4$, $\eta_p^2 = 0.02$), and all possible interaction effects (all ps > .2)

In **Fig. S2B right panel**, we plot the occlusion bias as a function of trial bins to visualize the time-on-task effect. We bin 40 consecutive trials, separately for the keypress block and reach block. For both keypress and reach, occlusion bias increased as the trial count increased. This observation was supported by a significant effect of bin on occlusion bias ($F(1.53, 35.19) = 29.20$, $p < .0001$, $\eta_p^2 = 0.56$) and a significant linear contrast ($F(1, 23) = 34.01$, $p < .0001$, $\eta_p^2 = 0.60$). This pattern of results may be pointing to an accumulation of error due to fatigue and/or lack of feedback.

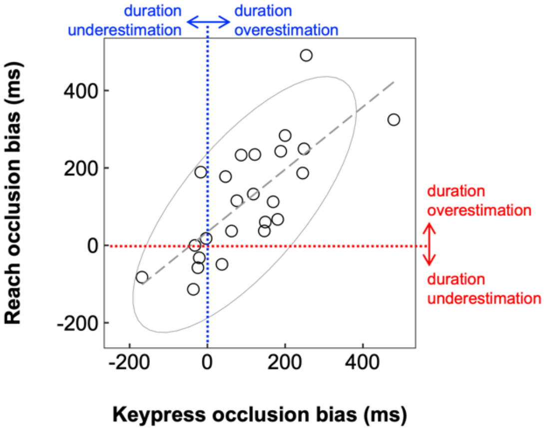

Figure S3. The positive correlation between occlusion bias observed in keypress and reach blocks is illustrated. Each data point reflects a single participant's occlusion bias value in keypress and reach blocks, collapsing across motion duration and directions. Note that 17 out of 24 participants in the keypress block and 18 out of 24 participants in the reach block show overestimation bias (values above 0 in either direction). 95%-confidence ellipse and linear regression line are shown in gray.

When examining the relationship between keypress and reach occlusion bias, collapsing across motion durations and directions, we found a significant positive correlation, $r(22) = .74$, $p < .0001$ (**Fig. S3**). In other words, participants who showed a greater occlusion bias with keypress responses also showed a greater occlusion bias with reach responses, indicating that there is a response-modality independent aspect of the bias. **Figure 3** also demonstrates the consistency of the duration overestimation across participants such that 17 out of 24 participants overestimated the occluded motion duration in the keypress block (data points to the right of the blue dotted line) and18 out of 24 participants overestimated the occluded motion duration in the reach block (data points above the red dotted line).

Lastly, we compared the CVs in keypress and reach responses in the occlusion blocks to test whether variability differed across the two response types. CVs in keypress (*M* = 0.09, *SE* = 0.002) and reach (*M* = 0.09, *SE* = 0.003) trials were not different (t(23) = 0.001, p >.99, *d* = 0.0002), indicating that keypress and reach responses in the occlusion conditions were equally variable.

Overall, these results align with the previous reports of duration overestimation (or speed underestimation) bias for occluded motion. Critically, our use of baseline condition reassures that the bias is present over and above a response delay. As for the hypothesized differences between discrete vs. continuous movements, we did not observe any difference in the amount of occlusion bias or the variability in responses between the keypress and reach responses. We discuss the potential reasons for the duration underestimation bias in the main text.

Note that the background color changes at the boundary of the goal position (the mid-gray window that surrounds the square stage). This design aspect may potentially explain the occlusion bias such that the observers may implicitly expect the bar to reappear at the end of the black occlusion area and thus overestimate the duration when it does not reappear. To rule out this possibility and to make the stimuli more ecologically valid, we extended the black occlusion section in Experiment 1 of the main text. Experiment 1 replicated the duration underestimation bias, which shows that the pattern observed here cannot be explained by the configuration of the stage display.

Post-Experiment Survey Responses

We asked participants to write down their strategies, if any, for the keypress and reach occlusion blocks after both action experiments (participants 1-24 participated in the action experiment with a square stage discussed in the supplementary material; participants 25-48 participated in the action experiment with an extended stage reported in the main paper). We summarized and categorized their responses.

The most commonly reported strategy was *counting* or *counting (specified beats/rhythms).* If participants explicitly mentioned beats or rhythms in addition to counting, we coded their strategy as *counting (specified beats/rhythms).* We then collapsed them into a single *counting* category (Supplementary action experiment-Keypress: 13 out of 24; Supplementary action experiment-Reach: 10 out of 24; Main action experiment-keypress: 9 out of 24; Main action experiment-reach: 7 out of 24).

Action Experiment with Square Stage (Supplementary)		
Participant ID	**Keypress Strategy**	**Reach Strategy**
1	counting	counting
2	none	started reach as soon as possible
3	stayed ready to press	waited near the goal position
4	counting (specified beats/rhythms)	counting (specified beats/rhythms)
5	counting	counting
6	tracking with head	tracking with reaching finger
7	tracking with eyes	tracking with eyes
8	counting	counting
9	tracking with eyes	tracking with eyes; tracking with reaching finger
10	none	waited near the goal position
11	none	tracking with eyes; tracking with reaching finger
12	counting; tracking with other finger (keypress)	tracking with reaching finger
13	tracking with eyes	tracking with reaching finger; matching speed of reaching
14	mentally tracking/visualizing, counting	mentally tracking/visualizing; counting
15	counting	none
16	tracking with eyes; counting	tracking with eyes; counting (specified beats/rhythms)
17	counting	counting
18	tracking with eyes	tracking with reaching finger
19	counting (specified beats/rhythms)	tracking with reaching finger
20	counting; mentally tracking/visualizing	counting; mentally tracking/visualizing
21	counting (specified beats/rhythms)	counting (specified beats/rhythms)
22	counting; tracking with eyes; tracking with head	counting; tracking with eyes; tracking with head; tracking with reaching finger
23	mentally tracking/visualizing	mentally tracking/visalizing
24	tracking with eyes	tracking with reaching finger

Action Experiment with Extended Stage (Main)		
Participant ID	**Keypress Strategy**	**Reach Strategy**
25	mentally tracking/visualizing	mentally tracking/visualizing; tracking with reaching finger
26	tracking with eyes	tracking with eyes
27	counting; mentally tracking/visualizing, tracking with other finger (keypress)	counting; mentally tracking/visualizing
28	tracking with eyes	tracking with eyes
29	counting	counting
30	mentally tracking/visualizing	tracking with reaching finger
31	tracking with eyes	tracking with reaching finger
32	tapping finger; counting (specified beats/rhythms); imagined playing laser tag	tracking with reaching finger; tracking with eyes
33	tracking with eyes	tracking with eyes
34	mentally tracking/visualizing; mentally timing	mentally tracking/visualizing, mentally timing
35	counting (specified beats/rhythms); mentally tracking/visualizing	counting (specified beats/rhythms); mentally tracking/visualizing
36	mentally tracking/visualizing	mentally tracking/visualizing
37	counting (specified beats/rhythms); tracking with eyes	matching speed of reaching
38	none	none
39	imagining sound to track time	imagining sound to track time
40	tracking with other finger (keypress)	tracking with reaching finger
41	tried to stay patient	tried to stay patient
42	tracking with eyes, counting	tracking with eyes, counting
43	tracking with eyes, imagining sound	matching speed of reaching
44	counting	counting
45	counting	counting
46	mentally timing; tracking with eyes	mentally timing; tracking with reaching finger
47	none	none
48	counting (specified beats/rhythms); tracking with eyes	counting (specified beats/rhythms); tracking with eyes

Table S1. Strategies reported in the post-experiment survey. Participants were asked to write down the strategies they used in the occlusion blocks of keypress and reach, specifying similarities and differences between keypress and reach, in a few sentences. Their responses are summarized in the table.

The second most commonly reported strategy was *tracking object with eyes* (Supplementary action experiment-Keypress: 7 out of 24; Supplementary action experiment-Reach: 5 out of 24; Main action experiment-Keypress: 9 out of 24; Main action experiment-Reach: 6 out of 24). The second most commonly reported strategy when only considering reaching was *tracking with reaching finger* (Supplementary action experiment-Reach: 9 out of 24; Main action experiment-Reach: 6 out of 24). This is also evident in the reach trajectories.

Other common strategies included *mentally tracking/visualizing*; *tracking with head*, *tracking with other finger in keypress blocks*, *matching speed of reaching, tapping finger, mentally timing,* and *imagining sound to track time,* etc. Overall participants reported testing out multiple strategies within a given session and trying both similar and different strategies for keypress and reach.

We then explored whether there was a difference in the occlusion-block RT (duration-adjusted RT where motion duration was subtracted from RT) across participants who adopted a given strategy and those who did not, using independent samples t-tests. We focused on the most common three strategies: *(1) counting or counting (specified beats/rhythms), (2) tracking with eyes, and (3) tracking with reaching finger (only for reaching).* We separately looked at the supplementary action experiment and the main experiment, and also for keypress and reach blocks as strategies reported for different response modes could differ. Overall, we did not find evidence that the occlusion block RT differed as a function of the abovementioned strategies. We provide details below.

For the *counting* or *counting (specified beats/rhythms)* strategy, we did not find a difference for the Supplementary action experiment-Keypress, $t(22) = 0.67$, $p = .51$, or for the Supplementary action experiment-Reach, $t(22) = 0.61$, $p = .55$. Similarly, we did not find a difference for the Main action experiment-Keypress, $t(22) = 0.99$, $p = .33$, or for the Main action experiment-Reach block, $t(22) = 1.02$, $p = .32$. For the *tracking with eyes* strategy, we did not find a difference for the Supplementary action experiment-Keypress, $t(22) = 0.61$, $p = .55$, or for the Supplementary action experiment-Reach, $t(22) = 0.59$, $p = .56$. Similarly, we did not find a difference for the Main action experiment-Keypress, $t(22) = 1.02$, $p = .32$, or for the Main action experiment-Reach block, $t(22) = 1.56$, $p = .13$. For the *tracking with reaching finger* strategy, only focusing on reaching blocks, we did not find a difference for the Supplementary action experiment-Reach, $t(22) = 1.16$, $p = .26$, or for the Main action experiment-Reach, $t(22) = 0.17$, $p = .86$.

Overall, we did not find evidence that any particular strategy reported by the participants reliably led to different performance outcomes. We did not limit participants' strategies and only relied on their self-reports for this exploratory analysis. Experimentally manipulating particular strategies may be needed to reveal strategy-based effects on occluded motion perception.

Reach Trajectories and Strategy

Figures S4 and **S5** illustrate reach trajectories in the occlusion block for all trials included in the data analysis (black trajectories drawn with 30% opacity) and the average trajectory (overlayed red trajectory) per participant. **Figure S4** shows the data from those who participated in the action experiment with a square stage reported in the supplementary material; **Figure S5** shows the data from those who participated in the action experiment with an extended stage reported in the main paper.

We recorded 3-dimensional reach trajectories with a 60-Hz sampling rate using an electromagnetic position and orientation recording system (Liberty, Polhemus). We first resampled each trajectory to have 101 points equally spaced in z-dimension (axis bound by the participant and the display) using the normalization methods described in detail in

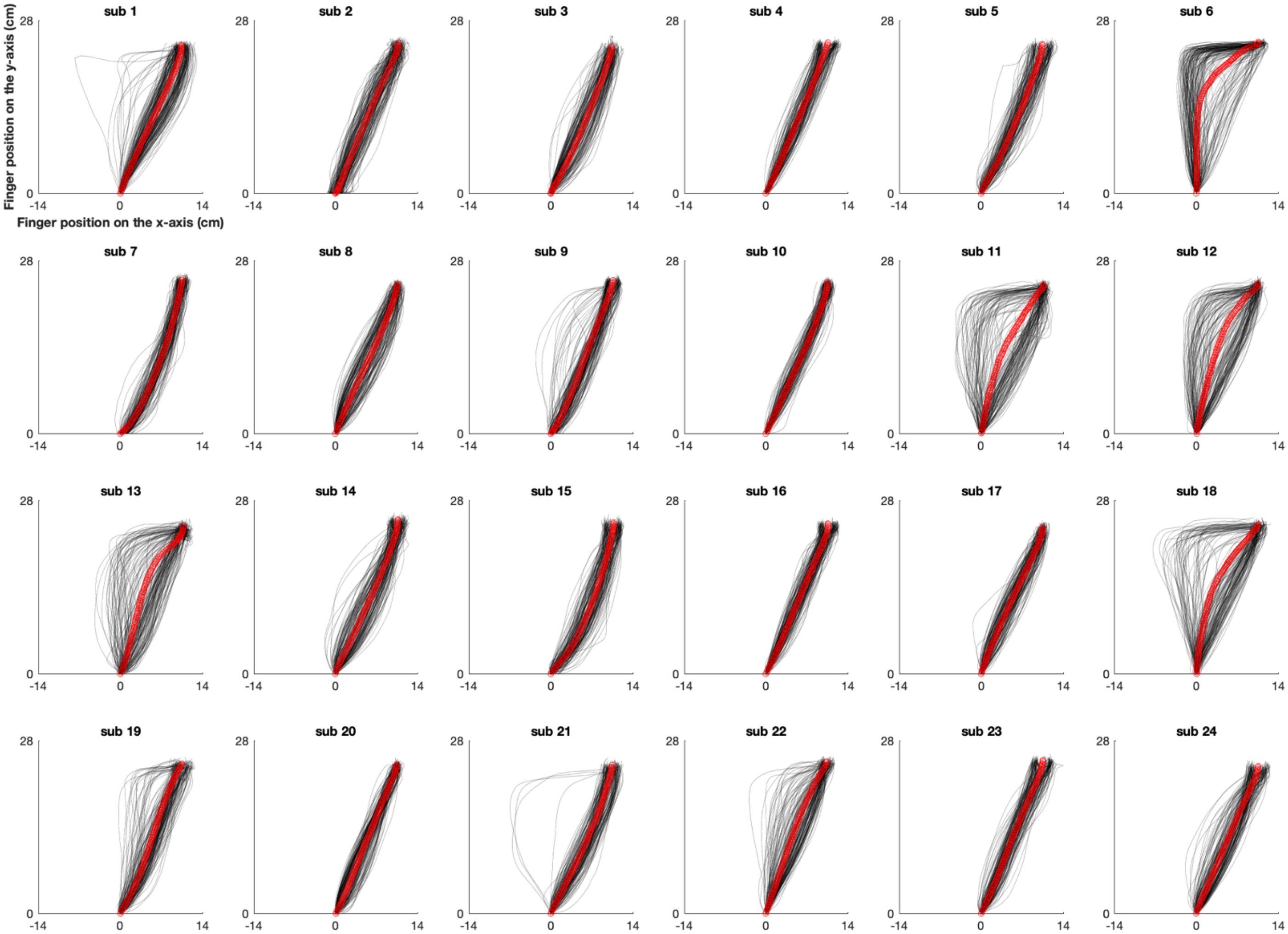

Figure S4. Reach trajectories of all the occlusion block trials included in the data analysis (black trajectories drawn with 30% opacity) and the average trajectory per participant (overlayed red trajectory) are shown for the supplementary action experiment (square stage). The 0,0 point indicates the finger's resting position, upper right corner corresponds to the goal position. Trajectories are zero-centered and right-aligned.

Gallivan and Chapman (2014). We then zero-centered and right-aligned the trajectories to clearly demonstrate their shape. The 0,0 point corresponds to the reaching finger's starting position and the upper right corner corresponds to the goal position (collapsing left and right movement direction trials). The zero point on the x-axis corresponds to the boundary where the object goes behind the occluder. Thus, trajectories that first go to the center, or more to the left of the center (i.e., negative values on x), then move toward the goal position on the right reflect trials in which participants track the bar with their finger while straight trajectories do not. When comparing occlusion block RT (duration-adjusted RT where motion duration was subtracted from RT), we did not find a difference between participants who adopted the tracking strategy and those who did not in either action experiments (see statistical details reported in the previous section).

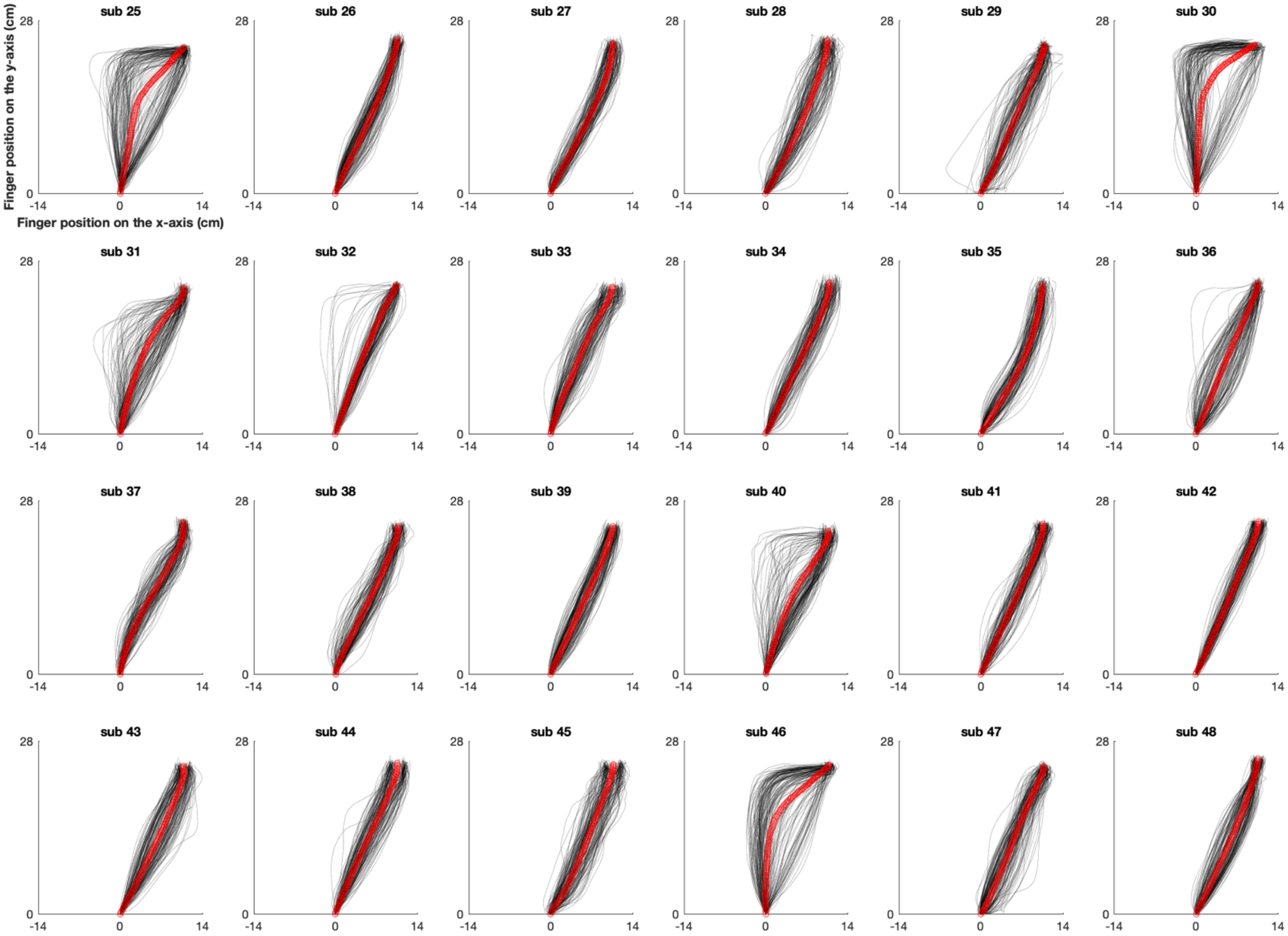

Figure S5. Reach trajectories for all the occlusion-block trials included in the data analysis (black trajectories drawn with 30% opacity) and the average trajectory per participant (overlayed red trajectory) are shown for the main action experiment (extended stage). The 0,0 point indicates the finger's resting position, upper right corner corresponds to the goal position. Trajectories are zero-centered and right-aligned.