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RESEARCH ARTICLE

Anticipatory gaze strategies when grasping moving objects

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Abstract Grasping moving objects involves both spatial and temporal predictions. The hand is aimed at a location where it will meet the object, rather than the position at which the object is seen when the reach is initiated. Previous eye–hand coordination research from our laboratory, utilizing stationary objects, has shown that participants' initial gaze tends to be directed towards the eventual location of the index finger when making a precision grasp. This experiment examined how the speed and direction of a computer-generated block's movement affect gaze and selection of grasp points. Results showed that when the target first appeared, participants anticipated the target's eventual movement by fixating well ahead of its leading edge in the direction of eventual motion. Once target movement began, participants shifted their fixation to the leading edge of the target. Upon reach initiation, participants then fixated towards the top edge of the target. As seen in our previous work with stationary objects, final fixations tended towards the final index finger contact point on the target. Moreover, gaze and kinematic analyses revealed that it was direction that most influenced fixation locations and grasp points. Interestingly, participants fixated further ahead of the target's leading edge when the direction of motion was leftward, particularly at the slower speed—possibly the result of mechanical constraints of intercepting leftward-moving targets with one's right hand.

Keywords Eye–hand coordination · Moving objects · Fixation locations · Grasping · Visuomotor control

Introduction

We usually take for granted our visual system's ability to guide hand movements when performing various everyday tasks. Whether we are picking up a morning cup of coffee or catching a ball while playing a game, we utilize visual information in our environment to interact with the world around us. When interacting with objects in our environment, we direct our gaze towards the object of interest and acquire visual information about its location and shape so that we may program the movement of our hand to reach out and grasp it (Desanghere and Marotta 2011; Hayhoe and Ballard 2005; Smeets et al. 1996).

Where we look is not random, but rather an active process by the visual system to seek out information in our environment relevant to the task at hand (Henderson 2003). In reaching and grasping tasks, programming eye movements to bring an object into our line of sight so that we may grasp it requires two main stages: first, selection of the object we want to look at and second, computation of a fixation and landing position on that object (Vishwanath and Kowler 2004). Fixating one's gaze on an object directs the high-acuity fovea region of the eye's retina towards that object, allocating greater attention to the task at hand. For this reason, we usually fixate on the object we want to interact with prior to reaching out to grasp it (Hayhoe and Ballard 2005; Hayhoe et al. 2003).

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Fixation locations appear to be tailored to meet the demands of specific tasks. For instance, fixations are typically directed towards the centre of mass (COM) of an object in perceptual tasks where participants are instructed to view the target as a whole, which may be ideal for determining the size and shape of the object (Brouwer et al. 2009; Desanghere and Marotta 2011; McGowan et al. 1998; Melcher and Kowler 1999; Vishwanath and Kowler 2004). In contrast, studies of object manipulation, where participants are instructed to grasp an object, have found that gaze is directed towards environmental features most important to manipulating hand movements, such as obstacles one must avoid, or specific grasp points on the objects (Brouwer et al. 2009; De Grave et al. 2008; Desanghere and Marotta 2011; Johansson et al. 2001). Recent experiments examining where participants look when grasping a stationary object with a precision grip—where only the index finger and thumb make contact with the object—find that fixations favour the eventual index finger landing position on the object (Brouwer et al. 2009; Desanghere and Marotta 2008, 2011; Johansson et al. 2001).

These investigations have provided valuable information concerning visually guided grasping with stationary objects, but it is equally important that we investigate the complex processes involved in grasping moving objects. Imagine you are tossing a frisbee with a friend and that the frisbee has just been thrown to you. To successfully grasp the frisbee, your motor system rapidly makes elaborate calculations based on visual information such as the frisbee's position, orientation, and velocity. Since grasping moving objects involves both spatial and temporal predictions, hand movements must be aimed at the location the target is going to be at the time of contact, rather than the target's location when the reach is initiated (Todd 1981). Thus, when grasping a moving object, it is crucial to find a balance between reaching quickly to maximize temporal accuracy and reaching carefully to maximize spatial accuracy (Tresilian et al. 2009). However, the kinematics of reaching and grasping moving objects is only half the story. The other half involves where we look and what visual information we use to coordinate our actions to grasp a moving object, which is less understood.

When an object of interest moves through our visual field, we track it by moving our eyes in an attempt to maintain fixation on the object and maximize its visibility (Murphy 1978). This is also the case when reaching to intercept moving targets with a stylus or finger (Brenner and Smeets 2007, 2009; Mrotek and Soechting 2007; Soechting and Flanders 2008). Previous research examining where participants look when catching a moving ball found that it was most essential for participants to obtain visual information about the ball at the beginning of its trajectory, and then again right before catching the ball (Lòpez-Moliner et al. 2010; Lòpez-Moliner and Brenner 2014). If the trajectory of a moving object is known, it is likely unnecessary to track the object throughout its entire movement (Brenner and Smeets 2011). However, if the time at which participants are cued to grasp a moving object is varied, it is possible that they will spend additional time tracking the object in order to successfully grasp it. Similarly, if the moment at which participants must move to intercept the object is unknown, it is likely that they will maintain close fixation of the object throughout its trajectory, as this will provide additional visual information that can be used to grasp the object in a more precise and stable fashion (Brenner and Smeets 2011).

Research in the visuomotor field has seen much progress in recent years, but still lacks a complete understanding of how a moving object influences human gaze and grasp locations. The present study examined how gaze and grasp locations were influenced by a horizontally translating computer-generated target block, moving at one of two speeds in different directions. It was hypothesized that whether viewing a slow- or fast-moving target, participants would initially fixate their gaze above the COM, towards the eventual index finger contact point—since the target would initially be stationary. This was based on previous research with stationary objects illustrating that initial fixations favoured the eventual index finger landing position on the object (Brouwer et al. 2009; Desanghere and Marotta 2008, 2011; Prime and Marotta 2013). Alternatively, we hypothesized that participants might anticipate the movement of the target and initially fixate the target's eventual leading edge—the edge facing the direction of eventual motion. For slow-moving targets, it was predicted that participants would track the leading edge or COM of the target until initiating their reach, at which point they would shift their fixation towards the top edge of the target, and the eventual index finger contact point. In contrast, it was hypothesized that for fast-moving targets, participants would make a series of quick eye movements placing their fixation further ahead of the target (in anticipation of the grasp tone) until initiating their reach, at which point they would shift their fixation towards the top edge of the target, towards the eventual index finger contact point. In sum, regardless of the gaze strategies participants made prior to reaching, it was expected that their final fixation locations would be biased towards the index finger landing position on the target. Overall, the goal of this experiment was to demonstrate the effects of target speed, direction, and translational movement in a novel way to further our understanding of eye–hand coordination.

Methods

Participants

Twelve undergraduate psychology students (7 females) between the ages of 19 and 27 years ($M = 22.6$) were recruited through the University of Manitoba's Psychology Department Participant Pool and received course credit as part of their Introductory Psychology course. All participants were strongly right-handed, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield 1971), and had normal or corrected-to-normal vision. Informed consent was obtained from all individual participants included in the study. All procedures were approved by the Psychology/Sociology Research Ethics Board (PSREB) at the University of Manitoba.

Stimuli and materials

Participants were required to perform a grasping task to a white computer-generated block (4 × 4 cm) presented on a black background on a 24-in. (60.96 cm) computer monitor. The block appeared with its trailing edge positioned 1 cm from either the far left or right edge of the screen. The monitor was positioned 55 cm away from a chin rest mounted on the edge of a table.

Grasping movements were recorded with an Optotrak Certus 3-D recording system (Northern Digital, Inc., Waterloo, ON, Canada). A total of six infrared light-emitting diodes (IREDs) were fastened onto each participant's right hand and wrist. Two IREDs were placed on the participant's index finger (positioned on the nail and left side of the cuticle), two on their thumb (positioned on the nail and right side of the cuticle), and two on their wrist (positioned on the radial portion of the wrist). An EyeLink II head-mounted eye tracking system (SR Research Ltd., Mississauga, ON, Canada) was used to record binocular eye movements. MotionMonitor (MM) software (Innovative Sports Training, Inc., Chicago, IL, USA) was used to integrate eye, head, and hand data into a common spatial and temporal frame of reference sampled at 130 Hz. MM was also used to generate the two-dimensional target block and calculate eye and finger positions relative to the target's COM for each trial. Custom software, developed using MATLAB (R2008a, The MathWorks Inc., Natick, MA, USA), was used to generate an 8-kHz auditory tone, which signalled the participants to make a grasping movement. The software was run on an Inspiron 545 Dell computer (Duo Core 3.16 GHz). Both eyes were calibrated using a nine-point calibration/validation procedure on the monitor. To ensure accurate calibration of less than 1-cm error and reliability of binocular eye data, accuracy checks were conducted immediately following calibration and at the beginning and end of each of the four blocks of trials. This was accomplished by having participants fixate on a dot at the centre of the monitor and comparing the position of their fixation to the position of the dot.

Procedure

Figure 1 shows the general experimental paradigm. Each experimental trial began with presentation of the computer-generated target block on either the far right or left edge of the monitor. The target remained stationary for 1.5 s and then moved horizontally towards the opposite end of the monitor at either a "slow" speed (5 cm/s, 5.2 deg/s) or a "fast" speed (10 cm/s, 10.4 deg/s). At the start of a trial, participants were unaware of the speed the target would move. They could, however, infer the direction of movement by the starting position of the stimulus. Participants kept their right hand on the start position on the tabletop 40 cm in front of the centre of the monitor until they were prompted to reach and "grasp" the target by an auditory tone. The tone (600 ms in duration) was programmed to sound 1 s or 3.5 s after the target's movement began, such that the target approached the central region of the monitor so that participants made mechanically consistent reaches

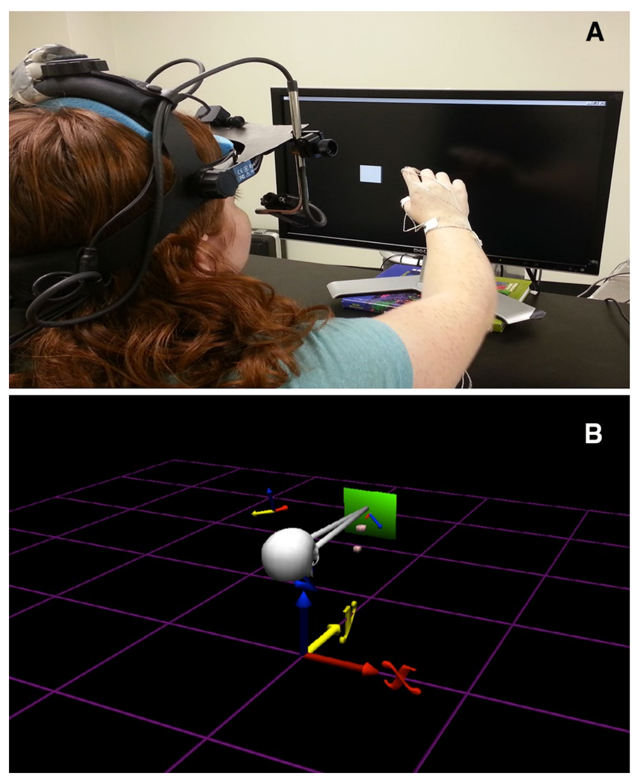

Fig. 1 Experimental set-up (**a**) and in the MotionMonitor virtual environment (**b**), demonstrating how the eye and hand data are integrated into a common reference frame in real time

when grasping the target (Fig. 1). The distance between the centre of the target block at its starting position on the edge of the screen and the centre of the screen was 24 cm (25 deg).

Participants were instructed to grasp the target upon hearing the tone using a vertical precision grip. They were not instructed about where to grasp on the target block, only to reach out and grasp the target "quickly but naturally" as if they were going to grab it off the screen. To make the task more closely resemble grasping a real object, the target block was programmed to stop moving just prior to participants' fingers making contact with the screen, detected by the Optotrak via position information when the index finger or thumb IREDS came within 6 cm (resultant vector) from the centre of the target. Participants were then required to return their hand to the starting position once target movement stopped to await the next trial. Participants were not instructed about how they should track or look at the target block.

Distractor trials were incorporated in a third of the total trials. Distractor trials were similar to the experimental trials except the auditory tone, which was presented either 1 or 3.5 s after the object's movement began, sounded when the object approached noncentral screen positions. In the slow condition, distractor trials had a tone delay of 1 s, resulting in reaches close to the object's starting position. In the fast condition, distractor trials had a tone delay of 3.5 s, resulting in reaches towards the far quadrant of the screen. The experimental and distractor trials were randomly interleaved to keep participants alert, and prevent them from being able to predict when the tone would sound.

Three practice trials were completed before beginning the experiment to acquaint participants with the task. Participants then completed 120 randomized trials, divided into four blocks with 20 experimental trials and 10 distractor trials per block. Sessions took approximately 1.5 h to complete.

Data analyses

A within-subjects design was utilized in which all participants completed 120 trials in a randomized order. There were eight different trial conditions in total, four of which were experimental trials: (a) Fast-leftward; (b) Fast-rightward; (c) Slow-leftward; and (d) Slow-rightward. The other four trial conditions were distractor trials excluded from analysis. Gaze coordinates (both horizontal X and vertical Y positions) were recorded for the full duration of each trial and were characterized into fixations based on a dispersion algorithm (see Salvucci and Goldberg 2000), with a minimum duration threshold of 100 ms and a maximum dispersion threshold of 1 cm. The dispersion algorithm identified fixations from the raw eye position data points when consecutive data points were located within a specified spatial window (maximum dispersion threshold) for a minimum period of time (minimum duration threshold). Analyses of eye fixation positions were conducted along the horizontal and vertical axes. Analyses of hand data were conducted on the index finger grasp position along the horizontal axis of the block, maximum grip aperture (MGA) between the index finger and thumb when participants reached for the moving target, the peak wrist velocity, and the total reach duration. Horizontal and vertical coordinates of the gaze and the hand were examined relative to the target block's centre (i.e. the block's COM).

Two separate three-way $4 \times 2 \times 2$ repeated measures ANOVAs (Time × Speed × Direction) were conducted on fixation locations in both horizontal and vertical dimensions, calculated relative to the target's COM. The four different time points for the Time factor were: when the target block appeared (Target Appears), when target movement was initiated (Target Moves), when hand movement was initiated (Reach Initiation), and at grasp (Target Grasped). Speed had two levels: Slow and Fast, and Direction had two levels: Right and Left. A detailed examination of the fixations at each time point will be discussed separately. Additionally, three separate 2×2 repeated measures ANOVAs (Speed × Direction) were conducted on the peak wrist velocity, MGA, and the total reach duration. Post hoc Tukey HSD tests were performed when necessary.

Results

Excluded fixations, frames, and trials

Any fixations that fell outside the boundaries of the monitor were excluded from analysis, as these values corresponded to eye angles exceeding the calibration range of the eye tracker. When combined with data lost due to equipment failures, 1.78 % of fixations, 0.39 % of frames (in root-mean-square error calculation), and 2.2 % of trials were excluded from the analysis. Prior to calculating the root-mean-square error, all frames containing gaze coordinates further than 15 cm away from the target block's COM once its movement began were filtered out to remove any noise, blinks, and drops of corneal reflection. Table 1 shows the mean horizontal and vertical fixation positions during the experimental trial conditions.

Overall gaze analysis

For horizontal fixation position, we found a significant main effect for Direction [$F(1, 11) = 1326.99$, $p < .01$], showing that overall gaze was left of the COM for leftward-moving target blocks ($M = -3.3$ cm, SE = 0.09)

Table 1 Mean horizontal (*X*) and vertical (*Y*) fixation positions (cm) during the four time points of interest throughout each experimental trial condition

Condition	Object Appears		Object Moves		Reach Initiation		Object Grasped	
	X	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
Fast-left	−10.25 (0.23)	0.32 (0.18)	−2.99 (0.19)	0.28 (0.18)	−0.47 (0.18)	0.80 (0.16)	0.16 (0.15)	1.05 (0.16)
Slow-left	−8.84 (0.21)	0.39 (0.19)	−3.31 (0.20)	0.28 (0.19)	−0.70 (0.17)	1.00 (0.17)	−0.35 (0.11)	1.27 (0.19)
Fast-right	9.12 (0.32)	0.77 (0.17)	1.93 (0.18)	0.63 (0.20)	−0.29 (0.18)	0.90 (0.16)	−0.94 (0.17)	1.15 (0.18)
Slow-right	8.30 (0.31)	1.02 (0.20)	2.34 (0.24)	0.75 (0.20)	−0.0048 (0.20)	0.99 (0.21)	−0.42 (0.18)	1.20 (0.19)

Positive and negative horizontal positions indicate right and left of object's COM, respectively. Positive and negative vertical positions indicate above and below object's COM, respectively. Standard errors of the means are in parentheses

and right of COM for rightward-moving target blocks ($M = 2.5$ cm, SE = 0.1) when collapsing across Time and Speed. However, as shown in Table 1, mean fixation position was directed to the leading edge of the target block at both the time points Target Appears and Target Moves (left of the COM for leftward motion and right of the COM for rightward motion), but gaze appeared closer and to the left of the COM in the Reach Initiation and Target Grasped time points, irrespective of direction and speed. These observations were confirmed by the significant interactions Time × Direction [$F(3, 33) = 1219.77$, $p < .01$] and Time × Speed × Direction [$F(3, 33) = 23.58$, $p < .01$]. Post hoc Tukey tests conducted to unpack the three-way interaction yielded significant differences when comparing the Target Appears and Target Moves time points against each other, and both of these time points against Reach Initiation and Target Grasped for all different levels of direction and speed. No significant effects were found for any of the comparisons between the time points of Reach Initiation and Target Grasped. No significance was found for main effect of Time [$F(3, 33) = 0.39$, $p = .76$] or Speed [$F(1, 11) = 2.64$, $p = .13$], nor was there a significant interaction for Time × Speed [$F(3, 33) = 0.941$, $p = .43$] or Speed × Direction [$F(1, 11) = 0.007$, $p = .94$].

For vertical fixation position, the three-way ANOVA yielded significance for Speed [$F(1, 11) = 16.71$, $p < .01$] and Direction [$F(1, 11) = 6.44$, $p = .02$]. Gaze was higher in the slow and rightward conditions ($M = 0.9$ cm, SE = 0.2) compared to the fast and leftward conditions ($M = 0.7$ cm, SE = 0.15). The main effect for Time was significant [$F(3, 33) = 27.007$, $p < .01$] and follow-up post hoc Tukey tests yielded significant results ($p < .05$) when Target Appears ($M = 0.62$ cm, SE = 0.16) and Target Moves ($M = 0.49$ cm, SE = 0.18) were compared to Target Grasped ($M = 1.17$ cm, SE = 0.18) and a marginal significant comparison ($p = .059$) between Target Moves and Reach Initiation ($M = 0.92$ cm, SE = 0.16), collapsing across Speed and Direction. In general, gaze was directed more towards the top edge of the target block at the Target Grasped time point. Other patterns that are revealed in Table 1 show that mean vertical fixation positions appear to be generally higher in the slow and the rightward conditions compared to fast and leftward, particularly at the earlier time points of Target Appears and Target Moves. These observations were confirmed by the significant Time × Direction [$F(3, 33) = 8.87$, $p < .01$] and Time × Speed × Direction [$F(3, 33) = 5.85$, $p < .01$] interactions. No significant differences were found for the Time × Speed [$F(3, 33) = 1.04$, $p = .39$] and the Speed × Direction [$F(1, 11) = 0.006$, $p = .94$] interactions.

The results from the three-way ANOVAs for both horizontal and vertical fixation positions revealed significant two-way interactions between Time and Direction and three-way interactions between Time, Direction, and Speed. Since we were primarily interested in examining gaze behaviour at the four selected time points, and to show more clearly how gaze changed within the trial, we included more specific post hoc Tukey tests that were conducted to follow up these significant interactions separated for each time point in the following sections.

Fixations when the target block first appeared

Since participants had no way of knowing whether the target block would eventually move at a fast or slow speed at this time point, we collapsed speed and calculated their fixation positions according to the side of the screen the target appeared at the start of the trial. Mean fixation positions were 0.3 cm above (SE = 0.18) and 8.7 cm (SE = 0.26) to the right of the COM, when the object appeared on the left side, and 0.9 cm (SE = 0.19) above and 9.5 cm (SE = 0.14) to the left of the COM, when the target appeared on the right side of the screen. These differences in both the horizontal and vertical dimensions were statistically significant ($p < .01$).

Fixations when the target block began to move

Figure 2 shows the mean horizontal and vertical fixation positions for both speeds when the target block began moving leftward (Fig. 2a) and rightward (Fig. 2b). For both fast- and slow-moving targets, mean horizontal fixations were to the left of the COM for leftward-moving targets and to the right of the COM for rightward-moving targets. Post hoc Tukey comparisons between the four mean horizontal fixation positions revealed no significant differences between speeds within the same direction condition (i.e. the comparisons between fast-moving and slow-moving conditions in the leftward direction, and between fast-moving and slow-moving conditions in the rightward direction, all $p > .05$), while all other comparisons differed significantly from one another (all $p < .01$). Nonsignificant results were also found for mean vertical fixation positions when comparing speeds within each direction condition ($p > .05$): participants fixated above COM in all conditions.

Fixations when participants initiated reaches

Mean horizontal fixation positions in the leftward direction condition were 0.7 cm (SE = 0.17) and 0.47 cm (SE = 0.18) left of COM for slow- and fast-moving speeds, respectively. Mean horizontal fixations in the rightward direction condition were 0.005 cm (SE = 0.2) and 0.29 cm (SE = 0.18) left of COM for slow- and fast-moving speeds, respectively. No significant differences were found for horizontal fixations between any of the four different combinations of speed and direction. Mean vertical fixation positions in the leftward direction condition were 0.8 cm (SE = 0.16) and 1 cm (SE = 0.21) above COM and in the rightward direction condition were 1 cm (SE = 0.17) and 0.9 cm (SE = 0.17) above COM for slow- and fast-moving speeds, respectively. No significant differences were found for vertical fixations between any of the four different combinations of speed and direction ($p > .05$), except between slow- and fast-moving targets in the leftward direction condition ($p < .05$).

Fixations when participants grasped the target block

Figure 2 shows the mean horizontal and vertical fixation positions for both speeds when participants grasped leftward-moving (Fig. 2c) and rightward-moving (Fig. 2d) targets. Unlike the other time points, the mean horizontal fixation positions when grasping a leftward-moving target were to the right of the COM during the fast-moving condition and to the left of the COM during the slow-moving

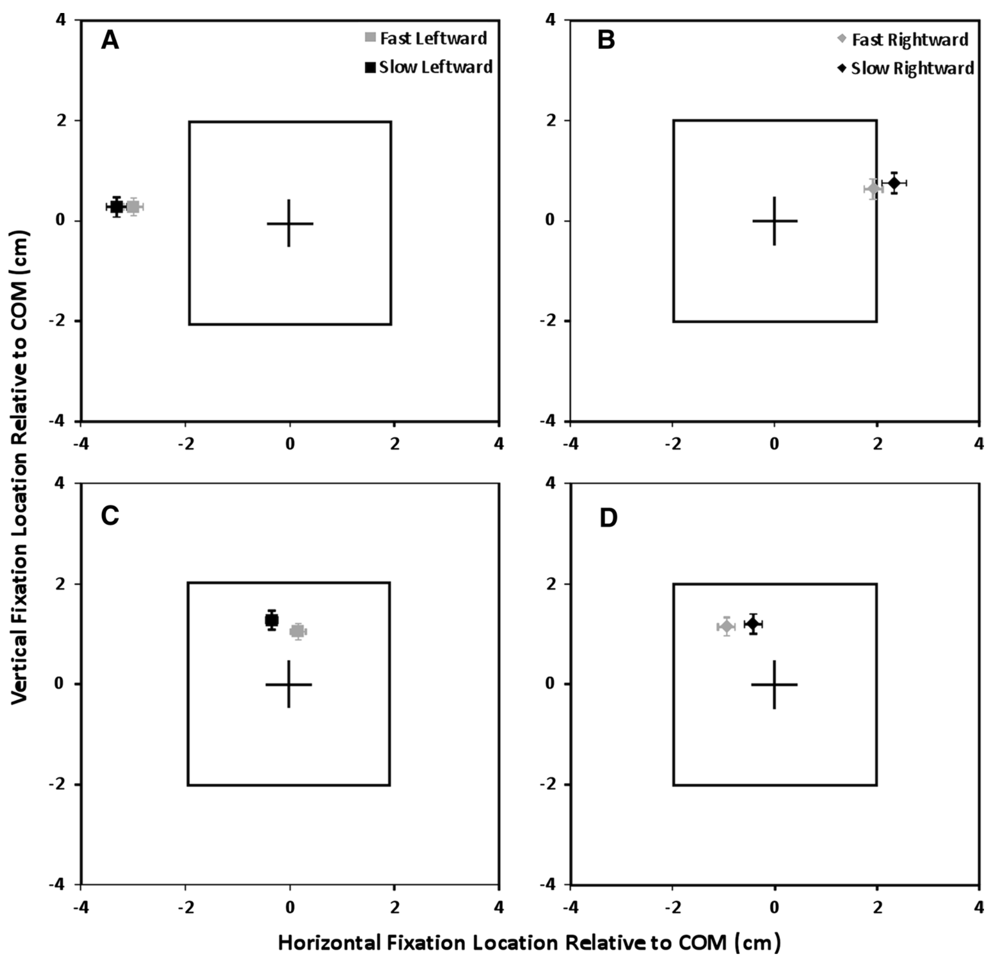

Fig. 2 Mean fixation positions when (**a**) the target block began moving leftward, (**b**) the target block began moving rightward, (**c**) participants grasped a leftward-moving target, and (**d**) participants grasped a rightward-moving target. Centre of mass = COM. Positive fixation location values on the *y*-axis indicate that fixations were above the target block's COM. Negative fixation location values on the *x*-axis indicate that fixations were to the left of the target block's COM. *Error bars* represent the standard error of the mean

condition. In both the slow- and fast-moving rightward conditions, mean horizontal fixations were to the left of the COM. No significant differences were found between these horizontal fixations ($p > .05$), except between leftward and rightward directions in the fast speed condition ($p < .01$). For leftward-moving targets, the mean vertical fixations were significantly higher in the slow-moving condition than they were in the fast-moving condition ($p < .01$). In the rightward condition, the mean vertical fixations were above the COM for both fast- and slow-moving speeds. No significant differences were found between all other comparisons ($p > .05$).

Gaze relative to grasp position

To determine how closely participants' fixations corresponded to their final index finger contact point when grasping the target block, difference scores between final fixation locations and final index finger contact points in the horizontal axis were calculated and run through a 2 × 2 repeated measures ANOVA to compare the effects of Speed (slow and fast) and Direction (leftward and rightward). The analysis showed that there was a significant main effect for Speed [$F(1, 11) = 9.95$, $p = <.01$], but no significance was found for main effect of Direction [$F(1, 11) = 0.27$, $p = .61$], nor was there a significant interaction for Speed × Direction [$F(1, 11) = 1.45$, $p = .25$]. Collapsing across Direction, it was found that participants fixated on average 0.17 cm (SE = 0.2) right of the final index finger contact point when grasping fast-moving targets and 0.04 cm (SE = 0.2) left of the final index finger contact point when grasping slow-moving targets. On average, participants grasped the target block 0.46 cm (SE = 0.2) left of its COM across all conditions. Additionally, participants' final fixations in the vertical axis when grasping the targets were 1.17 cm (SE = 0.2) above the COM.

Root-mean-square error analysis

To examine the extent to which participants' eyes did not reproduce the target block's motion, root-mean-square error (RMSE) values of participants gaze locations relative to the target's COM were computed (Fig. 3). Significant main effects were found for Speed [$F(1, 11) = 49.59$, $p < .001$] and Direction [$F(1, 11) = 9.81$, $p < .01$]. Additionally, a significant Speed × Direction interaction was found [$F(1, 11) = 9.21$, $p < .01$] (Fig. 3). Post hoc Tukey pair-wise comparisons between the four average RMSEs revealed that all conditions differed significantly from one another ($p < .05$), except for the fast-moving rightward and slow-moving rightward conditions ($p > .05$). Overall, it was found that participants consistently fixated towards the leading edge of the moving targets.

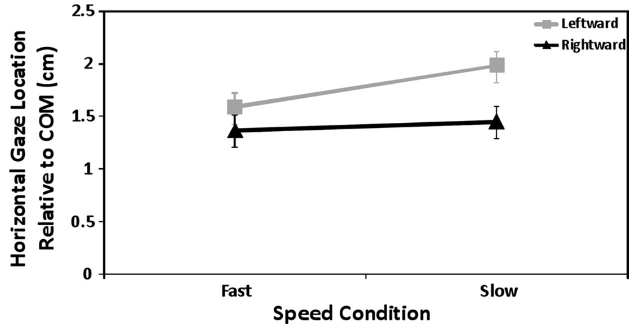

Fig. 3 Root-mean-square error for horizontal gaze locations as a function of speed and direction throughout all four experimental conditions. Centre of mass = COM. *Error bars* represent the standard error of the mean. Positive gaze location values indicate how far participants looked ahead of the target's COM during target motion

Reach and grasping kinematics

We were also interested in examining how the reaching and grasping kinematics might differ between the four target movement conditions. We analysed the MGA, peak wrist velocity, and total reach duration. For MGA, a significant main effect for Speed was found [$F(1, 11) = 6.74$, $p < .05$], but no significance was found for main effect of Direction [$F(1, 11) = 0.72$, $p = .42$], nor was there a significant interaction for Speed × Direction [$F(1, 11) = 2.30$, $p = .16$]. Collapsing across Direction, it was found that participants had an average MGA of 5.27 cm (SE = 0.1) when grasping fast-moving target blocks and an average MGA of 5.17 cm (SE = 0.1) when grasping slow-moving target blocks.

The analysis of peak wrist velocity showed a significant main effect for Speed [$F(1, 11) = 8.66$, $p < .05$] and Direction [$F(1, 11) = 14.19$, $p < .01$], as well as a significant Speed × Direction interaction [$F(1, 11) = 10.61$, $p < .01$]. Post hoc Tukey pair-wise comparisons between the peak wrist velocity averages for the four conditions revealed that all conditions differed significantly from one another ($p < .05$), except for the fast-moving rightward and slow-moving rightward conditions ($p > .05$). The average peak wrist velocities for each of the experimental conditions are shown in Table 2. Overall, it was found that participants moved faster for the leftward-moving targets than for the rightward-moving targets.

The analysis of total reach duration showed a significant main effect for Direction [$F(1, 11) = 6.13$, $p < .05$], but no significance was found for main effect of Speed [$F(1, 11) = 0.73$, $p = .41$], nor was there a significant interaction for Speed × Direction [$F(1, 11) = 3.66$, $p = .08$]. Collapsing across Speed, it was found that participants reached more quickly towards leftward-moving targets ($M = 528$ ms, SE = 33) compared to rightward-moving targets ($M = 552$ ms, SE = 32).

Table 2 Mean peak wrist velocity (cm/s) for each experimental trial condition

Condition	Mean
Fast-left	34.5 (3.8)
Slow-left	28.9 (2.5)
Fast-right	24.9 (1.5)
Slow-right	25.4 (1.6)

Standard errors of the means are in parentheses

Summary

To bring together all of these findings and better illustrate what occurred in a typical trial, Fig. 4 presents the key frames (i.e. the four fixation locations of interest) of an animation of a randomly selected typical slow-moving trial. The animations were created using a custom data analysis program made in the Perception and Action Laboratory at the University of Manitoba using MATLAB® (R2011a, The MathWorks Inc., Natick, Massachusetts, USA). The program used the collected eye and hand data to construct an animation of each trial, showing where participants' gaze, index finger, and thumb were relative to the target block at any point during the trial. In the illustrated slow-moving target trial, the participant first fixated ahead of the leading edge of the target block (Fig. 4a). Once the target began moving, the participant adjusted his or her gaze to fixate towards the leading edge of the target (Fig. 4b) and fixated there quite consistently according to the RMSE analysis. Upon hearing the tone and initiating movement of his or her hand, the participant fixated towards the top edge of the target block, closer to the COM (Fig. 4c). Finally, the participant looked towards the top edge of the target, near the contact point of the index finger (Fig. 4d).

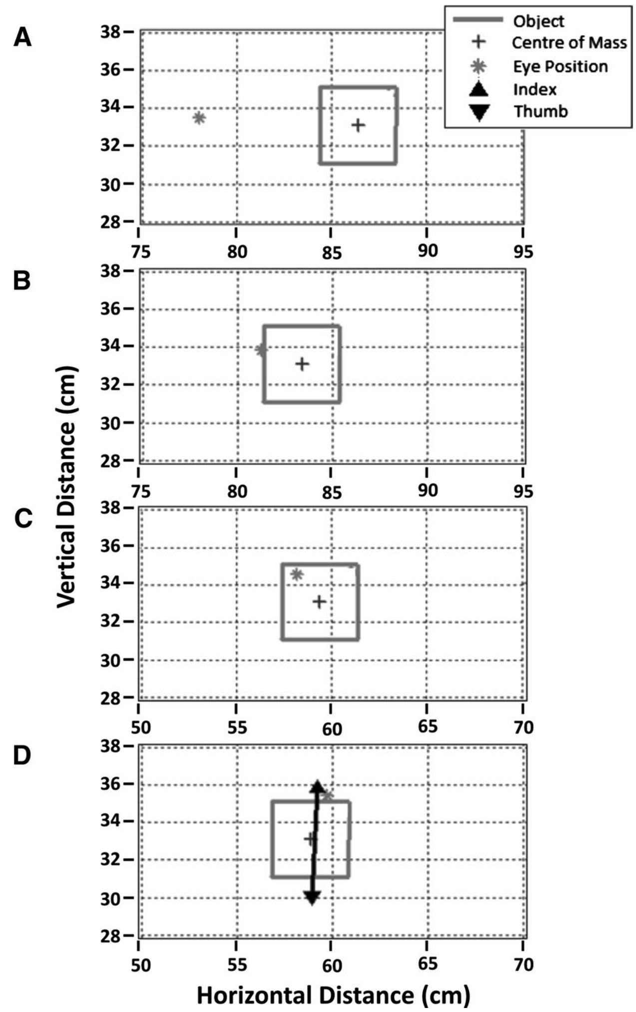

Fig. 4 Snapshots from an animation of a typical slow leftward-moving trial showing adjustments in gaze position from the time the target block appeared on the screen (**a**), to when the target started to move (**b**), to when the reach was initiated and (**c**), to the when the target was grasped (**d**). Axes are labelled in world coordinates

Discussion

The goal of the present study was to gain new insight into how vision is used to guide hand movements when reaching to grasp moving targets. To accomplish this, we examined how people use vision to guide their grasping of slow- and fast-moving computer-generated blocks travelling horizontally across a monitor. It was hypothesized that for both slow- and fast-moving targets, participants would initially fixate their gaze above the COM, towards the top edge, favouring the eventual index finger contact point. Alternatively, participants may have anticipated the movement of the targets and initially fixated what would be the leading edge of the moving target—the edge facing the middle of the monitor.

Surprisingly, participants anticipated the movement of the target even more than expected by fixating an average of 7.1 cm ahead of the target block's leading edge (9.1 cm ahead of the block's COM). By initially fixating "ahead" of the target block, rather than on it, participants would reduce the likelihood of expending the cognitive effort to "catch-up" to a target that has already started moving (Daye et al. 2014; De Brouwer et al. 2002; Schütz and Souto 2011). Anticipatory look-ahead fixations have been described in previous research as reflecting early planning that provides behavioural advantages for later movements (Mennie et al. 2007).

The analysis of fixation locations at specific time points of interest combined with the RMSE tracking error analysis suggests that participants consistently tracked the leading edge of the moving targets, regardless of target speed.

However, it was found that participants preferred to look further ahead of the target block's leading edge when the direction of motion was leftward, particularly for the slow-moving target. This may be the result of mechanical constraints involved when intercepting leftward-moving objects with one's right hand (Brenner and Smeets 2007). Since all participants used their right hand, it was necessary to reach across their bodies to grasp a target approaching the left edge of the screen, while they could simply move their arm forward to grasp an object approaching the right edge of the screen. Thus, a position further ahead of the leftward-moving target may have been selected to accommodate for this mechanical requirement. This possibility is further supported by the finding that participants moved faster to reach leftward-moving targets compared to those moving rightward.

One reason why slow- and fast-moving target blocks may have produced such similar patterns of behaviour is that the fast condition may not have been "fast enough" to require different gaze behaviour. In studies examining eye movements only, targets have to be moving at speeds greater than 30 deg/s to warrant such movements (De Brouwer et al. 2002; Rashbass 1961). However, because this study sought to examine gaze strategies for grasping moving target blocks, it was necessary to provide participants with sufficient time to reach and grasp the targets, while they were still visible and within reach on the screen. Additionally, if the movement of the target was too fast, participants' reaching movements would likely have become more ballistic and interceptive, changing the nature of the type of action being studied (i.e. a precision grasp). Thus, the arm length of participants, as well as the size of the monitor, limited the speed at which the moving targets could be presented. Even though fast- and slow-moving targets produced similar gaze patterns, it should be noted that there was a small but significant effect of target speed on MGA. Participants tended to open their hand a little wider when grasping the fast-moving targets—a possible reflection of stimulus uncertainty (Schlicht and Schrater 2007).

When the tone sounded and participants initiated their reach towards the target blocks, they fixated towards the top edge of the block, above the COM, under both slow and fast conditions. Furthermore, it was shown that participants fixated towards the eventual index finger contact point when they grasped the target under all of the experimental conditions. The fact that fixations upon reach initiation were closer to the eventual index finger contact point than fixations prior to the tone suggests that participants tended to make online adjustments during the trajectory of their grasp such that their gaze closely monitored the eventual index finger contact point on the target. By the time participants completed their grasp, their fixations fell even closer to where their index finger had landed, further suggesting that previous research findings regarding stationary objects may generalize to moving objects, particularly that gaze functions to guide the index finger for the specific needs of a task (Brouwer et al. 2009; Desanghere and Marotta 2008, 2011; Johansson et al. 2001; Prime and Marotta 2013). Overall, it can be concluded that participants typically began looking towards their intended grasp site (where the index finger would make contact) when initiating their reach. Additionally, participants fixated their gaze towards the eventual index finger grasp site rather than the thumb's, consistent with previous research (Brouwer et al. 2009; De Grave et al. 2008; Desanghere and Marotta 2008, 2011; Johansson et al. 2001; Prime and Marotta 2013).

Of course, when conducting a grasping study with 2D targets, one does have to be concerned whether these findings will generalize to the 3D objects we interact with in our everyday lives. With 2D targets, the visual system is missing depth information about the object's structure provided when viewing 3D objects, and the motor system is missing the haptic feedback that would come from actually picking up the object. Furthermore, there have been several studies that have demonstrated that 3D grasping and 2D pantomimed grasping differ in both kinematics and their neural underpinnings (e.g. Goodale et al. 1994; Króliczak et al. 2007; Vingerhoets 2014). To address some of these concerns, the target blocks were programmed to stop moving just as participants' fingers made contact with the screen. In addition, the fact that on average, participants grasped the target 0.46 cm left of its horizontal COM demonstrates that they were grasping close to the midline of the target block, which is considered a stable grasp. A stable grasp is important when grasping real 3D objects, since an unstable grasp could result in the object slipping out of the person's hand. In contrast, grasping computer-generated targets with an unstable grasp does not have any negative consequences; the target will stop its movement when the hand contacts the screen regardless of the stability of the grasp. However, the fact that participants grasped close to the midline of the target blocks in the current study suggests that they were making stable grasps, treating the computer-generated target targets as if they were "real", despite not being instructed about where to grasp on the target (Desanghere and Marotta 2008, 2011; Richtsfeld and Vincze 2011). Other studies have also shown support for the use of 2D objects in grasping studies. For instance, after comparing grasping of symmetrical 3D and 2D objects, Kwok and Braddick (2003) suggested that the underlying processes driving perception of both stimuli are the same in both grasping and perceptual size-estimation tasks. Another study by Westwood et al. (2002) found similar results and suggested that the visual control of grasping does not require haptic or depth information. The gaze and grasping behaviours made towards the 2D target blocks used in the present study are comparable to much of the previous work in our laboratory utilizing 3D objects (Desanghere and Marotta 2008, 2011; Prime and Marotta 2013).

Conclusion

This study has provided a novel exploration of eye–hand coordination when grasping moving computer-generated targets. When grasping stationary objects, participants typically direct their gaze towards the top edge of the object, above the object's COM, and near the index finger contact point on the object. The findings from the present study show that participants first fixate the leading edge of moving target blocks until they initiate their reach, at which point they also fixate closer to the index finger contact point, towards the top edge of the target block. Grasping studies incorporating complexity, such as object movement, are essential to gaining greater insight into how people interact with the world around them, and the pursuit of a more detailed model of visually guided grasping.

Eye–hand coordination plays a crucial role in our everyday lives. Therefore, an understanding of the fundamental processes involved has widespread implications. Additionally, an improved understanding of eye–hand coordination when interacting with moving objects may lead to new training strategies for various sports, as well as the development of new free-moving robotics and control systems in dangerous or menial work environments.

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Compliance with ethical standards

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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