THE EFFECTS OF ALLOCENTRIC CUE PRESENCE ON EYE-HAND COORDINATION:

DISAPPEARING TARGETS IN MOTION

By

Ryan Langridge

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF ARTS

Department of Psychology
University of Manitoba
Winnipeg

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 close (Experiment 1) or far (Experiment 2) above and below the target's path was manipulated. 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. Final gaze and grasp positions were more accurate when reaching for leftward moving targets, suggesting individuals use different grasp strategies when reaching for targets travelling away from the reaching hand. 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, resulting in inaccurate grasps. New information is provided about the eye-hand strategies used when reaching for moving targets in unpredictable visual conditions.

ACKNOWLEDGEMENTS

I would like to first thank my advisor, Dr. Jonathan Marotta, for his invaluable support, guidance, and patience. I would also like to thank the members of my advisory committee, Dr. Lorna Jakobson and Dr. Steven Passmore, whose continued advice and feedback was crucial for the completion of this project. Special thanks to Melissa Bulloch, Tiffany Carther-Krone, Charlotte Leferink, Alexie Touchette, and Roman Belenya for all your help and feedback throughout this process. Finally, I would like to thank my family and friends for their never-ending enthusiasm and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

GENERAL INTRODUCTION

Visually guided hand movements are an important part of our ability to successfully interact with the immediate environment. Reaching, grasping, and even simply directing visual attention toward objects in our surroundings are all common yet complicated actions, the complexities of which are often taken for granted. During any given day humans reach and grasp for cups, door handles, pencils, and other objects that we wish to hold or use to complete a task. This is accomplished more often than not without much reflection about the various unconscious processes involved. For example, the simple act of reaching for the handle of a coffee cup requires an understanding of the cup's orientation in space, knowledge of how far and in what direction to reach accurately, and how to position the hand and coordinate the digits so that a stable grasp can be made. Prior to reaching, coordinated eye movements are made toward the cup, and gaze is directed towards specific areas of the object relative to the task at hand.

After this consideration, it becomes clear that an action as simple as picking up a coffee cup actually involves an intricate series of coordinated eye and hand movements, as well as appropriately planned and executed mechanical reach and grasp kinematics. When reaching for an object in motion, additional judgements must be made, including a determination of object speed and direction of motion when attempting to intercept the target object (Soechting & Flanders, 2008). In our daily life, we often interact with moving objects, and humans are fairly adept at making these required judgments. For example, most people are able to catch a ball thrown to them, by using initial movement cues (Soechting & Flanders, 2008) to predict where the ball will be when planning and initiating the reach, and making the necessary online adjustments during the reaching motion (Abekawa, Inui, & Gomi, 2014). If we were to guide our hand towards the ball's location at the time at which we started the reaching motion, by the time our hand arrived at its destination the ball would no longer be there. Instead, judgments must be made about how fast the object is moving and its direction, and the trajectory of the reach must be updated accordingly to coordinate an appropriately placed hand and catching motion.

When continuous vision of the object is interrupted however, online adjustments become more difficult (imagine reaching for a ball thrown in front of the sun, or thrown through the leaves of a tree). Under incomplete visual conditions, additional visual cues likely become more useful in determining where and how to grasp for an object. A variety of visual stimuli can be used as cues to provide helpful information when directing sensorimotor movements, such as the approaching hand (Churchill, Hopkins, Ronnqvist, & Vogt, 2000; Tang, Whitwell, & Goodale, 2015) or surrounding objects in the environment (Fiehler, Wolf, Klinghammer, & Blohm, 2014).

Eye Movement

To view something clearly and with high acuity, humans orient their eyes so that the target of interest becomes centered on the fovea, an area of the retina with an especially high concentration of photoreceptors (Krauzlis, 2003). Generally, this direction of focus is accomplished either by a spontaneous direction of gaze toward the target – known as a 'saccade – or by continuous motion of the eyes – known as 'smooth pursuit' – to maintain focus on a moving target. Saccades are quick shifts made by the eyes towards generally stationary targets, and are often measured in terms of latency, peak velocity, and accuracy (Bahill, Clark, & Stark, 1975; Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006). Saccadic eye movement can serve numerous specific purposes (Kojima, Fuchs, & Soetedjo, 2015), such as orienting visual attention to a single, or between multiple stimuli (Howe, Drew, Pinto, & Horowitz, 2011; Zelinsky, & Todor, 2015), or minimizing any growing position error when visually tracking a moving target (Becker & Fuchs, 1985; Havermann, Volcic, & Lappe, 2012). In addition to saccadic movements, smooth pursuit eye movements are generated by motion (Rashbass, 1961), and are used to maintain a moving object's image on the fovea, via smooth and continuous eye movements.

Previously, saccadic movement and smooth pursuit were considered separate processes for fixating visual attention on stationary and moving objects respectively. However, recently there has been an increasing amount of evidence suggesting significant interaction between the two systems (Havermann, et al., 2012), and a single sensorimotor process has been proposed as being responsible for both types of visual orientation on the basis of shared retinal inputs, and common neural correlates (Orban de Xivry & Lefèvre, 2007).

The Role of Intention in the Direction of Gaze

Individuals do not view all objects in the same way, and how and where we look when viewing an object is influenced by our intended interaction with that object, whether it be to passively view, or initiate a physical interaction. (Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2011; Hayhoe & Ballard, 2005). Desanghere and Marotta (2011) demonstrated that when simply viewing a 3-D block, gaze is directed towards the object's center of mass (COM), whereas when grasping the same object, a secondary fixation is made towards the area on the object where the index finger will eventually make contact during the grasp.

The shift of visual attention toward the eventual point of index finger contact has been replicated in studies involving the grasping of stationary (Desanghere & Marotta, 2011), as well as translating targets (Bulloch, Prime, & Marotta, 2015). When grasping for targets in motion, Bulloch et al. (2015) demonstrated that subjects first fixate ahead of the target's leading edge, anticipating the impending motion, followed by a second fixation at the target's leading edge, where gaze remains fixated as the target follows a horizontal path. Finally, upon initiation of the reach a third fixation is made toward the top of the target, where the index finger makes contact during the grasp. These findings suggest that the locations at which we fixate on an object are 'task-dependent', and these locations are an important element in the reaching and grasping process.

Visual Feedback During the Reach

Visual feedback is undeniably useful for actions involving reaching and grasping, and not surprisingly, reaches made toward targets are most accurate when vision is unimpaired (Desmurget, Turner, Prablanc, Russo, Alexander, & Grafton, 2005). When reaching for an object, a saccade toward the target object is associated with the onset of wrist movement. When eye movement toward that object is inhibited at reach onset, components of the reach such as wrist rotation accuracy are impaired (Abrams, Meyers, & Kornblum, 1990). Further, saccades made during coordinated eye-hand movements reach peak velocities that are 4% faster than those of saccades not associated with coordinated hand movements (Snyder, Calton, Dickinson, & Lawrence, 2002).

There appears to be an important relationship between vision and coordinated hand movements, but when is vision most important during the reaching process? Altering the amount of visual feedback provided when reaching is associated with changes in trajectory during the end of the reach – specifically after peak acceleration (Desmurget et al., 2005) – and vision of the hand is especially crucial following peak wrist deceleration when grasping (Churchill et al., 2000). During complete visual occlusion, the time it takes to make a reaching action increases significantly, as the result of a slower approach of the hand at the end of the reach (Winges, Weber, & Santello, 2003). Presumably, a decrease in speed during the final portion of the reach serves to account for an increased likelihood of error when visual feedback is removed.

Visual Feedback During the Grasp

As with reaching, uninterrupted visual feedback of a target object is important when executing an accurate grasp, as certain properties of the object's appearance such as object shape (Borchers, Verheij, Smeets, & Himmelbach, 2014; Verheij, Brenner, & Smeets, 2014), or 'graspability' (Desanghere & Marotta, 2011), influence aspects of grasp execution. For example, mean grip aperture (MGA) – the average distance between the index finger and thumb when grasping – is largely influenced by the shape of the object being grasped (Borchers et al., 2014; Verheij, et al., 2014). Several studies have suggested however that continuous and uninterrupted visual feedback of the target is not always required when executing a successful grasp (Churchill et al., 2000; Winges et al., 2003). Imagine if picking up an object required constant visual attention from the onset of the reach until the object was firmly held in your hand. This would be largely time consuming and impractical. Humans are quite capable of simply glancing at an object, making the required spatial judgments, and then shifting their visual attention elsewhere during the grasping motion. This is possible because the type of grasp required to pick up a specific object is unconsciously determined during the first viewing of the object, prior to the onset of movement. Following onset of movement, the evolution of hand position and digit configuration is developed gradually during the reach, regardless of visual feedback (Winges, et al., 2003).

This is not to say that visual feedback provides no benefit when grasping an object. As mentioned above, when making a grasping action toward an object the eyes fixate towards the eventual location the index finger will make contact. Several studies have investigated the effects of removing the visibility of contact points when grasping objects, and the results are varied. Volcic & Domini (2014) demonstrated that removing the visibility of grasp contact points influences grasping behaviour. In particular, the way in which the digits were directed toward the object was effected, thus implying visible contact points are an important aspect of grasping. In contrast, Voudouris, Smeets, and Brenner (2012) concluded that when grasping objects that have grasp contact points occluded (i.e., when reaching for a cylinder so that the final index position is occluded), the location where the fingers make contact on the object is independent of where visual feedback is available, suggesting visibility of contact points is in fact *not* crucial. The occlusion of grasp points did however cause subjects to grasp more cautiously in this case, with a larger grip aperture and a slightly altered grip orientation.

It is evident that eye-hand coordinated movements, though often executed unconsciously and accurately, are in fact the product of a series of interactions between multiple visual and motor processes. As already highlighted, visual feedback of the object being grasped provides important information about how to successfully direct an accurate reach and execute a successful grasp. However, successful interaction with an object requires the interpretation of information not only about the target object itself, but also of the object's location in space.

Spatial Reference in the Environment

When interacting with a target object, the immediate environment can provide a rich display of visual information. Although this information tends to be complex (and potentially overwhelming) the human brain is able to interpret various helpful visual cues based on information provided by the eyes, and use them to construct a highly organized spatial representation of the surroundings. When viewing an object, two frames of spatial reference are interpreted to make an accurate judgment about its location. An *egocentric* reference refers to the distance between the target object and the observer, while *allocentric* information refers to information about the distance between the target object and other visual aspects of the environment. When considering the location of a cup on a table, both the distance between the cup and the observer, as well as the distances between the cup and other surrounding objects positioned on the table, are important for establishing and maintaining a spatial reference in regards to the cup's position. The combined information provided by these two reference frames contribute to our ability to judge object movement, distance, and direction (Neely, Heath, & Binsted, 2008), as well as priming the spatial location of a target's location during visual search (Ball, Smith, Ellison, & Schenk, 2009).

Brain imaging studies have identified separate neurological networks believed to be responsible for processing egocentric and allocentric information. Functional

Magnetic Resonance Imaging (fMRI) studies suggest egocentric information is processed largely in the parietal cortex (Neggers, Van der Lubbe, Tamsey, & Postma, 2006; Zaehle, Jordan, Wustenberg, Baudewig, Dechent, & Mast, 2006), while allocentric information is thought to be processed by a diverse network of brain areas (for a review see Ekstrom, Arnold, & Iaria, 2014) including the superior and inferior parietal cortices, occipito-temporal cortices, and the hippocampus (Zaehle et al., 2006).

The Dual Stream Hypothesis of Vision (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982) separates the processes of visual perception and action into two streams, each beginning in the striate cortex of the occipital lobe, and projecting separately toward different brain areas. The Dorsal Stream, projecting from the striate cortex to the posterior parietal region, utilizes visual information for the execution and guidance of motor movements, while the Ventral Stream projects ventrally toward the occipitotemporal cortices, and is responsible for the maintenance of stable, meaningful visual representations. When framed in relation to the Dual Stream Hypothesis, egocentric information is thought to be used predominantly by the dorsal stream, responsible for visually guided actions, and allocentric information is thought to be used predominantly by the ventral stream, responsible for the meaningful perception of the object. This dissociation makes intuitive sense, as the continuous updating of a target object’s location via egocentric visual information is more important for interacting with that object, while information in regards to that object's location in relation to its immediate surroundings is more pertinent for the ‘object-centered’ representation formed by the ventral stream. Patient DF, an individual who suffers from lesions to the ventral stream, shows impaired performance on tasks requiring allocentric spatial processing compared to controls, and performs on par with controls on tasks requiring the processing of egocentric information (Murphy, Carey, & Goodale, 1998). These findings support the hypothesis that the ventral stream is more so responsible for the processing and effective utilization of allocentric information.

Though the integration of both egocentric and allocentric information is important, research has suggested that information provided by each type of reference may contribute to certain actions in different ways. For example, Gangitano, Daprati, and Gentilucci (1998) proposed that when grasping for target objects, the grasp component relies more so on allocentric cues than that of the reach component. Allocentric information is also regarded as being important for learning the layout of a novel environment (Mou, McNamara, Rump, & Xiao, 2006), and memory guided reaching for targets in naturalistic scenes (Fiehler et al., 2014). In impoverished visual conditions, when visual feedback is limited or unpredictable, allocentric information becomes increasingly important for the planning of reach trajectories (Nealy, Tessmer, Binstead, & Heath, 2008).

Occlusion

Perception of depth is another cue that is used to generate an accurate spatial orientation. Depth perception is achieved by inferring information from binocular cues such as eye convergence (the angles at which the eyes converge when looking at a target), and monocular cues such as the object’s relative size in comparison to another object, and occlusion. When a target object moves behind another ‘occluding’ object, we can infer that the target object is positioned behind the ‘occluder’, and therefore a farther distance from the observer. The ability to interpret information about an object either partially or completely hidden behind another object is advantages in numerous scenarios, and would have been selected for during evolution.

Occlusion of stationary objects. Vishwanath, Kowler, & Feldman (2000) investigated where participants were fixating when looking at partly occluded triangles. Their work demonstrated that participants initially focus their gaze toward the center of the visibly available portion of the triangle, rather than the triangle's true center. In other words, when making an initial saccade toward the object, participants did not use the occluded portion of the shape as cues to determine the object's actual center, but instead made a saccade toward the center of the visible portion of the object.

When *grasping* for partially occluded objects however, research suggests that individuals direct their gaze first toward the object's true center, followed by a shift toward the index finger's eventual point of contact, suggesting they are able to extrapolate object information to account for the occlusion (de Grave, Hesse, Brouwer, & Franz, 2008). However, when these index contact points are occluded, the shift of fixations toward the eventual contact point is less pronounced. The authors concluded that partial occlusion of an object does not prevent fixations from being made toward the occluded areas when grasping, however the occlusion does influence the location of these fixations.

Extrapolation of Target Motion Through Occlusion. In daily life, a target we are looking at will often move behind a closer object, resulting in an obstruction of view, and removal of visual feedback. When visually tracking a target object that encounters an occluding object, eye velocity has been shown to decrease significantly (Becker & Fuchs, 1985; Bennet & Barnes, 2003; Churchill Chou, & Lisberger, 2003), followed by saccadic eye movements generated at an overall residual velocity to continue extrapolation of the now-invisible target's movement (Becker & Fuchs, 1985). However, if there is an expected point of reappearance – for example the opposite side of the occluding object – eye velocity will recover to previous levels in anticipation of object's reappearance (Bennet & Barnes, 2003, 2004).

Does the way in which an object disappears have an effect on how we visually pursue it? Churchland, et al. (2003) monitored the eye velocity of rhesus monkeys visually pursuing a horizontally translating target that either moved in and out from behind an occluder or was simply 'extinguished' for a short duration before reappearing at the appropriate point along its trajectory. Extinguishing the target caused eye velocity to significantly decline or stop entirely. Transient occlusion of the target (implied by the presence of a visual occluder), though causing a slight decrease in eye velocity, did not cause as dramatic a decrease as was shown by simply extinguishing the target, and most of the monkeys in this condition showed an anticipatory eye acceleration preceding target reappearance.

The ability to track moving targets through a transient occlusion has been demonstrated in studies involving Multiple Object Tracking (MOT) as well. In certain scenarios, there is a need to visually track multiple objects in motion, and though the objects may be moving in completely different directions, humans are able to maintain attention toward several objects at once, as long as the number of targets is not too large (Scholl & Pylyshyn, 1999). In their 1999 study demonstrating MOT, Scholl and Pylyshyn asked participants to visually track a number of moving target items amongst several distractor items, both of which disappeared in different ways during travel.

Participants were better able to track targets (demonstrated by their ability to identify them as target items rather than distractor items upon completion) that appeared to move behind an occluder than if the object simply vanished for a short duration, or if some other visual effect was imposed, i.e., implosion/explosion cues.

These results suggest humans possess a mechanism that allows for object permanence when visually pursuing a target through occlusion. Scholl and Pylyshyn argued that the presence of visual information implying an occlusion has occurred (i.e., accretion/deletion cues) allows the establishment of a *spatiotemporal continuity mechanism,* and suggests that the object is still present and behaving in a similar way as when it was visible. In scenarios where the object simply vanishes or ‘implodes’, the assumption of object permanence is not maintained, and it becomes more difficult to track the disappeared target.

The Current Study

Though complete and uninterrupted visual feedback is ideal for the execution of such actions as reaching and grasping for an object, we do not always have continuous vision of the objects we wish to grasp. An object becoming occluded is an example of such visual interruption, one that has the potential to occur in daily life. In these situations, visual cues in the environment providing information about a target object’s location that can aid in performing a successful grasp are likely to be relied on more heavily. Based on the evidence highlighted earlier suggesting that allocentric information is beneficial when interacting with aspects of the environment in impoverished visual conditions, it is reasonable to suggest that the presence of environmental cues providing allocentric information will improve an individual’s ability to extrapolate the motion of, and accurately grasp for a target that moves behind an occluder and out of view.

CHAPTER II

GENERAL METHODOLOGY

Two experiments were conducted to examine how individuals use visual cues in the immediate environment to aid in the visual tracking and grasping of translating objects – some of which disappear from view. Both experiments involved performing a grasping task in which participants executed precision grasping movements with their right hand toward a translating white computer-generated target in the shape of a 4 x 4 cm square block (2.75 deg) presented on a black background on a 24 in. (60.96 cm) computer monitor with a height of 12 in. (30.48 cm) and a width of 21 in. (53.34 cm). All testing was conducted in the *Neuropsychology of Vision Perception and Action Lab* at the University of Manitoba. This study was approved by the Psychology/Sociology Research Ethics Board (PSREB) of the University of Manitoba.

Materials and Procedure

At the beginning of the session, participants were presented with a consent form (Appendix A), and after providing their signature were asked several demographic questions regarding sex, age, as well as visual acuity (Appendix B). Handedness was also assessed. Participants were seated with their head stabilized by a chinrest, 50 cm away from the computer monitor. Six infrared light-emitting diodes (IREDs) were placed on the participant's right hand (2 IREDS each positioned on the cuticle towards the left side of the index finger, the cuticle towards the right side of the thumb, and distal radial portion of the wrist), which was then placed with the index finger and thumb pinched together in the 'starting position' on the desk in front of them. Grasping movements were recorded using an Optotrak Certus 3-D motion tracking system (100 Hz sampling rate, spatial accuracy up to 0.01 mm; Northern Digital Inc., Waterloo, Ontario, Canada).

Binocular eye movements were recorded by using Eyelink II software (250 Hz sampling rate, spatial resolution < 0.05 deg; SR Research Ltd., Missisauga, Ontario, Canada) using a head-mounted eye tracking system to which three additional IREDS were placed to measure head movement. Horizontal and vertical gaze coordinates were characterized as fixations if they remained focused on a single location within a 1 cm radius, for a minimum duration of 100 milliseconds, based on a predetermined dispersion algorithm (Salvucci & Goldberg, 2000). The Eyelink was calibrated using a nine-point calibration/validation procedure presented on the computer monitor, followed by an accuracy check, involving participants fixating on a centrally located ‘fixation dot’ for 7 seconds to ensure accurate calibration. Data collection would not begin until calibration/validation was achieved with less than 1 cm of error. Eye, head, and hand data was integrated into a common spatial and temporal frame of reference using the MotionMonitor (MM) software (Innovative Sports Training Inc., Chicago, Illinois, USA), sampled at 100 Hz. The program Sensegraphics was used by MotionMonitor to generate the target and dictate its movement.

Data collection was separated into three blocks, each containing 20 randomized trials. Each block began with an accuracy check to ensure proper Eyelink setup had been achieved, and the gaze data being collected were accurate. The presence of any error exceeding the error threshold (1 cm for Experiment 1, and 0.5 cm for Experiment 2) during an accuracy check resulted in recalibration of the Eyelink, and any data collected immediately preceding or following an accuracy check with unacceptable error values was excluded from analysis. Following accuracy confirmation, the first block of 20 trials began. Participants were not given any instructions regarding where to focus their gaze at the beginning of a trial. A standard trial began with the target appearing on either the far left or far right side of the screen. After approximately 1.5 seconds, the target began to translate horizontally towards the opposite edge of the screen, at a constant speed of 6.49 cm/s (7.43 deg/s). Experimental trials were randomly interspersed with distractor trials, during which the target moved at an accelerated speed of 13 cm/s (14.89 deg/s). Inclusion of the randomly presented distractor trials served to prevent participants from expecting the target to behave predictably on every trial.

During experimental trials, 5.5 seconds after block appearance (4 seconds after onset of block movement) a tone generated by a custom software developed using MATLAB (R2008a, The MathWorks Inc., Natick, Massachusetts, USA) with a duration of 1500 ms was presented, signalling participants to make a natural precision grasping movement toward the on-screen target. During distractor trials, the tone was presented 3.5 seconds after block appearance (approximately 2 seconds after onset of block movement). The timing of tone presentation was manipulated as such to promote consistent reaching towards the centre of the screen during experimental trials, and towards non-central screen positions for distractor trials to prevent participants from habitually reaching towards the same screen location for every trial.

In trials involving occlusion (see *Experimental Design*, Conditions 3 and 4 below), upon hearing the tone (presented 2 seconds following the target's encounter with the occluder – 1.4 seconds after total occlusion of target – for experimental trials) participants executed a reach-to-grasp movement towards the location on the screen where they believed the target to be, as if they were trying to grasp a three dimensional object that had been removed from view. Once the IREDs attached to the index finger reached a designated distance from the screen (threshold of 2 cm), the trial was considered finished, and data collection for that trial ended. Though data collection finished once this threshold was reached, participants were given permission to execute the grasp fully, and make contact with the screen when grasping. Once the threshold was reached, the target (when visible) stopped moving and participants returned their hand to the starting position to await the next trial or accuracy check.

Experimental Design

Both Experiment 1 and 2 were executed as within-subjects, repeated measure designs. This meant that each participant was exposed to both leftward and rightward moving experimental and distractor trials belonging to each of the four conditions described below. Participants completed three blocks of trials, each consisting of 20 randomized trials, including four of each condition type (two rightward moving and two leftward moving trials), and four distractor trials. The result was a total of six leftward moving and six rightward moving trials per participant for each of the following experimental conditions (Figure 1).

Condition 1: Visual feedback (Minimal Cue).

This condition was similar to the design used by Bulloch, et al. (2015), and involved continuous visual feedback of the target for the duration of the trial. The target appeared alone on either the left or right edge of the screen, and after a brief pause began to translate across the screen uninterrupted. Participants were provided with full vision of the target when executing reach-to-grasp movements.

Condition 2: Visual feedback (Enhanced Cue). Condition 2 was identical to Condition 1, with the addition of a number of 1 cm wide and 10.5 cm long visual cues generated by the Sensegraphics program in the form of vertical blue blocks dispersed horizontally by 1.5 cm and displayed along the top and bottom of the screen. Participants were again provided with full vision of the target when grasping.

Condition 3: Occlusion (Minimal Cue). Approximately 2 seconds after onset of target motion the target block encountered an invisible occluding object, and disappeared from view (600 ms transpired from initial encounter to complete target occlusion). The occluder was also a computer-generated block; positioned 17 cm from the edge of the screen (14 cm from the initial position of the target's COM) set to be the same colour as the background, and therefore 'appeared' invisible. The decision to make the target look like it moved behind an occluder rather than simply disappear was based on research by Scholl and Pylyshyn (1999) suggesting that subjects are better able to track disappearing targets that are made to look like they are moving behind an occluding object, rather than targets that simply vanish or disappear by other means. Participants were still required to reach for the target upon hearing the tone, however in this condition visual feedback of the target was not provided at this time and participants were forced to make a judgement regarding its current location behind the occluder when grasping. The additional computer-generated cues were not provided on the screen in this condition.

Condition 4: Occlusion (enhanced cue). This condition involved the target moving behind an invisible occluder as in Condition 3, with the addition of the same computer generated visual cues that were provided in Condition 2 present along the top and bottom of the screen.

Participants were exposed to three blocks of trials, each involving a total of three accuracy checks, 48 experimental trials, and 12 distractor trials by the end of the experiment. Participants were given a short break following completion of the first and second blocks, during which the next set of trials was prepared. Each session took no longer than 90 minutes, and afterwards participants were debriefed, thanked for their participation, and received a copy of the consent form (Appendix A).

The observation could be made that in conditions without any computer generated on-screen cues, participants may still have been be able to extract allocentric information from the immediate environment (e.g., edges of the computer screen) when reaching for the target. With this consideration, any effect associated with the presence of additional cues in the *Enhanced Cue* conditions was attributed to an *increased* amount of allocentric information provided by the computer-generated blocks along the top and bottom of the screen. Conditions which involved the absence of on-screen cues were considered to be providing minimal amounts of allocentric information compared to the *Enhanced Cue* conditions, rather than be regarded completely void of any possible allocentric information.

Additionally, the argument may be made that people do not grasp for two-dimensional targets the same way they would for three-dimensional objects, and therefore any observations made here may not translate to interactions with 3-D objects in the real world. For example, cues providing depth information regarding the object’s structure, and haptic feedback provided when making contact with the object that would normally be present when interacting with 3-D objects are not present when viewing and grasping

2-D targets. Several studies have suggested kinematic differences, as well as separate neural correlates responsible for the grasping of 3-D and 2-D objects (Goodale, Meenan, Bulthoff, Nicolle, Murphy, & Racicot, 1994; Kroliczak, Cavina-Pratesis, Goodman, & Culham, 2007; Vingerhoets, 2014; Whitwell, Ganel, Byrne, & Goodale, 2015).

However, Desanghere and Marotta (2011) demonstrated that the gaze and grasp strategies used when perceiving and grasping 2-D objects are similar to those used when interacting with 3-D objects, suggesting that similar strategies are being utilized. Nevertheless, to address these concerns, the target (when visible) was programmed to stop when the participant's fingers reached within 2 cm of the screen, and participants were allowed to make contact with the screen, providing terminal feedback which has shown to improve grip scaling when executing pantomimed grasps (Whitwell et. al., 2015). Additionally, participants were instructed to grasp for the target as if it were a 'natural 3-D object' at the beginning of each session.

Data Analysis

Two separate 2 x 2 x 2 repeated measures ANOVAs were conducted to analyze the influence of Visual Feedback (visible target versus occluded target), Cue Presence (additional cues present versus absent), and Direction of target motion (leftward versus rightward movement) on the average horizontal and vertical distances from final index placement to target COM, and from the average final fixation locations to the average final index placements. A single 2 x 2 x 2 repeated measures ANOVA was conducted on average wrist deceleration periods. Average Horizontal and vertical fixation locations in relation to the target's COM were analyzed at two separate time points using two repeated measures 2 x 2 x 2 x 2 (Visual Feedback by Cue Presence by Direction by Time

Point) repeated measures ANOVAs. In conditions involving occlusion, a 2 x 2 repeated measures ANOVA was run to test for an influence of Cue Presence and Direction on the average duration participants remained fixated at the point of target occlusion.

To examine how well participants were able to extrapolate the motion of the target across conditions, a Root-Mean-Square-Error (RMSE) analysis was conducted on horizontal gaze position relative to the target's COM during three separate time periods: 1) From the onset of target movement to the point of occlusion (duration approx. 2 seconds), 2) From the point of occlusion to the presentation of the reach tone (duration approx. 1 second), and 3) From the presentation of the reach tone to the time of contact (duration approx. 1 second). This analysis involved determining the horizontal distance from participant's gaze to the target's COM at each frame (collection occurred at 100 frames per second), the result of which was a position-error value for each frame of data collected. Error values per frame within each time period were then squared, averaged, and the square root of this mean error value was calculated to determine a RMSE value indicative of overall pursuit error for each time period within a particular trial. Average RMSE values were compared at the three time periods using a 2 x 2 x 2 x 3 (Visual Feedback by Cue Presence by Direction by Time Period) repeated measures ANOVA. When interactions were present, post-hoc pair-wise comparisons were carried out using a Bonferroni correction. All analyses were conducted using alpha = .05.

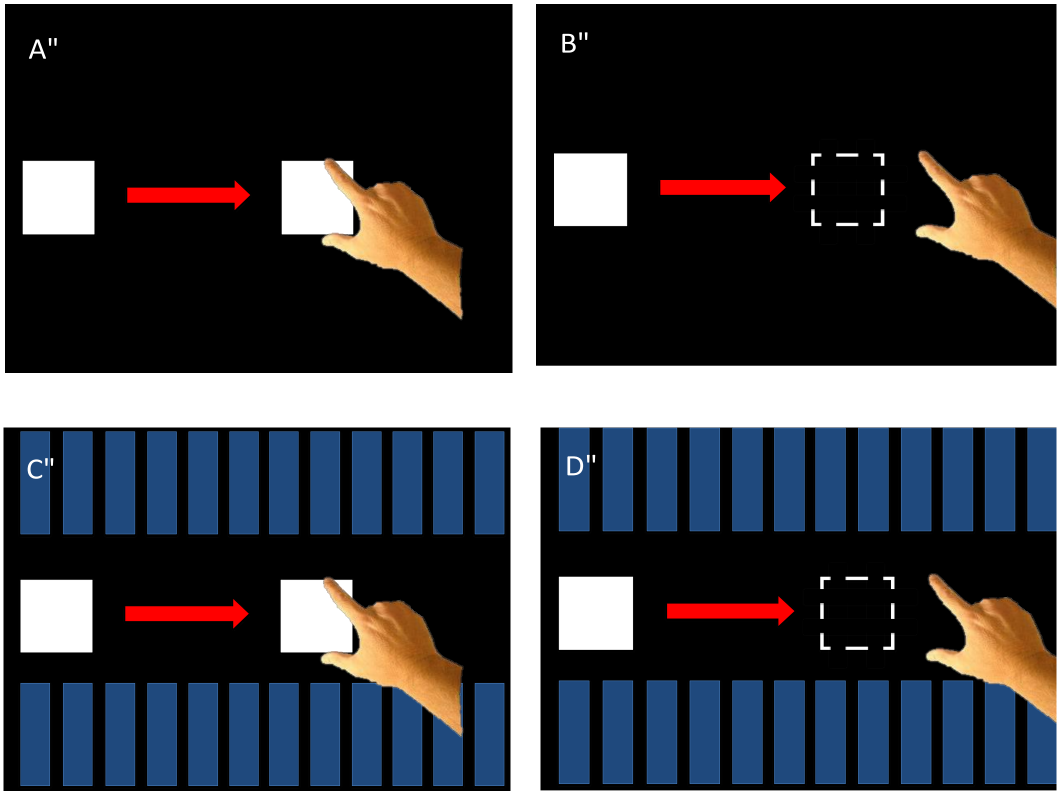

Figure 1. Representation of the four experimental conditions. Arrows represent direction of target motion (all examples are rightward moving trials). In conditions involving occlusion, outlined target represents actual location of occluded target at time of grasp. A) Visual Feedback (Minimal Cue): The target remains visible for the duration of the trial, and when participants hear the auditory tone they reach for the visible target, demonstrated here by the grasping hand. There are no additional cues provided on the screen. B) Occlusion (Minimal Cue): The target appears to move behind an invisible occluder during travel, and participants reach for where they believe the target to be when the tone is sounded. No additional cues are provided on the screen. C) Visual Feedback (Enhanced Cue): The target is visible for the duration of the trial. Allocentric cues in the form of blue blocks are provided along the top and bottom of the screen. D) Occlusion (Enhanced Cue): The target appears to move behind an invisible target, and once they hear the tone, participants reach for where they believe the target to be. Allocentric cues are provided.

CHAPTER III

EXPERIMENT 1

Participants

Nineteen adults (14 female; aged from 18 to 38, mean age 20.5 years) were recruited from the undergraduate psychology research subject pool at the University of Manitoba and participated in exchange for credit towards a course requirement. All participants had normal or corrected to normal vision, and were right-hand dominant, as determined by a modified version of the Edinburg handedness inventory (Oldfield, 1971). Corrective lenses were permitted, however eyeglasses were not.

Allocentric Cue Presence

In Experiment 1, the additional allocentric cues (1 cm wide and 10.5 cm long) present in Conditions 2 and 4 were lined along the top and bottom of the screen, leaving a 9 cm space along the middle of the screen for the target to travel. This meant that in conditions involving cue presence, a 2.5 cm space separated the target from the cues above and below.

Hypotheses

Hypothesis 1: In conditions involving occlusion, grasps will be more accurate when allocentric cues are present on the screen than when absent, as measured by final index finger location and wrist deceleration period (WDP). Previous research has demonstrated the benefit of providing allocentric information when grasping target objects (Gangitano et al., 1998). Based on these findings, it was expected that participants would make more accurate grasps when there were an increased number of cues on the screen than when there were none. In particular, cue presence was expected to provide a benefit in conditions involving occlusion, as allocentric information has been suggested to aid in pointing (Camors, Jouffrais, Cottereau, & Durand, 2015) and grasping accuracy in situations when visual information is either absent or unreliable (Fiehler et al., 2014; Neely, et al., 2008).

When precision grasping 3-D objects (i.e., grasping with the index finger and thumb), people prefer to grasp an object with their index finger above, and their thumb below the object, located at grasp locations that if connected by an invisible grasp line, would pass through that object's COM, achieving the most stable grasp possible (Endo, Wing, & Bracewell, 2011). When grasping a square, as was the case here, optimum stability would be achieved with grasp points located directly above and below the target's COM. Therefore, for the purpose of the current experiment, an 'accurate grasp' was one that placed the index finger in such a way that its horizontal coordinates were close to those of the target's COM. In the vertical axis, a grasp was considered more accurate the closer the index finger's vertical coordinates were to the top edge of the target (2 cm above target COM).

For this study, the index finger rather than the thumb was chosen as an indicator of grasp accuracy due to numerous studies highlighting the importance of the index finger when executing an accurate grasp. As already mentioned, individuals tend to fixate their gaze toward the eventual location of the index finger when grasping (Bulloch et al., 2015; Desanghere & Marotta, 2011; Voudouris et al., 2015). Additionally, the index finger is usually the first digit to make contact with the object being grasped (Cavina-Pratesi & Hesse, 2013). For these reasons, an 'accurate grasp' was expected to have a minimal horizontal distance between final index finger location and target COM, and a vertical distance of approximately 2 cm above target COM.

It is relevant to note that the current design involves a 2 cm ‘index-to-screen’ threshold, which will cause data collection to end slightly before the digits reach the screen. Though this threshold was minimized from previous studies to 2 cm, there may have potentially been some minor variance when it came to determining the final location of the index finger at the end of the grasp, and its relation to the target’s COM. During the reach, the participant’s digits may have approached the screen at an angle that caused the index finger to reach the threshold before reaching the top edge of the target (i.e., ‘swooping’ upward at the end of the reach). Participants were monitored for any ‘swooping’ behaviour and trials of this nature were omitted from analysis, in attempts to keep final index finger data as accurate as possible.

When grasping for a target object, an extended reach duration can be interpreted as a lack of confidence about the location of the target, demonstrating the need for more time to correct for error and succeed in making an accurate reach (Tijtgat, Bennet, Savelsbergh, Clercq, & Lenoir, 2011). When cues were present on the screen, shorter deceleration periods when reaching for targets would suggest that the allocentric information being provided was helpful to the grasping process, and reduced the amount of uncertainty when reaching for the invisible target. Therefore, WDP was used as an indication of participant’s confidence regarding the position of the target.

Hypothesis 2: In conditions involving occlusion, the eyes will revert from smooth pursuit to saccadic movement in attempts to extrapolate the motion of the disappeared target. Previous work with target occlusion has demonstrated that eye velocity drastically decreases once the target is removed from view (Becker & Fuchs, 1985; Bennet & Barnes, 2003; Churchill et al., 2003), and focus on a moving stimulus is required for the eyes to execute smooth pursuit tracking (Rashbass, 1961). It was expected that the removal of visual feedback caused by occlusion would create a scenario in which the eyes would no longer be able to achieve smooth pursuit when following the target, and participants would revert to horizontal saccadic eye movements to decrease the developing position error.

In studies involving transient occlusion, an increase in eye velocity has been associated with object reappearance, and participants tend to move their gaze toward the opposite edge of the occluding object, where they expect the target to reappear (Bennet & Barnes, 2003, 2004; Churchill, et al., 2003). In the real world, objects being visually pursued often disappear or become occluded without a definitive point from which to reappear from. For example, it would be more beneficial for a predator to be able to judge the location of its prey in a patch of tall grass, rather than be forced to wait for it to reappear at the edge. As such, there was no expected point of target reappearance in the current design, and a ‘jump’ to a particular location after target disappearance was not predicted.

Hypothesis 3: In conditions involving occlusion, final fixation points at time of contact will be closer to target’s COM (in both the horizontal and vertical axes) when allocentric cues are provided on the screen (Condition 4) than when they are absent (Condition 3). When grasping stationary objects, following a shift toward the target’s top edge at onset of reach, the eyes have been shown to shift downward, toward the target’s COM (Desanghere & Marotta, 2011). Assuming the additional cues provided on the screen are helping participants track and accurately judge where the invisible target is as it moves across the screen, final gaze position was expected to be more accurate in the presence of cues than in trials where the cues were absent. Distances between final fixations and the target's COM were calculated in both the horizontal and vertical dimensions allowing for an analysis of where in relation to the target's COM participants were directing their gaze at time of contact with the screen.

Results

Gaze Measurement Accuracy

Accuracy checks were conducted at the beginning of each block of trials, and an observed error of 1 cm or higher in either axis resulted in re-calibration and validation of the Eyelink system before further data collection was carried out. The average absolute error combined across all participants was 0.43 cm in the horizontal axis, and 0.54 cm in the vertical axis. The average displacement error across participants was 0.27 cm (SE = 0.05) to the left and 0.01 cm (SE = 0.01) below the fixation dot in the horizontal and vertical axes respectively.

Grasp Accuracy

For the purposes of this study grasp accuracy was considered as the distance from final index placement at time of contact to the target's COM in the horizontal plane, and to the top of the target (2 cm above the COM) in the vertical plane.

Horizontal axis. When grasping visible targets, average final horizontal index placement was always positioned to the left of the target's COM (i.e., ahead of the COM for leftward moving targets and behind the COM for rightward moving targets), and within 1 cm of the target’s COM, demonstrating what would be a considered a reasonably ‘stable grasp.’ When grasping occluded targets, mean final index placement was always behind the target’s COM (i.e., to the left of the target’s COM for rightward moving trials and to the right of the target’s COM for leftward moving targets.

Overall, average final index finger placement was more accurate when grasping for leftward moving targets. This was confirmed by a significant [F(1,18)=6.250, p = .022] Cue Presence by Direction interaction (Figure 2), which suggested a significant effect of Direction when collapsing across Visual Feedback in both the presence (p < .001) and absence (p = .002) of cues. Additionally, when reaching for rightward moving targets, average index placement was positioned significantly (p = .047) closer to the target’s COM in the absence of cues, compared to when the cues were present. No effect of Cue Presence was found for leftward moving targets, and Visual Feedback had no significant influence on final index placement.

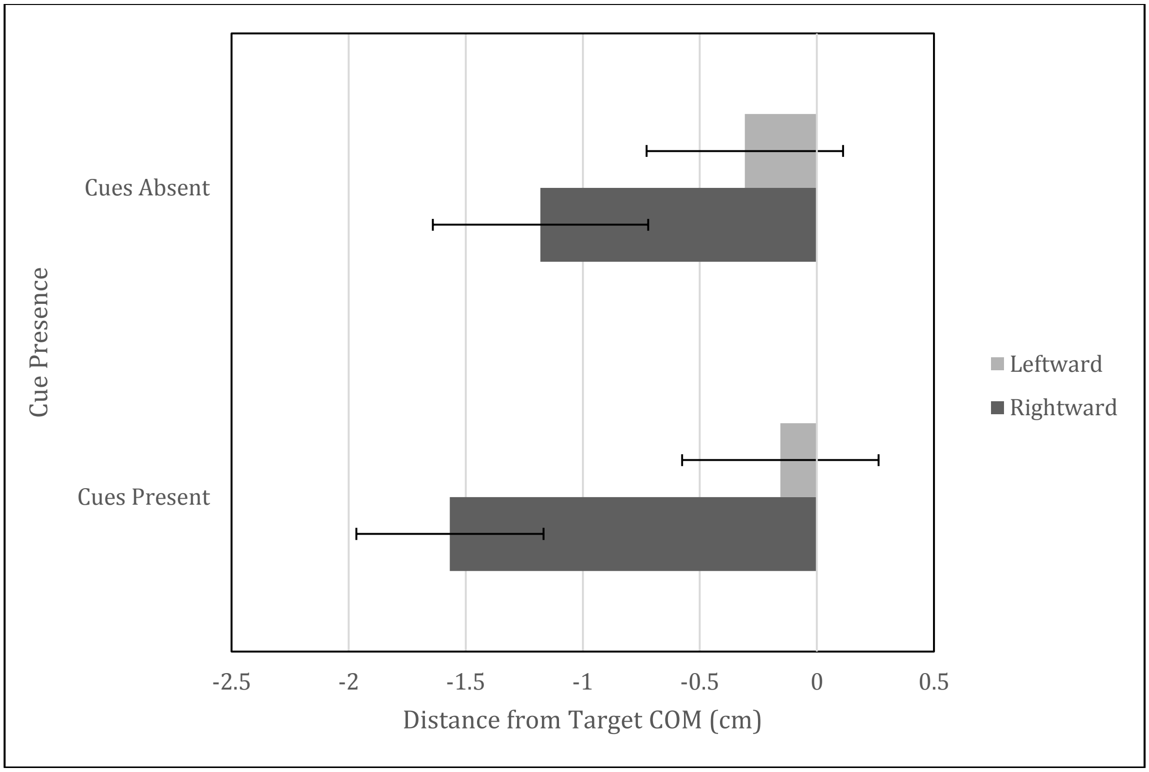

Figure 2. Average horizontal distance from final index position to target COM collapsing across target visibility. Negative values refer to distance *behind* target COM. Error bars represent standard error of the mean.

Vertical axis. The three-way repeated measures ANOVA revealed a significant Visual Feedback by Cue Presence interaction [F(1,18)=8.465, p = .009], suggesting mean final vertical index placement was positioned significantly higher when grasping visible and occluded targets in the absence of cues (Figure 3). Direction of target motion had no significant influence on vertical index position when grasping.

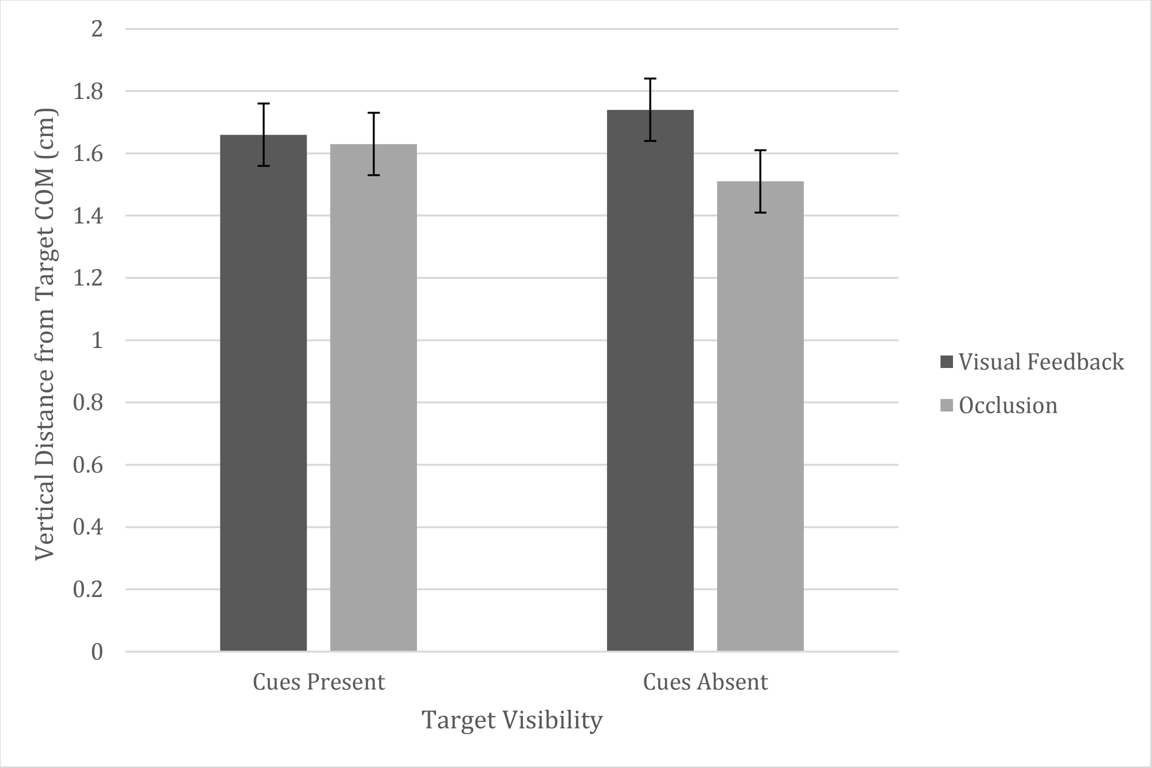

Figure 3. Average vertical distance from final index placement to target COM collapsing across direction. Error bars represent standard error of the mean.

Overall Gaze Analysis

Figure 4 represents the visual pursuit strategies utilized during a typical trial involving available visual feedback throughout. Smooth pursuit (Rashbass, 1961) is maintained for the duration of the trial, accompanied by several ‘catch-up’ saccades. Figure 5 represents the visual pursuit strategies during a typical trial involving occlusion of the target. While visual feedback of the target was available, participants were able to maintain smooth pursuit eye movements to visually pursue the target. However, the removal of visual feedback by occlusion was associated with a transition from smooth pursuit to saccadic eye movements to extrapolate the target’s motion.

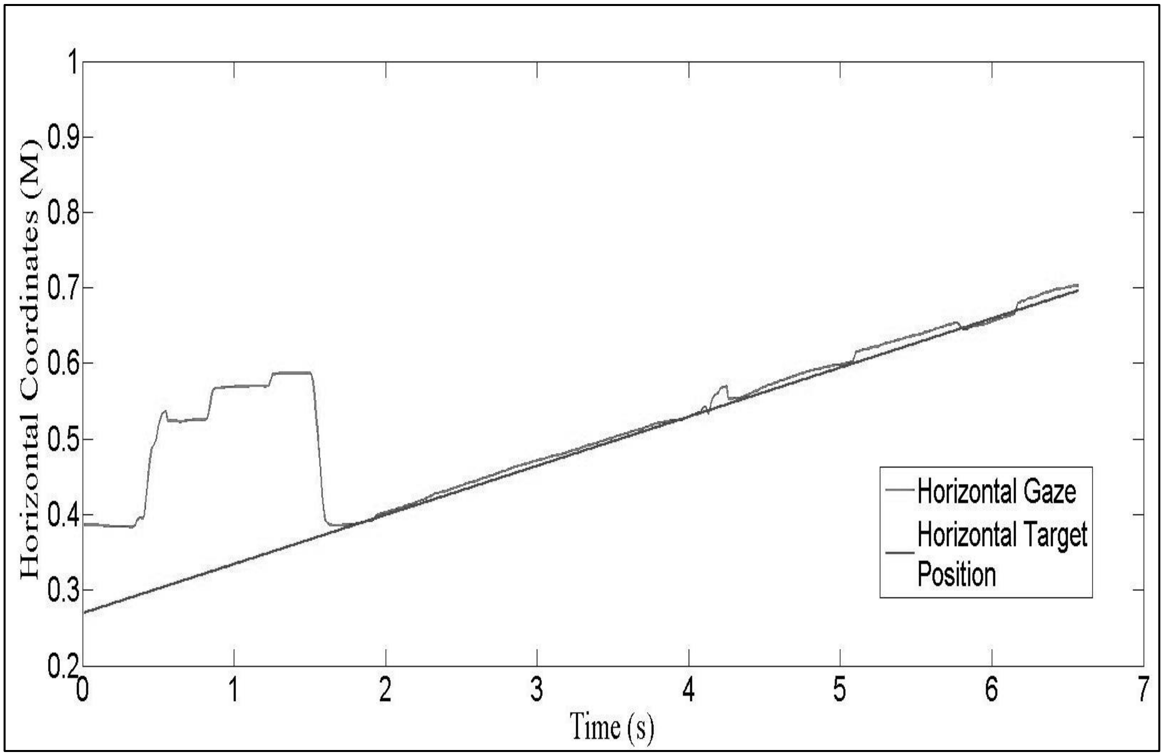

Figure 4. Example of a rightward moving trial with visual feedback throughout. Vertical axis refers to horizontal position, and therefore increasing values indicate movement in the rightward direction. ‘Reach tone’ presentation occurs at 5.5 seconds.

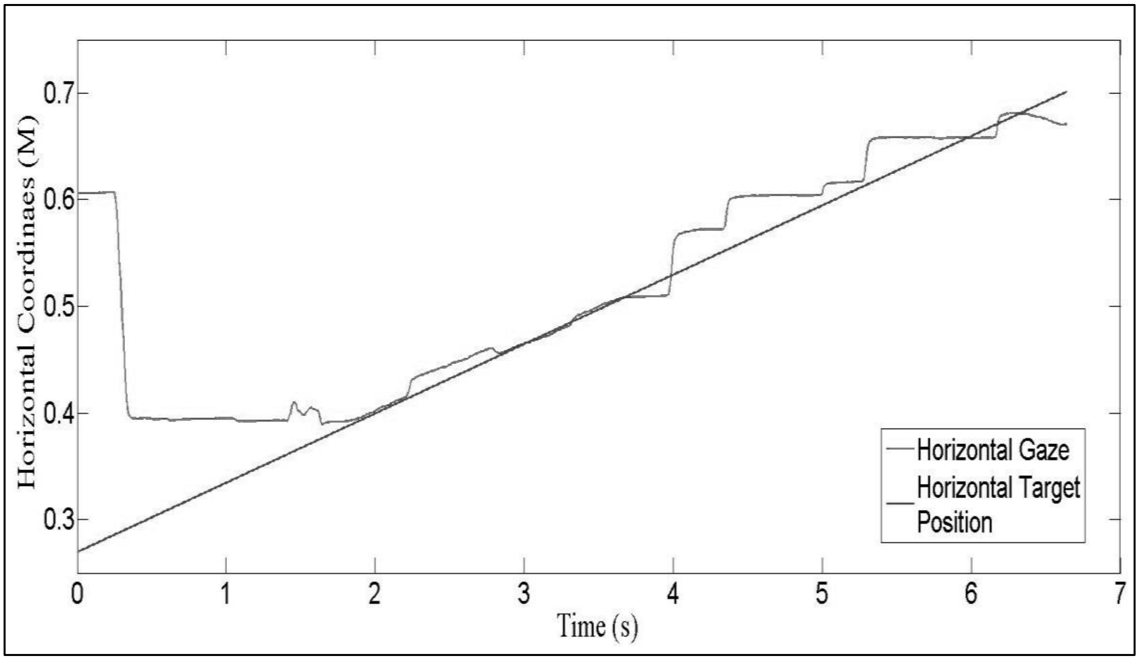

Figure 5. Example of a rightward moving trial with occlusion. Vertical axis refers to horizontal position, and therefore increasing values indicate movement in the rightward direction. Occlusion begins at 3.7 seconds, and 'reach tone' presentation occurs at 5.5 seconds.

Fixations Made at Target Occlusion.

Previous studies involving transient occlusion have demonstrated a tendency for eye velocity to diminish following occlusion, followed by a movement of the eyes to the expected point of target reappearance (i.e., the opposite side of the occluding object). However, because there was no obvious point of reappearance in our study, this behaviour was not observed. Once the target encountered the occluding object, participants abandoned the use of smooth pursuit eye movements and maintained an initial fixation on the front edge of the occluding object (M=445.16 ms, SE=11.31), presumably attempting to maintain sight of the target as long as they could before reverting to saccadic movement to extrapolate its motion. A 2 x 2 (Direction by Cue Presence) repeated measures ANOVA indicated no significant differences in fixation duration across Direction of target movement or Cue Presence.

Root-Mean-Square-Error Analysis

A 2 x 2 x 2 x 3 repeated measures ANOVA was conducted to examine the influence of Visual Feedback, Cue Presence, and Direction on visual pursuit error during three specific time points. Neither Direction nor Cue Presence had any significant influence on mean RMSE values. However, a significant Visual Feedback by Time interaction (Figure 6) was revealed [F(2,17)=30.298, p < .001], and post hoc analyses indicated significant differences in mean RMSE values between visual feedback and occlusion conditions during Time Periods 2 (p < .001) and 3 p (<.001), but not during Time Period 1, when the target was visible in all conditions.

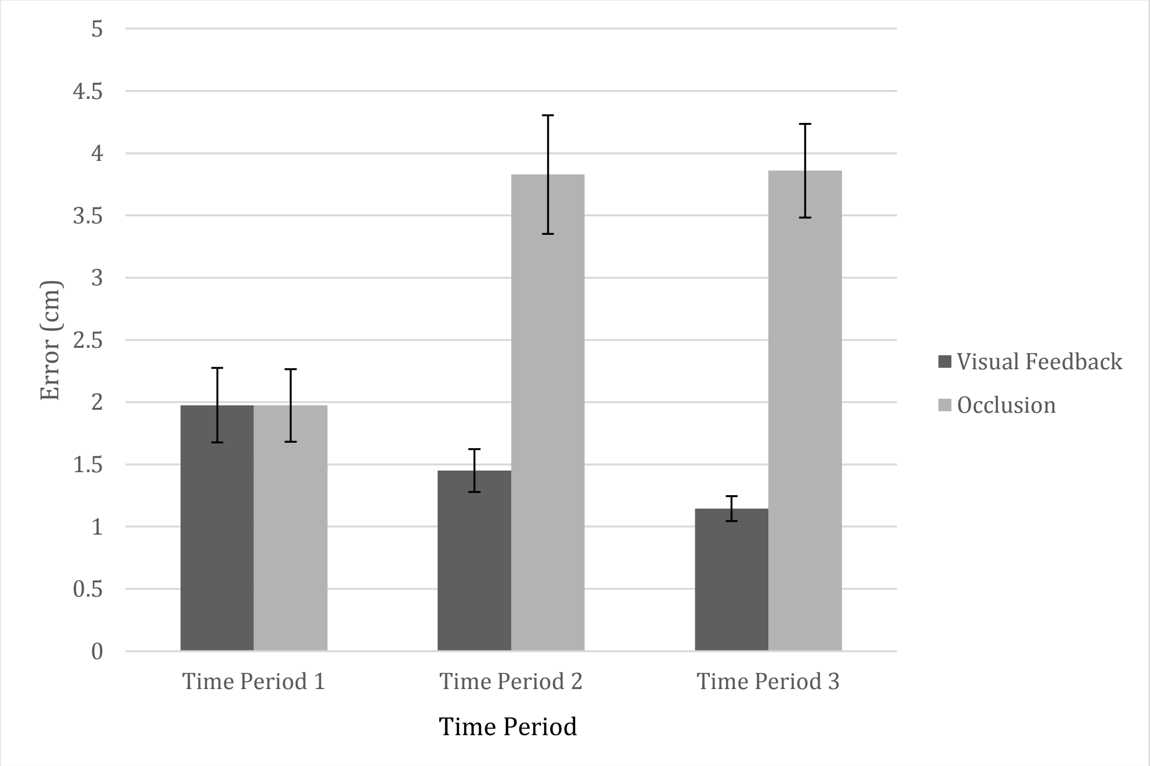

Figure 6. Average RMSE per time period collapsing across direction and cue presence. Error bars represent standard error of the mean.

During occlusion trials, average RMSE values for Time Period 1 were significantly lower than average RMSE values for Time Periods 2 ($p = .001$) and 3 ($p < .001$). There were no significant differences between average RMSE values for Time Periods 2 and 3 when the target was occluded. Interestingly, in regards to visual feedback trials, RMSE values for Time Period 1 were significantly larger than for Time Periods 2 ($p = .043$) and 3 ($p = .007$), even though the target was visible for each of these periods. Further, average RMSE for Time Period 2 were significantly ($p = .05$) larger than for Time Period 3 when the target was visible.

Fixations in Relation to Target COM

In addition to measuring how well participants were able to reproduce the target's movement across conditions, the average horizontal and vertical distances from fixation location to the target's COM were investigated at: 1) Initiation of reach: The point in time participants' wrists reached a speed of 5 cm/s, and 2) Time of contact: The time at which the participant's finger reached within 2 cm of the screen, at which point the block (when visible) stopped moving, and data collection ended. To achieve this, two 2 x 2 x 2 x 2 repeated measures ANOVA were run to test for the effects of Visual Feedback, Cue Presence, and Direction on fixation locations at reach onset and time of contact.

Horizontal axis. A Visual Feedback by Time interaction (Figure 7) was found to be significant [$F(1,18)=89.317$, $p = < .001$], and post-hoc analyses revealed significant differences between gaze position at reach onset and time of contact when the target was visible ($p < .001$) as well as occluded ($p < .001$). Collapsing across Direction and Cue Presence, mean horizontal gaze was consistently focused ahead of the target's COM at reach onset, and behind the target's COM at time of contact for both visual feedback and occlusion conditions. Though not significantly different, horizontal fixations made at both time points were closer to the target's COM when visual feedback was available, compared to when the target was occluded. However, average gaze at both time points remained 'on target' (i.e., positioned within a 2 cm horizontal displacement of the targets COM) even when visual feedback of the target was unavailable. Direction and Cue Presence had no significant influence on horizontal fixation location at reach onset or time of contact.

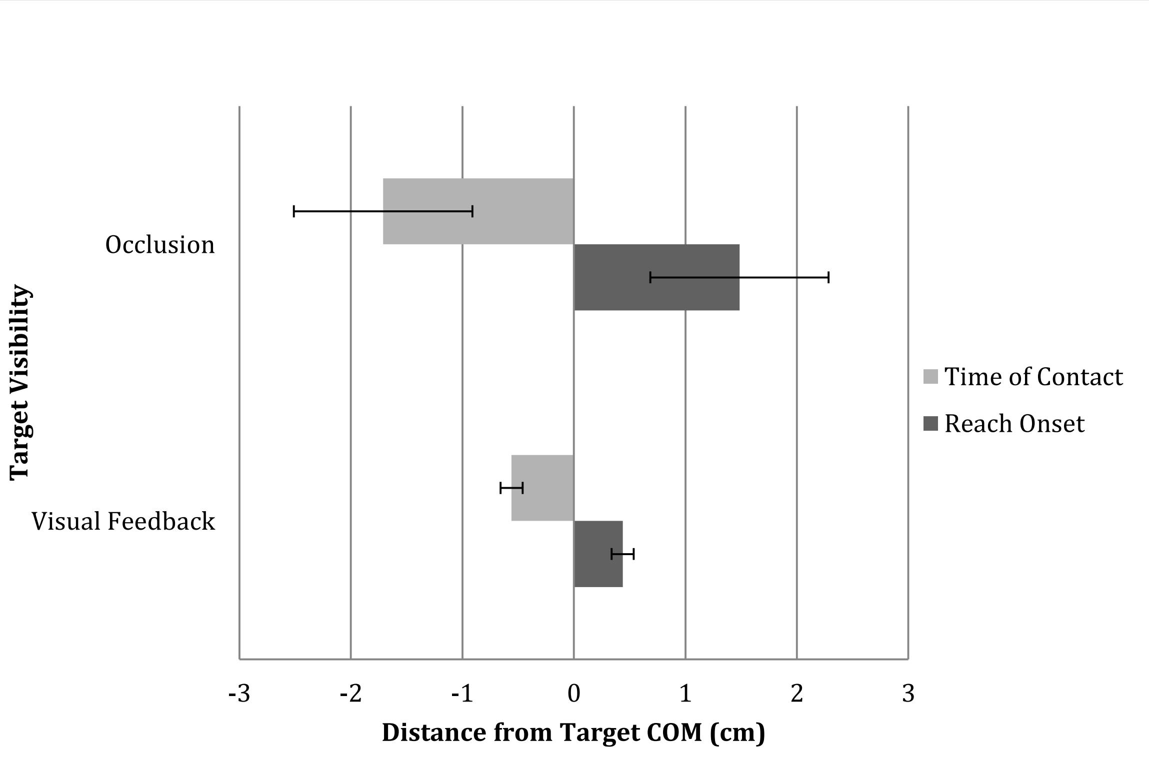

Figure 7. Average horizontal distance from fixation to target COM at reach onset and time of contact collapsing across direction and cue presence. Negative values refer to distance *behind* target COM. Error bars represent standard error of the mean.

Vertical axis. Vertical fixations at both reach onset and time of contact were positioned above the target's COM, and remained 'on target' (i.e., positioned within a 2 cm vertical displacement of the target's COM). A main effect of Visual Feedback was found to be significant [F(1,18)=9.794, p = .006) and on average, participants fixated higher on the target when visible feedback was provided, at a mean height of 1.33 cm (SE = 0.14) above the target's COM compared to a mean height of 1.10 cm (SE = 0.15) when the target was occluded.

A marginally significant [F(1,18)=3.968, p = .062) Visual Feedback by Cue Presence interaction was found, and despite not reaching significance at the p < .05 level, a non-significant trend emerged, suggesting that in the absence of cues, participants tended to fixate their gaze higher above the target's COM when it was visible (M = 1.35 cm, SE = 0.15, above the target's COM) than when occluded (M = 1.0 cm, SE = 0.15, above the target's COM), though no significant differences were found between visible and occluded targets when the cues were present. When the target was occluded, cue presence was associated with fixations made higher above the target's COM (M = 1.20 cm, SE = 0.16) than when the cues were absent (M = 1.0 cm, SE = 0.15), and Cue Presence had no significant effect when the target was visible.

Also revealed was a significant three-way Cue Presence by Direction by Time interaction [F(1,18)=4.474, p = .049], however Post-hoc analyses revealed only a single significant mean wise comparison. Collapsing across visual feedback, when reaching for leftward moving targets, gaze at time of contact was associated with significantly (p = .012) higher fixations when cues were present (M = 1.37 cm, SE = 0.17) compared to when the cues were absent (M = 1.13, SE = 0.15).

Distance from Fixations at Time of Contact to Final Index Placement

Horizontal axis. A significant main effect of Direction was revealed [F(1,18)=7.784, p = .012]. On average, when grasping rightward moving targets participants focused their gaze at the same horizontal location they placed their index finger when grasping the target (Mean distance of 0.02 cm ahead of index, SE = 0.15). However, when grasping leftward moving targets, horizontal gaze position was focused an average of 0.7 cm (SE = 0.13) behind the final horizontal index position (i.e., participants were grasping *ahead* of where they were looking). Visual feedback and Cue Presence had no significant influence on the average horizontal distance from fixation at time of contact to final index placement.

Vertical axis. A Cue Presence by Direction interaction was found to be significant [F(1,18)=4.528, p = .047], and post-hoc analyses revealed that when grasping leftward moving targets, participants were looking on average significantly (p = .033) closer to where they placed their index finger in the presence of cues (M = 0.32 cm below final index placement, SE = 0.19) than when the cues were absent (M = 0.51 cm below final index placement, SE = 0.19). This difference was not significant for rightward moving targets. Visual feedback had no significant influence on vertical distance from fixations made at time of contact to final index placement.

Wrist Deceleration Period

A Visual Feedback by Direction interaction was found to be significant [F(1,18)=10.709, p = .004]. Post-hoc analyses revealed that when reaching for leftward moving targets, average WDPs were significantly (p = .001) longer when reaching for occluded targets (M = 437.43 ms, SE = 23.68) than for visible targets (M = 393.88 ms, SE= 22.01), though reaches for rightward moving targets showed no significant difference in average deceleration periods between visible and occluded conditions. Reaches for occluded targets moving leftward (M = 437.43 ms, SE = 23.68) yielded significantly ($p < .001$) longer average WDPs than reaches for occluded rightward moving targets (M = 382.0 ms, SE = 21.73), though this effect of Direction was not found for visible targets. Cue Presence had no significant influence on WDPs.

Discussion

The goal of Experiment 1 was to observe how participants use eye-movements to extrapolate the motion of, and grasp for a horizontally translating target that was either visible for the duration of the trial or disappeared behind an occluding object during travel. The presence of additional computer generated blocks along the top and bottom of the screen was manipulated to observe how an increased amount of allocentric information influences visual pursuit strategies and grasp accuracy when interacting with visible compared to disappeared targets

In general, the results suggest that participants were fairly accurate at judging the location of the moving target regardless of whether it was visible or occluded. Both average final index placement and average fixations made at time of contact were positioned within 2 cm to the left or right of the occluded target's COM along the horizontal axis (with the exception of grasps made for rightward moving occluded targets in the presence of cues, which on average were placed slightly behind the target's trailing edge). Though not significantly different, a trend was observed suggesting participants executed grasps located closer to the target's COM in conditions involving visual feedback compared to occlusion trials.

Previous work in our lab has demonstrated that when grasping for moving targets, index placement is consistently to the left of the target's COM for both rightward and leftward moving targets (Bulloch et al., 2015). This finding was replicated here in trials involving continuous visual feedback. When reaching for occluded targets however, grasps were consistently made behind the target's COM (i.e., to the left for rightward moving trials, and to the right for leftward moving trials). Grasps were also made consistently closer to the target's COM when reaching for leftward moving targets in both visible and occlusion conditions.

Consistent with the Hypothesis 2, smooth pursuit was predominantly used to pursue the target when visual feedback was provided. In the event of target occlusion, participants discontinued their pursuit of the target, and remained fixated on the edge of the occluding object until visual feedback of the target was completely removed, at which point horizontal saccadic eye movements were used to extrapolate target movement. In trials involving continuous visual feedback, smooth pursuit was achieved throughout the trial.

A Root-Mean-Square-Error analysis was used to observe how accurately participants were able to reproduce the target's movement with their eyes, and to compare the amount of pursuit error in the horizontal axis between visual feedback and occlusion conditions. Prior to target occlusion (Time Period 1), pursuit error was similar in both visual feedback and occlusion trials, as the target was visible in both conditions. Average pursuit error at both levels of visual feedback was approximately 2 cm, suggesting participants were focusing their gaze toward the leading edge of the target when visible. In occlusion trials, RMSE values were significantly higher following target disappearance (Time Periods 2 and 3), whereas in visual feedback trials, RMSE values decreased significantly from Time Period 1 to 2, and again from 2 to 3, suggesting that participants pursued the target more accurately toward the end of the trial. Presumably, participants felt they could casually pursue the target during Time Period 1, when they could be certain it would be visible in both visual feedback and occlusion conditions. The transition from Time Period 1 to 2 likely drew their attention to the target, as the potential for the target to disappear was increased. The fact that Time Period 3 resulted in the lowest error values when the target was visible is likely due to participant's focusing their gaze towards the horizontal coordinates of the visible target's COM (Bulloch et al., 2015; Desanghere & Marotta, 2011) to ensure an accurately placed grasp was carried out.

Of particular interest was the location participants focused their gaze in relation to the target's COM at the time they initiated their reach toward the target as well as once they made contact with the screen. Mean fixations made at reach onset were positioned ahead of the target's COM, whereas average fixations were made behind the target's COM at time of contact, regardless of Direction or Visual Feedback. As was found with final index position, fixations made at both time points were closer to the target's COM along the horizontal axis when visual feedback was provided, however this difference did not reach significance. Mean horizontal and vertical fixation position at both time points were made consistently 'on-target'.

Whereas final horizontal index placement was positioned closer to the target's COM when grasping leftward moving targets, this influence of Direction was not observed in regards to the horizontal distance from fixations made at time of contact to the target’s COM. When grasping leftward moving targets, final horizontal index position was found to be significantly ahead (i.e., to the left) of where participants focused their gaze at time of contact. When grasping rightward moving targets however, this separation was not observed, and participants placed their index finger at the same horizontal position as their fixation at this time. This extra ‘push’ of the hand ahead of horizontal gaze position when grasping leftward moving targets may have contributed to the increased grasp accuracy seen when reaching for leftward moving targets.

Previous research has linked visual uncertainty to extended reach duration, in particular during the end stages of the reach (Churchill et al., 2000; Desmurget et al., 2005; Tijtgat, et al., 2011). For the purposes of this study, mean WDP was used as an indicator of how confident participants were about the location of the target when grasping, and therefore longer WDPs were expected when participants were not confident about the location of the target. Mean WDPs were longer when reaching for occluded targets than for visible ones, but only for leftward moving targets, and reaches for occluded leftward moving targets were associated with longer WDPs than reaches for occluded rightward moving targets. This influence of direction of target movement is potentially due to mechanical constraints associated with executing a visually guided reach across the body (Carey, Hargreaves, & Goodale, 1996), and participants may have required more time to execute an accurate reach when visual feedback of the target was unavailable. As mentioned previously, grasps made for leftward moving targets were placed consistently closer to the target’s COM, perhaps due to the execution of a more cautious reach. The fact that WDPs were not significantly different across the levels of visual feedback when reaching for rightward moving targets suggests that reaches made using the right hand for targets on the ipsilateral side are quicker and impose less mechanical constraints than reaches for targets on the contralateral side.

It was hypothesized that providing an increased amount of on-screen allocentric cues would help participants judge the location of the occluded targets, and enable them to make grasps that were more accurate than when the cues were absent. Surprisingly, Cue Presence had limited influence on where participants focused their gaze or their grasp accuracy, and in some cases, the presence of cues even appeared to impair grasp accuracy. For example, when the additional cues were present, mean horizontal index finger placement when grasping occluded rightward moving targets was significantly farther from the target's COM than when the cues were absent.

Rather than provide a benefit, the additional allocentric cues may have acted as a distraction, making it harder for participants to pursue the block. When grasping leftward moving targets, vertical fixations were made higher on the target in the presence of cues compared to when the cues were absent, suggesting attention was being directed towards the presence of the cues. Alternatively, participants may have treated the cues as 'obstacles' when reaching for the target (Tipper, Howard, & Jackson, 2010), which would explain the impaired grasp accuracy observed in the presence of cues. The results observed in Experiment 1 give rise to the following question: If the on-screen cues were acting as a distraction or obstacle when visually pursuing and reaching for the targets, would a larger separation between the cues and the target eliminate any interference being caused? To address this issue, a second experiment was conducted, in which the additional allocentric cues were placed farther above and below the targets path, in an effort to produce a beneficial influence of allocentric cue presence, rather than the potential interference observed in Experiment 1.

CHAPTER IV

EXPERIMENT 2

Participants

Eighteen adults (15 female; aged from 18 to 33, mean age 20 years) were recruited from the undergraduate psychology research subject pool at the University of Manitoba and participated in exchange for course credit. As in Experiment 1, all participants had normal or corrected to normal vision, and were right-hand dominant, as determined by a modified version of the Edinburg handedness inventory (Oldfield, 1971). Corrective lenses were permitted, however eyeglasses were not.

Allocentric Cue Presence

The experimental procedure carried out in Experiment 2 was identical to the one used in Experiment 1, with the exception of the on-screen cue positions. In attempts to avoid any possible interference or distraction caused by cue presence, the cues were resized (1.5 cm wide by 8 cm long) to produce a larger separation (5 cm) between the cues and the target’s top and bottom edge.

Hypotheses

The hypotheses for Experiment 2 were the same as those for Experiment 1 (*see Experiment 1: Hypotheses*). It was predicted that when additional allocentric cues were present, final grasp and gaze accuracy would prove more accurate, which was not the case in Experiment 1. WDPs were expected to be shorter in the presence of cues than when absent, as the on-screen cues would no longer act as a distraction or obstacle when visually pursuing and reaching for the target, which may have caused the trend seen in Experiment 1.

Results

Gaze Measurement Accuracy

To ensure participant eye data was being collected with optimum accuracy, the observed error that would result in re-calibration and validation of the Eyelink system was reduced from 1 cm to 0.5 cm. The average absolute error combined across all participants was 0.38 cm in the horizontal axis, and 0.59 cm in the vertical axis. The average displacement error across participants was 0.09 cm (SE = 0.05) and 0.25 cm (SE = 0.07) in the horizontal and vertical axes respectively.

Grasp Accuracy

Horizontal axis. As in Experiment 1, when grasping visible targets, average horizontal index placement was consistently positioned to the left (behind the target's COM for rightward moving trials and ahead of the target's COM for leftward moving trials) and within 1 cm of the COM in each condition. Grasps made for occluded targets were associated with mean final horizontal index placements consistently behind the target's COM, and 'off the target' (i.e., placed farther than 2 cm behind the target's COM).

As seen in Experiment 1, average index placement was more accurate when grasping leftward moving (M = 1.27 cm behind the target's COM, SE= 0.29) than rightward moving (M = 2.54 cm behind the target's COM, SE = 0.40) targets, and this was confirmed by a significant main effect of Direction [F(1,17)=26.273, p = <.001].

The three way repeated measures ANOVA also revealed a significant Visual Feedback by Cue Presence interaction [F(1,17)=6.982, p = 0.017], displayed in Figure 8. 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 < .001) and absence (p <.001) of cues. However, when grasping for occluded targets, index placement was significantly (p = .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 index accuracy when grasping for visible targets.

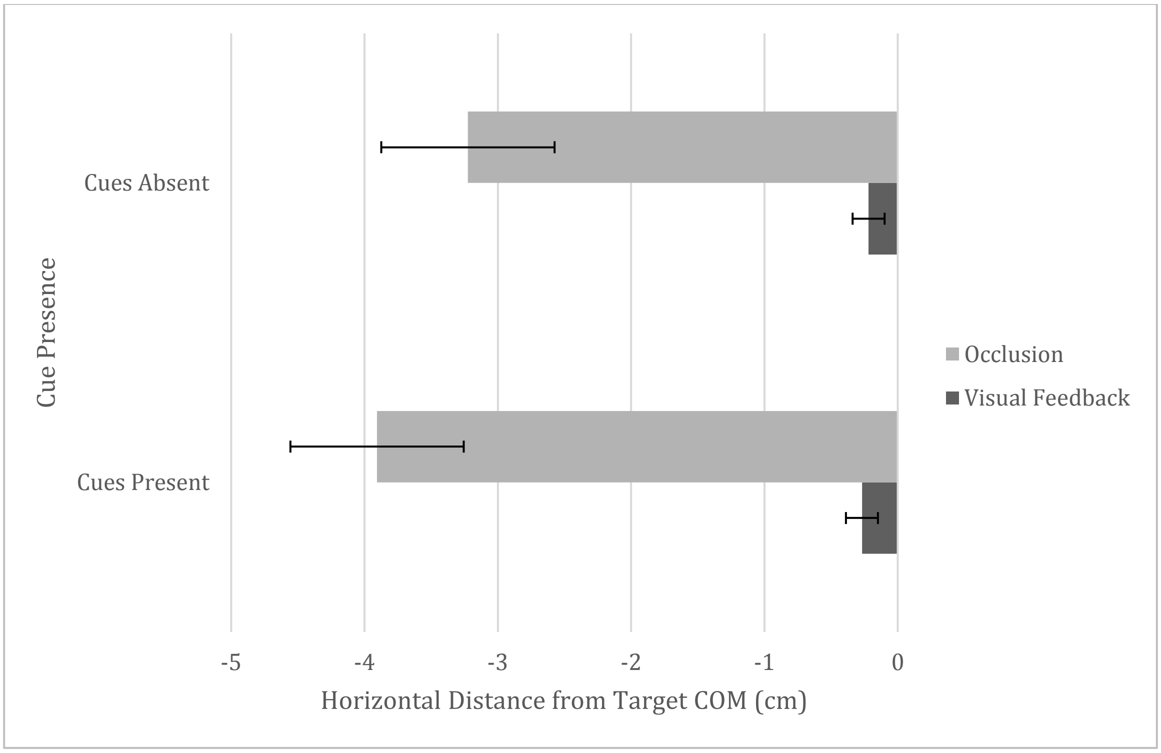

Figure 8. Average horizontal distance from final index placement to target COM collapsing across direction. Negative values refer to distance *behind* target COM. Error bars represent standard error of the mean.

Vertical axis. A significant main effect of Visual Feedback [F(1,17)=7.721, p = .013] was revealed, suggesting that 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

Participants utilized the same visual pursuit strategies in Experiment 2 as they did in Experiment 1 (i.e., smooth pursuit when visual feedback of target was available, and prolonged fixation at target occlusion followed by saccadic eye movements to extrapolate the target's motion in conditions involving occlusion).

Fixations Made at Target Occlusion.

As in Experiment 1, upon target occlusion participants fixated on the edge of the occluding object as the target disappeared (M=447.00 ms, SE=11.47). A 2 x 2 (Direction by Presence) repeated measures ANOVA indicated no significant differences in fixation duration at point of occlusion across Direction of target movement or Cue Presence.

Root-Mean-Square-Error Analysis

As in Experiment 1 a RMSE analysis was conducted on horizontal gaze to determine how accurately participants reproduced the target's movement with their eyes during each of the three time periods (movement onset to occlusion, occlusion to reach onset, and tone presentation to time of contact). RMSE data for two participants were excluded due to an insufficient amount of usable data, and therefore analysis was carried out on the remaining 16 participants. Similar to Experiment 1, the 2 x 2 x 2 x 3 repeated measures ANOVA revealed a significant Visual Feedback by Time interaction [F(2,14)=21.638, p < .001]. Post-hoc analyses revealed that, as was the case in Experiment 1, average RMSE values were significantly larger during Time Periods 2 (p <.001) and 3 (p < .001) when the target was occluded than when visible (Figure 9), and there was no significant difference between RMSE values for visible and occluded targets for Time Period 1. The mean pursuit error during Time Period 1 in both visual feedback and occlusion conditions was 2.5 cm, suggesting that, similar to Experiment 1, participants were focusing their gaze on the leading edge of the target when visible.

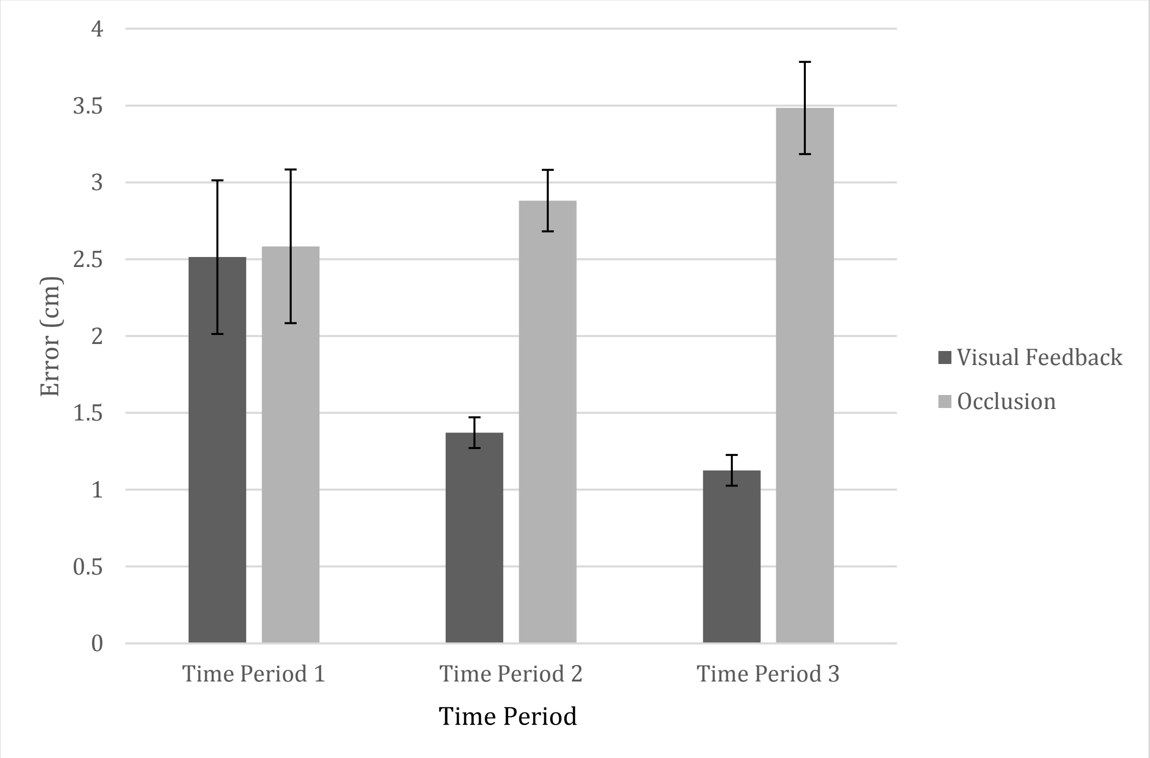

Figure 9. Average RMSE values per time period collapsing across direction and cue presence. Error bars represent standard error of the mean.

No significant differences were found between time periods for trials involving occlusion. For trials involving continuous visual feedback average RMSE values were significantly larger for Time Period 1 than Time Periods 2 (p = .037) and 3 (p = .015), which did not differ significantly when the target was visible. Direction and Cue Presence had no significant influence on RMSE values.

Fixations in Relation to Target COM

Horizontal axis. A significant main effect was found for Direction [F(1,17)=12.395, p = .003], suggesting 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 during rightward moving trials (M = 1.29 cm behind the target's COM, SE = 0.35). The four-way ANOVA also revealed a significant three-way Visual Feedback by Cue Presence by Time interaction [F(1,17)=4.357, p = .05].

Post-hoc analysis of the three-way Visual Feedback by Cue Presence by Time interaction (Figure 10) revealed several significant mean wise comparisons. Collapsing across Direction, average horizontal fixations at time of contact when visual feedback was available were made closer to the target's COM than those made when the target was occluded in both the presence (p < .001) and absence (p < .001) of cues. Visual Feedback 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, a significant difference (p = .003). Cue presence had no influence on horizontal gaze position at reach onset or time of contact when reaching for visible targets.

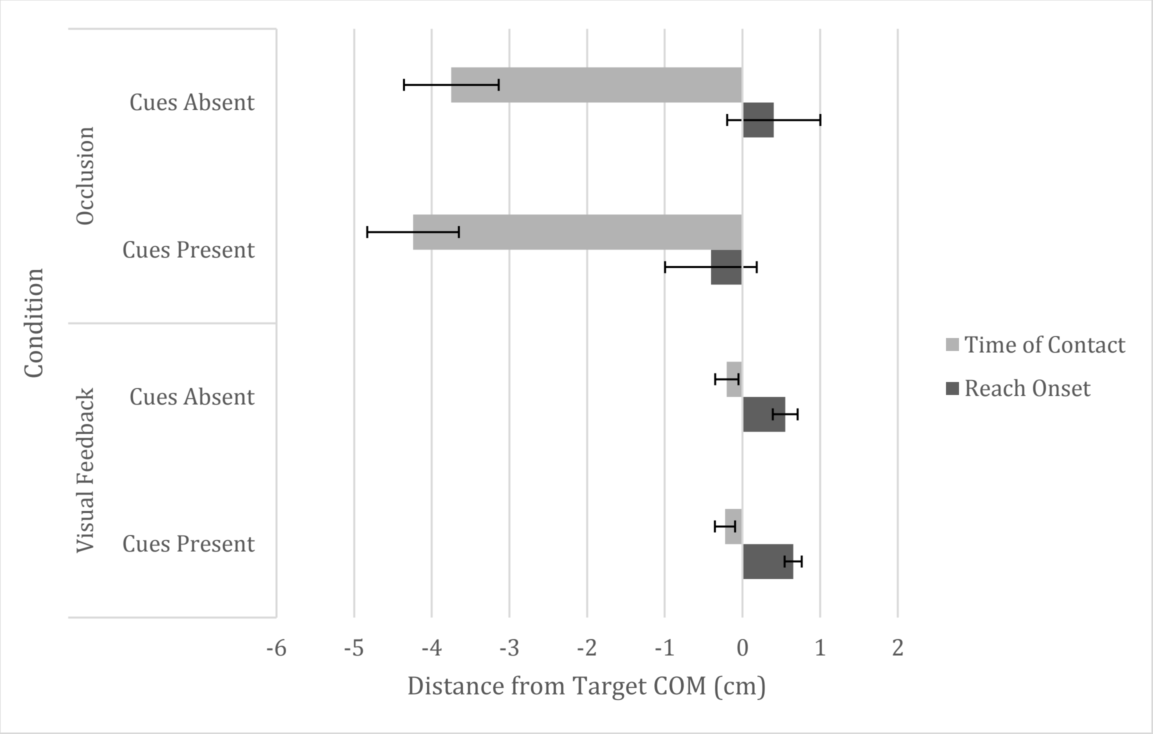

Figure 10. Average horizontal distance from fixation to target COM collapsing across direction. Negative values refer to distance behind target COM. Error bars represent standard error of the mean.

Finally, average horizontal fixation locations at reach onset were consistently and significantly different from those at time of contact for conditions involving visible targets in the presence (p < .001) and absence (p < .001) of cues, as well as when the target was occluded in the presence (p < .001) and absence (p < .001) of cues. In particular, fixations made at reach onset were consistently made ‘on the target’, whether visual feedback was provided at this point or not. When visual feedback of the target was provided, fixations at time of contact remained ‘on the target’, whereas in conditions involving target occlusion, fixations at time of contact were made ‘off target’, i.e., a horizontal displacement farther larger than 2 cm from the target’s COM.

Vertical axis. A three-way Visual Feedback by Cue Presence by Time Point interaction (Figure 11) was found to be significant [F(1,17)=6.287, p = .023]. Post-hoc analyses revealed that when collapsing across Direction, average vertical fixations made at reach onset when reaching for occluded targets were made significantly (p = .023) higher on the target when the cues were present than when the cues were absent, though there was no significant difference at time of contact. When grasping visible targets, average vertical fixations made at time of contact were significantly higher (p = .009) in the presence of cues than when the cues were absent though there was no significant difference at reach onset. When reaching for occluded targets in the absence of cues, average vertical fixations were made significantly (p = .017) higher on the target at time of contact than at reach onset, though there was no significant difference between reach onset and time of contact when the cues were present. When reaching for visible targets in the *presence* of cues, average vertical fixations were made significantly higher (p = .019) on the target at time of contact in comparison to reach onset, though this difference was not significant in the absence of cues.

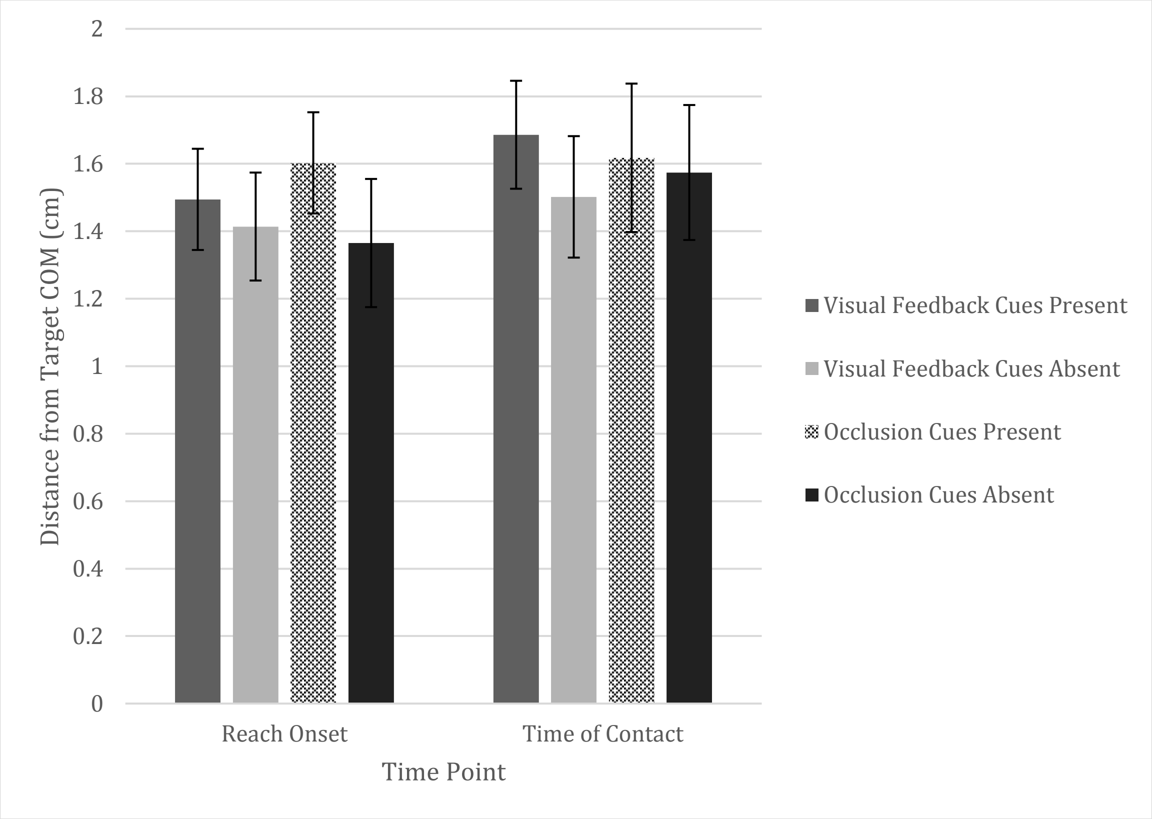

Figure 11. Average vertical distance from fixation to target COM collapsing across direction. Error bars represent the standard error of the mean.

Distance from Fixations at Time of Contact to Final Index Placement

There was no significant influence of Visual Feedback, Cue Presence, or Direction on average distances from fixations at time of contact in either the horizontal or vertical axes.

Wrist Deceleration Period

In general, the presence of additional cues on the screen was associated with longer WDPs (M = 427.20 ms, SE = 24.85 when the cues were 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)=6.536, p = .02]. Additionally, the three-way repeated measures ANOVA revealed a significant Visual Feedback by Direction interaction [F(1,17)=8.783, p= .009], and post-hoc analyses suggested that when reaching for leftward moving targets, WDPs were significantly (p < .001) longer when the target was occluded than when visual feedback was available, though this difference was not significant for rightward moving targets (Figure 12). Further, when reaching for occluded targets, WDPs were significantly longer when the target was moving leftward (p = .003), though Direction had no significant influence when reaching for visible targets.

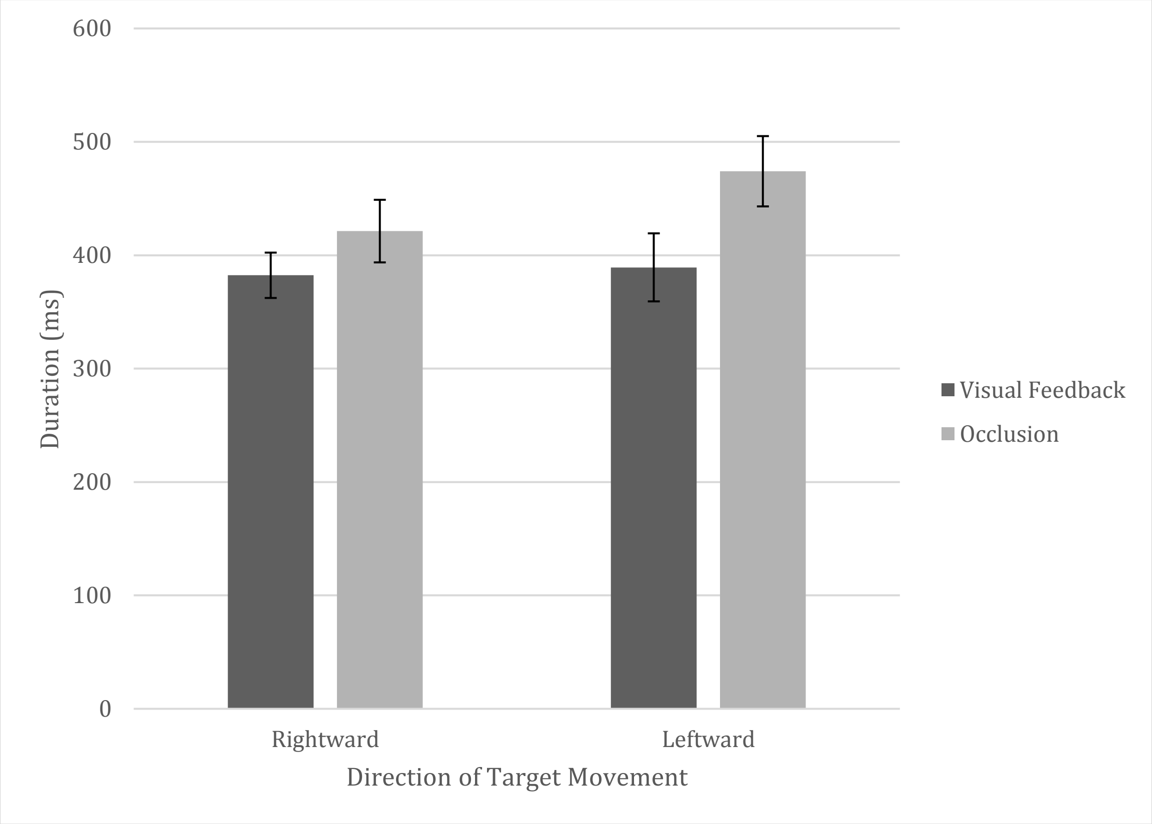

Figure 12. Average wrist deceleration period collapsing across cue presence. Error bars represent standard error of the mean.

Discussion

Experiment 2 aimed to examine the influence of Direction, Visual Feedback, and increased Allocentric Cue Presence on participant's ability to visually pursue and grasp for a translating target that disappears during travel. The experimental design for this experiment was identical to that of Experiment 1, with the exception of the presentation of allocentric cues. When present, the computer-generated blocks were positioned at a new location, farther above and below the path of the target, allowing for more space between the target and the cues.

Similar to Experiment 1, mean grasp placements were consistently positioned to the left of the target's COM when visual feedback was provided, and behind the COM in trials involving target occlusion. As was also seen in the first experiment, grasps were consistently more accurate when grasping leftward moving targets than rightward moving targets. Unlike in Experiment 1 however, this trend was now observed for overall horizontal fixation positions as well. Whereas Direction had no influence on horizontal gaze position in Experiment 1, overall horizontal gaze was more accurate (closer to the target's COM) when reaching for leftward moving targets in Experiment 2.

When grasping visible targets, both mean horizontal final index placement and mean horizontal fixation position at time of contact were located 'on target', within 0.5 cm from the target COM. However, unlike in Experiment 1, mean final index placement when grasping occluded targets was significantly displaced from the target's COM, resulting in an inaccurate grasp that missed the target entirely. This was also the case for mean horizontal fixation locations at time of contact, suggesting that participants were focusing their gaze to the same location they were placing their index finger (Voudouris, Smeets, & Brenner, 2015). Though horizontal gaze was significantly displaced from the target at time of contact, gaze at reach onset was consistently within 1 cm of the target's COM. In fact, the manipulation of Visual Feedback had no influence on horizontal fixation position at reach onset, suggesting participants were fairly accurate at tracking the occluded target up to this point in its travel, whether visible or not.

As in Experiment 1, mean RMSE values for Time Period 1 did not differ between visible and occluded conditions (mean pursuit error approximately 2.5 cm, once again indicating a focus on the leading edge of the target when visible), and error values for Time Periods 2 and 3 were significantly larger for occlusion trials than when the target was visible. When pursuing visible targets, mean error values decreased substantially from Time Period 1 to Time Period 2, however unlike Experiment 1, Time Periods 2 and 3 did not have significantly different error values. Though pursuit error appeared to increase from Time Period 1 to 2, and again from 2 to 3 in trials involving occlusion, no significant differences were found between any of these time points.

Despite the new, less intrusive location of the allocentric cues, average grasps for occluded targets in the presence of cues were significantly farther from the target's COM than grasps made when the cues were absent (though 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). Though not significant, when grasping occluded targets, the mean horizontal fixation location at time of contact was also further displaced from the target's COM in the presence of cues than when the cues were absent.

Mean final vertical index placement was found to be significantly higher on the target when grasping visible targets compared to occluded targets. Overall mean vertical gaze position was influenced by both Visual Feedback and Cue Presence. In particular, cue presence appeared to cause an upward shift of gaze at reach onset when the target was occluded, which remained elevated at time of contact. When reaching for occluded targets in the *absence* of cues, this upward shift did not occur until time of contact. When reaching for visible targets in the presence of cues, this upward shift also did not occur until time of contact. Reaches made for visible targets in the absence of cues did not demonstrate any notable changes in vertical fixation position between the two time points. These findings suggest that the presence of the on-screen cues does in fact draw participant's attention upwards, and does so at different stages of the reach, dependant on the visibility of the target.

Unlike in Experiment 1, cue presence had a significant influence on average WDP. Specifically, the presence of the on-screen cues was associated with a longer WDP, suggesting that participants were still regarding the cues as obstacles when reaching. As was seen in Experiment 1, reaches for leftward moving targets had longer WDPs when the target was occluded than when visible, and when reaching for occluded targets, WDPs were longer when reaching for leftward moving targets. Taken together, this suggests participants were more cautious when reaching for leftward moving targets, and the amount of time taken during the end stage of the reach was exaggerated when they could not see the target.

CHAPTER V

GENERAL DISCUSSION

The aim of the present study was to investigate the eye-movement and grasp strategies used when interacting with translating targets in unreliable visual conditions. In particular, the following questions were asked: How efficient are people at extrapolating the motion of a target that becomes occluded during travel, and how accurate are they when executing reach-to-grasp movements for moving targets they cannot see? Based on previous findings suggesting that allocentric information provided by the environment (i.e., visual landmarks) is helpful when interacting with target objects in uncertain visual conditions (Camors et al., 2015; Fiehler et al., 2014; Neely et al., 2008), the presence of additional allocentric cues above and below the target's path was manipulated to test if additional allocentric information would help individuals extrapolate the motion of the target, and increase grasp accuracy when visual feedback was removed.

Two separate experiments were conducted to answer these queries, the first of which involved cues positioned immediately above and below the translating target's path, and the second providing a substantially larger distance between the position of the cues and the target's path. Though both experiments were methodologically identical, some obvious differences were observed that were unrelated to cue presentation, i.e., differences between experiments that were observed in both cue present and cue absent conditions. Due to several technical difficulties, Experiment 1 involved a period of data collection lasting approximately twelve months, whereas data for Experiment 2 was collected over the span of 3 months, with minimal technical issues. It is possible that the combination of technical issues and the prolonged data collection period associated with Experiment 1 resulted in a larger amount of participant data being lost in the collection process, resulting in an unusually ‘accurate’ sample. Additionally, a larger number of subjects may have met the inclusion criteria following correction of any technical issues, resulting in a wider (and ultimately, less accurate) range of participants providing data over a shorter period of time in Experiment 2. These issues could potentially explain the overall higher accuracy rate observed in Experiment 1 compared to Experiment 2. As such, any comparison of results between the two experiments should be interpreted with caution. With this being said, numerous patterns were observed in both Experiment 1 and 2, suggesting these behavioural results are a reliable indication of the visuomotor strategies being used by all participants.

Visual Pursuit

In general, smooth pursuit eye movements were utilized when the target was visible, and saccadic eye movements were used to extrapolate the target’s motion following target disappearance in trials involving target occlusion and removal of visual feedback. This shift from smooth pursuit to saccadic eye movements following occlusion is consistent with previous research involving visual pursuit through occlusion (Becker & Fuchs, 1985; Bennet & Barnes, 2003). Without an expected point of target appearance however, participant’s did not have a specific location to direct their gaze in anticipation of target reappearance, and were forced to extrapolate the target’s motion using saccades up to the point of grasp execution. By comparing the amount of pursuit error across conditions using a Root-Mean-Square-Error analysis, it was possible to determine how well participants were reproducing the target’s movement with their eyes when provided with visual feedback of the target and without. Not surprisingly, subjects were able to more accurately pursue the target when visible feedback was provided, compared to when the target was occluded.

As was demonstrated in Bulloch et al.'s (2015) study involving strictly visible translating targets, the combined analysis of average fixation positions at reach onset and the RMSE analysis of pursuit error suggest that during pursuit, participants consistently focused their gaze toward the leading edge of the target when visible. Similarly, Bulloch et al. reported a tendency for participants to focus farther ahead when the target was moving leftward, a pattern which was observed here (even when overall horizontal fixations were made behind the target, this was observed to a lesser degree for leftward moving targets), based on average horizontal fixations made at reach onset and time of contact. However, Direction of target movement had no influence on average RMSE values.

In order to accurately extrapolate the motion of the disappeared target, participants would have been forced to constantly predict and update the target's perceived location as it translated, using previously available visual information, such as the target's speed and direction while visible. Previous research has demonstrated that when judging the final location of a moving target, responses tend to be biased in the direction of target motion, a phenomenon referred to as Representational Momentum (RM; Freyd & Finke, 1984). In other words, the final position of a rightward moving target is judged to be farther rightward than the actual final location, and the final position of a leftward moving target is judged as being farther to the left of the actual final location. This phenomenon has been replicated in regards to targets moving in a circular path (Freyd & Finke, 1984), as well as vertical (Hubbard & Bharucha, 1988) and horizontal directions (Hubbard & Bharucha, 1988; Halpern & Kelly, 1993), and while RM has been shown to have a larger influence on horizontal motion than on vertical motion, conclusions regarding a directional bias are mixed. Though direction has been shown to have no influence on RM (Hubbard & Bharucha, 1988), Halpern and Kelly (1993) demonstrated a larger influence of RM for rightward than for leftward motion. Addressing the role of RM in the execution of goal-directed movements, Ashida (2004) demonstrated a more pronounced RM bias during an open-loop reaching task than compared to a perceptual judgment task, and concluded that when reaching for a pursued target, the tendency to over estimate its final location may serve to compensate for any potential neural or mechanical delays during the reaching motion.

This raises the question of whether RM was influencing participants' judgements of target position when reaching for occluded targets in the current study. Contrary to what previous research involving RM would suggest, the results of this study demonstrated that average horizontal fixations when reaching for occluded targets were consistently positioned *behind* the target's center of mass, suggesting that participants were *undershooting* rather than overshooting the target's horizontal position. Additionally, although a directional bias was observed in both Experiment 1 and 2 of the present study, final grasp (Experiment 1 and 2) and gaze (Experiment 2) positions were significantly closer to – though on average, behind – the target's center when reaching for leftward moving targets. This would suggest that if in fact an influence of RM was biasing participants' perceptions of occluded target position, participants were exaggerating the distance travelled by leftward moving targets more so than for rightward moving targets, in conflict with what has been demonstrated previously (Halpern & Kelly, 1993). As such, it is unlikely that participants' perception of occluded target location when grasping was influenced by any momentum effects during the current study. Had this been the case, participants would have been expected to direct their gaze, and place their grasps *ahead* of the target's actual position, the reverse of what was observed.

Studies demonstrating RM have either involved participants making a judgment about the location at which a previously pursued target disappeared (Hubbard & Bharucha, 1988), or determining the next location a target would be expected based on a series of previously presented static images representing target movement (Halpern & Kelly, 1993). These experimental procedures differ considerably from the current study, during which participants were required to consistently update their perception of the moving target, in order to plan and execute an accurately placed grasp. Representational Momentum may have had little influence on this task, as participants were extrapolating the motion of a target moving at a constant speed with the intention of manual interception, rather than making a judgment about its previous location (i.e., where it disappeared) or its future location based on inferred motion provided by static images.

Influence of Allocentric Cue Presence

It was hypothesized that, in comparison to when the additional cues were absent, cue presence would help participants be more accurate when grasping for translating targets they could not see. This however was not the case, and the presence of additional cues presented either close (Experiment 1) or far (Experiment 2) above and below the target's path provided no benefit to pursuit or grasp accuracy, and in fact appeared to impair accuracy in certain circumstances. Previous work in our lab has demonstrated that when non-target objects are present in the reaching environment, both final gaze and grasp positions are influenced, relative to the obstacle's position in relation to the reaching arm (Graham & Marotta, 2016). The results of Experiment 2 demonstrated that average vertical gaze position was drawn upward at time of contact when grasping visible targets, and at both time of contact and reach onset when grasping occluded targets in the presence of cues. If in fact participants were considering the on-screen cues as potential obstacles during the reach, the upward shift of gaze observed at these time points may indicate an unconscious monitoring of cue position at these times (Stigchel & Theeuews, 2005). When reaching for visible targets, cue monitoring would be most important once the fingers came close to the target, to avoid unwanted collision, whereas when reaching for an invisible target, cue monitoring may have been important at the initiation of the reach as well, as participants were required to plan and execute a reach for a target they could not see. This would potentially explain why fixations were elevated when cues were present at both reach onset and time of contact when the target was occluded, and only at time of contact when the target was visible.

Gaze and Grasp Accuracy

Though a beneficial influence of cue presence was not observed as expected, valuable insight about the locations participants focused their gaze and how their grasp strategies were influenced when reaching for both visible and occluded targets was provided, and several significant influences of Visual Feedback and Direction of target motion were observed. For example, analysis of horizontal gaze position at the point in time participants initiated their reach revealed horizontal fixation positions located 'on target' in both visual feedback and occlusion trials, suggesting that participants had a fairly good idea about the target's location at reach onset, regardless of visual feedback. However, while fixations at time of contact were also located close to the target's COM when grasping visible targets, fixations made at time of contact when grasping occluded targets were significantly behind the target's COM. This was especially evident in Experiment 2, in which participant's mean fixations at reach onset were made within 1 cm of the target's COM, whereas fixations made at time of contact were consistently made 'off target', and subjects executed grasps that missed the target entirely. A similar phenomenon was observed for occlusion trials in Experiment 1, though to a lesser degree.

It would seem that participants were able to accurately extrapolate the target's motion up to and including the point at which they initiated their reach. This observation is in agreement with previous work suggesting that individuals are fairly good at accurately extrapolating the motion of an invisible target (Battaglini, Campana, & Casco, 2013). The observed displacement of both grasp and gaze at time of contact suggests that during the reaching motion, participants became less able to follow the disappeared target, resulting in an inaccurately placed grasp, consistently located behind the target's COM. Visual feedback of the target object being reached for is especially important during the end stages of the reach, as it allows for online adjustments to be made during the reaching motion (Abekawa, et al., 2014; Churchill et al., 2000; Desmurget et al., 2005). It is possible that while reaching for an occluded target, the lack of visual feedback available prevents these online adjustments from being made, and participant's ability to accurately extrapolate the motion of a moving target becomes impaired due to an increased allocation of attentional resources toward the execution of the reach (Long & Ma-Wyatt, 2014).

It would be expected that if visual pursuit of the occluded target was less accurate during the reaching motion, RMSE pursuit error values would be larger within the time period between reach onset and time of contact than the period between occlusion and reach onset, during which participants were passively extrapolating the target's motion. Though not reaching significance, Experiment 2 did reveal a trend suggesting average RMSE values that were larger in Time Period 3 than Time Period 2. This lack of significance may be due to the nature of saccadic eye movements being used by participants to pursue the invisible target. Fixations maintained between saccades as well as the sporadic movement characteristic of saccadic eye movements most likely contributed to an increasing pursuit error value, making it hard to determine exactly how accurately participants were extrapolating the target's motion during occlusion.

Directional Influence

As already mentioned, previous work from our lab involving visual targets in motion has demonstrated a leftward bias when visually pursuing horizontally translating targets. The current study demonstrated that grasps were made closer to the target's COM when grasping leftward moving targets than when grasping rightward moving targets. In Experiment 2, this directional influence was also found for horizontal gaze position at both reach onset and time of contact. Participants consistently grasped visible targets to the left of the COM as was observed by Bulloch et al. (2015), and grasps made for occluded targets, though consistently placed behind the target COM for both leftward and rightward moving targets, were located closer to the target's COM for leftward moving trials. These observations may be due to mechanical restraints associated with reaching for leftward moving targets with the right hand (Carey, Hargreaves, & Goodale, 1996). Though all reaches were directed toward the centre of the screen, reaching for a target moving in a direction contralateral to that of the reaching hand may elicit more of a ‘catching’ response than that of a grasp made on the ipsilateral side, and participants my direct their reaching hand further ahead of a leftward moving target than they would when reaching for a rightward moving target. Doing so would hypothetically allow for a longer ‘adjustment period’ as the target approaches the hand, than a grasp directed directly towards the target. Reaches for rightward moving targets may not require this additional adjustment, as these mechanical restraints are not present. This extra ‘push’ in the horizontal direction when reaching for leftward moving targets may be responsible for what seems to be a more accurately placed grasp when reaching for leftward moving targets without visual feedback. In reality, perceived location of the target is equally displaced behind the target for both left- and rightward moving targets, however because participants are directing their gaze and reaching further ahead for leftward moving targets, the result is a final grasp location closer to the target’s COM. As demonstrated in Experiment 1, participants placed their grasps ahead of where they were looking when grasping leftward moving targets, though not when grasping targets moving rightward. This result was not replicated in Experiment 2, however horizontal fixations at time of contact demonstrated the same leftward bias as final grasp position in Experiment 2, suggesting that this horizontal ‘push’ applied to gaze position as well, removing any discrepancy between final index placement and fixations at time of contact.

Finally, analysis of the average reach deceleration periods suggests that when reaching for leftward moving targets, subjects used more time to slow their approaching hand when reaching for occluded targets than when they are visible. Visual Feedback had no significant influence on WDPs when reaching for rightward moving targets, suggesting participants were less cautious with the execution of their reaches for targets moving toward the ipsilateral side of their reaching hand. These results reinforce the idea that reaches made for leftward moving targets may be unconsciously executed more cautiously, allowing for a more 'safe' grasp in conditions where visual feedback is unavailable.

2-D Versus 3-D Grasping

As mentioned previously, several studies have addressed the differences between reaching for 3-D objects and 2-D targets, and have challenged the generalizability of grasping studies involving virtual targets. For example, higher activation is found in the anterior intraparietal area when grasping real objects compared to pantomimed grasps, whereas pantomimed grasping is associated with right parietal cortex activation (Króliczak et al. 2007). Whitwell et al. (2015) demonstrated that compared to natural grasps, the removal of haptic feedback when reaching for virtual targets was associated with slowed reaction times and peak hand velocity, an increased amount of time participants took to scale their grasp to the target, and reduced peak and final grip aperture. For these reasons, the current study did not directly address variables such as grip aperture or reach velocity, and focused more so on the gaze and grasp locations chosen by participants when grasping, as these variables have been shown to be similar when grasping both 2-D and 3-D objects (Bulloch et al., 2015; Desanghere & Marotta, 2011).

Future Directions

Numerous studies have demonstrated the beneficial nature of allocentric information in memory-guided reaching (Fiehler et al., 2014), spatial priming (Ball et al., 2009), and goal-directed movements in unpredictable visual conditions (Camors et al., 2015; Neely et al., 2008). Nevertheless, the results of the present study suggest that the presence of additional allocentric cues failed to provide any observable benefit to participant's ability to judge the location of a translating invisible target, and in certain conditions even resulted in impaired accuracy. Future work in this area will include investigating the beneficial nature of allocentric information, and what characteristics separate a 'cue' from an 'obstacle' or 'distractor'. In particular, our lab is currently experimenting with the nature of cue presentation, saliency, and location, when reaching for disappeared targets.

The results of this study suggest that participants were able to accurately extrapolate the motion of the invisible target up the point of reach initiation, however both gaze and grasp accuracy at time of contact was impaired. These results suggest that at some point during the reaching motion, participants become less able to accurately judge the movement of an invisible target, the result of which is an inaccurately placed grasp. Further research is required to investigate at what point individuals become unable to accurately extrapolate target motion, and how the execution of a reaching motion contributes to this inaccuracy.

CHAPTER VI

GENERAL CONCLUSIONS

In summary, the results of this study provide new information about how individuals visually pursue targets that are removed from sight by occlusion, and how environmental information is interpreted when executing reach-to-grasp movements for targets they cannot see. In particular, this study indicates that not all environmental information may be useful when interacting with moving stimuli (visible or not), and aspects of the immediate environment that may have been thought to provide useful allocentric information may in fact result in the use of object-avoidance strategies, which ultimately impair accuracy when visual feedback is limited. Research of this nature is useful for demonstrating how visual information is used to create and maintain spatial references within an environment, and to execute accurate reach-to-grasp movements when visual feedback is unpredictable or unavailable. An improved concept of how allocentric information contributes to our spatial reference can potentially lead to a further understanding of how certain impairments to these processes can occur, as well as provide the opportunity to model and replicate (i.e., the development of robotic grasping under visual guidance) such eye-hand coordinated processes.

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APPENDIX A: Participation Consent Form

Eye-hand coordination: Moving/Disappearing Objects.

University of Manitoba | Department of Psychology

190 Dysart Road
Winnipeg, Manitoba
Canada R3T 2N2
Telephone (204) 474-9338
Fax (204) 474-7599

PRINICIPAL INVESTIGATORS:

Ryan Langridge, 2nd-year Graduate Student, Psychology
University of Manitoba

Dr. Jonathan Marotta, Associate Professor, Psychology
University of Manitoba

SOURCE OF SUPPORT: NSERC Discovery Grant

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

PURPOSE: We are interested in where you are looking when reaching out to grasp objects.

DESCRIPTION: This study will take place in the Perception and Action Lab in the Duff Roblin Building on the Fort Garry Campus. During the study, you will be asked to reach out and grasp a computer-generated target object. An eye tracker will be used to record your eye movements when performing these tasks and an OPTOTRAK 3-D motion recording system will be used to record your finger and hand movements. Prior to this task, you will be asked to fill out a brief demographics questionnaire that inquires about your age, gender, handedness, whether you wear glasses, and your stereo acuity. The whole procedure will take less than an hour and a half to complete. You will earn 3 experimental credits for your participation in this study.

RISKS AND BENEFITS: There are no risks (physical, psychological and/or emotional) inherent in the tasks you will perform but some of the tests may be repetitive. Even though this may be frustrating to you, there will always be an investigator with you to assist you and support you.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will not receive payment.

CONFIDENTIALITY: Your information will be kept confidential. You will be referred to by a code number. All files containing identifying information will be stored in a locked cabinet separate from data with your code number. Your files will only be accessible by the investigators and will be destroyed 5 years after the completion of the study (approximately September, 2020). All papers containing personal information will be shredded. All electronic files will be deleted. Any cds or dvds containing data will be physically destroyed.

VOLUNTARY CONSENT: Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. This means that should you choose to withdraw at any point from the study, you will still receive 3 participation credits. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way.

This research has been approved by the Psychology/Sociology Research Ethics Board of the University of Manitoba. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC) at 474-7122. A copy of this consent form has been given to you to keep for your records and reference.

____________________ __________ ____________________ __________
Signature of the Participant Date Signature of Investigator Date

If you would like to receive general summary of the results from this study when it is completed, please complete your mailing (or email) address below:

Mailing Address: ____

____

APPENDIX B: Demographics Questionnaire

ID: ____________

Sex: _________________

Age: _________________

Do you have normal or corrected to normal vision? ___________________

Handedness Inventory: Which hand do you use to do the following?

1. Throw a ball.	**L/R**
2. Brush your teeth.	**L/R**
3. Eat your soup with a spoon.	**L/R**
4. Comb your hair.	**L/R**
5. Cut bread with a knife.	**L/R**
6. Swing tennis/badminton racquet or bat.	**L/R**
7. Hammer a nail.	**L/R**
8. Point to something accurately.	**L/R**
9. Write your name.	**L/R**

Is there anything you do consistently with your left hand?
____

IPD: _______________

APPENDIX C: Experimental Condition Means (Experiment 1)

Table 1

Mean Distance from Final Index Placement to Target COM

	Horizontal		Vertical	
Condition	Average Distance from Target COM (cm)	SE	Average Distance from Target COM (cm)	SE
Visual Feedback				
Cues Present				
Leftward Moving Target	.68	.18	1.68	.15
Rightward Moving Target	-.96	.19	1.65	.14
Cues Absent				
Leftward Moving Target	.43	.18	1.81	.14
Rightward Moving Target	-.77	.15	1.67	.15
Occlusion				
Cues Present				
Leftward Moving Targets	-.99	.80	1.70	.13
Rightward Moving Targets	-2.18	.82	1.56	.12
Cues Absent				
Leftward Moving Targets	-1.04	.87	1.47	.17
Rightward Moving Targets	-1.60	.87	1.55	.13

Note. Positive values refer to distance *ahead* of target COM, and negative values refer to distance *behind* target COM.

Table 2

Horizontal Distance from Fixation Location to Target COM

Condition	Reach Onset: Average Distance from Target COM (cm)	Reach Onset: SE	Time of Contact: Average Distance from Target COM (cm)	Time of Contact: SE
Visual Feedback				
Cues Present				
Leftward Moving Target	.75	.22	-.23	.12
Rightward Moving Target	.36	.15	-.89	.25
Cues Absent				
Leftward Moving Target	.28	.17	-.42	.11
Rightward Moving Target	.37	.15	-.70	.20
Occlusion				
Cues Present				
Leftward Moving Target	1.31	.93	-1.68	.85
Rightward Moving Target	1.33	.83	-2.19	.80
Cues Absent				
Leftward Moving Target	1.63	.84	-1.33	.87
Rightward Moving Target	1.68	.91	-1.64	.89

Note. Positive values refer to distance *ahead* of target COM, and negative values refer to distance *behind* target COM.

Table 3

Vertical Distance from Fixation Location to Target COM

	Reach Onset		Time of Contact	
Condition	Average Distance from Target COM (cm)	SE	Average Distance from Target COM (cm)	SE
Visual Feedback				
Cues Present				
Leftward Moving Targets	1.32	.15	1.39	.16
Rightward Moving Targets	1.23	.16	1.31	.17
Cues Absent				
Leftward Moving Targets	1.39	.16	1.34	.18
Rightward Moving Targets	1.25	.16	1.41	.16
Occlusion				
Cues Present				
Leftward Moving Targets	1.22	.16	1.34	.20
Rightward Moving Targets	1.14	.18	1.10	.20
Cues Absent				
Leftward Moving Targets	.98	.19	.93	.15
Rightward Moving Targets	1.02	.17	1.60	.17

Note. Positive values refer to distance *ahead* of target COM, and negative values refer to distance *behind* target COM.

Table 4

Average Wrist Deceleration Period

Condition	Duration (ms)	SE
Visual Feedback		
Cues Present		
Leftward Moving Targets	391.19	21.44
Rightward Moving Targets	390.47	18.23
Cues Absent		
Leftward Moving Targets	396.56	23.45
Rightward Moving Targets	376.66	20.83
Occlusion		
Cues Present		
Leftward Moving Targets	439.21	24.34
Rightward Moving Targets	390.12	19.00
Cues Absent		
Leftward Moving Targets	435.66	24.48
Rightward Moving Targets	373.96	25.77

APPENDIX D: Experimental Condition Means (Experiment 2)

Table 5

Mean Horizontal Distance from Final Index Placement to Target COM

Condition	Average Distance from Target COM (cm)	SE	Average Distance from Target COM (cm)	SE
Visual Feedback				
Cues Present				
Leftward Moving Targets	.37	.17	1.35	.09
Rightward Moving Targets	-.91	.20	1.45	.13
Cues Absent				
Leftward Moving Targets	.39	.17	1.42	.09
Rightward Moving Targets	-.83	.18	1.40	.10
Occlusion				
Cues Present				
Leftward Moving Targets	-.33	.64	1.37	.11
Rightward Moving Targets	-4.55	.69	1.20	.14
Cues Absent				
Leftward Moving Targets	-2.59	.60	1.27	.10
Rightward Moving Targets	-3.86	.76	1.17	.16

Note. Positive values refer to distance *ahead* of target COM, and negative values refer to distance *behind* target COM.

Table 6

Horizontal Distance from Fixation Location to Target COM

Condition	Reach Onset: Average Distance from Target COM (cm)	Reach Onset: SE	Time of Contact: Average Distance from Target COM (cm)	Time of Contact: SE
Visual Feedback				
Cues Present				
Leftward Moving Target	.90	.15	.21	.17
Rightward Moving Target	.40	.17	-.66	.17
Cues Absent				
Leftward Moving Target	.75	.21	.23	.17
Rightward Moving Target	.35	.19	-.64	.20
Occlusion				
Cues Present				
Leftward Moving Target	-.01	.67	-3.79	.58
Rightward Moving Target	-.80	.59	-4.69	.63
Cues Absent				
Leftward Moving Target	.94	.60	-3.38	.63
Rightward Moving Target	-.14	.66	-4.12	.66

Note. Positive values refer to distance *ahead* of target COM, and negative values refer to distance *behind* target COM.

Table 7

Vertical Distance from Fixation Location to Target COM

	Reach Onset		Time of Contact	
Condition	Average Distance from Target COM (cm)	SE	Average Distance from Target COM (cm)	SE
Visual Feedback				
Cues Present				
Leftward Moving Target	1.56	.16	1.73	.18
Rightward Moving Target	1.43	.14	1.65	.16
Cues Absent				
Leftward Moving Target	1.45	.18	1.61	.17
Rightward Moving Target	1.38	.16	1.39	.20
Occlusion				
Cues Present				
Leftward Moving Target	1.65	.19	1.74	.21
Rightward Moving Target	1.55	.15	1.50	.26
Cues Absent				
Leftward Moving Target	1.33	.22	1.57	.25
Rightward Moving Target	1.41	.19	1.58	.20

Note. Positive values refer to distance *above* target COM.

Table 8

Average Wrist Deceleration Period

Condition	Duration (ms)	SE
Visual Feedback		
Cues Present		
Leftward Moving Targets	395.46	33.51
Rightward Moving Targets	391.93	19.21
Cues Absent		
Leftward Moving Targets	383.15	27.24
Rightward Moving Targets	372.70	21.70
Occlusion		
Cues Present		
Leftward Moving Targets	485.82	32.16
Rightward Moving Targets	435.61	27.63
Cues Absent		
Leftward Moving Targets	462.34	32.17
Rightward Moving Targets	406.98	28.46