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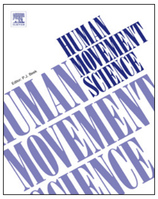

Full Length Article

Grasping a 2D virtual target: The influence of target position and movement on gaze and digit placement

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ABSTRACT

While much has been learned about the visual pursuit and motor strategies used to intercept a moving object, less research has focused on the coordination of gaze and digit placement when grasping moving stimuli. Participants grasped 2D computer generated square targets that either encouraged placement of the index finger and thumb along the horizontal midline (Control targets) or had narrow "notches" in the top and bottom surfaces of the target, intended to discourage digit placement near the midline (Experimental targets). In Experiment 1, targets remained stationary at the left, middle, or right side of the screen. Gaze and digit placement were biased toward the closest side of non-central targets, and toward the midline of center targets. These locations were shifted rightward when grasping Experimental targets, suggesting participants prioritized visibility of the target. In Experiment 2, participants grasped horizontally translating targets at early, middle, or late stages of travel. Average gaze and digit placement were consistently positioned behind the moving target's horizontal midline when grasping. Gaze was directed farther behind the midline of Experimental targets, suggesting the absence of a flat central grasp location pulled participants' gaze toward the trailing edge. Participants placed their digits at positions closer to the horizontal midline of leftward moving targets, suggesting participants were compensating for the added mechanical constraints associated with grasping targets moving in a direction contralateral to the grasping hand. These results suggest participants minimize the effort associated with reaching to non-central targets by grasping the nearest side when the target is stationary, but grasp the trailing side of moving targets, even if this means placing the digits at locations on the far side of the target, potentially limiting visibility of the target.

1. Introduction

When grasping an object, visual information about its shape is used to infer the position of the object's center of mass (COM) and select appropriate contact points for the fingers (Cuijpers, Smeets, & Brenner, 2004; Desanghere & Marotta, 2015; Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Smeets & Brenner, 1999). When using a precision grip, an effective grasp typically involves digit placement on opposite sides of the object, with a grasp axis (an imaginary line connecting the index finger and thumb) bisecting or falling close to the object's COM. Placement of the digits in this manner ensures the force applied by the opposing digits is applied to the object's COM, and limits the amount of torque around the grasp axis, reducing the risk of mishandling the object (Endo, Wing, & Bracewell, 2011; Goodale et al., 1994; Kleinholdermann, Brenner, Franz, & Smeets, 2007; Lederman & Wing, 2003).

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Situational variables such as the reason for grasping the object, or its position in relation to the reaching hand will also influence where the digits are placed. For example, when grasping centrally positioned horizontal rods, participants tend to grasp locations that, while close to the rod's COM, are biased in the direction of the reaching hand (Glowania, van Dam, Brenner, & Plaisier, 2017; Paulun, Kleinholdermann, Gegenfurtner, Smeets, & Brenner, 2014). These biases likely occur in order to limit the amount of the object occluded by the hand, while still minimizing the amount of torque when grasping (Maiello, Paulun, Klein, & Fleming, 2019). In other words, the importance of placing the digits at locations near the object's COM is weighted against the importance of placing the digits at points that did not obstruct the view of the bar, resulting in a grasp axis in close proximity but not exactly aligned with its COM. When the task is made to be more difficult, such as when grasping heavy objects (Glowania et al., 2017; Paulun et al., 2014), objects with low surface friction (Paulun, Gegenfurtner, Goodale, & Fleming, 2016), or when participants are then required to move or balance the object (Paulun et al., 2014; Paulun et al., 2016), the digits are placed closer to the object's COM, suggesting the need for increased stability is associated with digit placement and a grasp axis that correspond more closely to the object's COM.

Grasping behaviour of this nature has been demonstrated primarily by research investigating goal-directed reaching and grasping movements toward stationary objects presented at stable, central locations, usually aligned with the midsagittal plane of the participant (Desanghere & Marotta, 2011, 2015; Endo et al., 2011; Lederman & Wing, 2003; Voudouris, Smeets, & Brenner, 2016). In the real world however, people often reach for objects at non-central locations, and in these cases, digit placement may drift away from the object's COM and toward positions located on the side of the object closest to the approaching hand. These contact points may be considered more ‘convenient’, as less energy is required to transport the hand toward, and place the digits at these locations compared to a more central position aligned with the object's COM. If there is a bias toward the nearest side of the object being grasped, then when grasping a symmetrical object, it is reasonable to assume digit placement will be predicted by the location of the object in relation to the hand used to grasp it. Considering the mechanical constraints associated with reaching toward the contralateral hemispace (e.g., recruitment of additional muscle groups, number of joints and joint amplitudes required for movements crossing the body axis; Happee & Van der Helm, 1995; Kim, Buchanan, & Gabbard, 2011), this bias may be most pronounced when grasping objects located contralateral to the reaching hand (e.g., grasping a leftward positioned object with the right hand), as this type of action inherently requires an increased amount of effort.

While the shape of the object will influence digit placement during goal-directed reach-to-grasp movements, the visual system is not limited by the same constraints as those of the hand. Nevertheless, gaze is typically directed to regions relevant for the execution of a successful grasp, such as the locations the digits make contact with the object (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Johansson, Westling, Bäckström, & Flanagan, 2001), and behaviours such as the guidance of the hand to the target object, grip aperture, and orientation of the grasp are influenced by the visibility of these contact points (Volcic & Domini, 2014; Voudouris, Smeets, & Brenner, 2012). In particular, when using a precision grasp, fixations are typically directed toward the index finger's eventual point of contact, rather than that of the thumb's, both when this contact point is visible (Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2011, 2015), and even when hidden behind the object being grasped (Voudouris et al., 2016). It is therefore reasonable to predict that in scenarios where digit placement is biased toward a particular region of the object as a result of the object properties (e.g., size, shape, distribution of mass), gaze will be directed toward similar positions, and biased toward the index finger's contact point.

1.1. ‘Grasping’ 2D virtual targets

As highlighted above, the shape and size of a 3D object provides information about its COM, and previous research indicates these variables play a significant role in determining how the object is grasped. 2D computer generated stimuli on the other hand, such as those viewed on a computer screen, do not have true physical properties such as a COM. However, these properties may still be implied by the shape and size of the virtual stimuli, which are visually available. When grasping 2D computer generated targets, does digit placement still coincide with the implied COM of the virtual shape, as demonstrated when grasping physical objects?

There are clear, previously established differences in the way people reach toward and grasp 2D stimuli compared to 3D objects (e.g., Whitwell, Ganel, Byrne, & Goodale, 2015; Ozana & Ganel, 2017). In particular, when grasping 2D stimuli, participants' reaction times and reach velocity are slowed, and grip aperture is reduced (however there is evidence to suggest that when real-time vision and terminal haptic feedback are available, grip scaling is preserved; Whitwell et al., 2015). Despite these differences, previous work has demonstrated that when grasping a 2D square target, for which the COM does not technically exist but rather is implied by the shape of the target, participants still place their digits at locations coinciding with the target's center (i.e., contacting the top and bottom edges of the target with the index finger and thumb respectively, at positions close to the target's horizontal midline (Bulloch, Prime, & Marotta, 2015; Langridge & Marotta, 2017). As observed with 3D objects, these studies demonstrated gaze directed towards the top edge of the 2D target at the time of the grasp, corresponding to the index finger's eventual contact point.

While the research exploring gaze and digit placement when grasping 2D square targets have primarily involved grasping horizontally moving targets, reaches to the central region of the screen were the only ones analyzed. Thus, the question remains: How is direction of gaze and digit placement influenced by the direction of a target's movement, especially when this movement transports the target to non-central locations? Previous research of this nature has focused primarily on the interceptive movement itself (e.g., Brenner & Smeets, 2018) and capitalize on the use of ‘pointing’ (Soechting & Flanders, 2008) or ‘hitting’ (Brenner & Smeets, 2011; Brouwer, Brenner, & Smeets, 2002; Fialho & Tresilian, 2017) movements as indicators of accurate interception rather than the placement of the digits when grasping a virtual target presented on a computer screen. The direction of target movement, and the time at which the target is grasped (e.g., while it is approaching the reaching hand, or at later stages of travel when the target is at risk of moving out of one's reach) will potentially influence where the digits are placed in relation to it's center.

When grasping both leftward and rightward moving 2D targets at the center of a screen (i.e., at middle stages of target travel), we have shown that participants tend to direct their gaze, and place their index finger, to the left of the target's horizontal midline, thus placing their digits *ahead* of the leftward moving target's COM and *behind* the rightward moving target's COM (Bulloch et al., 2015; Langridge & Marotta, 2017). This bias may be indicative of a ‘catching’ strategy involving digit placement closer to the leading edge of targets moving away from the reaching hand and into the contralateral hemispace, where the mechanical constraints associated with reaching across the body are increased (Carey, Hargreaves, & Goodale, 1996; Carey & Liddle, 2013).

The goal of the current study was to determine where participants direct their gaze and place their digits when grasping vertically presented 2D targets positioned to the left, right, or aligned with the central starting position of the reaching hand. Participants were presented with either square Control targets that had 4 flat edges, or Experimental targets that had narrow notches in the middle of the top and bottom surfaces of the target. The purpose of these notches was to exaggerate any directional biases in fixation and digit placement away from the target's horizontal midline that may go unnoticed when grasping uniform square targets. It was hypothesized that participants would avoid the notched region in favour of the flat surfaces on either side when grasping the Experimental targets, and that fixations and digit placement would be directed toward more central locations coinciding with the horizontal midline when grasping Control targets.

In Experiment 1, participants were presented with stationary 2D targets presented at the far left, far right, or middle (aligned with the hand's start position) of a computer monitor. When grasping non-central targets, participants were expected to fixate and place their digits at locations shifted toward the target's nearest side at the time of the grasp, as this would require less energy expenditure than grasping the middle or far sides of the target. These biases were expected to be exaggerated when grasping Experimental targets (i.e., participants would avoid the center notch in favour of the flat region closest to the reaching hand when placing their digits). Fixations and digit placement were expected to be located close to, or slightly to the right of the horizontal midline of centrally located targets, as participants were using their right hand (Desanghere & Marotta, 2015; Glowania et al., 2017; Paulun et al., 2014).

Experiment 2 explored how the direction of a horizontally translating target's movement influences how gaze and digit placement is directed when grasping, and how the stage of target travel (early, middle, or late) influences these gaze and grasp strategies. Based on previous research using 2D target movement, it was expected that final gaze and digit placement would favour the trailing edge of rightward moving targets, and the leading edge of leftward moving targets. This bias was expected to be most evident at late stages of a leftward moving target's travel, and it was hypothesized that participants would ‘catch’ the leading side of the target (i.e., place their digits farther ahead of the target's midline) when the risk of missing the target was most prevalent. As in Experiment 1, these directional biases were expected to be exaggerated when grasping the Experimental targets compared to when grasping the Control targets.

2. Experiment 1: Grasping stationary targets

2.1. Methods

2.1.1. Participants

Twenty-three undergraduate psychology students (12 female; age range 17–26 years old; $M = 19.3$ years) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and received course credit toward their Introductory Psychology course in exchange for participation. 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). All procedures were approved by the psychology/sociology research ethics board (P/SREB) at the University of Manitoba.

2.1.2. Stimuli and materials

Participants were seated in a height-adjustable chair, 55 cm away from a Dell U2414H 24″ monitor, with their head stabilized in a chin rest, ensuring their eye-level was aligned with the middle of the screen. Reaching and grasping movements were recorded using an Optotrak Certus (Northern Digital Inc., Waterloo, ON, Canada) sampled at 130 Hz. Six infrared light-emitting diodes (IREDS) were attached to the participants' right hand and wrist (2 IREDs each placed on the proximal edge of cuticle of the index finger, the proximal edge of cuticle of the thumb, and on the distal radius of the wrist). Only one IRED at each position was used to analyze the participants' movement. If there was a significant loss of data using the first IRED at one of these locations (e.g., missing or extreme values due to rotation of the hand), the second IRED would be used for analysis of that participant. An Eyelink II (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's headset to account for any incidental head movement during data collection. MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA) was used to integrate the motion tracking data into a common spatial and temporal frame of reference using a 7 Hz Butterworth filter, and to generate the on-screen stimuli. Both eyes were calibrated using a nine-point calibration/validation procedure. This was followed by an accuracy check that involved fixating on a centrally located dot for 8 s. The presence of an average gaze displacement error exceeding 1 cm would result in the recalibration/validation of the Eyelink II.

The 2D computer generated virtual target stimuli consisted of either a ‘Control’ target, presented as a 4 × 4 cm white square with 4 uniform edges, or an ‘Experimental’ target, which matched the Control target in colour, size and shape, with the exception of a 1 cm notch in the middle of the top and bottom edges, leaving two 1.5 cm wide ‘graspable’ regions on either side (Fig. 1). Targets were presented against a black background.

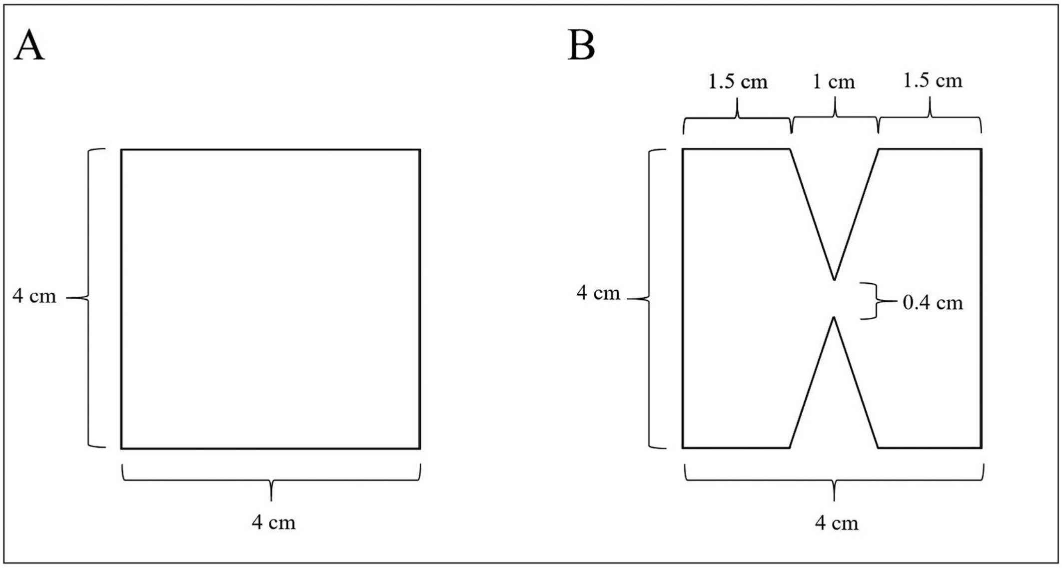

Fig. 1. *Control* (a) and *Experimental* (b) target stimuli. Targets were always presented as white against a black background.

2.1.3. Procedure

Prior to data collection, participants were shown and given the opportunity to hold 3D versions of the 2D target stimuli (height: 4 cm, width: 4 cm, depth: 0.5 cm). Participants began each trial with their right hand placed on the tabletop, 40 cm directly in front of the monitor, along the sagittal plane of the body, with their index finger and thumb pinched together in the 'start position'. No viewing instructions were given, and participants were allowed to freely view the monitor. Each trial was initiated manually by the experimenter and began with either a Control or Experimental target appearing at the center of the screen, or 20 cm to the left or right of center (always at a position 34 cm above the tabletop). The target remained stationary for the duration of the trial. Participants were instructed to execute a natural reach-to-grasp movement with their index finger and thumb once the target appeared on the screen, "as if they were grasping an actual 3D object". Otherwise, no instructions regarding execution of the task were given. Once the IREDs located on the participant's index finger cuticle were within 1.5 cm from the screen, the trial ended and data collection ceased. Participants' fingertips always made contact with the screen. Following execution of the 'grasp', participants returned their hand to the start position and awaited the next trial to begin.

Each block began with an accuracy check to ensure the eye-data being collected was accurate. Each target shape was presented at each of the three locations 4 times (24 trials in total) per block. An entire session involved 3 blocks of trials, resulting in a total of at least 3 accuracy checks, and 72 experimental trials (12 trials belonging to each condition) by the end of the experiment. Each session took no longer than 1.5 h to complete.

2.1.4. Data analysis

This experiment utilized a within-subject repeated measures design, and all participants were exposed to each unique trial type. Raw horizontal and vertical gaze positions were recorded for the duration of each trial, and 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), with a minimum duration threshold of 100 ms and a maximum dispersion threshold of 1 cm. These fixations were then examined relative to the target's center at the time participants made contact with the screen (TOC). The final horizontal and vertical coordinates of the index finger and thumb relative to the target's center were also collected at TOC. As an additional indicator of grasp accuracy, custom programming developed using MATLAB used the final index finger and thumb positions to create an imaginary line connecting the two digits (the grasp axis) and determine the shortest absolute distance between this line and the target's center. This distance has been used previously to indicate grasp stability when grasping 3D objects (Goodale et al., 1994; Marotta, McKeeff, & Behrmann, 2003). In this case, this distance was used as an additional source of information about where participants were placing their index finger and thumb in relation to the target's center.

Trial data within each condition was averaged to create a mean value per condition for each participant, which were used in the following analyses. Five 2 × 3 repeated measures ANOVAs (Shape x Position) were conducted using SPSS (version 23.0) to investigate the final horizontal and vertical index finger positions, both the horizontal and vertical coordinates of the fixations made at TOC, and the distance between the grasp axis and the target's COM. In the case of a violation to sphericity, a Greenhouse-Geiser correction was applied to correct the degrees of freedom. A Bonferroni correction was used to analyze all significant interactions. The Shapiro-Wilk test was used to test the data for normality. All analyses were conducted using alpha = 0.05.

2.1.4.1. Multiway frequency analysis. In addition to analyzing the average gaze and grasp positions, a Multiway Frequency Analysis

(MWF Analysis; Vokey, 2003) was used to determine how often participants fixated and placed their index finger within a particular ‘Grasp Region’ on the target. This method was used because it allows for the analysis of frequency data with more than 2-dimensions without collapsing across independent variables, and therefore prevents any potential misinterpretation of results (Vokey, 1997). Additionally, MWF Analysis allows the use of within-subject designs, and assesses each factor for their respective main and interactive effects in a manner analogous to ANOVA.

Three Grasp Regions of interest were included: 1) The 1 cm space in the center of the target: between 0.5 cm to the left and 0.5 cm to the right of the target's horizontal midline (this region corresponded to the ‘notched’ area of the Experimental targets, 2) The left side of the target: the area to the left of the 1 cm middle region, and 3) The right side of the target: the area to the right of the 1 cm middle region.

The overall frequency all participants fixated and placed their index finger within one of these 3 regions (Count) was recorded and analyzed using R (R Core Team, 2019); version 3.6.1. The following Generalized Log-Linear Model (GLM; Poisson Distribution) was used to fit the data: Frequency ~ Subject*Target Position*Target Shape*Grasp Region. The deviances between the observed frequencies and the expected (no effect) frequencies were analyzed using an ANOVA (Type II Sum of Squares), run in R using the ‘car’ package (Fox & Weisberg, 2019). By using this method and including Frequency as the dependent variable in the model, any observed interactions involving Grasp Region (e.g., Position x Grasp Region or Shape x Grasp Region) represent a main effect (of the variable interacting with Grasp Region) on the relative frequency each region was chosen (Frequency). As such, the influence of each factor, i.e., the target's position and shape, on gaze and grasp position can be determined by comparing the frequency at which participants direct their gaze or place their index finger in a particular region compared to the frequency that would be expected if there were no effect. Due to an unequal number of observations across all participants, and to avoid the associated risk of committing a Type I error, the results of this analysis were interpreted using alpha = 0.01.

2.2. Results and discussion

2.2.1. Excluded data

Experimental data was excluded from analysis if the task was not executed properly during a particular trial or when data were lost due to equipment failure. Any fixations that occurred outside the limits of the computer monitor were not included in the analysis. In total, 5% of all experimental trials were excluded from the final analysis.

2.2.2. Kinematic variables

Participants' average reaction time, average reach duration, average maximum wrist velocity and wrist height are provided in Table 1. These traditional kinematic measures are included here to provide additional information about the way participants reached toward the targets. However, as this data does not present a direct relevance to our present hypotheses, formal analyses were not conducted and are thus provided only for context. All reach data was collected using the IREDs attached the participants' right wrist.

2.2.3. Digit placement

2.2.3.1. Average horizontal index finger placement. The average positions participants fixated and placed their index finger at TOC in all conditions are presented in Fig. 2a. The 2 × 3 repeated measures ANOVA revealed a significant main effect of Position, $F(2,44) = 42.893$, $p < .001$, $\eta_p^2 = 0.672$, confirming the hypothesis that participants would minimize the amount of energy required to transport the hand to the target by grasping non-central targets on the side nearest to the reaching hand. Horizontal index finger placement was aligned with the midline when grasping Center targets ($M = 0.05$ cm to the right of the horizontal midline, SE = 0.14 cm). In comparison, index placement was positioned significantly more rightward when grasping Left targets ($M = 0.71$ [0.13] cm to the right of the target's horizontal midline, $p < .001$), and significantly more leftward when grasping Right targets ($M = 0.41$ [0.13] cm to the left of the horizontal midline, $p < .01$). Horizontal index finger placement when grasping Left and Right targets were significantly different ($p < .001$). Participants likely preferred to grasp the closest side of the target because digit placement on the far side of a non-central target in this task would involve exerting the unnecessary effort required to transport the fingers to a location aligned with, or past the target's midline. Despite this influence of target position however, index finger placement was always positioned relatively close to the target's horizontal midline.

Participants placed their index finger slightly farther rightward when grasping Experimental shapes ($M = 0.26$ cm to the right of

Table 1
Grasping stationary targets: Average reaction time, reach duration, maximum wrist velocity and wrist height.

	Left		Center		Right	
	Experimental	Control	Experimental	Control	Experimental	Control
Average Reaction Time (s)	0.60 (0.05)	0.59 (0.04)	0.56 (0.04)	0.57 (0.04)	0.60 (0.04)	0.58 (0.04)
Average Reach Duration (s)	0.98 (0.04)	0.96 (0.04)	0.83 (0.03)	0.84 (0.03)	0.81 (0.03)	0.80 (0.03)
Average Maximum Wrist Velocity (m/s)	0.91 (0.04)	0.93 (0.05)	0.88 (0.04)	0.88 (0.04)	0.90 (0.04)	0.92 (0.04)
Average Maximum Wrist Height (cm)	27.86 (0.24)	27.80 (0.21)	27.21 (0.25)	27.27 (0.24)	27.27 (0.27)	27.08 (0.26)

Note. Standard errors of the means presented in parentheses.

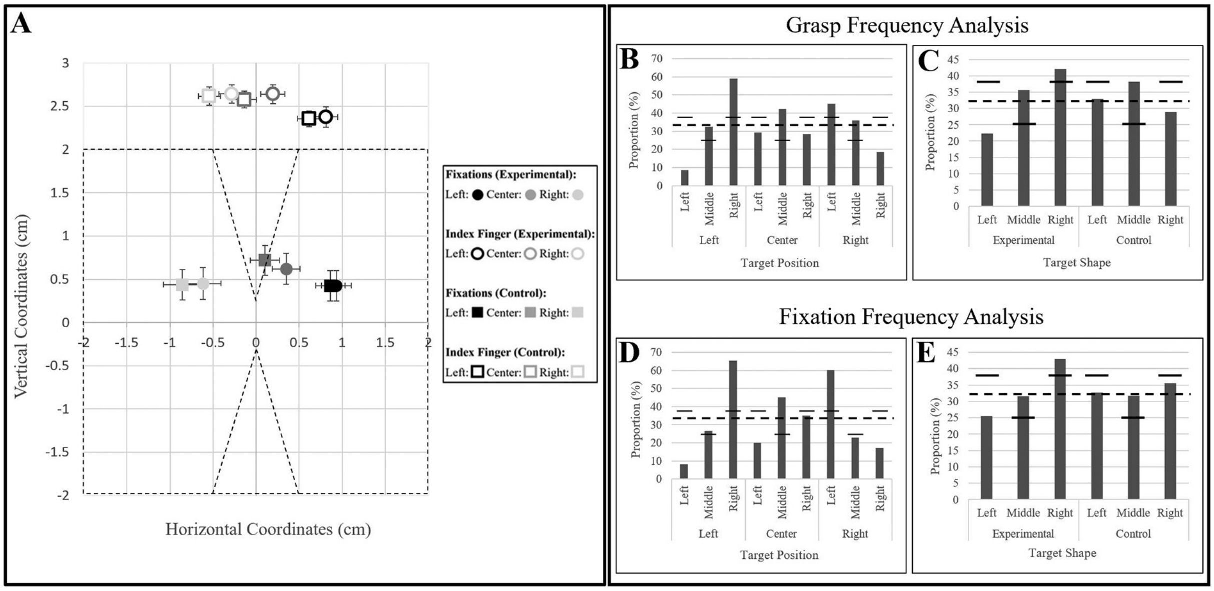

Fig. 2. Average fixation positions and index finger placement (a) and frequency analysis (b-e) at TOC. In the panel on the left (a), negative values in the horizontal and vertical axes refer to distance to the left and below the target's center respectively, and *Error bars* represent standard error of the means. Dashed lines represent the border of either *Control* or *Experimental* targets. In the panels on the right (b-e), the dashed line represents the expected frequency values if all observations were distributed evenly (no effect) within each condition, and the solid lines represent this expected frequency accounting for the horizontal size of each region. Index finger placement frequency is presented collapsed across target shape (b) and target position (c). Final fixation frequency is presented collapsed across target shape (d) and target position (e).

the horizontal midline, SE = 0.12 cm) in comparison to Control shapes ($M = 0.02$ [0.12] cm to the left of the horizontal midline), as indicated by a significant main effect of Shape, $F(1,22) = 19.310$, $p < .001$, $\eta_p^2 = 0.464$. This was surprising, as it was expected that when grasping the Experimental targets with notches on the top and bottom edges of the target, digit placement would shift away from the midline in the direction of the approaching hand. While this was the case when grasping Left and Center targets, the opposite was true for Right targets, and participants still placed their digits at more rightward positions when grasping the Experimental targets. It is possible that because all participants used their right hand, grasping a more pronounced leftward position, as would be expected of participants were solely minimizing effort, would obstruct a larger portion of the target from view (Maiello et al., 2019; Paulun et al., 2014). As a result, participants shifted their digit placement rightward when grasping Experimental targets, even when positioned on the Right side of the screen.

2.2.3.2. Grasp region frequency analysis: Horizontal index finger placement. When considering the frequencies at which participants placed their index finger on the Left, Middle, and Right side of the target, both Position x Grasp Region, $\chi^2(4) = 457.76$, $p < .001$, and Shape x Grasp Region, $\chi^2(2) = 84.46$, $p < .001$, interactions were significant. As can be seen in Fig. 2b, a higher proportion of grasps occurred on the right side of the target when it was positioned on the Left side of the screen, while a higher proportion of grasps occurred in the middle of targets located in the Center of the screen, and a higher proportion of grasps occurred on the left side of targets presented on the right side of the screen. As shown in Fig. 2c, index finger placement was positioned most frequently on the right side when grasping Experimental targets, while grasp frequency was distributed more evenly when grasping Control targets. As expected, the regions participants most frequently placed their index finger coincided with the biased direction of average horizontal index finger placement.

2.2.3.3. Distance from the grasp axis to the target's COM. As suggested by horizontal index finger placement, a significant main effect of Position, $F(2,44) = 6.580$, $p < .01$, $\eta_p^2 = 0.230$, indicated participants executed grasps that generated grasp axes significantly closer to the target's center when grasping Center targets ($M = 0.67$ cm from the target's center, SE = 0.06 cm) compared to when grasping Left ($M = 1.0$ [0.09] cm, $p < .01$) or Right ($M = 1.01$ [0.08] cm, $p < .01$) targets. There was no difference in the distances between the grasp axis and the target's center when grasping Left compared to Right targets ($p > .05$). The shape of the target did not significantly influence the distance between the grasp axis and the target's center, $F(1,22) = 0.213$, $p > .05$, $\eta_p^2 = 0.010$.

2.2.3.4. Average vertical index finger placement. A significant main effect of Position indicated that participants placed their index finger significantly lower when grasping Left targets ($M = 2.37$ cm above the target's center, SE = 0.09 cm) compared to when grasping Center ($M = 2.63$ [0.11], $p < .05$) or Right ($M = 2.63$ [0.10] cm, $p < .01$) targets¸ $F(2, 44) = 8.613$, $p < .001$, $\eta_p^2 = 0.284$. There was no significant difference between Center and Right targets ($p > .05$). As these were 2D targets being grasped, a lowered index finger placement would not have the same repercussions as when grasping an actual 3D square (e.g., collision with the front of the object, rather than placement on its top edge), and therefore participants may have placed their index finger lower when grasping targets presented on the left side of the screen as a result of the increased effort required to raise the hand toward a position on the contralateral side of the body.

2.2.4. *Fixation positions*

2.2.4.1. Gaze accuracy. Mean absolute gaze displacement error as measured during the accuracy checks (see 2.1.2 Methods: Stimuli and Materials) combined across all participants was 0.27 cm in the horizontal axis, and 0.41 cm in the vertical axis. The average gaze displacement error across participants was 0.10 cm to the right (SE = 0.06 cm) and 0.10 cm below (SE = 0.08 cm) in the horizontal and vertical axes respectively.

2.2.4.2. Average horizontal fixations at time of contact. Both the shape and position of the target influenced the horizontal positions participants directed their fixations when grasping, as indicated by a significant main effect of Shape, $F(1,22) = 9.552$, $p < .01$, $\eta_p^2 = 0.303$, and a significant main effect of Position, $F(2,44) = 38.848$, $p < .001$, $\eta_p^2 = 0.638$. As was expected, participants' fixations matched the horizontal placement of the index finger and were biased toward the approaching hand, suggesting participants were looking at task-relevant locations on the target, as demonstrated previously with 3D objects (Hayhoe et al., 2003; Johansson et al., 2001). Fixations were positioned close to the horizontal midline of Center targets ($M = 0.23$ cm to the right of the horizontal midline, SE = 0.16 cm), and in comparison were significantly farther rightward when grasping Left targets, ($M = 0.90$ [0.17] cm to the right of the horizontal midline, $p < .01$), and significantly farther leftward when grasping Right targets ($M = 0.74$ [0.21] cm to the left of the horizontal midline, $p < .001$). Average horizontal fixations significantly differed between Left and Right targets ($p < .001$). As was the case with index finger placement, when collapsing across Position, average horizontal fixations were directed more rightward of the Experimental target's horizontal midline ($M = 0.22$ [0.14] cm to the right of the horizontal midline) compared to the Control target's horizontal midline ($M = 0.04$ [0.15] cm to the right of the horizontal midline).

2.2.4.3. Fixation region frequency analysis: Horizontal fixations at time of contact. Similar to the frequency of index finger placement, participants fixated more frequently within regions corresponding to the final average horizontal fixation positions. As can be seen in Fig. 2d, participants fixated more frequently on the right side of Leftward targets, the left side of Rightward targets, and toward the middle of Center targets, as confirmed by a significant Position x Grasp Region interaction, $\chi^2(4) = 765.29$, $p < .001$. Additionally, as shown in Fig. 2e, a significant Shape x Grasp Region interaction, $\chi^2(2) = 49.63$, $p < .001$, demonstrated that participants fixated more frequently on the right side of Experimental targets, compared to Control targets, toward which fixations were distributed more evenly across regions.

2.2.4.4. Average vertical fixations at time of contact. All average fixations were positioned above the target's center, however a significant main effect of Position, $F(2,44) = 8.142$, $p < .001$, $\eta_p^2 = 0.270$, indicated that participants directed their fixations significantly higher when grasping Center targets ($M = 0.70$ cm above the target's center, SE = 0.17 cm) compared to Left targets ($M = 0.43$ [0.16] cm, $p < .01$) and Right targets ($M = 0.44$ [0.18] cm, $p < .05$). Participants did not know at which position the target was going to appear at the beginning of any given trial, and generally fixated toward the middle of the screen until it appeared. The fixations may have been positioned lower on Left and Right targets (there was no significant difference between these positions, $p > .05$) because in these trials, participants needed to saccade to locations 20 cm to the left or right of where they were initially fixating. When the target appeared at the center of the screen, participants may not have needed to adjust their gaze as dramatically, and simply continued to fixate at a higher position on the target. Another possibility is participants were taking a more ‘holistic’ approach when grasping non-central targets. Fixations made closer to the target's center would allow a larger portion of the target – including the thumb's contact point in addition to that of the index finger's– to be viewed when grasping.

3. Experiment 2: Grasping horizontally translating targets

The results of Experiment 1 confirmed the hypothesis that digit placement would be shifted in the direction the reaching hand when grasping non-centrally located targets. This was likely the preferred type of grasp because the targets remained stationary, and participants were thus free to choose nearby contact points that required less effort. Despite the shift toward the near side of the target, average final index finger placement remained positioned near the target's horizontal midline (within 1 cm to the right or left), agreeing with previous studies that have demonstrated digit placement coinciding with a square target's COM (Bulloch et al., 2015; Langridge & Marotta, 2017). Considering the added spatiotemporal challenges associated with grasping moving targets, placement of the digits may not be as strongly influenced by the position of a moving target, but rather the direction the target is travelling at the time it is grasped. In Experiment 2, participants executed reach-to-grasp movements for horizontally translating targets at early, middle, or late stages of travel. The timepoints at which participants were cued to reach produced grasps that occurred at roughly the same positions as in Experiment 1. Participants' fixations were also measured at the onset of the target's movement, and at the initiation of the reaching movement toward the target. It was hypothesized that participants would fixate toward the leading edge of the target at movement onset, as this region would provide the most relevant information about the target's movement. At reach onset, fixations were predicted to be positioned near the top of the target, and toward flat areas of the top edge suitable for index finger placement, i.e., close to the midline of control targets, and biased away from the notches of experimental targets. Final gaze and index finger placement were hypothesized to be biased toward the trailing edge of rightward moving targets, and toward the leading edge of leftward moving targets, especially at late stages of target travel.

3.1. Methods

3.1.1. Participants

Twenty-five undergraduate psychology students (21 female; age range: 16–32 years old; $M = 19.72$ years) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and received course credit toward their Introductory Psychology course in exchange for participation. 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). All procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

3.1.2. Stimuli, materials, and procedure

The stimuli and materials were the same as those described in Experiment 1. The procedure was similar to that of Experiment 1, with the following exceptions. Each trial began with either a Control or Experimental target presented at either the far right, or far left side of the screen. After remaining stationary for 1.5 s, the target then began translating horizontally toward the opposite side of the screen at a constant speed of 10 cm/s (10.4°/s). Participants were presented with a 'reach tone' generated by the MotionMonitor software at one of three timepoints; Early: 1.5 s post target appearance, at the onset of target movement (at this point the target was positioned 24 cm to the left or right of the screen's center), Middle: 3 s post target appearance, 1.5 s post onset of target movement (at this point the target had moved 15 cm toward the opposite side of the screen and was positioned 9 cm away from the screen's center), and Late: 4.5 s post target appearance, 3 s post target movement onset (at this point the target had moved 30 cm toward the opposite side of the screen, 6 cm past the screen's center). The timing of the Early and Late reach tones was intended to produce grasps occurring at the far left or far right of the screen, while the Middle reach tone produced grasps occurring at the center of the screen, regardless of the direction the target was moving.

To make the task as natural as possible, the target was programmed to stop moving when grasped – when the participant's index finger IRED reached within a 1.5 cm distance from the screen. This threshold was also used to end the current trial and cease data collection.

Each participant completed 3 practice trials to familiarize themselves with the task, followed by 3 blocks of experimental trials. Each block of trials began with an accuracy check to ensure the eye-data being collected was accurate. Each block consisted of 24 trials, including 2 experimental trials per unique trial type. An entire session involved 3 blocks of trials, resulting in a total of at least 3 accuracy checks, and 72 experimental trials by the end of the experiment. Each session took no longer than 1.5 h to complete.

3.1.3. Data analysis

As in Experiment 1, a within-subject repeated measures design was utilized, and each participant's mean condition values were used for the analysis of each dependent variable. Four three-way $2 \times 2 \times 3$ repeated measures ANOVAs (Direction x Shape x Reach Cue) were used to examine the horizontal and vertical coordinates of the fixations relative to the target's center at the following timepoints: 1) The onset of target movement (MO), and 2) Reach onset (RO), characterized as the point in time at which the participants' wrist reached a speed of 5 cm/s. Another 2 three-way $2 \times 2 \times 3$ (Direction x Shape x Reach Cue) repeated measures ANOVAs were run using the final raw horizontal and vertical gaze coordinates to determine where participants were looking relative to the target's center at TOC. The raw gaze coordinates were used for this timepoint to account for any final eye movements not included by the I-DT algorithm occurring within the final milliseconds of the trial. Horizontal and vertical index finger placement were once again analyzed at TOC using 2 three-way (Direction x Shape x Reach Cue) repeated measures ANOVAs, and a single three-way (Direction x Shape x Reach Cue) repeated measures ANOVA was used to analyze the distance between the grasp axis and the target's center across conditions. As in Experiment 1, any violations to sphericity were corrected using a Greenhouse-Geiser correction. The data was tested for normality using the Shapiro-Wilk test. A Bonferroni correction was used to analyze all significant interactions, and all analyses were conducted using alpha $= 0.05$.

A MWF Analysis was again conducted to explore the frequency at which participants placed their index finger and directed their gaze toward each of the three Grasp Regions specified in Experiment 1. For the current experiment, these three regions were redefined as the 'trailing side', 'leading side', and 'middle' of the target. In order to analyze how the direction of target movement and the time at which the target was grasped influenced these frequencies, the previous GLM was modified to the following: Frequency ~ Subject * Direction of Target Movement * Reach Cue * Shape * Grasp Region. All other aspects of the analysis remained the same, including using alpha $= 0.01$ to determine statistical significance.

3.1.3.1. Comparison between stationary and moving targets. In order to compare digit placement when grasping stationary compared to moving targets, 2 independent-sample *t*-tests were conducted at each on-screen position (left, middle, and right) to compare horizontal index finger position when grasping the stationary target (Experiment 1) with index finger position when grasping the moving targets (Experiment 2) of the same shape (i.e., Control or Experimental), grasped at the same on-screen position. For example, Stationary Control Targets presented on the Left side of the screen were compared to Leftward moving Control targets grasped at Late stages of travel, and Rightward moving Control targets grasped at Early stages of travel. The result was a total of 12 independent samples t-tests (4 per each on-screen position) comparing index finger placement. Another 12 independent samples t-tests were conducted in the same manner to compare horizontal gaze positions. A Bonferroni adjusted alpha of 0.0125 (0.05/4) was used to account for the 4 tests (2 comparing Control, and 2 comparing Experimental) occurring at each on-screen position, and Cohen's *d* was used to determine effect size.

Table 2
Grasping moving targets: Average reaction time, reach duration, maximum wrist velocity and wrist height.

	Leftward						Rightward					
	Experimental			Control			Experimental			Control		
	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
Average Reaction Time (s)	0.45 (0.02)	0.32 (0.01)	0.29 (0.01)	0.45 (0.02)	0.33 (0.01)	0.288 (0.01)	0.47 (0.02)	0.33 (0.01)	0.29 (0.01)	0.45 (0.02)	0.34 (0.01)	0.29 (0.01)
Average Reach Duration (s)	0.51 (0.02)	0.53 (0.022)	0.58 (0.02)	0.51 (0.02)	0.53 (0.02)	0.58 (0.03)	0.61 (0.03)	0.56 (0.02)	0.54 (0.02)	0.64 (0.03)	0.56 (0.03)	0.53 (0.02)
Average Maximum Wrist Velocity (m/s)	1.27 (0.05)	1.23 (0.042)	1.28 (0.04)	1.27 (0.05)	1.23 (0.04)	1.26 (0.04)	1.28 (0.05)	1.19 (0.04)	1.20 (0.04)	1.26 (0.05)	1.20 (0.04)	1.20 (0.04)
Average Maximum Wrist Height (cm)	27.47 (0.30)	28.07 (0.32)	28.79 (0.29)	27.48 (0.24)	28.35 (0.32)	28.75 (0.27)	28.92 (0.30)	28.09 (0.34)	27.62 (0.29)	28.87 (0.28)	28.10 (0.28)	27.51 (0.29)

Note. Standard errors of the means presented in parentheses.

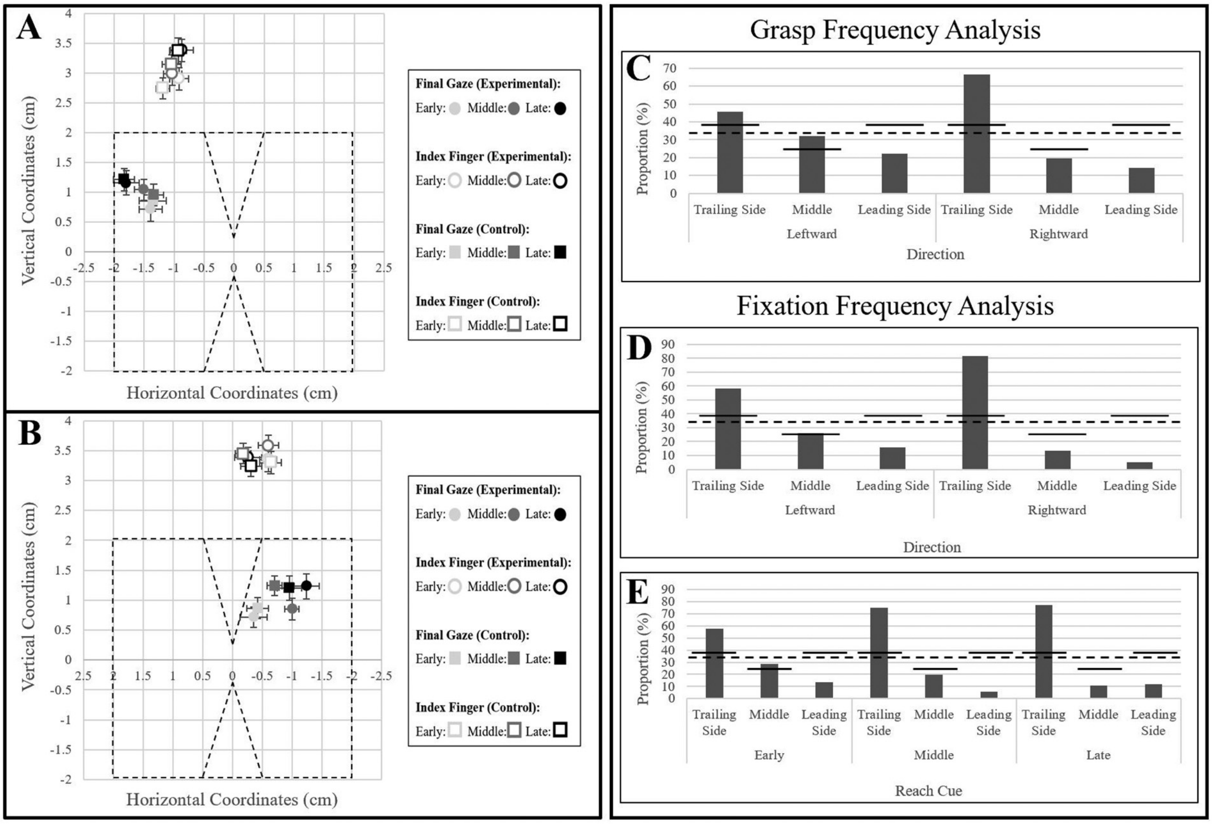

Fig. 3. Average gaze positions and index finger placement when grasping *Rightward* (a) and *Leftward* (b) moving targets, and frequency analysis (c-e) at TOC. In the panels on the left (a-b), negative values in the horizontal and vertical axes refer to distance to the behind and below the target's center respectively, and *Error bars* represent standard error of the means. Dashed lines represent the border of either *Control* or *Experimental* targets. In the panels on the right (c-e), the dashed line represents the expected frequency values if all observations were distributed evenly (no effect) within each condition, and the solid lines represent this expected frequency accounting for the horizontal size of each region. Index finger placement frequency is presented collapsed across target shape and reach cue (c). Final gaze frequency is presented collapsed across target shape and reach cue (d), and across target shape and direction (e).

3.2. Results and discussion

3.2.1. Excluded data

Experimental data that met any of the exclusion criteria listed in Experiment 1 was removed from analysis. In total, 10% of all experimental trials were excluded from the final analysis.

3.2.2. Kinematic variables

As in Experiment 1, participants' average reaction time, average reach duration, average maximum wrist velocity and wrist height are provided for additional context in Table 2.

3.2.3. Digit placement

3.2.3.1. Average horizontal index finger placement. Average index finger placement and final gaze positions when grasping rightward and leftward moving targets at TOC are presented in Fig. 3a and b, respectively. Average final horizontal index finger placement was consistently positioned behind the target's midline; participants placed their index finger to the right of the Leftward moving target's midline, and to the left of the Rightward moving target's midline. However, a significant main effect of Direction, $F(1,24) = 7.520$, $p < .05$, $\eta_p^2 = 0.239$, indicated that index finger placement was closer to the midline of Leftward moving targets ($M = 0.43$ cm behind the target's midline, SE = 0.13 cm) compared to Rightward moving targets ($M = 1.0$ [0.11] cm behind the target's midline).

A significant Shape by Time interaction, $F(2, 48) = 5.178$, $p < .01$, $\eta_p^2 = 0.177$, was also observed. When grasping targets at Middle stages of travel (i.e., when grasps occurred at the middle of the screen), horizontal index finger placement was positioned farther behind the midline when grasping Experimental targets ($M = 0.81$ cm behind the target's horizontal midline, SE = 0.08 cm) compared to when grasping Control targets at the same stage of travel ($M = 0.61$ [0.07] cm behind the midline), suggesting participants avoided the notched region, and placed their digits farther behind the target's horizontal midline compared to when grasping Control targets when the target was in the middle of the screen. There was no influence of target shape when the target was

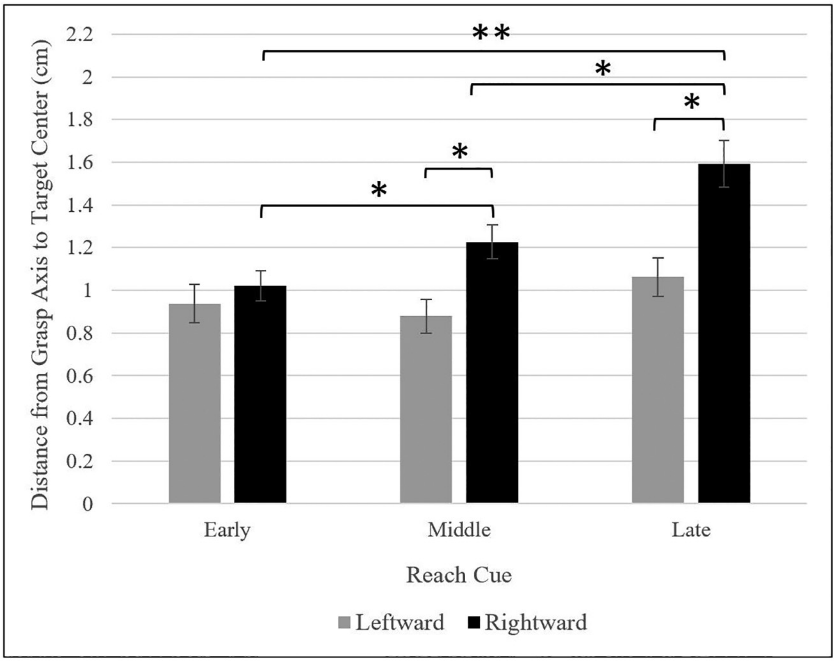

Fig. 4. Average absolute distance from grasp axis to target center. *Leftward* and *Rightward* refer to direction of target travel, *Early, Middle,* and *Late* refer to timing of the reach cue. *Error bars* represent standard error of the mean. $^{*}p < .01$, $^{**}p < .001$.

positioned at the far edges of the screen; participants consistently grasped the trailing side of the target at both Early (Experimental: $M = 0.76$ [0.11] cm behind the horizontal midline, Control: $M = 0.91$ [0.09] cm behind the midline, $p > .05$) and Late (Experimental: $M = 0.57$ [0.15] cm behind the midline, Control: $M = 0.62$ [0.12] cm behind the midline, $p > .05$) stages of travel. Final index finger placement did not significantly differ between timepoints when grasping Experimental targets. When grasping Control targets, final index finger placement was significantly farther behind the midline when grasping the target at Early stages of travel compared to at Middle stages of travel ($p < .05$).

When the target was grasped at Late stages of travel, digit placement behind the midline would require less effort than reaching farther ahead to grasp the leading side as the target moved away from the reaching hand. In this sense, the current results agree with those of Experiment 1, when the targets were stationary at these non-central positions, and digit placement was shifted toward the reaching hand. On the other hand, placement of the digits behind the midline of targets grasped at Early stages of travel would require reaching *past* the target's midline as it approached the reaching hand, in order to grasp its trailing side. Regardless of the direction of travel however, targets grasped at Early stages of travel were moving toward the participants' hand. It is possible that grasps were aimed toward the near side of the target, or positions closer to the targets' midline at these timepoints, and simply landed behind the intended position as a result of the target's continued movement.

3.2.3.2. *Grasp frequency analysis: Horizontal index finger placement.*

A significant Direction x Grasp Region interaction, $\chi^2(2) = 86.01$, $p < .001$, revealed that the direction of target movement influenced how often participants grasped a particular region of the target. As can be seen in Fig. 3c, while the trailing side of the target was grasped most frequently when the target was moving either both directions, a higher proportion of grasps occurred on the trailing side when the target was moving Rightward.

3.2.3.3. *Distance from the grasp axis to the target's center.*

The three-way repeated measures ANOVA revealed a significant interaction between Direction and Time, $F(2,48)$, $p < .01$, $\eta_p^2 = 0.186$, displayed in Fig. 4. Post-hoc analyses indicated that while there was no significant difference between Leftward and Rightward moving targets at Early stages of travel ($p > .05$), the average grasp axis was located significantly closer to the target's center when grasping Leftward moving targets at Middle ($p < .01$) and Late ($p < .01$) stages of travel compared to Rightward moving targets.

The distances between the grasp axis and the target's center did not significantly differ between any of the three stages of target travel when the target was moving leftward (all comparisons $p > .05$). However, when grasping Rightward moving targets, the distance between the grasp axis and the target's center significantly increased the farther it travelled. When grasped at Middle stages of travel, the average grasp axis was positioned significantly farther from the Rightward moving targets' center than when grasped at Early stages of travel ($p < .01$), and significantly closer to the target's center than when grasped at Late stages of travel ($p < .01$). The average grasp axis when the Rightward moving target was grasped at Late stages of travel was significantly farther from the target's center than when grasped at Early stages of travel ($p < .001$). In other words, participants placed their digits at locations that generated grasp axes positioned closer to the target's center when the Rightward moving target was approaching the grasping hand,

and farther from the target's center when moving away from it. The distance between the grasp axis and the target's center remained consistent when grasping Leftward moving targets at each stage of travel, suggesting participants may have been compensating for the added difficulty of grasping a target moving toward the contralateral hemispace, and placed their digits closer to the horizontal midline regardless where the target was at the time of the grasp.

3.2.3.4. Average vertical index finger placement. A significant Direction by Time interaction, $F(2, 48) = 5.347$, $p < .01$, $\eta_p^2 = 0.182$, indicated that participants placed their index finger significantly higher when grasping Leftward moving targets compared to Rightward moving targets at Early (Leftward: $M = 3.33$ [0.17] cm above the target's center; Rightward: $M = 2.82$ [0.17] cm, $p < .01$) and Middle (Leftward: $M = 3.52$ [0.16] cm; Rightward: $M = 3.07$ [0.16] cm, $p < .01$) stages of target travel. No significant differences in vertical placement of the index finger were observed at Late stages of target travel between Leftward ($M = 3.31$ [0.15] cm) and Rightward ($M = 3.38$ [0.19] cm) moving targets.

The stage of travel at which the target was grasped did not significantly influence the vertical placement of the index finger when the target was moving Leftward. When grasping Rightward moving targets, average vertical index finger placement was positioned significantly lower when grasping targets at Early stages of travel compared to when grasping targets at Late stages of travel ($p < .001$).

3.2.4. Gaze and fixation positions

3.2.4.1. Gaze accuracy. Mean absolute gaze displacement error combined across all participants was 0.29 cm in the horizontal axis, and 0.53 cm in the vertical axis. The average gaze displacement error across participants was 0.11 cm to the left (SE = 0.06 cm) and 0.18 cm above (SE = 0.12 cm) in the horizontal and vertical axes respectively.

3.2.4.2. Visual pursuit of the target. Consistent with previous research investigating the visual pursuit of these types of square targets, participants used smooth pursuit eye-movements to track the target's leading edge, as this likely provided the most information about the target's movement (Bulloch et al., 2015; Langridge & Marotta, 2017). Catch-up saccades were used throughout the trial (DeBrouwer, Yuksel, Blohm, Missal, & Lefèvre, 2002; Schütz & Souto, 2011).

3.2.4.3. Average horizontal fixations at movement onset. The average fixations made at the onset of Rightward and Leftward target movement are provided in Fig. 5a and b respectively. As predicted, participants directed their gaze toward the leading edge of the target as it started moving. Bulloch et al. (2015) reported similar fixations toward the leading edge of a horizontally translating square target during pursuit. These results suggest participants prefer to visually track the leading edge of a moving target, as this side likely provides the best information about the speed, direction, and future position of the target. A significant main effect of target Shape, $F(1,24) = 16.297$, $p < .001$, $\eta_p^2 = 0.404$, indicated that average horizontal gaze was directed closer to the horizontal midline of Experimental targets ($M = 0.67$ cm ahead of the target's midline, SE = 0.32 cm) compared to Control targets ($M = 1.13$ [0.30] cm ahead of the target's midline). At this timepoint, the 'notches' at the midline of Experimental targets may have made this area more visually salient, and perhaps provided additional edges which participants could have used to obtain additional information regarding the movement of the target, not present when viewing Control targets which only had one 'leading edge'.

3.2.4.4. Fixation frequency analysis: Movement onset. As seen in Fig. 5, at the onset of target movement, participants fixated most frequently on the leading side of the target. However, a significant Shape x Grasp Region interaction was present, $\chi^2 (2) = 41.495$, $p < .001$, indicating participants fixated more frequently on the leading side of Control targets compared to Experimental targets (Fig. 5c). This agrees with the finding that participants fixated at an average position closer toward the midline of Experimental targets. Further, while over 50% of fixations were directed toward the leading side of Leftward moving targets, slightly less than half were directed toward the leading side of Rightward moving targets (significant Direction x Grasp Region interaction, $\chi^2 (2) = 17.790$, $p < .001$ (Fig. 5d)). This increased frequency of fixations toward the leading side of the leftward moving target suggests participants were anticipating these target's movements to a greater degree in comparison to when the target began moving rightward, perhaps suggesting an increased motivation to efficiently track these targets. For example, anticipation of target movement would reduce the need for 'catch-up saccades' following onset of movement (DeBrouwer et al., 2002), and likely contribute to overall success of the task (Mennie, Hayhoe, & Sullivan, 2007).

Finally, as can be seen in Fig. 5e, a significant Reach Cue x Grasp Region interaction, $\chi^2 (4) = 20.943$, $p < .001$, suggests that in comparison to Middle and Late stages of travel, when cued to grasp the target at Early stages of travel participants were slightly more likely to fixate toward the middle or leading side of the target compared the target's trailing side. Participants likely fixated more frequently on the leading side of these targets as a result of the simultaneous onset of target movement and presentation of the reach cue, requiring them to at once track the initial movement of the target and execute the reach-to-grasp movement.

3.2.4.5. Average vertical fixations at movement onset. On average, participants fixated 0.60 cm (SE = 0.06) above the target's center at MO. There were no significant effects of Direction, $F(1,24) = 0.322$, $p > .05$, $\eta_p^2 = 0.085$, Shape, $F(1,24) = 3.144$, $p > .05$, $\eta_p^2 = 0.398$, or Reach Cue, $F(2,48) = 1.793$, $p > .05$, $\eta_p^2 = 0.357$.

3.2.4.6. Average horizontal fixations at reach onset. The average fixations made at the onset of the reaching motion are provided in Fig. 6a and b for rightward and leftward moving targets respectively. The three-way repeated measures ANOVA revealed a significant Direction x Shape interaction, $F(1,24) = 7.71$, $p < .05$, $\eta_p^2 = 0.243$, at RO. Post hoc analyses revealed that average horizontal gaze

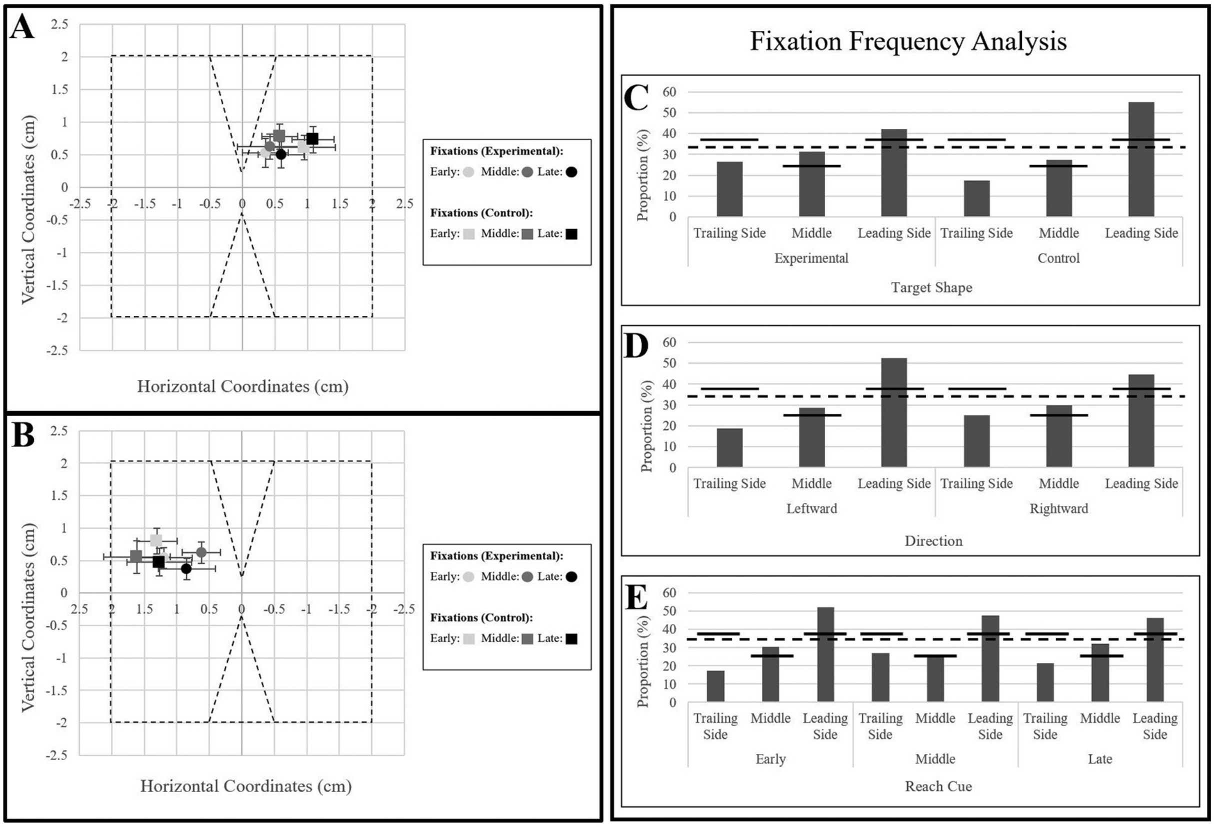

Fig. 5. Average fixation positions at the onset of *Rightward* (a) and *Leftward* (b) target movement, and frequency analysis (c-e). In the panels on the left (a-b), negative values in the horizontal and vertical axes refer to distance to the behind and below the target's center respectively, and *Error bars* represent standard error of the means. Dashed lines represent the border of either *Control* or *Experimental* targets. In the panels on the right (c-e), the dashed line represents the expected frequency values if all observations were distributed evenly (no effect) within each condition, and the solid lines represent this expected frequency accounting for the horizontal size of each region. Final gaze frequency is presented collapsed across direction and reach cue (c), across target shape and reach cue (d), and across target shape and direction (e) .

was directed near the midline of Leftward moving Control targets ($M = 0.16$ cm ahead of the horizontal midline, SE = 0.22 cm), and behind the midline of Rightward moving Control targets ($M = 0.70$ [0.25] cm behind the midline), a significant difference ($p < .01$). Horizontal gaze positions did not significantly differ when reaching toward Experimental targets, and were directed toward the trailing edge of both Leftward ($M = 0.65$ [0.16] cm behind the midline) and Rightward (M = 0.96 [0.24] cm behind the midline, $p > .05$) moving targets.

Horizontal fixations were directed significantly closer to the horizontal midline of Leftward moving Control targets compared to Experimental targets ($p < .001$). Fixations were also directed significantly closer to the midline of Rightward moving Control Targets compared to Experimental Targets ($p < .05$). This is the opposite of what was seen at MO, where participants fixated closer to the midline of Experimental targets, and may indicate a priority shift, such that once cued to reach for the target, participants shifted their gaze from more salient regions to more task related locations to which the index finger could be guided when grasping (i.e., the top edge of the target, near the horizontal midline of Control targets, and the flat, non-central regions of the Experimental targets). These fixations toward task-dependant locations at the onset of the guided movement are similar to those observed when using a series of visually guided actions to complete a specific task (Hayhoe et al., 2003; Land, Mennie, & Rusted, 1999).

3.2.4.7. Fixation frequency analysis: Reach onset. While participants most frequently fixated toward the leading side of the target at MO, this pattern was reversed at RO, and fixations were most frequently directed toward the trailing side of the target. Significant Direction x Grasp Region, χ^2 (2) = 13.91, $p < .001$, Shape x Grasp Region, χ^2 (2) = 67.69, $p < .001$, and Reach Cue x Grasp Region, χ^2 (4) = 43.41, $p < .001$, interactions were present (Fig. 6c–e). Fixations were more frequently directed toward the trailing side of targets moving Rightward compared to targets moving Leftward (Fig. 6c) and were more frequently directed toward the trailing side of Experimental targets compared to Control targets (Fig. 6d). As seen in Fig. 6e, while fixations were most frequently directed toward the trailing side of the target, these frequencies were slightly more evenly distributed when the participant was cued to grasp at Middle stages of travel.

3.2.4.8. Average vertical fixations at reach onset. Participants' average fixations were positioned slightly higher at RO when reaching

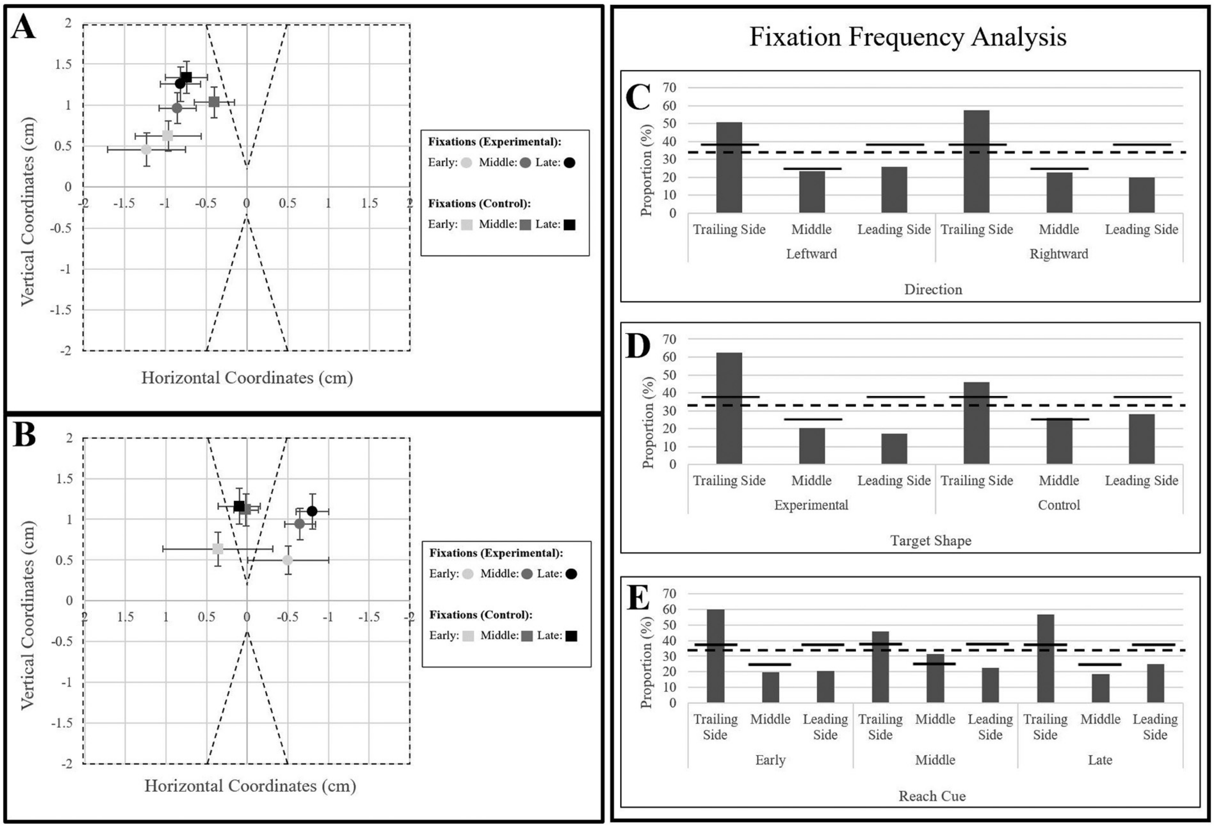

Fig. 6. Average fixation positions at the initiation of the reaching movement toward *Rightward* (a) and *Leftward* (b) moving targets, and frequency analysis (c–e). In the panels on the left (a–b), negative values in the horizontal and vertical axes refer to distance to the behind and below the target's center respectively, and *Error bars* represent standard error of the means. Dashed lines represent the border of either *Control* or *Experimental* targets. In the panels on the right (c–e), the dashed line represents the expected frequency values if all observations were distributed evenly (no effect) within each condition, and the solid lines represent this expected frequency accounting for the horizontal size of each region. Fixation frequency at RO is presented collapsed across target shape and reach cue (c), across direction and reach cue (d), and across target shape and direction (e).

for Control targets ($M = 0.98$ cm above the target's center, SE = 0.18 cm) compared to Experimental targets ($M = 0.87$ [0.18] cm), as confirmed by a significant main effect of Shape, $F(1,24) = 4.870, p < .05, \eta_p^2 = 0.169$. Once again, the saliency of the notches above and below the target's center may have drawn participants' gaze toward the intersection of these points. Another possibility is that Experimental targets required a higher degree of precision when grasping, and these differences represent a preference for a more holistic view of targets that require more accurate digit placement. Interestingly, no differences were observed in average vertical fixations at MO.

A main effect of Reach Cue was also significant at this timepoint, $F(1.574, 37.775) = 33.661, p < .001, \eta_p^2 = 0.584$. Gaze was directed significantly lower (i.e., closer to the vertical center of the target) when initiating the reaching movement at Early stages of travel ($M = 0.55$ cm above the target's center, SE = 0.17 cm) compared to Middle ($M = 1.01$ [0.18] cm, $p < .001$) and Late ($M = 1.21$ [0.20] cm, $p < .001$) stages of travel. This is most likely because in the Early condition participants were cued to grasp the target at the same time the target began its movement, and were tasked with establishing visual pursuit of the target in addition to executing the reaching movement toward it. Vertical gaze at Middle and Late stages of target travel did not significantly differ ($p > .05$).

3.2.4.9. Average horizontal gaze at time of contact. At TOC, average horizontal gaze was consistently directed behind the target's horizontal midline, however main effects of Direction, Shape, and Reach Cue were significant. As seen with horizontal index finger placement, a main effect of Direction, $F(1,24) = 13.407, p < .01, \eta_p^2 = 0.358$, indicated that gaze was directed significantly closer to the midline of Leftward moving targets ($M = 0.78$ cm behind the target's midline, SE = 0.11 cm) compared to Rightward moving targets ($M = 1.54$ [0.11] cm behind the midline). A main effect of Shape, $F(1,24) = 10.02, p < .01, \eta_p^2 = 0.295$, indicated that gaze was directed significantly closer the midline of Control targets ($M = 1.10$ [0.07] cm behind the target's midline) compared to Experimental targets ($M = 1.21$ [0.06] cm behind the midline).

Finally, a main effect of Reach Cue, $F(1.19,28.531) = 4.564, p < .05, \eta_p^2 = 0.160$, suggested that average horizontal gaze was directed closest to the target's horizontal midline when cued to grasp targets at Early stages of target movement ($M = 0.88$ [0.14] cm behind the target's midline), followed by targets grasped at Middle stages of travel ($M = 1.14$ [0.09] cm behind the midline), and gaze was directed furthest behind the target's midline when grasped at Late stages of travel ($M = 1.45$ [0.015] cm behind the midline). However, the post-hoc comparisons between horizontal gaze at these timepoints were not significant (all $ps > 0.05$).

3.2.4.10. Gaze frequency analysis: Time of contact. Overall, participants most frequently directed their gaze toward the trailing side of the target when grasping, but gaze was more frequently directed toward the trailing side of Rightward moving targets compared to Leftward moving targets (Direction x Grasp Region interaction, χ^2 (2) = 139.56, $p < .001$ (Fig. 3d). A significant Reach Cue x Grasp Region interaction was also observed, χ^2 (4) = 99.55, $p < .001$, suggesting that gaze was more distributed among the three grasp regions when grasping targets at Early stages of travel, compared to those grasped at Middle and Late stages (Fig. 3e). This result agrees with the above result that average horizontal gaze was positioned closer to the target's midline when grasping targets at Early stages of travel.

3.2.4.11. Average vertical gaze at time of contact. The three-way repeated measures ANOVA revealed significant main effects of Shape, $F(1,24) = 4.99$, $p < .05$, $\eta_p^2 = 0.172$, and Reach Cue, $F(2,48) = 10.43$, $p < .001$, $\eta_p^2 = 0.303$. Consistent with vertical fixations made at Reach Onset, gaze at TOC was directed significantly lower when grasping Experimental targets ($M = 0.95$ cm above the target's center, SE = 0.16 cm) compared to when grasping Control targets ($M = 1.06$ [0.15] cm). Final gaze was directed significantly lower when grasping targets at Early ($M = 0.79$ [0.15] cm) compared to Middle ($M = 1.02$ [0.17] cm, $p < .05$) and Late ($M = 1.2$ [0.18] cm, $p < .01$) stages of travel. Final vertical gaze did not significantly differ when grasping targets at Middle or Late stages of target travel ($p > .05$). As speculated previously, the tendency to fixate lower on targets being grasped at Early stages of travel may reflect an urgency not present when grasping targets at later stages of travel. These targets may also have required a higher precision when grasping, and therefore a more central gaze position.

3.3. Comparison of final horizontal gaze and grasp points: Stationary versus moving targets

Participants' final average horizontal fixations and index finger placement when grasping stationary targets presented at the left, center, and right side of the screen (Experiment 1; Fig. 2) were compared to participants' final gaze and index finger positions when grasping horizontally translating targets of the same shape at the same locations (Experiment 2; Fig. 3). Table 3 presents the conditions being compared between the experiments, which coincide with the target being grasped on the left side, middle, and right side of the screen.

3.3.1. Comparisons when the target was on the left side of the screen

3.3.1.1. Index finger placement. When grasping stationary Experimental targets, participants placed their index finger on the nearest side of the target (i.e., the right side, biased toward the reaching hand), whereas when grasping rightward moving Experimental targets grasped at Early stages of travel, participants grasped the target's left side (i.e., its trailing side), $t(46) = 8.240$, $p < .001$, $d = 2.39$. Horizontal index finger placement did not significantly differ when grasping leftward moving Experimental targets grasped at Late stages of travel compared to when grasping stationary Experimental targets; $t(38.997) = 2.064$, $p > .0125$, $d = 0.60$.

Participants also placed their index finger on the nearest (right) side of stationary Control targets, but grasped rightward moving Control targets at Early stages of travel on the left (trailing) side $t(46) = 10.155$, $p < .001$, $d = 2.93$. Index finger placement was not significantly different when grasping stationary Control targets compared to leftward moving Control targets grasped at Late stages of travel, $t(46) = 1.364$, $p > .0125$, $d = 0.40$; index finger placement in both cases was biased toward the target's nearest side (i.e., trailing side of the leftward moving target).

3.3.1.2. Fixation position. Participants' fixations did not significantly differ when grasping stationary and leftward moving targets grasped at Late stages of travel; gaze was directed toward the nearest (right) side of the stationary target (biased toward the approaching hand), which coincided with the trailing side of the leftward moving target, $t(46) = -1.115$, $p > .0125$, $d = 0.32$. Compared to the stationary target, gaze was directed toward the far left side of rightward moving Experimental targets grasped at Early stages of travel $t(46) = 9.008$, $p < .001$, $d = 2.61$. The same pattern was true when grasping stationary Control targets compared to leftward moving Control targets grasped at Late stages of travel, $t(46) = -0.337$, $p > .0125$, $d = 0.04$, and rightward moving Control targets grasped at Early stages of travel, $t(46) = 7.742$, $p < .001$, $d = 2.38$.

Table 3
Summary of comparisons between experimental conditions.

On-Screen Position	Direction of Target Movement: Reach Cue
(Experiment 1)	(Experiment 2)
Left	Leftward: Late Rightward: Early
Center	Leftward: Middle Rightward: Middle
Right	Leftward: Early Rightward: Late

3.3.2. *Comparisons when the target was in the center of the screen*

3.3.2.1. Index finger placement. Index finger placement was not significantly different when grasping stationary Experimental targets compared to leftward moving Experimental targets grasped at Middle stages of travel, $t(46) = -1.794, p > .0125, d = 0.52$; both types of targets were grasped relatively close to, and slightly to the right of the midline. However, rightward moving Experimental targets grasped at Middle stages of travel were grasped significantly farther leftward (toward the targets trailing edge) compared to when the target was stationary, $t(46) = 5.866, p < .001, d = 1.70$.

Index finger placement also did not significantly differ between stationary Control targets and leftward moving Control targets grasped at Middle stages of travel $t(46) = -1.641, p > .0125, d = 0.47$, however there was a significant difference in index finger placement when comparing stationary Control targets to rightward moving targets grasped at Middle stages of travel $t(46) = 4.220$, $p < .001, d = 1.22$, which again were grasped farther behind the midline, toward the trailing edge.

3.3.2.2. Fixation position. Whereas fixations were directed toward the midline of stationary targets in the center of the screen, participants fixated at non-central positions biased toward the trailing edge of the target when it was moving (i.e., the right side of leftward moving targets and the left side of rightward moving targets). Horizontal fixations were significantly different when grasping stationary Experimental targets compared to leftward moving, $t(46) = -3.256, p < .01, d = 0.93$, and rightward moving, $t(46) = 8.194$, $\mathrm{p} < .001$, $d = 2.37$, Experimental targets grasped at Middle stages of travel. Horizontal fixations when grasping Control targets followed the same pattern, and were also significantly different when grasping stationary targets compared to leftward moving, $t(46) = -2.822, p < .01, d = 0.81$, and rightward moving, $t(46) = 6.161, p < .001, d = 1.78$, targets grasped at Middle stages of travel.

3.3.3. *Comparisons when the target was on the right side of the screen*

3.3.3.1. Index finger placement. Participants placed their index finger at significantly different positions when grasping stationary Experimental targets compared to leftward moving Experimental targets grasped at Early stages of travel $t(46) = -4.173, p < .001$, $d = 1.21$; grasps were directed toward the center of stationary targets, and farther to the right, toward the trailing side of the target when moving leftward. Index finger placement when grasping rightward moving Experimental targets at Late stages of travel was not significantly different compared to when grasping stationary targets $t(46) = 2.410, p > .0125, d = 0.70$.

When grasping Control targets, index finger placement was significantly farther rightward (toward the trailing side) when grasping leftward moving Control targets grasped at Early stages of travel compared to stationary Control targets, $t(46) = -5.364$, $p < .001, d = 1.56$. Index finger placement when grasping Rightward moving Control targets at Late stages of travel did not significantly differ from grasping stationary Control targets, $t(46) = 2.068, p > .0125, d = 0.60$.

3.3.3.2. Fixation position. Participants again fixated toward the near (i.e., left) side of the stationary target (biased toward the reaching hand), and significantly farther rightward, toward the trailing edge of the leftward moving target grasped at Early stages of travel, $t(46) = -3.111, p < .01, d = 0.90$. Fixations when grasping the rightward moving target at Late stages of travel were also directed toward its nearest (i.e., trailing) side, however these positions were significantly farther from the target's center (closer toward its trailing edge) compared to those when grasping the stationary target, $t(46) = 3.959, p < .001, d = 1.15$. The same pattern was observed for Control targets; horizontal fixations were significantly different when grasping stationary Control targets compared to leftward moving Control targets grasped at Early stages of travel, $t(46) = -4.435, p < .001, d = 1.28$, and rightward moving Control targets grasped at Late stages of travel, $t(46) = 3.489, p < .01, d = 1.01$.

4. General discussion

The main goal of this study was to investigate how participants directed their gaze toward, and where they placed their digits when grasping 2D computer generated targets positioned at central or non-central locations, as well as how these gaze and grasp strategies differed when the target's remained stationary versus when they were in motion. As hypothesized, in Experiment 1 participants fixated toward the near side of non-central stationary targets, and toward the midline of targets presented centrally, and these fixations matched placement of the index finger when grasping, suggesting that participants were fixating at locations particularly relevant for the specific task. By placing the digits on the near side of the target, participants avoid expending the energy required to transport the digits to the middle or far side of the target. These results agree with those of studies exploring the speed-accuracy trade offs associated with goal-directed aiming, i.e., Fitts' Law (Fitts, 1954), which demonstrate participants' tendency to initially undershoot the target's position during an aiming task, presumably because these errors are less costly to correct than when overshooting the target's position (Elliot, Hansen, Mendoza, & Tremblay, 2004).

In Experiment 2 when the target was moving however, the average index finger placement and gaze positions were consistently positioned behind the target's horizontal midline. In fact, participants placed their index finger at the same positions when grasping non-central stationary targets and when grasping moving targets grasped at late stages of travel, when the target's near side was also its trailing side. When grasping moving targets at early stages of travel however, participants continued to grasp the target's trailing side, which meant digit placement toward the farther side of target, the opposite of what was observed when grasping stationary targets at these positions.

Why did participants prefer the trailing side of the moving target when grasping, especially since this meant reaching to the far side of targets grasped at early stages of travel? The shift toward the target's trailing edge at RO and TOC was likely a product of participants' current intention to grasp the target, not yet present at MO (except for targets grasped at Early stages of travel). Due to the nature of the targets' movement, digit placement that was initially directed toward regions closer to the target's horizontal midline may have slipped toward the trailing edge at the time the digits actually made contact with the screen. Participants may have directed their digits toward ‘convenient’ locations (i.e., biased toward the approaching hand; the leading side of targets grasped during early stages of travel, and the trailing side of targets grasped during late stages of travel), and the point of actual contact with the target was shifted behind these locations at the time of the grasp. This could explain why in some cases (i.e., when grasping rightward moving targets) the grasp axis connecting the index finger and thumb was closest to the target's center when grasping targets at Early stages of travel; digit placement was perhaps directed ahead of the target's midline as it approached the reaching hand but landed close to or behind the horizontal midline at the actual time of contact. This would also explain why the grasp axes were farthest from the target's center when grasping rightward moving targets at late stages of travel; digits already directed toward more ‘convenient’ positions behind the target's center would land even farther behind the target's horizontal midline at the time of the grasp.

Participants may have also directed their grasps behind the target's midline because this provided a safer, more predictable location to make contact with the target. It could be argued that the trailing side of a moving target is a safer location for one to place their digits, as it limits the potential for collision with its leading edge, and the fingers are less likely to miss the target in the event of any perturbation of its movement, though participants were given no reason to expect the target to stop moving or change direction in the present experiment. While it could be argued that a grasp directed toward the trailing side of the target may in fact *increase* the consequences of missing the target (e.g., if it passes by the grasping hand and out of reach), a misplaced grasp positioned behind the target would likely be easier to correct than a missed grasp positioned *ahead* of the target, if considering the energy required for each type of correction as speculated above (Elliot et al., 2004).

The fact that in Experiment 1, participants' fixations and final index finger placement were shifted rightward when grasping the notched Experimental targets compared to the Control targets – even when presented on the right side of the screen – suggests that digit placement favoured locations that maximized participants' view of the target (i.e., the right side), as has been demonstrated when grasping 3D rods (Maiello et al., 2019; Paulun et al., 2014). No such bias was demonstrated for index finger placement in Experiment 2, and participants consistently prioritized digit placement at a position behind the midline of both Control and Experimental targets, even if it meant largely obstructing their view of rightward moving targets. This suggests that when grasping moving targets, the motivation to direct the digits toward a safe location behind the target's midline may outweigh the preference to make contact with the target at locations promoting visibility of the target.

It was hypothesized that digit placement would occur ahead of the horizontal midline of Leftward moving targets at late stages of travel. Instead, gaze and digit placement were consistently directed toward the trailing side of moving targets regardless of at what stage of travel the target was grasped. Despite this, participants continued to direct their gaze and place their index finger closer to the horizontal midline of all Leftward moving targets, as has been observed previously (Langridge & Marotta, 2017) and the grasp axes were generally positioned closer to the target's center when the target was moving leftward. Only when the target was moving rightward did the distances between the grasp axis and the target's center increase the farther the target had moved before it was grasped.

We have previously suggested this bias may arise as compensation for the potential mechanical constraints associated with reaching for a target moving away from the reaching hand, toward the contralateral hemispace (Langridge & Marotta, 2017). Reaching movements toward locations ipsilateral to the reaching hand are typically faster and more accurate than when reaching toward a contralateral space, and work by Carey and Liddle (2013) suggest these differences are products of the different biomechanical constraints required for each type of movement. Though not analyzed formally, our data suggests a similar trend of longer reach durations when reaching toward the left side of the screen. Longer reach durations when reaching for Leftward compared to Rightward moving targets at late stages of travel may have meant more visual feedback, and an increased opportunity for online corrections when grasping the leftward moving targets. When required to grasp a target moving toward the hemispace contralateral to the reaching hand, the execution of an accurate grasp may become increasingly difficult, and participants may grasp the target closer to the midline, establishing a more ‘stable’ grasp in anticipation of these difficulties. In support of these ideas, the current results show the distance between the grasp axis and the target's center – often used as an indicator of grasp stability when grasping 3D objects – generally increased as the rightward moving target travelled farther from the contralateral hemispace toward the ipsilateral hemispace, while the position of the grasp axis remained close to the leftward target's center, even at early stages when there was no immediate danger of crossing the participants' midline. In other words, participants appeared to place their digits at less stable positions as the rightward moving target moved toward regions ipsilateral to the reaching hand.

It is worth noting that ‘convenience’ and ‘grasp stability’ are concepts generally considered when grasping 3-D objects, rather than virtually presented 2-D targets as in the present study. Stability is critical for the successful grasp and manipulation of a 3-D object, while unobstructed visual feedback of the object prior to, and during the grasp means the visual object properties (i.e., COM, weight distribution and density) can be used to appropriately scale anticipatory grip force in order to minimize the possibility of the object slipping, or tilting/rolling during a subsequent movement (Crajé, Santello, & Gordon, 2013; Lee-Miller, Marneweck, Santello, & Gordon, 2016), and to efficiently lift and manipulate the object once grasped (Paulun et al., 2014; Sartori, Straulino, & Castiello, 2011). The computer generated 2-Dimensional targets used in this study did not have a true COM, and participants were not required to perform any type of manipulation once contact was made and the ‘grasp’ was completed. Nevertheless, we observed digit placement that not only promoted stability by positioning the digit placement near the target's horizontal midline, resulting in a grasp axis near the COM, but in some cases suggested participants were prioritizing increased visibility of the target when grasping, as has been demonstrated when grasping 3-D shapes, when these variables are relevant to the success of the grasp (Maiello et al., 2019). However, in certain circumstances (i.e., when grasping rightward moving targets at early stages of travel), an unobstructed view of the target may be sacrificed for digit placement on the trailing side of the target. It appears participants interacted with these targets as if the potential for further manipulation was present, even if this was not possible considering the stimuli being grasped. Based on these similarities, we predict similar eye-hand coordination strategies (i.e., horizontal gaze and index finger placement close to the horizontal midline of the object, while biased toward the direction of the reaching hand, and promoting an unobstructed view of the target) would be observed when grasping horizontally translating 3-D objects as well. However, future research using 3D objects is needed to confirm these predictions.

5. Conclusion

While much has been learned about the visual and motor strategies used to intercept a moving object, less research has focused on the specific relationship between the coordination of gaze and digit placement when grasping moving stimuli. The results of this study suggest participants prefer to minimize the amount of effort used when performing reach-to-grasp movements toward 2D computer generated stationary targets by placing their digits at positions on the target shifted toward the reaching hand, while still prioritizing visual feedback of the target. When grasping horizontally translating targets however, participants consistently placed their digits behind the target's center, even if this meant grasping the far side of the target as it approached the hand. While 2D computer generated targets were used in this study, participants placed their digits at positions close to the target's center, executing what would be considered a stable grasp when grasping 3D objects. Gaze was also consistently directed toward task relevant positions (i.e., the index finger's contact point) as has been demonstrated previously when grasping 3D objects. Together, these results provide novel information about the eye-hand coordination strategies used when grasping stationary and moving computer generated targets and demonstrate several grasping behaviours similar to those seen when grasping 3D objects.

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Ethical approval

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.

Declarations of Competing Interest

None.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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