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RESEARCH ARTICLE

Grasping occluded targets: investigating the influence of target visibility, allocentric cue presence, and direction of motion on gaze and grasp accuracy

Ryan W. Langridge[1] · **Jonathan J. Marotta**[1]

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Abstract Participants executed right-handed reach-to-grasp movements toward horizontally translating targets. Visual feedback of the target when reaching, as well as the presence of additional cues placed above and below the target's path, was manipulated. Comparison of average fixations at reach onset and at the time of the grasp suggested that participants accurately extrapolated the occluded target's motion prior to reach onset, but not after the reach had been initiated, resulting in inaccurate grasp placements. Final gaze and grasp positions were more accurate when reaching for leftward moving targets, suggesting individuals use different grasp strategies when reaching for targets traveling away from the reaching hand. Additional cue presence appeared to impair participants' ability to extrapolate the disappeared target's motion, and caused grasps for occluded targets to be less accurate. Novel information is provided about the eye-hand strategies used when reaching for moving targets in unpredictable visual conditions.

Keywords Eye-hand coordination · Motion extrapolation · Fixation locations · Reaching · Grasping · Visuomotor control

✉ Ryan W. Langridge
ryanw.langridge@gmail.com

Jonathan J. Marotta
Jonathan.Marotta@umanitoba.ca

[1] Perception and Action Lab, Department of Psychology, University of Manitoba, Winnipeg, MB R3T-2N2, Canada

Introduction

Imagine throwing a Frisbee back and forth with a friend. It is your turn to catch, however, as the Frisbee is thrown a gust of wind re-directs it toward the space immediately next to you. Your ability to successfully reach out and catch the Frisbee as it moves past you relies on your ability to make spatiotemporal judgments about its future location based on the currently available visual information, such as the current speed and the direction in which it is traveling (Soechting and Flanders 2008). Although we may not consciously calculate the time it will take the Frisbee to arrive, or the distance and direction in which to place our outstretched hand when catching it, these unconscious processes are carried out every time we execute a visually guided motor movement. For example, establishing an accurate representation of an object's location in space involves the processing of egocentric visual information (i.e., visual cues indicating the distance from the observer to that target object), and allocentric visual information (i.e., visual cues indicating the distance between the target object as well as any surrounding sources of visual information). By integrating visual information in each of these reference frames, the distance and direction in which to direct a reach toward a desired object is specified (Neely et al. 2008a, b). During the reaching motion, unconscious judgments regarding object size, shape, and orientation are made to ensure the hand is positioned in such a way that ensures a stable grasp, and prevents the digits from colliding with any parts of the object (Verheij et al. 2014).

Compared to the grasping of stationary objects, the additional spatiotemporal qualities of a moving object increase the complexity of coordinating an accurate reach, as now judgments about the object's speed and direction of travel must be made. However, we are usually still able to

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extrapolate the object's motion efficiently enough to intercept it. Previous work in our lab has demonstrated that when reaching for a horizontally moving target, anticipatory fixations are made ahead of the target in the expected direction of travel, prior to the onset of target movement. This anticipatory gaze strategy is likely employed in attempts to avoid the need for the eyes to 'catch-up' to the target once in motion (Bulloch et al. 2015). During pursuit, participants focus their gaze toward the leading edge of the target. At the initiation of the reach, fixations are made toward the top of the target, slightly to the left of the top edge's horizontal center regardless of direction of travel, and remain at this position at the time of grasp. In agreement with recent visually guided grasping research regarding stationary objects, these fixations tend to be congruent with the eventual point the index finger makes contact with the target (Bulloch et al. 2015; Brouwer et al. 2009; Cavina-Pratesi and Hesse 2013; Desanghere and Marotta 2011; Voudouris et al. 2016).

When vision of the target is uninterrupted, on-line manual adjustments can be made during the reaching motion to correct for any inaccuracy related to target movement (Lee et al. 1997; Teixeira et al. 2006). The eye and hand movements during these adjustments are both spatially and temporally coordinated in such a way that allow for an accurate grasp to be executed (for a review of these coordinated adjustments see Bekkering and Sailer 2002). In cases where vision of the moving object is interrupted however, the execution of any required on-line adjustments becomes more difficult. To return to the previous example, imagine playing catch with a friend. This time however, the Frisbee is thrown in front of the sun, or behind the leaves of a tree, and visual feedback of the Frisbee is removed. When trying to decide where to direct your reach, previous visual information provided when the Frisbee was visible must be used to make a judgment about its future location. A large amount of research has been focused on how we are able to extrapolate the motion of an invisible stimulus (Ashida 2004; Makin and Chauhan 2014; Makin and Poliakoff 2011; see Bosco et al. 2015 for a review). During the transient disappearance of a moving target, eye velocity has been shown to decrease significantly (Bennett and Barnes 2003; Churchland et al. 2003), followed by a recovery to previous levels if an expected point of reappearance is evident (Bennett and Barnes 2003, 2004). Several studies investigating the nature of target disappearance have demonstrated improved pursuit of an invisible target when occlusion is implied visually, i.e., when the target disappears—and potentially reappears from—behind an occluding object, whether the occluding object is visible (Churchland et al. 2003) or invisible (Scholl and Pylyshyn 1999). These findings have led to the suggestion of a spatial continuity mechanism, which allows for a more accurate representation of the disappeared target compared to when disappearance occurs by other, less realistic means, such as simply 'blinking' out of existence (Erlikhman and Caplovitz 2016; Scholl and Pylyshyn 1999).

Although a considerable amount of previous work has focused on the types of eye movements used during the transient disappearance of a target, little research has focused on investigating the visual pursuit and grasp strategies used when grasping for an invisible target in motion during the execution of a 'natural' reach-to-grasp task. When visual feedback of a moving target is removed, additional visual information provided by the surrounding environment may provide a benefit when making judgments regarding the target's location. For example, under incomplete or unpredictable visual conditions, additional sources of allocentric visual information, such as visual features of the environment, become relied on more heavily during goal-directed reaching tasks (Camors et al. 2015; Fiehler et al. 2014; Klinghammer et al. 2016; Neely et al. 2008a, b). The aim of the current study was to investigate the visual pursuit and grasp strategies used when reaching for horizontally translating targets that became occluded during travel.

Based on previous research exploring the eye movements used to track a target's position during transient disappearance, we expect saccadic eye movements to be used when extrapolating the invisible target's motion (Bennett and Barnes 2003, 2004; Churchland et al. 2003) and when grasping the target, final horizontal and vertical gaze positions will correspond with the location of final index placement (Bulloch et al. 2015). In particular, we hypothesize that gaze accuracy along the horizontal axis will be associated with grasp accuracy (i.e., the horizontal distance between participants' gaze and the target's center will correspond with the distance between the target's center of mass (COM) and participants' final index finger placement when grasping). Furthermore, the influence of additional allocentric information on gaze and grasp accuracy will be investigated by manipulating the presence of on-screen visual cues when grasping for both visible and disappeared targets. Although it is predicted that grasps for occluded targets will be less accurate in comparison to when the target is visible, previous research demonstrating the beneficial influence of allocentric information on spatial awareness would suggest that in the presence of additional allocentric cues, participants will be better able to extrapolate the occluded target's motion. We therefore predict that when executing a reach-to-grasp movement toward an occluded target in motion, average gaze at the initiation of the reaching movement, as well as at the time of grasp, will be more accurate in the presence of cues, and this improved gaze accuracy will be associated with an improvement in grasp accuracy.

Methods

Participants

Eighteen undergraduate psychology students (15 female) between the ages of 18 and 33 years ($M = 20$, SD = 3.54) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and received course credit toward their Introductory Psychology course. All participants had normal or corrected to normal vision, and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield 1971). Prior to participation, all participants provided informed consent. All procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Stimuli and materials

The target was a white horizontally translating 2-D computer-generated block (4 × 4 cm) presented on a black background on a Dell U2414H 24-in. computer monitor. Participants were seated in a height-adjustable chair, 55 cm away from the computer monitor, with their head stabilized in a chin rest mounted to the tabletop, which positioned their eye level to the center of the screen. Reaching and grasping movements were recorded using an Optotrak Certus 3-D motion tracking system (Northern Digital Inc., Waterloo, ON, Canada) sampled at 100 Hz. Six infrared light-emitting diodes (IREDs) were attached to each participant's right hand and wrist (2 IREDs each placed on the left side of the cuticle of the index finger, the right side of the cuticle of the thumb, and on the radial portion of the wrist). An Eyelink II head-mounted eye tracking system (SR Research Ltd., Mississauga, ON, Canada) sampled at 250 Hz was used to record binocular eye movements. Three additional IREDS were placed on the Eyelink II headset to account for any incidental head movement. Eye, head, and hand data were integrated into a common spatial and temporal frame of reference using MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA). The MotionMonitor software was also used to generate the on-screen stimuli, and calculate the distances from participants' gaze and final finger position relative to the target's COM for every trial.

Prior to data collection, both eyes were calibrated using a nine-point calibration/validation procedure presented on the computer monitor. To ensure accurate calibration, accuracy checks were conducted immediately following the calibration/validation process, and prior to each block of experimental trials. An accuracy check involved participants fixating on a centrally located dot for 8 s. The presence of a gaze displacement error exceeding 0.5 cm at any point during the session resulted in the recalibration/validation of the Eyelink II system.

Participants were instructed to execute reach-to-grasp movements toward the target once presented with a 8-kHz auditory tone, which was generated by custom software developed using MATLAB (R2008a, The MathWorks Inc., Natick, MA, USA). The software used to generate the tone was run on an Inspiron 545 Dell computer (Duo Core 3.16 GHz).

Procedure

Participants began each trial with their right hand in the 'start position' on the tabletop, centered 40 cm in front of the monitor and aligned with the mid-sagittal plane of the participant. Participants were allowed to freely view the monitor prior to, and for the duration of the trial. A standard trial began with the presentation of the target on either the far left or far right edge of the screen. The target remained stationary for 1.5 s and then began to translate horizontally toward the opposite side of the screen, at a constant speed of 6.5 cm/s (7.43°/s). Participants were instructed to initiate their reaching motion at the onset of an auditory tone (1500 ms in duration), presented 4 s after onset of target motion. This ensured that reaches were mechanically consistent, and directed toward locations within 8 cm to the left or right of the screen's center (i.e., all grasps included in the analysis—whether for left- or rightward moving targets were made within a centrally located space of 16 cm). Each block of trials was randomly interspersed with four distractor trials, during which the target moved at an accelerated speed of 13 cm/s (14.89°/s), and presentation of the auditory tone occurred 2 s after onset of target movement, resulting in reaches toward non-central screen locations.

Half of the experimental trials involved the occlusion of the target during travel. Two seconds following onset of target movement, the target encountered an invisible square object, and disappeared behind it in such a way that all visual feedback of the target was removed within 600 ms following initial encounter with the occluder's edge. The target traveled 13.0 cm before encountering the occluding object in both left and rightward moving trials.

The presence of additional allocentric information—in the form of 1.5 cm wide by 8-cm-long vertical blue blocks dispersed in 1.5 cm increments along the top and bottom of the screen—was manipulated in both visual feedback and occlusion trials. The target traveled within a vertical 14-cm space between the cues, with a distance of 5 cm separating the target from the cues positioned above and below.

Participants were not given any instructions regarding where or how to grasp the target in either visible or occluded target conditions, other than to make a 'quick but natural' reach-to-grasp motion once presented with the tone, as if they were grasping a 3-D object. In trials involving occlusion, participants were instructed to grasp for the disappeared target at its perceived location. In order to make the task as natural as possible, the target (when visible) was programed to stop moving once the IRED positioned on the participant's index finger reached within 2 cm from the screen. However, participants were allowed to execute the grasp fully, and make contact with the screen during the grasping motion. Following the execution of the grasp, participants returned their hand to the 'start position' and awaited the next trial or accuracy check to begin.

Each block of trials began with an accuracy check to ensure accurate calibration of the Eyelink, followed by 16 experimental and 4 distractor trials, presented in a randomized order. A single block included two leftward and two rightward moving trials belonging to each of the four experimental conditions: (1) no occlusion: additional cues absent, (2) no occlusion: additional cues present, (3) occlusion: additional cues absent, and (4) occlusion: additional cues present. A typical session involved three blocks of trials, resulting in a total of six leftward and six rightward moving trials per participant for each experimental condition. An entire session involved three blocks of trials, the result of which was a total of three accuracy checks, 48 experimental trials, and 12 distractor trials by the end of the experiment. Each session took no longer than 1.5 h to complete.

Data analyses

A within-subject repeated measures design was utilized, such that all participants were exposed to experimental trials belonging to each of the four experimental conditions. Horizontal and vertical gaze positions were recorded for the duration of the trial and raw eye positions were characterized into fixations based on a dispersion-threshold identification algorithm (see Salvucci and Goldberg 2000), with a minimum duration threshold of 100 ms and a maximum dispersion threshold of 1 cm. Horizontal and vertical gaze positions relative to the target's COM were examined at both reach onset: the point in time the participant's wrist reached a speed of 5 cm/s, and at the time of grasp: the point at which the participant's index finger reached within 2 cm of the screen, at which point the target (when visible) stopped moving, and data collection ended. Final horizontal and vertical index positions in relation to the target's COM were examined at the time of grasp. As such, two separate four-way 2 × 2 × 2 × 2 repeated measures ANOVAs (visual feedback of the target × cue presence × direction of target movement × time) were carried out to analyze gaze position, and two separate three-way 2 × 2 × 2 repeated measures ANOVA (visual feedback of the target × cue presence × direction) were utilized to analyze final grasp position. A two-way 2 × 2 repeated measures ANOVA (direction × cue presence) was conducted to analyze fixation durations upon target occlusion. Additionally, a three-way 2 × 2 × 2 repeated measures ANOVA (visual feedback of the target × cue presence × direction) was conducted on the average wrist deceleration period (WDP), characterized as the duration of time between the point at which peak wrist velocity was achieved during the reach and time of grasp. A total of 32 post hoc pairwise comparisons were carried out using a Bonferroni correction to analyze all significant interactions. In order to test the association between horizontal gaze and grasp accuracy when grasping invisible targets, a bivariate Pearson product-moment correlation analysis was conducted between the average final horizontal index finger displacement and average final horizontal fixation displacement within each condition involving occluded targets. All analyses were conducted using alpha = 0.05.

Results

Excluded data

Experimental data were excluded from analysis if the participant executed the task incorrectly (i.e., initiated the reach prior to tone presentation) or when data were lost due to equipment failure. In total, 7.5% of all experimental trials were excluded from final analysis.

Grasp accuracy

Horizontal index position

When grasping for visible targets, average index position at Time of Grasp was consistently positioned to the left (behind the COM of rightward moving targets and ahead of the COM of leftward moving targets) and within 1 cm of the target's horizontal center. Grasps for occluded targets were associated with average horizontal index placements consistently behind the target's COM. Average index positions when grasping for occluded targets were always placed farther than 2 cm behind the invisible target's COM along the horizontal axis, resulting in grasps that missed the target entirely. An overall significant main effect of Direction was revealed [$F(1,17) = 26.27$, $p \leq 0.001$], and average index placement was significantly more accurate when grasping leftward moving targets ($M = 1.27$ cm behind the target's COM, SE = 0.29) than rightward moving targets ($M = 2.54$ cm behind the target's COM, SE = 0.40).

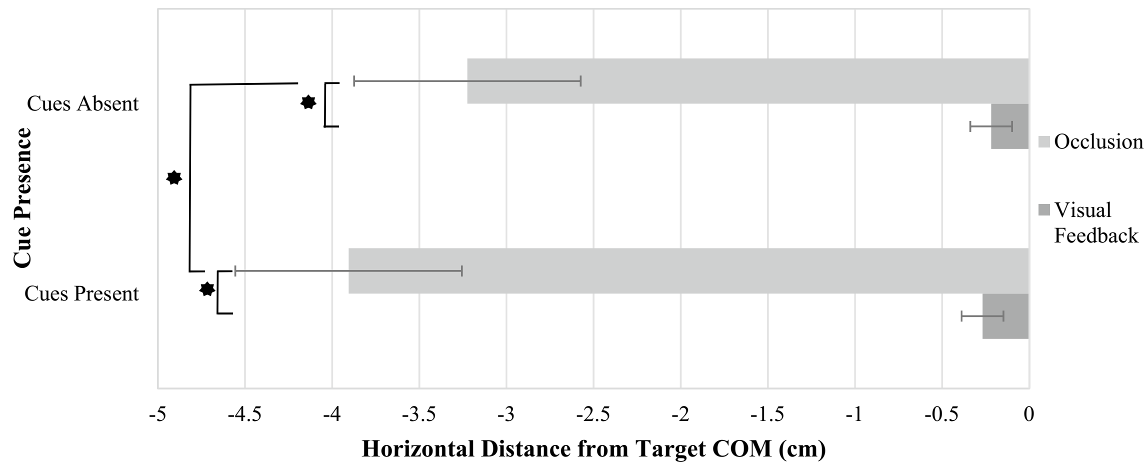

Fig. 1 Average horizontal distance from final index placement to target COM collapsing across direction. *Negative values* refer to distance behind target COM. *Error bars* represent standard error of the mean

A visual feedback of target × cue presence interaction was found to be significant [$F(1,17) = 6.98$, $p = 0.017$] and is shown in Fig. 1. Collapsing across direction, final horizontal index finger placement was significantly more accurate when visual feedback of the target was provided compared to when occluded in both the presence ($p < 0.001$) and absence ($p < 0.001$) of cues. However, when grasping for occluded targets, index placement was significantly ($p = 0.005$) closer to the target's COM in the absence of cues compared to when the cues were present. Cue Presence had no significant influence on final horizontal index position when grasping for visible targets.

Vertical index position

A significant main effect of visual feedback of target [$F(1,17) = 7.72$, $p = 0.013$] was revealed, suggesting that on average, participants placed their index finger significantly higher on the target, and closer to the top edge when grasping visible targets ($M = 1.4$ cm above the target's COM, SE = 0.09) compared to when grasping occluded targets ($M = 1.25$ cm above the target's COM, SE = 0.1). Cue presence and direction of target movement had no significant influence on final vertical index placement.

Overall gaze analysis

Mean absolute gaze displacement error combined across all participants was 0.38 cm in the horizontal axis, and 0.59 cm in the vertical axis. The average gaze displacement error across participants was 0.09 cm to the right (SE = 0.05) and 0.25 cm above (SE = 0.07) in the horizontal and vertical axes, respectively.

Figure 2 represents the typical visual pursuit strategies used during a trial involving continuous visual feedback of target (Fig. 2a), and a trial involving occlusion of the target during travel (Fig. 2b). Participants utilized smooth pursuit eye movements to pursue the target when visible, and saccadic eye movements were used to extrapolate the motion of the target once visual feedback of the target was removed by occlusion.

Fixations at target occlusion

Once the target encountered the occluding object, participants abandoned the use of smooth pursuit eye movements and maintained an initial fixation focused on the front edge of the occluding object (i.e., the edge behind which the target was disappearing), presumably in attempts to maintain sight of the target for as long as they could before it disappeared completely. The average fixation at this time lasted for 447.00 ms (SE = 11.47). A two-way 2 × 2 repeated measures ANOVA (direction × cue presence) indicated no significant differences in fixation duration across both levels of direction or cue presence.

Horizontal gaze position

A significant main effect of direction [$F(1,17) = 12.40$, $p = 0.003$] indicated that average fixations were made closer to the target's COM during leftward moving trials ($M = 0.5$ cm behind the target's COM, SE = 0.29) than rightward moving trials ($M = 1.29$ cm behind the target's COM, SE = 0.35). The four-way repeated measures ANOVA also revealed a significant three-way visual feedback of target × cue presence × time interaction [$F(1,17) = 4.36$, $p = 0.05$] shown in Fig. 3 and post hoc analysis revealed several significant mean-wise comparisons. Collapsing across direction, mean horizontal

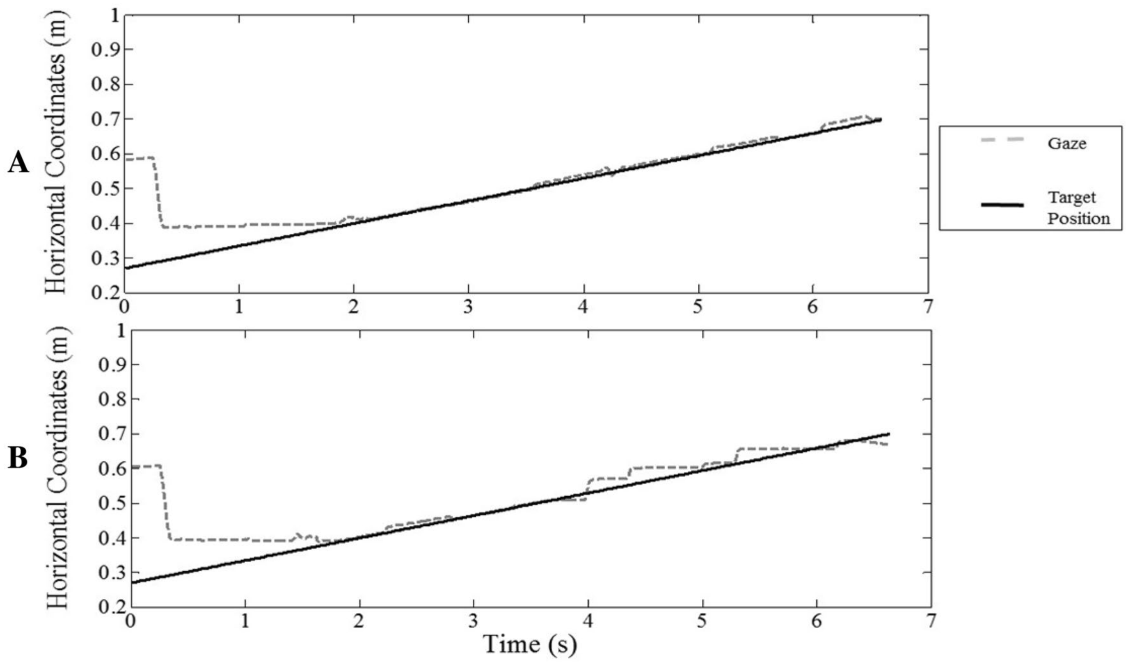

Fig. 2 Example of a rightward moving trial involving continuous visual feedback of target (**a**) and occlusion (**b**). *Vertical axis* refers to horizontal position, and therefore increasing values indicate movement in the *rightward* direction. Occlusion begins at 3.7 s, and 'reach tone' presentation occurs at 5.5 s

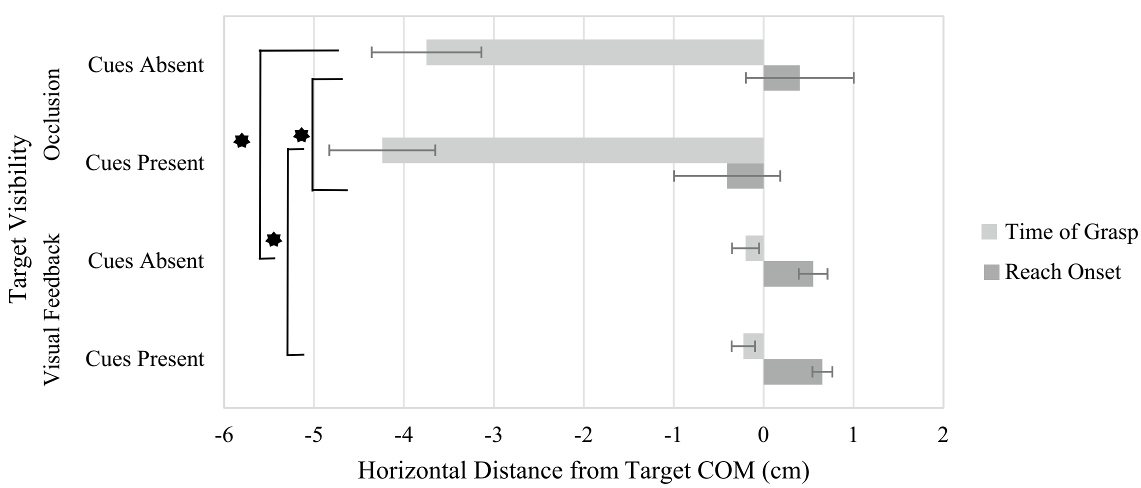

Fig. 3 Average horizontal distance from fixation to target COM collapsing across direction. Negative values refer to distance behind target COM. *Error bars* represent standard error of the mean

fixations at time of grasp when visual feedback of the target was available were made closer to the target's COM than those made when the target was occluded in both the presence ($p < 0.001$) and absence ($p < 0.001$) of cues. Visual Feedback of the Target did not significantly influence the horizontal distance from fixation location to target COM at reach onset. However, when initiating reaches for occluded targets, fixations were made on average 0.4 cm (SE = 0.59) behind the target's COM in the presence of cues, and 0.4 cm (SE = 0.60) ahead of the target's COM in the absence of cues. This difference was significant ($p = 0.003$). Cue Presence had no influence on horizontal gaze position at reach onset or time of grasp when reaching for visible targets.

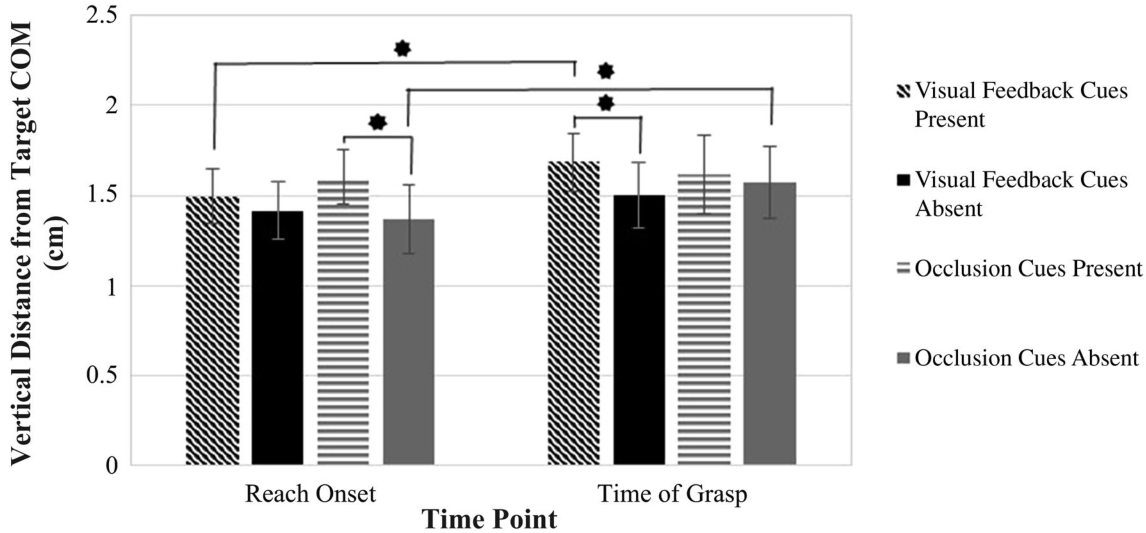

Fig. 4 Average vertical distance from fixation to target COM collapsing across direction. *Error bars* represent the standard error of the mean

Vertical gaze position

A three-way visual feedback of target × cue presence × time interaction (Fig. 4) was found to be significant [$F(1,17) = 6.29$, $p = 0.023$]. Post hoc analyses revealed that when collapsing across direction, mean vertical fixations made at reach onset when reaching for occluded targets were made significantly higher on the target when the cues were present compared to when absent ($p = 0.023$), though there was no significant difference at time of grasp. When grasping visible targets, mean vertical fixations made at time of grasp were significantly higher in the presence of cues compared to the absence of cues ($p = 0.009$), though there was no significant difference at reach onset. When reaching for occluded targets in the absence of cues, mean vertical fixations were made significantly higher ($p = 0.017$) on the target at time of grasp than at reach onset, though there was no significant difference between reach onset and time of grasp when the cues were present. When reaching for visible targets in the presence of cues, average vertical fixations were made significantly higher on the target at time of grasp in comparison to reach onset ($p = 0.019$), though this difference was not significant in the absence of cues.

Association between final horizontal index finger and fixation displacement when grasping occluded targets

Horizontal gaze displacement was compared with horizontal index finger displacement within each condition (i.e., grasping for left- and rightward moving occluded targets in both the presence and absence of additional on-screen cues) to investigate if participants' average horizontal gaze displacement was associated with the horizontal placement of their index finger when grasping occluded targets (Table 1). The average final gaze displacement within each condition was significantly and positively correlated with the average final index finger position within each condition, suggesting that across all conditions involving target occlusion, the farther the horizontal gaze was displaced from the target's COM, the less accurate the final index finger placement would be.

Wrist deceleration period

Overall, the presence of the additional cues was associated with longer WDPs ($M = 427.20$ ms, SE = 24.85 when cues present, and $M = 406.29$ ms, SE = 24.61 when absent) and this was confirmed by a significant main effect of cue presence [$F(1,17) = 6.54$, $p = 0.02$]. The three-way repeated measures ANOVA also revealed a significant visual feedback of target × direction interaction [$F(1,17) = 8.78$, $p = 0.009$]. Post hoc analyses indicated that when reaching for leftward moving targets, mean WDPs were significantly ($p < 0.001$) longer when the target was occluded than when visual feedback of the target was available. Further, when reaching for occluded targets, average WDP was significantly longer when the target was moving leftward than rightward ($p = 0.003$).

Table 1 Bivariate Pearson product-moment correlation analysis of horizontal displacement from occluded target COM

Final horizontal index finger placement	Final horizontal fixation				*M*	SD
	Cues present		Cues absent			
	Leftward	Rightward	Leftward	Rightward		
Cues present						
Leftward	0.933**	0.862**	0.620*	0.820**	−3.30	2.76
Rightward	0.875**	0.932**	0.760**	0.937**	−4.55	2.93
Cues absent						
Leftward	0.864**	0.857**	0.827**	0.851**	−2.59	2.55
Rightward	0.787**	0.794**	0.722*	0.965**	−3.86	3.22
M	−3.79	−4.69	−3.38	−4.12		
SD	2.81	2.50	2.55	2.80		

* Correlation significant at the $p < 0.01$ level

** Correlation significant at the $p < 0.001$ level

Discussion

The goal of this study was to investigate how participants use eye movements to extrapolate the motion of a horizontally translating occluded target during the execution of a reach-to-grasp movement. In addition to comparing grasp accuracy when grasping occluded and visible targets, the horizontal and vertical locations participants fixated when initiating the reaching motion were compared with the fixations made at the time the participant grasped the target.

Grasping visible vs. occluded targets

As has been shown when grasping for stationary 2-D and 3-D objects, as well as translating 2-D targets, when grasping visible targets in the current paradigm, the horizontal position of the index finger landed in close proximity to the target's midline, executing what would be a 'stable' grasp when interacting with real-world objects (Bulloch et al. 2015; Desanghere and Marotta 2011; Endo et al. 2011). On average, participants' grasps missed the target entirely when grasping occluded targets, and index position was consistently positioned behind the target's COM (i.e., to the left of the rightward moving target's trailing edge and to the right of the leftward moving target's trailing edge) when the target was occluded. This was also the case for final average horizontal gaze position, which was located 'on-target' when grasping visible targets—within 0.5 cm from the horizontal position of the target's COM. Congruent with final index position when grasping occluded targets, average final gaze positions were significantly horizontally displaced from the target's COM, resulting in an inaccurate grasp that missed the target entirely. In other words, participants were unable to efficiently extrapolate the motion of the occluded target as efficiently as required to execute an accurately placed grasp, and visual feedback of the moving target was needed for participants to execute a grasp that was positioned 'on-target'. This lack of accuracy was unexpected, as previous research has demonstrated that individuals are able to retain illusory speed information regarding a target's movement with a considerably high degree of accuracy (Battaglini et al. 2013). Although horizontal gaze was significantly displaced from the target at the time of grasp, horizontal gaze at reach onset was consistently positioned within 1 cm of the target's COM, regardless of whether the target was visible at this time or not. In fact, manipulating the visual feedback of the target had no influence on horizontal fixation position at Reach Onset, suggesting that participants were accurately directing their gaze toward the target's horizontal position when they initiated their reach, whether the target was visible at this point in time or not.

In the present study, participants were required to grasp the occluded target at its perceived location. As such, participants' perceptions of target position were inferred by their horizontal fixations during pursuit in addition to final grasp positions. Most research involving the extrapolation of an invisible target relies either on eye movements alone (Makin and Poliakoff 2011; Mrotek and Soechting 2007) or a button-press response, signaling the perceived location at which the participant believes the target to have traveled (Battaglini et al. 2013; Makin and Chauhan 2014; Makin and Poliakoff 2011). The incorporation of an additional goal-directed movement may have contributed to the impaired perceptual and behavioral performance observed when participants were required to extrapolate the motion of the occluded target. When reaching for a moving object, visual feedback provided by the object allows the reaching individual to continuously update their perception of the its position, and this feedback can be used in turn to update the trajectory of the hand during the reaching motion (Lee et al. 1997). When reaching for an invisible target, however, these moment-to-moment updates must be made without visual feedback of the target. Instead, reaches must be directed toward the target's perceived location, which must be updated continuously using only the previously available knowledge about the target's motion, a task which already demands a high degree of attentional resources (Flombaum et al. 2008). Pressing a button is likely less cognitively taxing than executing a reaching movement toward the perceived location of a target, without visual feedback provided by the target itself to help guide the reach. The significant horizontal displacement of final gaze and grasp positions when reaching for occluded targets suggest that participants were unable to accurately update the position of perceived target movement while executing the reach, perhaps due to an increased allocation of attentional resources toward the execution of the reach, when trying to grasp an invisible target.

Influence of direction on grasp strategies

Consistent with previous research conducted by Bulloch et al. (2015), when reaching for visible targets, average index finger placement was consistently positioned to the left of the target's COM in trials involving both leftward and rightward movement (i.e., ahead of the COM of leftward moving targets, and behind the COM of rightward moving targets). Various cases have also observed a leftward bias in regard to spatial attention (Foulsham et al. 2013; Jewell and McCourt 2000); however, it is important to note that in this experiment, as well as in the study by Bulloch et al. (2015), all grasps included in the analysis were directed toward the center of the screen, therefore removing any potential mechanical restrains associated with reaching across the body. Nevertheless, a significant leftward bias was consistently demonstrated, suggesting that specific grasping strategies were being utilized dependent on the direction of target motion. This directional bias may be explained by the following hypothesis: When reaching for a target moving away from the reaching hand (i.e., when grasping for a leftward moving target with one's right hand), participants may utilize what could be considered more of a 'catching', rather than a 'grasping' strategy. Faced with the potential mechanical restraints of reaching toward a location contralateral to the reaching arm (Brenner and Smeets 2007), participants may be directing their grasps further to the left—and therefore further ahead of the target's COM—to allow for any error that may occur during the reaching or grasping motion. When reaching for a target moving toward the grasping hand, there may be a lesser likelihood of error, and as a result, participants tend to grasp the target closer to the trailing edge, in what could be considered a 'riskier' grasp placement. In agreement with this hypothesis is the overall effect of direction found for both horizontal gaze and grasp location, demonstrating that participants were looking and placing their index finger closer to the target's leading edge when grasping leftward moving targets, and closer to the target's trailing edge when grasping rightward moving targets. Although average horizontal gaze and grasp was positioned off-target when grasping occluded targets, grasps for leftward moving targets were inaccurate to a lesser degree, possibly because final index placement was positioned further ahead of the perceived target's center (and therefore closer to the actual target's center) than when grasping rightward moving targets. Interestingly, when reaching for occluded targets, average WDP was longer when reaching for leftward moving targets than rightward moving targets, suggesting the execution of a more 'cautious' grasp. This difference was not observed when reaching for visible targets.

Influence of allocentric cue presence

Previous research would suggest that by increasing the amount of allocentric visual information in the environment, the perceived location of a disappeared target should be more accurate than when this allocentric information is absent (Camors et al. 2015; Fiehler et al. 2014; Klinghammer et al. 2016). This was not the case in the current study, and rather than provide any benefit to gaze or grasp accuracy, grasps for occluded targets in the presence of the additional on-screen cues were positioned significantly farther from the target's COM along the horizontal axis than grasps made when the cues were absent. While grasps in both the presence and absence of cues were made 'off-target', grasps in the absence of cues were inaccurate to a lesser degree.

It has been demonstrated previously that contextual features of a scene, such as background texture, can potentially influence the perceived speed of both visible and occluded targets (Battaglini et al. 2016; Terao et al. 2015). It is possible that as the distance of the invisible target traveled increased, the presence of the on-screen cues resulted in an altered perception of target velocity, which could explain the tendency for participants to direct their grasps to a horizontal location behind that of the target's. This influence is usually observed when judging the motion of a target presented against a background texture moving in the same or opposite direction of the target however (Baker and Graf 2010; Battaglini et al. 2016), whereas all cues presented in the current study remained stationary.

It appears that when reaching for occluded targets, participants interpreted the on-screen cues as 'distractors' or 'obstacles,' rather than 'cues,' and participants unconsciously felt that they needed to monitor the position of the cues in relation to the reaching hand to avoid a collision. By focusing more attention on executing a careful reach, less attention was focused on the successful extrapolation of the target's motion.

Several results from this study support this hypothesis. First, average horizontal gaze position at reach onset indicated that participants were able to accurately judge the target's location up to this point. In this case, the presence of potential obstacles in the environment would likely have a lesser impact on gaze position than grasp position, because there is no potential for the eyes to collide with the obstacle, while the hand could potentially interact with the obstacle during the end stages of the reach. Second, when reaching for targets in the presence of cues, vertical gaze position was drawn higher toward the top edge of the target—and the location of eventual index finger placement—than in the absence of cues. This upward shift of gaze was seen at the time of grasp when grasping visible targets, and at both reach onset and time of grasp when grasping occluded targets. Participants may have been paying more attention to the location of their index finger when grasping in the presence of potential obstacles. When reaching for invisible targets, an increased allocation of attention toward the final index finger position, in addition to the consideration of any potential obstacles would be critical not only at the time of grasp, but at the initiation of reach as well, as the reach is being directed toward a perceived location, without the freedom to make feedback-based adjustments during the reach.

Finally, the presence of the on-screen cues was associated with longer WDPs, suggesting that participants were reaching with more caution and taking more time to slow their reach when the cues were present. These findings are consistent with the idea that participants were more cautious with their grasp placement when the on-screen cues were present, resulting in an additional allocation of attention at the cost of their ability to extrapolate the motion of the target.

2-D vs 3-D grasping

The argument could be made that we do not use the same visuomotor strategies to grasp 2-D targets that we use to grasp 3-D objects, and as a result the observations made in this study may not generalize to interactions with 3-D objects in the real world. It is true that cues providing depth information in regard to an object's structure, and haptic feedback provided when making contact with an object that would normally be present when interacting with 3-D objects are not present when viewing and grasping 2-D targets. In particular, kinematic differences such as slowed reaction time, slower reach velocity, and reduced in-flight and final grip aperture have been demonstrated between grasping 3-D objects and the pantomimed 'grasping' of 2-D objects (Whitwell et al. 2015).

However, Desanghere and Marotta (2011) demonstrated that the gaze and grasp strategies used when perceiving and grasping 2-D targets are similar to those used when interacting with 3-D objects, suggesting similarities in the processes being used. The results of the current study, as well as previous studies conducted in our lab utilizing 2-D targets (Desanghere and Marotta 2011; Bulloch et al. 2015) have demonstrated that people tend to focus their gaze toward the eventual point of index finger contact, and that when the target is visible, precision grasps are executed such that the index and thumb are positioned along the horizontal midline of the target's COM, as has been shown in work involving 3-D objects (Endo et al. 2011). Nevertheless, to address these concerns, the target (when visible) was programed to stop when the participant's fingers reached within 2 cm of the screen. Additionally, participants were allowed to make contact with the screen at the end of the reach, providing terminal feedback, which has been shown to improve grip scaling when pantomiming a grasp (Whitwell et al. 2015). Finally, participants were instructed to grasp for the target 'as if it were a natural 3-D object' at the beginning of each session.

Conclusion

While a great deal of work has involved exploring the gaze and grasp strategies used to grasp stationary objects, research focusing on how we interact with complex and sometimes unreliable aspects of the environment is an important step in understanding how visual information is interpreted to execute goal-directed movement. The results of this study suggest that the visual feedback provided by a moving target has a significant influence on an individual's ability to execute a stable grasp when reaching for that target. Catching an errant Frisbee thrown in front of the sun becomes a more difficult task without visual feedback of the Frisbee helping you direct an accurate reach toward its future location. These results suggest that when provided with only previously available information about the Frisbee's speed and direction of travel, the potential of missing the frisbee altogether becomes more likely.

The present study provides novel information about the gaze and grasp strategies used when grasping horizontally moving targets, and how these strategies are influenced by removing visual feedback of the target. These results suggest that different visual pursuit strategies are used to extrapolate the motion of an occluded target than when the target is visible. While the relationship between gaze and digit placement appears to be the same whether grasping visible or occluded targets (i.e., congruent final horizontal gaze position and index finger placement), an inability to effectively extrapolate the motion of the target when occluded resulted in impaired grasp accuracy. This result may be partially due to the novel design employed by the present study, which added a goal-directed reaching and grasping component to a visually guided motion extrapolation task. Allocation of attentional resources to the execution of a reach-to-grasp movement may interfere with one's ability to extrapolate the motion of a disappeared target, resulting in a misplaced or unstable grasp. Further, direction of target movement appears to influence the location of final gaze position and index finger placement in regard to the horizontal position of the target's COM, suggesting that alternative grasping strategies are used when reaching for targets moving away from the reaching hand. Finally, additional research is required to determine what characterizes a visuospatial 'cue', and how participants interpret visual information in a way that allows the differentiation of a cue from a 'distractor' or 'obstacle' when reaching.

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Compliance with ethical standards

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.

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

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