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Experimental Brain Research

ISSN 0014-4819
Volume 238
Number 6

Exp Brain Res (2020) 238:1433-1440
DOI 10.1007/s00221-020-05826-7

Springer

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Experimental Brain Research (2020) 238:1433–1440
https://doi.org/10.1007/s00221-020-05826-7

RESEARCH ARTICLE

Eye–hand coordination in reaching and grasping vertically moving targets

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Received: 16 February 2020 / Accepted: 28 April 2020 / Published online: 7 May 2020
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Abstract
Previous investigations have uncovered a strong visual bias toward the index finger when reaching and grasping stationary or horizontally moving targets. The present research sought to explore whether the index finger or thumb would serve as a significant focus for gaze in tasks involving vertically translating targets. Participants executed right-handed reach-to-grasp movements towards upward or downward moving 2-D targets on a computer screen. When the target first appeared, participants made anticipatory fixations in the direction of the eventual movement path (i.e. well above upwardly moving targets or well below downwardly moving targets) and upon movement onset, fixations shifted toward the leading edge of the target. For upward moving targets, fixations remained toward the leading edge upon reach onset, whereas for downward moving targets, fixations shifted toward the centre of the target. The same central fixation location was observed at the time of grasp for all targets. Furthermore, for downwardly moving targets, the placement of the thumb appears to have influenced fixation location in conjunction with, not replacement of, the influence of the index finger. These findings are indicative of the increasingly relevant role of the thumb in mediating reaching and grasping downwardly moving targets.

Keywords Eye–hand coordination · Reaching · Grasping · Vertical · Thumb

Introduction

Imagine picking up a cup of coffee or picking a piece of lint off your sweater. In both of these scenarios, to achieve the goal, one must visually scan the environment, fixate on the object of interest, and use the visual information present to direct the reaching and grasping movement. Where gaze fixations are directed on the object is specific to the particular task at hand. When looking at simple target shapes as a whole for example, fixations land near the target's centre of mass (COM), whereas during a manipulation task, gaze is directed toward locations that appear critical for the control of the task (Johansson et al. 2001). The object's physical characteristics, as well as its potential for movement or manipulation, will influence the eye–hand coordination strategies used when reaching toward and making contact with it (Milner and Goodale 2008; Voudouris et al. 2010; Brogaard 2011; Desanghere and Marotta 2011; Polanen and Davare 2015; Marotta and Graham 2016). It is not surprising, then, that the seemingly simple act of reaching to grasp a target object actually involves a number of complex and precise visuomotor processes.

Humans are particularly skilled in carrying out precise movements. In the case of picking lint off your sweater, the index finger and the thumb act in conjunction to execute the grasp; however, there has been differing evidence as to the specific role of either digit when performing such a task. When reaching for a 3-D object, a strong bias of gaze fixations toward the eventual index finger landing point on the target object has been demonstrated (Johansson et al. 2001; Brouwer et al. 2009; Desanghere and Marotta 2011; Cavina-Pratesi and Hesse 2013; Prime and Marotta 2013; Marotta and Graham 2016) likely in anticipation of the approaching

Communicated by Melvyn A. Goodale.

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digit's contact point on the object (Voudouris et al. 2016). The same result has been observed when 2-D targets are used (Bulloch et al. 2015; Langridge and Marotta 2017). Furthermore, in such grasping tasks, it has been shown that the index finger follows a more variable trajectory as it approaches the object or target, whereas the thumb takes a more stable and direct path toward the object or target, acting as a guide and support for the grasp rather than a focus of gaze (Galea et al. 2001; Brouwer et al. 2009; Melmoth and Grant 2012). However, some contrary evidence has suggested fixation biases toward the contact point of the thumb, rather than that of the index finger. For instance, Volcic and Domini (2016) showed that the thumb invited more on-line visual control than the index finger for both the movement toward a target object as well as manipulation of the grasp position on the target. Cavina-Pratesi and Hesse (2013) suggested the thumb might actually project a more variable trajectory toward an object in reach-to-grasp movements in comparison to the index finger, in situations where the hand is directed toward the body. Rather than one of these conflicting findings being the only strategy for gaze fixations in any given context, it may be that the differences in gaze fixations are driven by the particular task at hand.

Typically, eye–hand coordination studies have relied on simple paradigms incorporating solitary stationary target objects. However, as modern applications such as virtual gaming and robotics become increasingly prevalent, the exploration of more dynamic visual scenes may parallel more closely to natural conditions. Thus, extending this research to incorporate different kinds of motion may provide a better understanding of the roles of the index finger and the thumb for gaze and grasp strategies. In this study, we were interested in seeing whether the gaze and grasp strategy principles for horizontally moving targets extend to vertically moving targets, or whether they differed depending on the demands of the task. When grasping a falling target, for example, the thumb's eventual contact position on the target may become more of a focus for gaze than the eventual index finger's position, because an inaccurate thumb position would be more costly.

When tracking a 2-D target's horizontal motion, our previous research has shown that participants first fixate ahead of the target in anticipation of its movement (Bulloch et al. 2015) and subsequently move their gaze towards the leading edge of the target during its movement. When a target is moving downwards, its leading edge (i.e., the bottom edge of the target) may be of more importance, as it is the edge that would make first contact with the ground if not successfully caught. Therefore, we hypothesized that the contact point of the thumb would be more influential than that of the index finger when directing fixations toward a downward moving target. We predicted, in this case, that an anticipatory fixation would be made well below the target, prior to its movement, followed by a shift in fixation toward the eventual thumb contact along the bottom edge of the target upon reach initiation. For upward moving targets, we predict that an anticipatory fixation would be made well above the target prior to its movement, followed by a shift in fixation toward the eventual index finger contact point along the top edge of the target upon reach initiation.

Methods

Participants

Fifteen undergraduate psychology students (9 female) between the ages of 18 and 35 years ($M = 20.6$, $SD = 5.2$) were recruited through the University of Manitoba Department of Psychology Undergraduate Participant Pool and received course credit for their participation. Participants had normal or corrected-to-normal vision and were right-hand dominant, as confirmed by an adapted version of the Edinburgh Handedness Inventory (Oldfield 1971). Participants provided informed consent prior to participation. Research procedures were approved by the University of Manitoba Psychology/Sociology Research Ethics Board (P/SREB).

Stimuli and materials

A Dell U2414H 24-in. computer monitor rotated to a vertical orientation was used for the presentation of stimuli. Participants were seated 48.5 cm in front of the monitor in a height-adjustable chair with their head stabilized in a chin-rest mounted to the tabletop, so that they would face the centre of the screen. Six infrared light-emitting diodes (IREDs) were attached to each participant's right hand; 2 IREDs each on the proximal cuticle of the index finger and thumb, and 2 IREDs on distal radial portion of the wrist. The use of 2 IREDS per digit and wrist compensates for any missing data from one of the IREDs. Data for reach and grasp movements were recorded using an Optotrak Certus 3-D recording system (Northern Digital, Inc., Waterloo, ON, Canada) at a sampling frequency of 100 Hz. Binocular eye movements were recorded using an EyeLink II head-mounted eye tracking system (SR Research Ltd., Mississauga, ON, Canada) at a sampling frequency of 250 Hz. Three additional IREDs were placed on the Eyelink II headset to account for any incidental head movement. All head, eye, and hand data were integrated into a common frame of reference using MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL, USA).

The Eyelink II system registered participants' gaze coordinates using a nine-point calibration/validation procedure, conducted at the beginning of the experiment. To determine

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whether the calibration/validation was completed successfully, participants performed an accuracy check which consisted of fixating on a grey dot on the computer screen for 10 s. Three accuracy checks were conducted prior to every block of trials. To ensure that accuracy was maintained throughout the full vertical range of the computer screen, the first fixation dot was presented at the centre of the screen, followed by fixation dots presented 10 cm above, and finally 10 cm below the central position. Gaze displacement errors that exceeded 1 cm in either the horizontal or vertical axis resulted in a recalibration/validation of the Eyelink.

A white 2-D 4 × 4 cm square generated by the MotionMonitor was used as the target and was presented against a black background. The target was aligned with the horizontal midline of the screen and travelled along the vertical axis. Participants were instructed to reach and grasp for the target upon hearing a 500 ms auditory tone (370 Hz) generated by the MotionMonitor.

Procedure

Prior to initiating the reaching and grasping task, participants placed their right hand in the 'start position'. This entailed pinching the index finger and the thumb around a small circular notch on the tabletop, aligned with the mid-sagittal plane of the participant, 28 cm in front of the computer monitor. Participants were allowed to view the screen freely for the duration of the experiment, but were encouraged to keep their chin in the chin rest to avoid excessive head movement. Each experimental trial started with the target appearing at either the top (8.5 cm below the top edge) or bottom (8.5 cm above the bottom edge) of the computer screen. The target remained stationary for 1.5 s before translating vertically to the opposite end of the screen at a constant velocity of 6.5 cm/s. Participants were instructed to reach and grasp for the target utilizing a precision grasp at the onset of the auditory tone with a quick and natural motion, as if they were grasping an actual 3-D object, and were allowed to make contact with the computer screen when executing their grasp. No further instructions were given.

In each trial, the auditory tone was presented at one of three points during the target's travel; experimental trials included those in which the tone was presented after the target had travelled 13 cm, 2 s after the onset of target motion, so that grasps would be directed toward the centre of the screen. Distractor trials included those in which the tone was presented after the target had travelled either 4 cm (0.6 s) or 22 cm (3.4 s) after the onset of target motion, respectively, so that grasps would be directed toward locations above or below the centre of the screen. Distractor trials were included so that participants would be required to grasp the target at several on-screen locations throughout the experiment, rather than reach toward the same central location for each trial. Target motion and data collection ceased with the execution of the grasp, formulaically defined by the Motion Monitor as the point at which the IREDs on the index finger reached within 1.5 cm of the computer screen. Following the execution of a grasp, participants would reset their hand back to the start position and await the next trial. The experimental task consisted of three blocks of 20 trials. Each block of trials included 12 experimental trials, six each of downward and upward motion, as well as 8 distractor trials, for a total of 36 experimental trials and 24 distractor trials throughout the entire experiment. Trials were pseudorandomized, such that each participant was presented with the same order of randomized trials. Sessions for each participant were completed within 1.5 h.

Excluded data

Experimental trials were excluded from analysis for one or more of the following reasons: if the experimenter observed that the participant did not execute the task correctly (e.g. initiated reach prior to presentation of the reach tone, or directed gaze to an off-screen location), or when data were lost due to equipment or presentation software errors. In total, 11% of all experimental trials were excluded from analysis.

Gaze accuracy

Binocular gaze accuracy was tested at three on-screen locations prior to each block of experimental trials. The average gaze displacement error collapsed across target dot location and combined across all participants and was − 0.13 cm (SE = 0.03 cm) in the horizontal axis and − 0.13 cm (SE = 0.02 cm) in the vertical axis.

Data analysis

A within-subject repeated measures design was used, with all participants being exposed to the same randomized presentation of upward and downward moving targets. Raw horizontal and vertical gaze positions were recorded for the duration of the trial and were characterized into fixations using custom algorithms developed using MATLAB (R2008a, The MathWorks Inc., Natick, Massachusetts, USA) based on a dispersion-threshold identification (I-DT) algorithm (Salvucci Goldberg 2000). Gaze was classified as a stable fixation when positioned within a maximum dispersion threshold of 1 cm for a minimum duration of 100 ms. Data analysis was conducted using SPSS.

Separate two-way 2 × 4 repeated measures ANOVAs (direction of target movement x time point) were used to analyse the vertical and horizontal distances between

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participants' fixations and the target's COM at the following four time points: (1) the first fixation made toward the target following its appearance on the screen, (2) the first fixation made after the onset of target movement, (3) reach onset (RO): the point at which the participant's wrist reached an initial speed of 5 cm/s, and (4) the final fixation made when participants 'grasped' the target. Partial Eta squared (η^2) was used to determine effect size for the ANOVAs. Additionally, eight one-sample *t* tests were used to determine if the locations participants fixated at each time point were significantly vertically displaced from the target's centre in upward and downward conditions. Cohen's D (*d*) was used to determine effect size for the *t* tests. In the case of a violation to sphericity, a Greenhouse–Geisser correction was applied to correct the degrees of freedom. All analyses were conducted using alpha = 0.05. Pairwise comparisons were carried out using Bonferroni correction to analyse all significant interactions.

Results

Vertical fixations

The two-way repeated measures ANOVA revealed a significant interaction between direction and time [$F(3, 42) = 21.193$, $p < 0.001$, $\eta^2 = 0.602$], and the associated Bonferroni adjusted post hoc comparisons indicated several significant comparisons.

Comparisons between upward and downward moving targets

Participants' on-screen fixations followed a similar pattern in relation to the target's centre when tracking both downward and upward moving targets, resulting in fixations positioned at significantly different on-screen positions when the target was moving downward compared to when moving upward at the first three time points of interest (target appearance, onset of target movement, and at the onset of the reaching movement). As can be seen in Fig. 1, anticipatory initial fixations were directed well above upward moving targets, and well below downward moving targets, in expectation of the target's eventual movement. Vertical fixations at this time point were significantly different between upward and downward moving targets ($p < 0.001$). Once the target began moving, fixations shifted toward the leading edges of both upward and downward moving targets, and the fixation positions at this time point were also significantly different ($p = 0.009$). When initiating the reaching movement, average fixations were directed towards the top edge of the upward moving target, and just below the centre of the downward moving target, another significant difference ($p < 0.001$). Final fixations were positioned slightly above the target's centre when grasping both upward and downward moving targets. These fixation positions were not significantly different between upward and downward moving targets ($p = 0.591$), suggesting fixations at the time of the grasp did not differ as a result of the direction the target was moving.

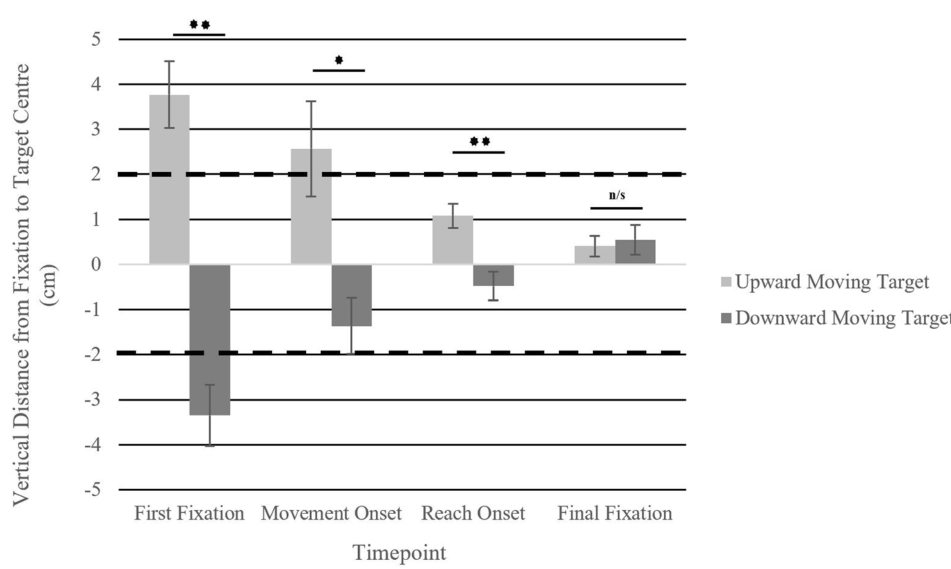

Fig. 1 Average vertical gaze position at the four time points of interest: first fixation made toward the target, onset of target movement, onset of reaching movement, final fixation at the time of the grasp. Positive and negative values refer to distances above and below the target's centre respectively. Dashed lines refer to the upper (+ 2 cm) and lower (− 2 cm) edges of the target. *Error bars* represent standard error of the mean. *$p < 0.01$, **$p < 0.001$

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Comparisons between each time point: downward moving targets

The average fixations made at each time point during the visual pursuit and grasping of the downward moving target are presented in Fig. 2a. Following the appearance of a downward moving target, initial fixations were significantly lower than fixations occurring at movement onset ($p=0.003$), reach onset ($p<0.001$), and final fixations made at the time of grasp ($p<0.001$). Fixations made once the target began moving downward were significantly higher than the initial fixation, and significantly lower than the final fixation ($p=0.035$) but did not significantly differ from fixations made at reach onset ($p=0.801$). In addition to being significantly higher than the initial fixation, fixations made at reach onset were significantly below those made at the time of the grasp ($p<0.001$).

Comparisons between each time point: upward moving targets

The average fixations made at each time point during the visual pursuit and grasping of the upward moving target are presented in Fig. 2b. Initial fixations associated with the appearance of an upward moving target were significantly higher than fixations occurring at reach onset ($p=0.008$) and at the time of the grasp ($p=0.003$), but not at the onset of target movement ($p=0.247$). Fixations made once the target began moving upward were also not significantly different from fixations made at reach onset ($p=0.868$) or at the time of grasp ($p=0.371$). In addition to being significantly lower than the initial fixation, fixations made at reach onset were significantly higher than final fixations ($p=0.037$).

Horizontal fixations

As seen in Fig. 2, fixations were positioned within 1 cm to the left of the target's horizontal midline at each time point for both downward and upward moving targets. The two-way repeated measures ANOVA showed no significant effects indicating that participants fixated towards the same horizontal location regardless of the vertical direction of target movement [$F(1,14)=0.114$, $p=0.740$, $\eta^2=0.008$] or timepoint [$F(1.328,\ 18.596)=1.475$, $p=0.248$, $\eta^2=0.095$]. The interaction between direction and time point was also not significant [$F(1.391,\ 19.478)=0.597$, $p=0.510$, $\eta^2=0.040$].

Vertical distances between fixations and target centre of mass (COM)

As seen in Fig. 2, participants' first fixations were significantly different from the target's centre in both upward [$t(14)=5.082$, $p<0.001$, $d=1.312$] and downward [$t(14)=-4.931$, $p<0.001$, $d=1.273$] conditions. Fixations at the onset of target movement were again significantly different from the target's centre in both upward [$t(14)=2.429$, $p=0.029$, $d=0.627$] and downward [$t(14)=-2.187$, $p=0.046$, $d=0.565$] conditions. At reach onset, fixations were positioned significantly above the centre of upward moving targets [$t(14)=3.985$, $p=0.001$, $d=1.029$] but were not significantly displaced from the downward moving target's centre [$t(14)=-1.535$, $p=0.147$, $d=0.396$]. Final fixations did not significantly deviate from the target's centre in either upward [$t(14)=1.732$, $p=0.105$, $d=0.447$] or downward [$t(14)=1.672$, $p=0.117$, $d=0.432$] conditions.

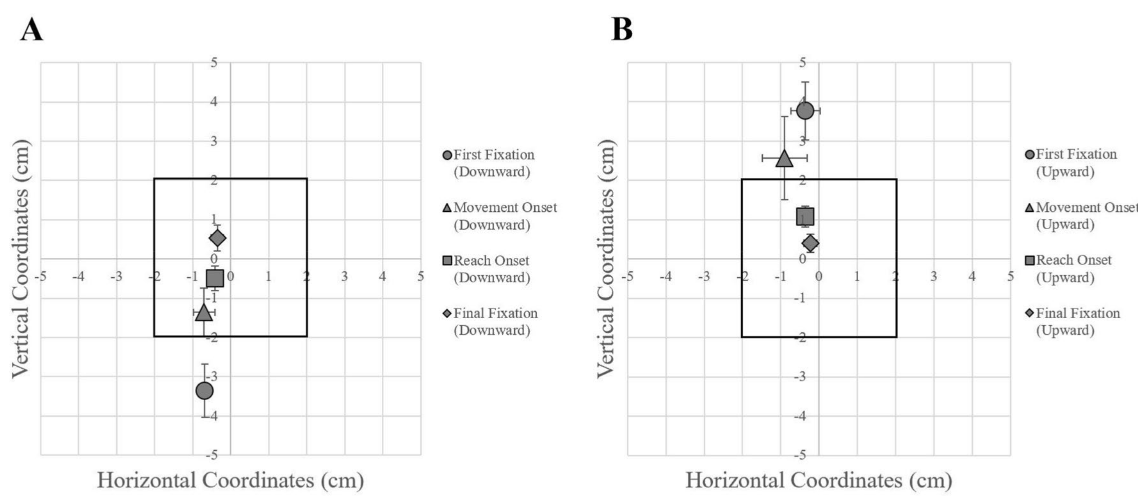

Fig. 2 Average fixations positions when grasping downward (**a**) and upward (**b**) moving targets at each time point: first fixation made toward the target, onset of target movement, onset of reaching movement, final fixation at the time of the grasp. *Error bars* represent standard error of the mean

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Discussion

The goal of the present study was to examine the gaze and grasp strategies utilized during reach-to-grasp movements toward vertically moving targets. We introduced a novel paradigm that incorporated 2-D computer-generated targets moving upward or downward to analyse how vision is used to support the action of a reaching and grasping movement. Our results show that anticipatory eye movements are made toward the target at the onset of target appearance and target movement. However, while fixations are predominantly directed toward the point of index finger contact when initiating the reaching movement toward upward moving targets, fixations are directed lower on the target and closer toward the target's centre when reaching toward downward moving targets.

First fixation and movement onset

When the target first appeared on the screen, participants made anticipatory fixations ahead of the leading edge of the target in both the upward moving and downward moving conditions: above the target for the upward moving condition and below the target for the downward moving condition. When the target started to move, fixations shifted toward the leading edge of the target in both upward and downward moving conditions. This is consistent with what we have previously observed in horizontally moving targets: the edge at the forefront of target movement is given greater visual focus when the target initially appears and begins moving, suggesting that participants were correctly judging the target's anticipated direction of travel, and allowing them to accurately track the target during movement (Bulloch et al. 2015; Langridge and Marotta 2017). Anticipating the eventual movement of a target by fixating toward its leading edge prior to and during movement likely prevents the eyes from needing to catch up to the target once it begins moving and limits the number of saccadic eye movements (i.e., catch-up saccades; De Brouwer et al. 2002) that would be required to ensure the target remains in view during travel.

Reach onset

When the target was moving upward, fixations at the onset of the reaching movement continued to be directed toward the upper half of the target, toward the target's leading edge. On the other hand, when the target was moving downward, fixations were directed toward the centre of the target, just slightly below the horizontal midline. The nature of this gaze strategy is consistent with the literature showing that the potential point of contact on a target at the time of grasp contact also serves as the site for visual focus to accurately prepare a motor plan (Johansson et al. 2001; Desanghere and Marotta 2011; Prime and Marotta 2013; Bulloch et al. 2015; Marotta and Graham 2016; Voudouris et al. 2016; Langridge and Marotta 2017). When reaching to grasp stationary or horizontally moving targets, it has been shown on numerous occasions that the index finger landing point is an important focus for gaze when preparing to grasp (Brouwer et al. 2009; Desanghere and Marotta 2011; Cavina-Pratesi and Hesse 2013; Prime and Marotta 2013; Bulloch et al. 2015; Marotta and Graham 2016; Voudouris et al. 2016; Langridge and Marotta 2017). This principle seems to extend to reach-to-grasp targets moving vertically in an upward direction. In conditions where the target is moving upward, the index finger landing point coincides with the target's leading edge. Therefore, participants can monitor the target's movement and guide the index finger by fixating on the same location toward the top of the target (i.e., its leading edge). In conditions where the target is moving downward, however, the thumb is the digit that will make contact with the target's leading edge and, therefore, also must be considered when guiding digit placement. Fixating on a more central location allows participants to simultaneously keep the index finger and the thumb contact points in view as the hand approaches the target and they prepare for the grasp (Johansson et al. 2001; Desanghere and Marotta 2011).

Final fixation

Participants fixated on the same central location on the target in both the upward and downward moving conditions at the final time point. These results support previous studies suggesting that focusing on a target's COM allows for both the index finger and the thumb to be monitored simultaneously (Johansson et al. 2001; Brouwer et al. 2009; Desanghere and Marotta 2011).

Leftward bias for fixation and gaze

It was observed that participants tended to look to the left of the target's centre throughout the duration of the experiment in both upward and downward moving target conditions. One explanation for this leftward bias may be because all participants grasped the target with their right hand, and fixations may have been shifted toward the left side of the target, as visual feedback of this region would be not be obstructed by the grasping hand. Another possibility that may explain this bias is a concept known as pseudoneglect, or the 'left-from-centre bias' exhibited by healthy individuals (Bowers and Heilman 1980). While no significant differences in the horizontal fixation positions were found in this experiment, this leftward bias appeared more prominent during first fixation and movement onset,

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where participants were tasked with monitoring the target's position, and fixations were directed closer toward the horizontal midline of the target at the onset of the reach and at the time of the grasp. The action of reaching and grasping the target at these later time points may have minimized participants' perceptual bias away from the midline. When performing line bisection tasks, it has been shown that participants are more accurate to identify the centre of a target when performing an action on it as compared to a perceptual marking task, while also maintaining a left-from-centre gaze (Jewell and McCourt 2000; Massen et al. 2014). Pseudoneglect could be a possible explanation for these observations; however, further experimentation would be required to come to this conclusion.

Conclusion

We report in this study that even in conditions where the thumb would be expected to become a more important factor for gaze (i.e., when grasping a downward moving target), the placement of the index finger still influences the locations participants fixate when grasping the target. However, the direction the target was moving did influence the locations at which participants fixated during visual pursuit of the target, and at the initiation of the reaching movement. When initiating a reaching movement toward a downward moving target, the need to monitor the eventual contact point of the thumb does not entirely replace the need to monitor placement of the index finger. Rather, there becomes a need to monitor both the index and thumb contact points simultaneously, which results in more centrally located fixations. At the time of grasp contact, fixations are directed toward similar central positions regardless of the direction of target motion. These results suggest that the previously pronounced role of the index finger as a visual focus for grasp is mediated by the increasingly relevant role of the thumb when grasping downward moving targets.

Acknowledgements This research was supported by the Natural Science and Engineering Research Council of Canada (NSERC) with an Undergraduate Student Research Award (MRT) and a Discovery grant (JJM).

Compliance with ethical standards

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

Ethical standards 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. **Raw data are available at** https://doi.org/10.5203/FK2/XHCNXE.

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