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RESEARCH ARTICLE

The effect of concurrent hand movement on estimated time to contact in a prediction motion task

Ran Zheng[1] · **Brian K. V. Maraj**[1]

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Abstract

In many activities, we need to predict the arrival of an occluded object. This action is called prediction motion or motion extrapolation. Previous researchers have found that both eye tracking and the internal clocking model are involved in the prediction motion task. Additionally, it is reported that concurrent hand movement facilitates the eye tracking of an externally generated target in a tracking task, even if the target is occluded. The present study examined the effect of concurrent hand movement on the estimated time to contact in a prediction motion task. We found different (accurate/inaccurate) concurrent hand movements had the opposite effect on the eye tracking accuracy and estimated TTC in the prediction motion task. That is, the accurate concurrent hand tracking enhanced eye tracking accuracy and had the trend to increase the precision of estimated TTC, but the inaccurate concurrent hand tracking decreased eye tracking accuracy and disrupted estimated TTC. However, eye tracking accuracy does not determine the precision of estimated TTC.

Keywords Prediction motion · Time to contact · Ocular manual · Anticipatory saccade

Introduction

In our daily life, many activities require us to reach to moving objects. Sometimes moving objects may be occluded by other objects during movements. For example, when we play soccer or basketball, our teammates or rivals may also block our vision of the ball. Similarly, when we cross the street, we see a coming car and it may be blocked by other cars. Therefore, we make an estimation of when the car will arrive at the crossing or when the ball will arrive at our designated spot, from the brief viewing information. We call such a task prediction motion (PM) task (Rosenbaum 1975; Tresilian 1995, 1999) or a motion extrapolation task (Makin and Poliakoff 2011; Makin and Chauhan 2014). More specifically, there are two typical laboratory settings. The first is a production task in which participants view a moving target for a certain amount of time after which it becomes invisible or occluded, after which they predict when the occlude target arrives at a designated spot (Rosenbaum 1975; Tresilian 1995). The second is called a discrimination task where participants judge whether the occluded target, which may change its velocity after occlusion, reappears on time, too early or too late (Makin and Poliakoff 2011).

Prediction motion

A prediction motion task is a special type of coincidence anticipation (CA) task. Moving objects, which are always visible in the CA task, will disappear at a prescribed point in prediction motion tasks. While time-to-contact (TTC) is the actual amount of time remaining before the moving object arrives at the prescribed spot (Tresilian 2012); estimated TTC is the participants' estimation of TTC. The discrepancy between the estimated TTC and the actual TTC of the moving object is an important criterion to determine accuracy in the PM tasks. Many factors may influence the estimated TTC in prediction motion tasks, such as target size, visible time and target velocity (Lyon and Waag 1995; Sokolov and Pavlova 2003). However, occlusion time appears to be the most important factor (Yakimoff et al. 1993). When Yakimoff et al. (1993) examined the timing accuracy of prediction motion tasks, they varied the occlusion distance and target velocities to get different occlusion times. These authors suggested that the timing error was similar if the occlusion

✉ Ran Zheng
rzheng1@ualberta.ca

1 Faculty of Kinesiology, Sport, and Recreation, University of Alberta, 4-245 Van Vliet Complex, Edmonton, AB T6G 2H9, Canada

time was the same, regardless of the velocity and occlusion distance. Tresilian (2012) stated that the timing errors of prediction motion tasks are small if the occlusion period is short.

There are two theories which have been put forward and may explain why we can accurately predict the time to contact of an occluded target. The first is called the internal clocking strategy (DeLucia and Liddell 1998). According to this strategy, it is possible to estimate the time to contact before the disappearance of moving targets. Participants count down the time and initiate their response when they think the time elapsed has reached the estimated time. Based on the "tau" hypothesis (Lee 1976), an optic variable can be used to estimate the TTC. More specifically, the change of the ratio of the visual angle between moving object and the contact point is perceived. The ratio is then used to estimate the time to contact and predict the arrival of the moving object. Thus, it is not necessary to continue tracking the target once it disappears (Tresilian 1995).

The second strategy is called the tracking strategy. This approach emphasizes that tracking with the eye or covert attention is involved in the prediction motion task. Individuals will continue to track the moving target as accurately as possible even when it becomes invisible (DeLucia and Liddell 1998; Makin and Chauhan 2014).

Although early researchers (e.g., Tresilian 1995) stated that tracking was not involved in the PM tasks, some recent studies have strong evidence to indicate that the clocking strategy is not enough to explain the results from PM tasks. DeLucia and Liddell (1998) examined whether the tracking or the cognitive clocking only is used in a prediction motion task. The researchers used an interruption paradigm (Cooper 1989), that is, an object moved at a constant speed and was occluded for a varying duration. Then the target reappeared at either the correct position or the wrong position (more advanced or less advanced). They then asked the participants to answer whether the target reappeared at the correct position or not. Participants did not know where or when the target would reappear. Therefore, they could not count down the time to predict time to contact. The authors found that participants had similar errors in the interruption paradigm and the production task where they were required to judge when the target arrived at a prescribed spot. Based on these results, the authors concluded that participants also used tracking (cognitive motion extrapolation) in addition to the clocking strategy in the prediction motion task.

In addition to the results above, converging evidence has demonstrated that the tracking is involved in PM tasks by studying ocular tracking (Bennett et al. 2010; Makin and Poliakoff 2011). It has been demonstrated that both smooth pursuit and catch-up saccades are used to track visible moving objects (de Brouwer et al. 2001). Tracking the occluded target, which disappears after moving for a short time, means that the eye could track the target for a small amount of time (100–200 ms) perfectly. Then participants track the occluded target with a combination of reduced velocity pursuit and catch-up saccades, but less accurate than the first 100–200 ms (Orban de Xivry et al. 2006; Makin and Poliakoff 2011; Bennett and Barnes 2003, 2005).

Bennett et al. (2010) investigated the influence of eye movement on the accuracy of prediction motion tasks. The authors required participants to perform prediction motion tasks with free eye movement or with a fixation point. The results showed that the velocity effect was only on the fixation group, that is, participants made greater underestimation errors for the slow-moving object compared with fast-moving object when the TTC was between 1 and 1.5 s. On the contrary, the free eye movements group was not influenced by different target velocities if the TTC was the same. In agreement with Bennett et al. (2010), Makin and Poliakoff (2011) had the similar conclusion that eye movements enhanced the accuracy of prediction motion tasks. If eye tracking was not adopted in PM tasks, eye fixation would not have an effect on the estimated TTC.

Eye hand coordination

Existing literature demonstrates evidence for eye hand coupling in tracking both self-generated and externally generated targets (Vercher et al. 1995; Bennett et al. 2012). Specifically, when tracking a self-generated moving target using the eye and hand together, the eye more closely follows the moving target when compared to eye tracking only (Gauthier and Hofferer 1976; Gauthier et al. 1988). Concurrent hand tracking also reduces the catch-up saccade (Mather and Lackner 1980). In addition to enhancing tracking of unpredictable targets (Niehorster et al. 2015), concurrent hand tracking can also facilitate smooth pursuit in tracking predictable moving objects. Bennett et al. (2012) investigated the influence of hand tracking on eye tracking during transient occlusion. Participants were asked to track constant velocity or accelerating targets using eyes only or with eyes and hands together. The target was viewed for 600 ms before being occluded. Then it reappeared and continued moving for another 400 ms, before finally disappearing again. The results showed that eye velocity in the ocular manual condition was closer to the target velocity compared to the ocular only condition when tracking a high constant velocity target. Moreover, concurrent hand movements assisted the eye by reducing saccadic distance in tracking constant velocity targets. Based on these results, Bennett and associates suggested that concurrent hand movements facilitated eye tracking.

Effect of concurrent hand movements on estimated TTC

Few studies have examined the effect of concurrent hand movement on temporal estimation in an anticipation-timing task. Bootsma (1989) found the concurrent hand movement improved the accuracy of the temporal estimation compared to a single button press task. On the contrary, Williams, Jasiewicz and Simmons (2001) reported the concurrent hand movement had a negative contribution to the temporal estimation. However, these authors asked participants to move their hands in the opposite direction with respect to the moving target. More recently, Rodríguez-Herreros and López-Moliner (2011) examined the contribution of proprioception (hand movement) to the temporal estimation in the anticipation-timing task. In the perceptual condition, participants made a single button press, while in the perception–action condition, the participant moved their hands either in the same direction as the moving object or perpendicular to the moving object before pressing the button. The authors found participants benefited from proprioception only when the hand moved in the same direction as the moving object.

We have uncovered only one study which examined the effect of hand movement in a discrimination task for prediction motion. Wexler and Klam (2001) compared the performance between passive and active prediction motion. The rotation motion of the target was actively produced by the hand in the active condition while participants could only observe the rotation in the passive condition. Participants were required to judge if the target position was backward or forward when the target reappeared after occlusion. To make the two conditions similar, the authors used replays of the active condition in the passive condition. The authors found that participants estimated positions further advanced in the active condition compared to the passive condition. However, participants did not pursue the target with eyes all the time in both conditions as they were not required to do so. Thus, it is still unclear as to whether concurrent hand movements facilitate performance in prediction motion tasks, or more specially the production task. To this end, the current study aimed to examine if concurrent hand movements would facilitate performance in a prediction motion task. To examine this, we compared the performance in an ocular only condition and ocular manual condition in a prediction motion paradigm. Given that eye tracking is involved in the prediction motion task and the hand can facilitate eye tracking, we hypothesized that concurrent hand movement with the eye would improve the accuracy and consistency of estimated TTC in the production task.

Method

Participants

Ten right-handed participants ($M = 25.3$-years-old, $SD = 2.8$) were recruited for the experiment, all had normal or corrected to normal vision. Participants signed a consent form prior to the experiment and were allowed to take breaks anytime during the experiment. All procedures were approved by the Research Ethics Board at the University of Alberta.

Apparatus

Participants sat 45 cm away from a touch screen (Acer, T232hl) with a refresh rate of 60 Hz and a resolution of 1920×1080. A blue circle (1.5 cm diameter) located 10 cm left to the center of the screen served as the start position. Another blue circle of the same size located 10 cm right to center was the end position; subtended a visual angle of 25 deg. The stimuli were generated using E-prime (v 2.0 Psychology Software Tools Inc., Sharpsburg, PA). Hand movements were recorded by a 3D motion analysis system (Optotrak, Northern Digital, Inc., Waterloo, ON, Canada) using one infrared light-emitting diode (IRED) placed on the index finger and using a sampling rate of 240 Hz. A head mounted eye tracker [Applied Sciences Laboratory (ASL) 6000], with a rigid body (including three IREDs) to allow free head movements, was used to record the position of the left eye at a sampling rate of 240 Hz. A nine point calibration grid on the screen was used to calibrate eye position for each participant before the experiment.

Procedure

At the beginning of each trial, participants looked at the start position (ocular only condition) or placed their finger on the start position (ocular manual condition). A red circle (target) with a diameter of 1.5 cm appeared at the start position for 2 s after the participants indicated that they were ready. After a random period between 1000 and 1500 ms, the target (red circle) started moving at a constant velocity of either 10, 13.3, or 20 cm/s (i.e., 12.5, 16.6, and 25 deg/s), creating three different movement times from start position to end position (i.e., 1, 1.5, and 2 s). At the initiation of the target's movement, the motion analysis cameras and the eye tracker started recording simultaneously. For each trial, Optotrak recorded for a duration of 3 s and the eye tracker stopped recording 0.5 s after the participant clicked the mouse or pressed on the screen. The moving target was no longer visible after traveling for 10 cm (midpoint). Participants were informed that the target would continue moving at its previous velocity after its disappearance and that they were required to track it even though they could not see it. Based on the position of the point of target occlusion (PTO), participants had the same viewing and occlusion times: 0.5 s for the fast-moving target, 0.75 s for the medium moving target or 1 s for the slow-moving target. Participants were asked to perform two different tasks, using a prediction motion paradigm in the horizontal plane. First, they were required to predict the arrival time of a moving target by clicking a mouse (ocular only condition). Second, the participants were asked to move their index finger to track the moving target from initiation to the end position and to touch the screen upon their estimated time to contact (ocular manual condition). Feedback of the actual target position relative to the estimated time to contact was provided at the end of each trial. A red circle representing the actual target location would appear after participants clicked the mouse (ocular only condition) or pressed on the screen (ocular manual condition). Prior to the test, the two tasks were clearly explained to each participant. Participants also had a small amount of practice trials (6) to familiarize themselves with the two tasks prior to the test trials. In the experimental portion, participants were required to perform 20 trials at each velocity for each task, giving a total of 120 trials. Order of the two tasks was presented in a counterbalanced fashion across each participant and target velocity presentation was totally randomized.

Data analysis

Accuracy and consistency

Constant error (CE) of the arrival time was defined as the time difference between the target's actual arrival time from the start position to the end position and the estimated arrival time by participants. A negative CE meant participants responded prior to the arrival of the target, whereas a positive CE indicated a late response by the participant. Variable error (VE) was the standard deviation of participant estimated arrival times. It indicated the consistency of estimated time to contact. In addition, hand accuracy was measured by the spatial difference between the endpoint position of hand and the center of the end position (blue circle). VE of endpoint position of the hand was also calculated. CE, VE and hand accuracy data were derived from E-prime software.

Kinematics

Hand and eye position data were filtered using Butterworth filter with a low pass frequency of 20 Hz. A central difference algorithm was used to obtain eye and hand velocity. Onset of the movement was defined as the first frame when velocity exceeded 30 mm/s for 20 ms. Offset of movement was defined as the first frame when velocity was lower than 10 mm/s and maintained for more than 20 ms. Root mean square error was the difference between the eye position and the center of the moving target determined at each kinematic sample (240 Hz). As illustrated in Fig. 1, root mean square error of the first half (RMSE1) was the determined by every kinematic sample from movement onset to the point of target occlusion (PTO). Root mean square error of the second half (RMSE2) was determined by every kinematic sample from PTO to the movement end. In addition, we also calculated the onset time of the anticipatory saccade after target occlusion. The onset of the anticipatory saccade was defined as the first frame after target occlusion when acceleration exceed 6000 mm/s^2 (750 deg/s^2) and maintained for more than 10 ms. All the kinematic variables were calculated by a custom written MATLAB (Mathworks Inc.) program for each trial. RMSE was used to measure the tracking performance. Smaller RMSE values indicated that the trajectory of eye/hand was closer to that of the moving target (Mazich et al. 2015) and that eye tracking accuracy was greater (Fooken et al. 2016).

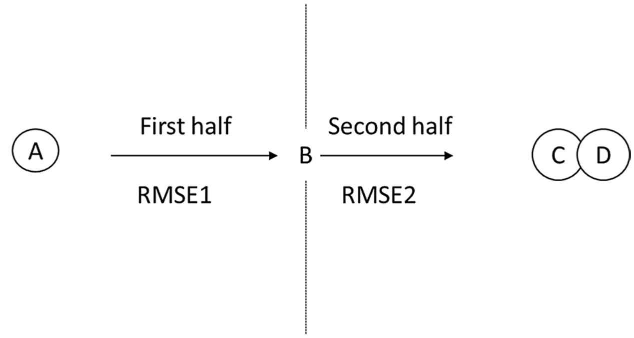

Fig. 1 Schematic representation of the task and dependent variables. A: Start position, B: point of target occlusion (PTO), C: end position. First half is from A to B, where the target is visible. RMSE for this distance is RMSE1. Second half is from B to C, where the target is occluded. RMSE for this distance is RMSE2. D: An example of the feedback of the actual target position. It is an overestimation for the current circumstance

Dependent variables were submitted to a two condition (ocular only and ocular manual) by three velocity (fast, medium, slow) repeated measures ANOVA. Alpha level was set at 0.05 for all analyses and Tukey's HSD post hoc procedure was used for main effects or interactions where appropriate.

Results

Eye and hand movement

Kinematic analyses of the eye movements indicated that a catch-up saccade followed the initial reaction to the

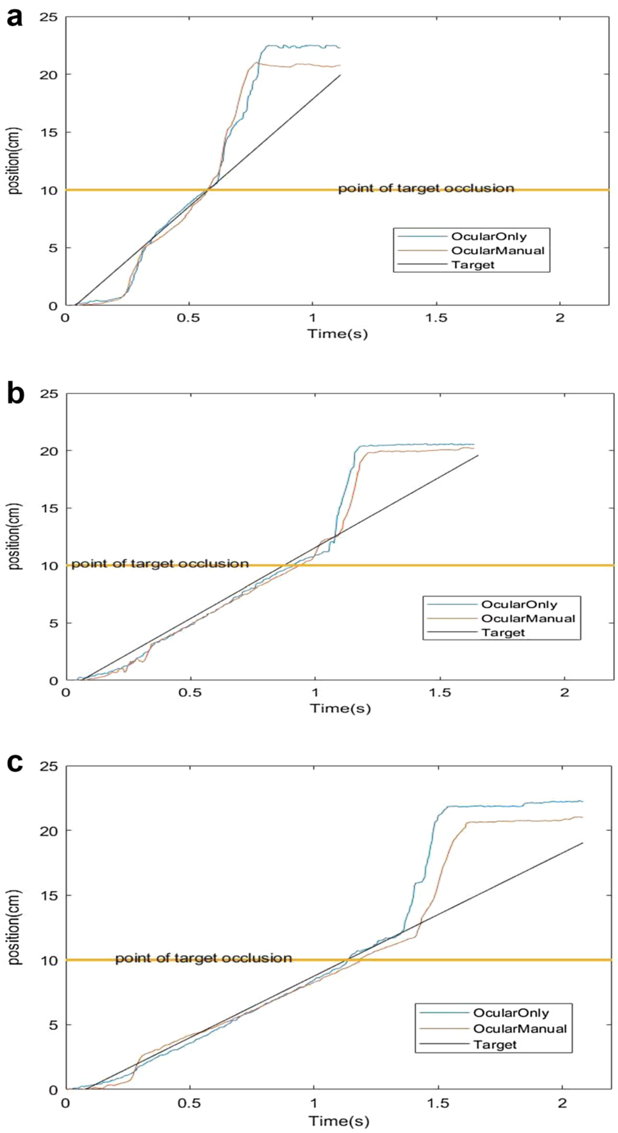

Fig. 2 Representative raw eye position trajectories for **a** fast, **b** medium and **c** slow-moving target from single trials from one typical participant. Horizontal line shows the point of target occlusion

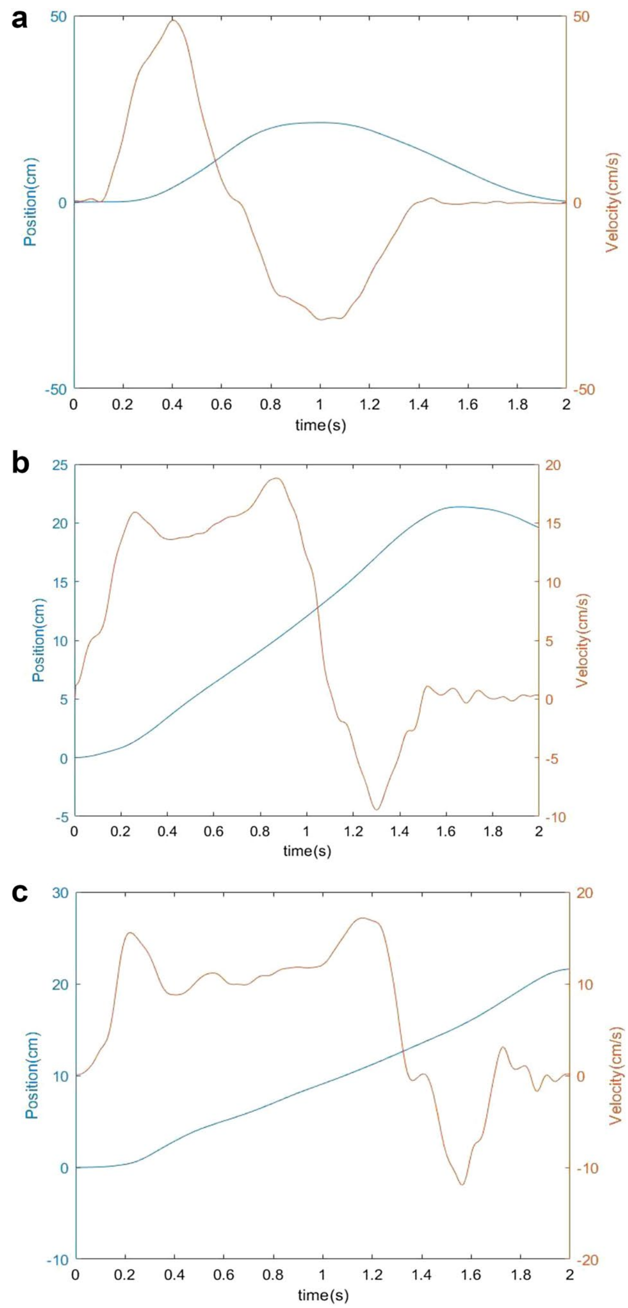

Fig. 3 Examples of hand position and velocity profile for the fast (**a**), medium (**b**) and slow (**c**) moving target from one typical participant

moving target after which the eye stayed close to the moving object until target occlusion. Moreover, the eye scaled its velocities to the target velocities (fast 23.85 cm/s, medium 15.25 cm/s, slow 10.56 cm/s) at the time of target disappearance. However, the eye could track the moving target for a short time after target occlusion. The eye then lagged behind the moving object and finally, an anticipatory saccade brought the eye to the end position before the arrival of the moving target in both tasks (Fig. 2). All the participants had the anticipatory saccade after target occlusions for the slow and medium moving target in both conditions, as well as the fast-moving target in the ocular only condition. However, two out of the ten participants had the anticipatory saccade just before the target occlusion in the ocular manual condition for the fast-moving target.

Similar to the data for the eye, the hand initiated its movement after stimulus onset. As illustrated in Fig. 3, the hand had a steady velocity phase for the medium and slow-moving targets. When the moving target was occluded (10 cm from the start position), the hand positions for the slow and medium moving targets were 10.16 and 10.26 cm, respectively. At the same time, the hand also scaled velocities

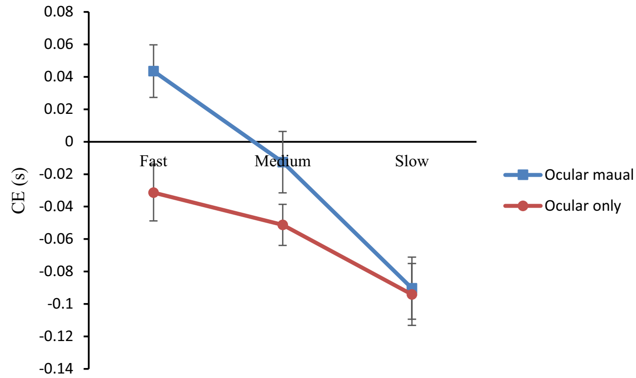

Fig. 4 Mean constant error (s) as a function of condition and velocity. Error bars represent standard error of mean. Negative CE indicates underestimation of TTC

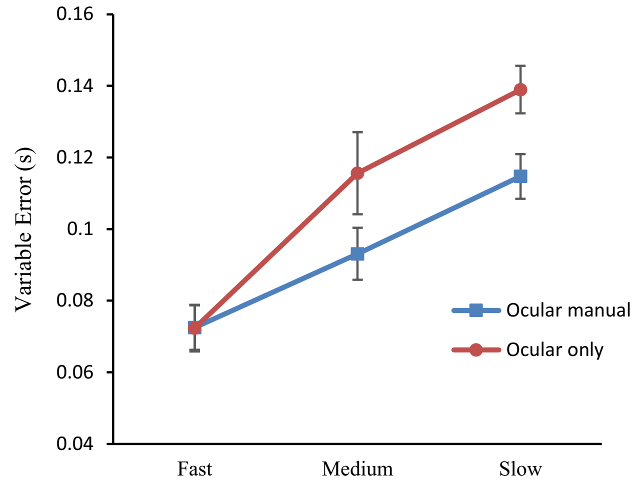

Fig. 5 Mean variable error(s) as a function of condition and velocity. Error bars represent standard error of mean

to the slow and medium moving target. The hand velocity for the slow and medium moving targets was 11.1 and 16.9 cm/s, respectively. However, for the fast-moving target, the hand position fell behind the moving target at the time of target disappearance (7.98 cm). In comparison, the hand also traveled at a much greater velocity (39.3 cm/s) than the other two conditions. Further, as depicted in Fig. 3, the velocity profile for the fast-moving target resembled a reaching movement in that it had both an acceleration and deceleration phase. When the hand finally landed on the end point, the constant error for the spatial hand end position of the slow, medium and fast-moving targets were 0.183, 0.198 and 0.176 cm, respectively.

Constant error of estimated time to contact (TTC)

There was a main effect for velocity, $F(2,18) = 15.83$, $\eta^2 = 0.638$ ($p < 0.01$) and significant condition by velocity interaction, $F(2,18) = 6.06$, $\eta^2 = 0.402$ ($p < 0.01$). Overall, estimated time to contact was more accurate for the fast-moving target (0.006 ± 0.06 s) compared to the slow-moving target (-0.09 ± 0.058 s). The interaction revealed that participants overestimated the TTC for fast-moving target in the Ocular manual condition, but underestimated in the Ocular only condition (see Fig. 4). In addition, there was a trend that participants were more accurate in the ocular manual (-0.02 s) condition than the ocular only (-0.06 s) condition ($p = 0.055$).

Variable error of estimated TTC

There were main effects for condition, $F(2,18) = 19.67$, $\eta^2 = 0.686$ ($p < 0.002$), and velocity $F(2,18) = 24.806$, $\eta^2 = 0.734$ ($p < 0.001$). The condition by velocity interaction $F(2,18) = 4.18$, $\eta^2 = 0.317$ ($p < 0.032$) was also significant. Overall, the main effect for condition showed that participants were more consistent in the ocular manual condition compared to the ocular only condition. The main effect for velocity revealed that VE decreased as a function of target velocity (fast 0.072 s, medium 0.104 s, slow 0.126 s). The three were significantly different from each other. In addition, the condition by velocity interaction $F(2,18) = 4.18$, $\eta^2 = 0.317$ ($p < 0.032$) was significant. Tukey's HSD analysis of the interaction indicated that VE was smaller in the ocular manual condition than the Ocular only condition, except for the fast-moving target condition (see Fig. 5).

Root mean-square error of the eye

There was a main effect for velocity on RMSE1 of the eye, $F(2,18) = 99.056$, $\eta^2 = 0.916$ ($p < 0.001$). Post hoc analysis of the main effect for velocity revealed that RMSE1 for the slow (1.6 cm) and medium moving targets (1.88 cm) were smaller compared to the fast-moving target (3.13 cm).

As for RMSE2, there was a main effect for the velocity as well, $F(2,18) = 17.56$, $\eta^2 = 0.661$ ($p < 0.001$). Similar to RMSE1, RMSE2 for the slow (2.96 cm) and medium moving targets (3.04 cm) were smaller compared to the fast-moving target (4.48 cm). In addition, a significant interaction of condition by velocity was also found on RMSE2, $F(2,18) = 11.12$, $\eta^2 = 0.553$ ($p < 0.001$). As illustrated in Fig. 1, RMSE2 for the slow-moving target was smaller in the ocular manual condition (2.70 cm) than the ocular only (3.22 cm), whereas RMSE2 for the fast-moving target was smaller in the ocular only condition (4.24 cm) than the ocular manual condition (4.72 cm).

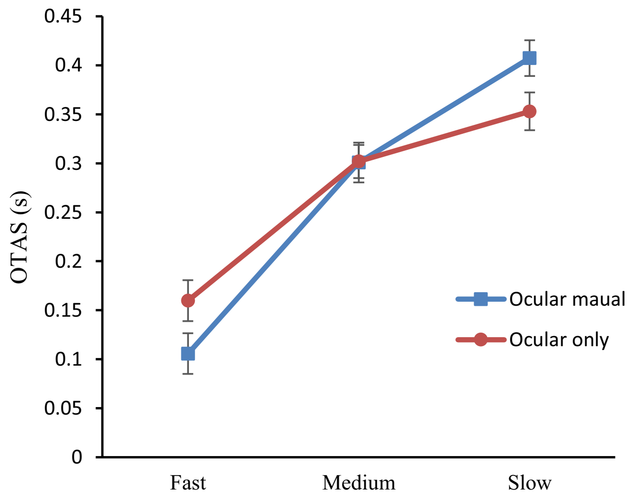

Fig. 6 Mean OTAS (s) as a function of condition and velocity. Error bars represent standard error of mean

Onset time of anticipatory saccade (OTAS) after target occlusion

The analysis of OTAS revealed a main effect for velocity, $F(2,18)=77.7$, $\eta^2=0.889$ ($p<0.001$), as well as a condition by velocity interaction, $F(2,18)=6.58$, $\eta^2=0.553$ ($p<0.01$). Tukey's HSD analysis of the interaction showed the OTAS increased with target velocity. Similar to the RMSE results, concurrent hand movements with different target velocities had different effects on the OTAS. That is, the OTAS for the slow-moving target was longer in the ocular manual condition than the Ocular only condition, but the OTAS for the fast-moving target was shorter in the ocular manual condition (Fig. 6). In addition, the OTAS increased with the decreasing of target velocity in both conditions, which meant the OTAS increased with the occlusion time in both conditions.

Discussion

The aim of the current study was to examine the effect of concurrent hand movement on performance in prediction motion tasks. To this end, we utilized a prediction motion paradigm to compare a traditional button press task to a new task which involved concurrent hand movement. We hypothesized that concurrent hand movement could facilitate the estimated time to contact (TTC) in prediction motion tasks. We based this on previous findings that tracking was involved in the PM task (Makin and Poliakoff 2011) and that concurrent hand movement could facilitate eye tracking to an occluded target (Bennett et al. 2012). Results of the current experiment indicated that concurrent hand movements with different target velocities had different effects on the estimated TTC. Specifically, concurrent hand movements with the medium and slow-moving targets were relatively more accurate when tracking and had the trend to increase the precision of estimated TTC in the ocular manual condition compared to the ocular only condition. On the contrary, concurrent hand movements with the fast-moving target were relatively inaccurate when tracking and disrupted the estimated TTC in the ocular manual condition.

Estimated time to contact

Participants increased the accuracy and consistency of estimated TTC as a function of velocity. It was possible that target occlusion time accounted for this change. The occlusion times were 1, 0.75 and 0.5 s for target velocities of 10, 13.3 and 20 cm/s respectively. It has been reported that the accuracy and consistency decrease with the occlusion time (Yakimoff et al. 1993; Tresilian 1995; Bennett et al. 2010; Makin and Poliakoff 2011). In the current study, participants had the shortest occlusion time when the target velocity was high, thus their estimated TTC was the most accurate and consistent for the fast-moving target. In addition, estimated TTC was more consistent in ocular manual condition compared to ocular only condition. This finding is supported by results from an anticipation-timing task (Rodríguez-Herreros and López-Moliner 2011), where the moving target is always visible. It appears that the online feedback is more specific in ocular manual condition compared to the ocular only condition as the refinement of the timing precision is better with concurrent hand movement (Tresilian 1995). Thus, participants had more consistent estimations in the ocular manual condition.

When the target velocity was high (shortest TTC), there was an underestimation of the estimated TTC in the ocular only condition, but an overestimation in the ocular manual condition. We suggest that the estimated TTC may have been disrupted by the inaccurate hand movement. Similarly, it has been reported the accuracy of estimated TTC in an anticipation-timing task was worse when the hand movement was incongruent with the moving target, compared to a single button press task (Williams et al. 2001) or compared to a task with congruent hand movement (Rodríguez-Herreros and López-Moliner 2011). Wexler and Klam (2001) stated that the concurrent hand movement was involved in a high-level mechanism that predicted the outcome. In addition, the store (representation of current moving target configuration) is continuously updating on the basis of the efference copy or the proprioceptive information, both before and after target occlusion. When the efference copy or the proprioception about the concurrent hand movement could not represent the moving object, the store was consequently disrupted by the inaccurate input, especially after target occlusion.

Unexpectedly, we did not find significantly more accurate estimated TTC with the accurate hand tracking movement. However, there was a trend ($p = 0.055$) that CE was smaller in the ocular manual condition than the ocular only condition. It is possible that this trend was biased by the positive CE for the fast-moving target in the ocular manual condition. But we cannot conclude the positive CE for the ocular manual condition was more accurate than the negative CE in the ocular only condition as the absolute error was similar in the two conditions.

Nevertheless, we found the CE for the medium moving target (medium TTC) had the trend to be more accurate in the ocular manual condition than the ocular only condition. The difference (42 ms) between these two conditions was very close to the critical value of Tukey's HSD test (44 ms). Therefore, it was possible to improve the accuracy of estimated TTC with the concurrent hand movement. However, it might be difficult to improve the estimated TTC (e.g., only when the hand movement was accurate, and the occlusion time was moderate) in the production task. In contrast, it is relative easier to disrupt the estimated TTC, e.g., eye fixation or free eye movement (Bennett et al. 2010), size of the moving target size (Sokolov and Pavlova 2003) and moving background during occlusion part (Battaglini et al. 2016).

Eye movement and eye hand coordination

Similar to results by Benguigui and Bennett (2010), we found that the eye did not maintain smooth pursuit after target occlusion, even with the accurate concurrent hand movements. An anticipatory recovery (anticipatory saccade in the current study)[1] brought the eye to the end position before the arrival of the target. It has been reported that the anticipatory recovery of the eye in tracking transient occluded target was modulated by an internal variable gain controller (Bennett and Barnes 2003). In an eye tracking task with a transient occluded target, the anticipatory recovery is timed to the moment of the target disappearance (Bennett and Barnes 2005). Moreover, occlusion duration does not affect its onset time (Bennett and Barnes 2003). These authors (Bennett and Barnes 2005) listed two advantages of this timing strategy. First, velocity and position errors started accumulating when the target disappeared. It was better to eliminate these errors as soon as possible. Second, participants did not have to count the duration of occlusion time if they timed the anticipatory recovery at the moment of target disappearance. However, in the current study, the onset times anticipatory saccade increased with occlusion times in both conditions (Fig. 6). It was possible that different internal variable gain controllers or mechanisms accounted for the timing of the anticipatory recovery in the production task and eye tracking task. Different from an eye tracking task, the moving target does not reappear after occlusion in the production task. The main purpose in the production task is to estimate the TTC accurately. If participants timed the anticipatory recovery to the moment of the target disappearance and did not time the occlusion duration, they could not estimate the TTC accuracy in the production task. We suggest that the anticipatory recovery was determined by the occlusion duration in the production task. In addition, instead of tracking the occluded target as accurately as possible, the eye finished its movement much earlier than the arrival of the moving target (Benguigui and Bennett 2010; Makin and Poliakoff 2011) in the production task.

It has been suggested that there may be reciprocal motor signals exchanged between the eye and the hand during tracking which involves an eye/hand synergy (Huang and Hwang 2013). We recognize that the eye uses retinal input to track the moving target when it was visible (Barnes 2008). However, it could only use extra-retinal input (e.g., short-term velocity memory system) to track the moving target after its disappearance (Barnes and Collins 2008). With the assistance of concurrent hand movement to track an occluded target, it is possible for the eye to have a greater source of extra-retinal input (e.g., proprioception) (Bennett and Barnes 2006) and stay closer to the moving target (Gauthier et al. 1988). In addition, proprioception could also be used to confirm the efferent copy when the moving target is occluded (Bennett et al. 2012; Wexler and Klam 2001). Consequently, concurrent hand movements would facilitate the eye to track the moving target after its disappearance.

In the current study, though the timing of anticipatory recovery was different from that of the eye tracking task and tracking the occluded target might not be the priority, we still found the hand movement affected the eye movements after target occlusion. First, the hand movement had different effects on the eye tracking accuracy based on the similarity between the hand movement and the moving target. That is, the eye tracking accuracy benefitted from the motor signals of hand for the slow-moving target and was deteriorated by the motor signals of the hand for the fast-moving target. As illustrated in Fig. 3, the hand had the longest time of steady-state velocity for the slow-moving target, which was scaled to velocity of the moving target. We suggest that the motor signals of the hand for the slow-moving target were closely related to the characteristics of the moving target. It has been reported that better eye tracking accuracy enhanced the precision of intercepting occluded targets (Fooken et al. 2016). However, more accurate eye tracking in the ocular manual condition did not enhance the precision of estimated TTC in

[1] In the current study, the time of minimum eye velocity after target occlusion was just before the onset time ofthe anticipatory saccade. Thus, we can regard the time of anticipatory recovery as the onset time of theanticipatory saccade.

the production task. It is possible that the size of interception region (a zone or a single point) or the movement trajectory (linear or parabolic) may account for the different results. For the fast-moving target, motor signals of the hand were not consistent with the characteristics of the moving target. Thus the hand had little or no steady-state hand velocity for the fast-moving target (Fig. 3).

Second, we found that the concurrent hand movement influenced the onset time of the anticipatory saccade (OTAS) in a manner similar to the eye tracking accuracy. This indicated that the internal variable gain controller that accounted for the velocity recovery was not invariant. Therefore, the hand movement had an influence on this controller. The discrepancy between OTAS and occlusion duration was smaller with the accurate hand movements and larger with the inaccurate movements. As stated before, the anticipatory recovery was related to the occlusion duration. We suggest that participants had a more accurate estimation of the occlusion duration with the accurate hand movement, but the estimation was less accurate with the inaccurate hand tracking.

In summary, the timing of the anticipatory recovery in the production task was different from that seen in tracking transient occluded targets and was influenced by the concurrent hand movements. Moreover, tracking the occluded target accurately might not be the priority in the production task. Different (accurate/inaccurate) concurrent hand movements had the opposite effect on the eye tracking accuracy and estimated TTC in the production task. However, the superior eye tracking did not increase the precision of estimated TTC.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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