AN INVESTIGATION OF VISUALLY GUIDED INTERACTION WITH 2-DIMENSIONAL STIMULI

By

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Abstract

This dissertation explores how vision is used to guide interactions with 2-D computer-generated targets, with the goal of furthering our understanding of how perception and action interact during visually guided action. Study 1: Participants used their right hands to grasp square targets that either remained stationary or travelled horizontally across the screen. Fixations and digit placement favoured the near side of stationary targets presented at non-central positions, and the trailing side of moving targets, suggesting participants minimized the energy required to grasp the stationary targets and selected 'safer' contact points when the target was moving. Gaze and grasp positions were shifted rightward when grasping target shapes that discouraged digit placement near the horizontal midline, suggesting participants tried to avoid obstructing the view of the target when grasping. Study 2: Fixations and grasp positions were compared when grasping 2-D targets versus 3-D versions of these targets. Fixations and digit placement were comparable when grasping 2-D and 3-D stimuli positioned in the center of the display. When grasping non-central stimuli however, participants fixated and placed their digits at more 'stable' locations near the 3-D object's midline compared to locations biased toward the near side of the 2-D targets. Intended manipulation of each stimulus type produced similar adjustments in fixation and digit placement, suggesting participants may have attributed physical properties to the 2-D targets in response to the manipulative task demands. Study 3: The Ebbinghaus illusion was used to explore how the perceived size of an on-screen target influences cursor movements toward that target. Participants' perceptual size judgments, but not accuracy or movement time, were influenced by the illusion. However, the illusion affected cursor trajectories toward the target, suggesting the illusion may have influenced the planning and early stages of the cursor movement. The results of each study are discussed regarding the Two Visual Streams Hypothesis (Goodale & Milner, 1992), and suggest that the context in which an action is directed toward a 2-D stimulus – particularly the target's position and the action end-goal – may determine the degree to which the visually guided action is mediated by perceptual influences.

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Dedication

To Kate, I look forward to watching you grasp many things.

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List of Abbreviations

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V1	Primary Visual Cortex	2
GA	Grip Aperture	3
COM	Center of Mass	3
JND	Just Noticeable Difference	5
PSREB	Psychology/Sociology Research Ethics Board	16
IRED	Infrared Light Emitting Diode	16
Hz	Hertz; Frequency	16
I-DT	Dispersion-Threshold Identification	19
TOC	Time of Contact	19
ANOVA	Analysis of Variance	19
hr	Hours	19
ms	Milliseconds	19
MWF	Multiway Frequency Analysis	20
GLM	Generalized Linear Model	20
s	Seconds	22
m	Meters	22
cm	Centimeter	22
MO	Movement Onset	29
RO	Reach Onset	29
px	Logical Pixels	93
DPR	Device-Pixel-Ratio	93
AUC	Area Under the Curve	99

List of Statistical Abbreviations and Symbols

Abbreviation	Meaning	Page
M	Mean	16
SD	Standard Deviation	16
F	F-Ratio	22
p	*p*-value; probability of committing a Type I Error	22
η_p^2	Partial eta Squared	22
SE	Standard Error	22
χ^2	Chi Square Test Value	24
d	Cohen's *d*	30
t	*t*-test value	44
n	Sample size	60
$p(H_1/D)$	Probability of Alternative Hypothesis being true given the data	65
$p(H_0/D)$	Probability of Null Hypothesis being true given the data	65
CI	Confidence Interval	101

Permission Statements

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Contributions of Authors

As primary author, I was responsible for the conceptualization of each study, literature reviews, conducting each experiment, formal analysis, interpretation of results and writing of the complete dissertation. J. J. Marotta was responsible for funding acquisition, project administration, resources, supervision and review/editing of the dissertation.

CHAPTER 1: GENERAL INTRODUCTION

When I see my freshly poured cup of coffee located on my desk, I am easily able to recognize the cup as mine. I'm able to do so because visual cues such as the shape of the cup, its colour, and any number of additional defining features are aligned with my perceptual understanding of what my cup looks like. I'm further able to distinguish this new cup of freshly poured coffee from yesterday's cup, sitting empty and forgotten on my desk, and characterized by its own set of visually defining features. Occasionally, I reach out and grasp the new cup, and as I do so, my fingers are effectively guided to its handle, allowing me to lift it to my mouth and drink from it. After returning the cup to the desk however, I realize I have placed it on a stack of important papers. Once again, I navigate my fingers toward the cup, however this time I grasp it from the top, so I can comfortably move it off the papers to another location.

As we go about our day, we are constantly using visual information to identify stimuli and interact with our environment in meaningful ways. Though little cognitive attention or intentional thought is directed toward the execution of these behaviours, our ability to recognize and act upon an object is the result of numerous interactions between cognitive, sensory, and motoric processes occurring in the brain and throughout the nervous system. The interactions between these processes allow the brain to construct perceptual representations of our environment (e.g., recognize a coffee cup), as well as to execute visually guided actions within the environment to serve a particular goal (e.g., grasp the coffee cup to drink from it compared to moving it). For years, investigations in a variety of research disciplines including psychology, as well as cognitive, behavioural, and computational neuroscience have focused on answering the question of how the brain processes incoming visual information and transforms such a wide breadth of sensory input into a meaningful behavioural response.

The Dual Streams Hypothesis: Perception and Action

Modern theories of visual processing in the brain generally accept the existence of two separate systems, each responsible for a unique set of computations that allow us to understand and interact with our surroundings. The notion of two functionally distinct visual systems in the brain was promoted by a number of theories in the late 1960s (e.g., Schneider, 1969; Trevarthen, 1968), however these early theories mainly focused on distinctions between the retinal projections travelling to the superior colliculus, believed to be involved in stimulus localization, and higher-level geniculostriate pathways, involved in stimulus identification (Schneider, 1969).

Based on the results of behavioural experiments conducted several years later, Ungerleider and Mishkin (1982) advanced these theories by proposing a similar dichotomy between stimulus identification and stimulus localization, but claimed these processes occurred at the cortical level, via projections stemming from the primary visual cortex (V1). According to Ungerleider and Mishkin, visual information relevant for the identification of a stimulus was processed via a ventral, or 'what' stream projecting from V1 to the inferior temporal lobe, and visual information regarding the spatial location of the stimulus was processed via a dorsal 'where' stream projecting from V1 to the posterior parietal lobe.

A decade later, Milner and Goodale (Goodale & Milner, 1992; Milner & Goodale, 2006) proposed what has become arguably one of the most influential theories of visual processing to date. Their 'perception-action' model shifted the focus away from the specific visual input received by each cortical stream and instead emphasized each stream's distinct behavioural output. Incoming visual information processed within the ventral stream is used to build long-term, enduring perceptual representations that allow us to recognize a given stimulus, while visual information processed in the dorsal stream is used to control visually guided action toward a stimulus on a moment-to-moment basis. Thus, my ability to recognize my favourite coffee cup relies on the processing of its visual features within the ventral stream, while my ability to accurately reach for and grasp its handle is the result of computations carried out within the dorsal stream, using visual information about its size, shape, weight, orientation, and so on. Although the ventral and dorsal streams may be responsible for functionally separate behaviours, the interactions between the two streams are key in producing the appropriate action in response to a specific goal or context. When grasping a hammer for example, the dorsal stream is responsible for the transportation of the hand and the accurate scaling of the grasp to the physical size of the hammer. However, these metrically precise actions are not sufficient on their own. Stored perceptual representations within the ventral stream, privy to semantic knowledge about the object as well as information about the specific task demands (i.e., hammering a nail or relocation), are required to determine whether the hammer should be grasped by its handle or its head. In turn, information about the physical characteristics of the object provided by the dorsal stream may be used to update and fine-tune the ventral stream's perceptual representation of that object (van Polanen & Davare, 2015). In other words, cooperation between the ventral and dorsal streams is necessary for meaningful interaction within an environment. In fact, a key tenet of the perception-action model is that humans' conscious, stable perceptual abilities ultimately evolved to serve the unconscious processing required to perform meaningful action.

Visually Guided Grasping: Gaze and Grasp Strategies

As the above examples suggest, a significant proportion of the research exploring perception-action interactions has focused on our ability to perform visually guided skilled grasp movements in response to a wide variety of object shapes and sizes. When grasping an object, visual information about its physical characteristics is used by the dorsal stream, with contribution by the ventral stream, when necessary, to produce an accurate reach-to-grasp action. For example, the size and shape of the object will influence how wide the fingers open as the hand approaches it, a measure known as 'grip aperture' (GA; (Borchers, Verheij, Smeets, & Himmelbach, 2014; Jeannerod, 1986; Jeannerod, Arbib, Rizzolatti, & Sakata, 1995). When using a precision grip (index finger and thumb) to grasp symmetrical objects, grasp stability is typically achieved by selecting grasp points that generate enough force to the object's center of mass (COM; Endo, Wing, & Bracewell, 2011; Lederman & Wing, 2003; Wing & Lederman, 2009), therefore limiting the amount of torque around the object's COM. These grasp points are also typically shifted in the direction of the grasping hand, to avoid the hand obstructing the view of the object at the time of the grasp (Maiello, Paulun, Klein, & Fleming, 2019; Paulun, Kleinholdermann, Gegenfurtner, Smeets, & Brenner, 2014). In other words, digits will be guided toward positions on the object that ensure stability of the grasp upon contact (i.e., close to the object's COM), while also promoting visibility. These grasp points will further be influenced by the specific grasping context or action end-goal (e.g., grasping the handle of the coffee cup to drink from it, or the handle of the hammer when hammering; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Sartori, Straulino, & Castiello, 2011). Attempts to model natural grasping behaviour typically focus on factors such as force closure (in regard to the COM), torque, the natural grasp axis, grasp aperture, visibility, and movement distance (Klein, Maiello, Paulun, & Fleming, 2020; Kleinholdermann, Franz, & Gegenfurtner, 2013). Not surprisingly perhaps, information regarding each of these factors is typically first acquired via visual feedback of the object prior to the grasp.

Clearly, visual feedback of the object being grasped provides critical information used by the visual system to coordinate an effective grasp, but where exactly does a person direct their gaze when grasping an object? The results of studies involving the precision grasping of symmetrical objects suggest gaze is directed toward the eventual index finger contact point, rather than the contact point of the thumb (Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2011; Voudouris, Smeets, & Brenner, 2016), and this is shown to be the case even when the index finger's contact point is occluded from view (e.g., behind the object; de Grave, Hesse, Brouwer, & Franz, 2008). Several arguments have been made as to why visual attention is directed specifically toward the index finger when grasping. For example, the index finger follows a more variable trajectory toward the to-be-grasped-object in comparison to the thumb (Galea, Castiello, & Dalwood, 2001) suggesting more guidance is required 'in-flight' prior to contact with the object. The index finger also is typically the first digit to contact the object (Cavina-Pratesi & Hesse, 2013; Schettino et al., 2013), and may therefore require a primary visual landmark to be established at its point of contact.

Grasping 3-D Objects Versus 2-D Targets

To date, most research investigating skilled grasping movements has involved the grasping of stationary objects, likely because such experiments are easier to conduct while ensuring a significant amount of experimental control is maintained, control that may be diminished by the incorporation of object movement. However, our interactions with the environment are not always static, and often involve the interception and grasping of moving objects. In fact, those who demonstrate an ability to intercept moving projectiles quickly and accurately are often lauded, and substantial amounts of funding are allocated to training programs that promise to increase an athlete's ability to visually pursue and intercept moving objects such as a baseball or football. There remains then the difficult task of investigating visually guided grasping movements toward moving stimuli in the laboratory setting. The use of 2-D computer generated on-screen targets is one potential option for studying such movements. By using 2-D virtual on-screen targets, experimenters can study visually guided action toward moving stimuli while maintaining a high degree of experimental control over the measurement of participants' movements, as well as the characteristics of the on-screen target, such as target shape and size, as well as target rotation (Leferink, Bruce, & Marotta, 2017), movement speed (Bulloch, Prime, & Marotta, 2015) and direction (Langridge & Marotta, 2017; Thulasiram, Langridge, Abbas, & Marotta, 2020), therefore making it possible to study a variety of complex real-world actions above and beyond the grasping of stationary objects.

However, the visual system does not treat 2-D stimuli the same as 3-D objects. As discussed above, visual information regarding the physical features of an object such as size, shape, weight, and orientation are used by the dorsal stream to perform an accurate visuomotor action when grasping. These physical features are typically absent when interacting with 2-D stimuli and can at best be inferred by the shape of the virtual image. Further, any haptic feedback that would be available when grasping a 3-D object (e.g., surface texture), is replaced by the terminal feedback provided by the screen's surface. The integration of haptic and visual feedback is important for the absolute specification of object size when grasping (Davarpanah Jazi, Yau, Westwood, & Heath, 2015). Research using functional neuroimaging to explore these differences has demonstrated differing activation in the left anterior intraparietal sulcus (aIPS) – a key dorsal stream region involved in planning and executing visually guided grasping – when planning grasping movements toward 3-D compared to 2-D stimuli, suggesting the processing of visual information for action in this brain region is sensitive to the 'realness' of the stimulus being grasped (Freud et al., 2018). Further, grip apertures when grasping 2-D stimuli have been shown to adhere to Weber's law, a psychophysical principle of human perception stating that the 'just noticeable difference' (JND) in response to a changing stimulus will scale in proportion to the change in stimulus intensity, or in the case of grasping, the change in stimulus size. Using the within-subject standard deviations in grip aperture to determine participants' sensitivity to a change in stimulus size (i.e., JNDs), has revealed that the JNDs when grasping 2-D stimuli scale proportionately to the change in object size. Conversely, the JNDs in grip aperture profiles when grasping 3-D objects do not change as a proportion of object size, thus violating Weber's Law and suggesting the computations used when grasping 3-D objects are tuned to the object's physical size, free from perceptual influence (Holmes & Heath, 2013; Ozana & Ganel, 2017; Ozana, Namdar, & Ganel, 2020). Altogether, these results suggest that certain measurable aspects of a visuomotor behaviour directed toward a 2-D target may not accurately reflect the same processing that is involved when performing the same action toward a 3-D version of that target.

Despite these reported differences, there is evidence to suggest some visuomotor behaviours are preserved when grasping 2-D stimuli. For example, Westwood, Danckert, Servos, & Goodale (2002) demonstrated accurate grip scaling when grasping both 3-D square objects, and 2-D images of those objects. This was also shown to be true for D.F., a neurological patient with visual-form agnosia resulting from damage to their ventral stream. Westwood et al., (2002) interpreted these results as support for the dorsal stream's ability to perform appropriately scaled grasps without an absolute volumetric representation of the object being grasped. More recent work has demonstrated that when using a precision grip to grasp virtual on-screen computer generated symmetrical square targets, participants direct their digits to horizontal positions on the top and bottom edges of the target that correspond to the target's horizontal midline (Bulloch et al., 2015; Langridge & Marotta, 2017; Thulasiram et al., 2020). These grasp points produce a grasp axis that intersects with the target's geometrical center, similar to how these contact points would produce a grasp axis intersecting a 3-D object's COM. This suggests participants can use the shape of the 2-D target to infer information about its geometric center and may use this information accordingly when selecting grasp points at its edges. These investigations also demonstrate a shift in fixation position toward the point of index finger contact, suggesting the importance of index finger placement when grasping 3-D objects is also a motivating factor when directing the digits toward a 2-D stimulus (but see Thulasiram et al., 2020 for a discussion regarding the increased importance of the thumb placement when grasping a downward moving target). In summary, while the visuomotor processes involved in grasping 2-D stimuli may be functionally distinct from those involved in grasping 3-D stimuli, the preservation of certain visuomotor behaviours such as fixation position and digit placement appear to suggest the visual system may perform similar computations for the execution of action toward both 2-D and 3-D stimuli. However, the extent to which the vision-for-perception ventral stream exerts an influence over these visually guided actions toward 2-D stimuli, typically carried out exclusively by the vision-for-action dorsal stream, remains unknown.

Current Investigations

In 3 research studies, the question of how the visual system processes information about a 2-D target's shape, size, and translational movement when executing visually guided actions are explored. Chapter 2 involves a focus on the gaze and grasp strategies used when grasping horizontally translating 2-D targets. Previous research has focused on the grasping of moving targets at the mid-way point of their movement, such that grasps always occurred in the center of the computer screen, within a region aligned with participants' mid-sagittal axis (Bulloch et al., 2015; Langridge & Marotta, 2017). The aim of this study is to explore eye-hand coordinated grasping movements directed toward horizontally translating targets at early, middle, and late stages of target movement, and to compare the grasping strategies that occur at these timepoints with those used to grasp stationary targets located at the same on-screen positions. By manipulating the shape of these targets, the importance of selecting grasp points near the target's horizontal midline is also tested. Using 2-D targets to explore how we use vision when grasping moving stimuli provides insight into how stimulus position and direction of movement are incorporated during interceptive actions.

Chapter 3 addresses the aforementioned incongruencies between grasping 2-D and 3-D stimuli, by directly comparing fixations and digit placement when grasping 3-D shapes and 2-D virtual versions of those shapes. The extent to which the intention for stimulus manipulation influences these differences is explored using a 'grasp only' versus 'slide' task, in which participants slide the stimulus to another location. By incorporating stimulus manipulation in both 3-D and 2-D grasping conditions, this study aims to further bridge the gap between 2-D and 3-D grasping experiments.

Finally, Chapter 4 explores how participants' perception of an on-screen targets' size influences their accuracy and movement time during a point-and-click task performed using their device's trackpad to control an on-screen cursor. Control of an on-screen cursor requires participants to use finger movements on the horizontal surface of the trackpad to execute coordinated cursor movements on a vertically positioned computer screen. This transformation from an egocentric reference frame (physical finger movements) into an allocentric, scene-based reference frame (cursor movement on the computer screen) likely reflects a switch from a naturally proximal action controlled by the dorsal stream into a perceptually influenced action mediated by top-down processes via the ventral stream. By incorporating the Ebbinghaus illusion, a size-contrast illusion proven to effectively alter the perceived size of a target, the degree to which the vision-for-perception ventral stream influences the vision-for-action dorsal stream's performance of the task is measured.

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CHAPTER 2: GRASPING A 2-D VIRTUAL TARGET: THE INFLUENCE OF TARGET POSITION AND MOVEMENT ON GAZE AND DIGIT PLACEMENT

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

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

Grasping behaviour of this nature has been demonstrated primarily by research investigating goal-directed reaching and grasping movements toward stationary objects presented at stable, central locations, usually aligned with the midsagittal plane of the participant

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

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

'Grasping' 2-D Virtual Targets

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

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

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

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

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

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

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

Experiment 1: Grasping Stationary Targets

Methods

Participants

Twenty-three undergraduate psychology students (12 female; age range 17-26 years old; *M* = 19.3 years, *SD* = 2.03) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and received course credit toward their Introductory Psychology course in exchange for participation. All participants had normal or corrected to normal vision, and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix A). All participants provided informed consent prior to participation (Appendix B). All procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

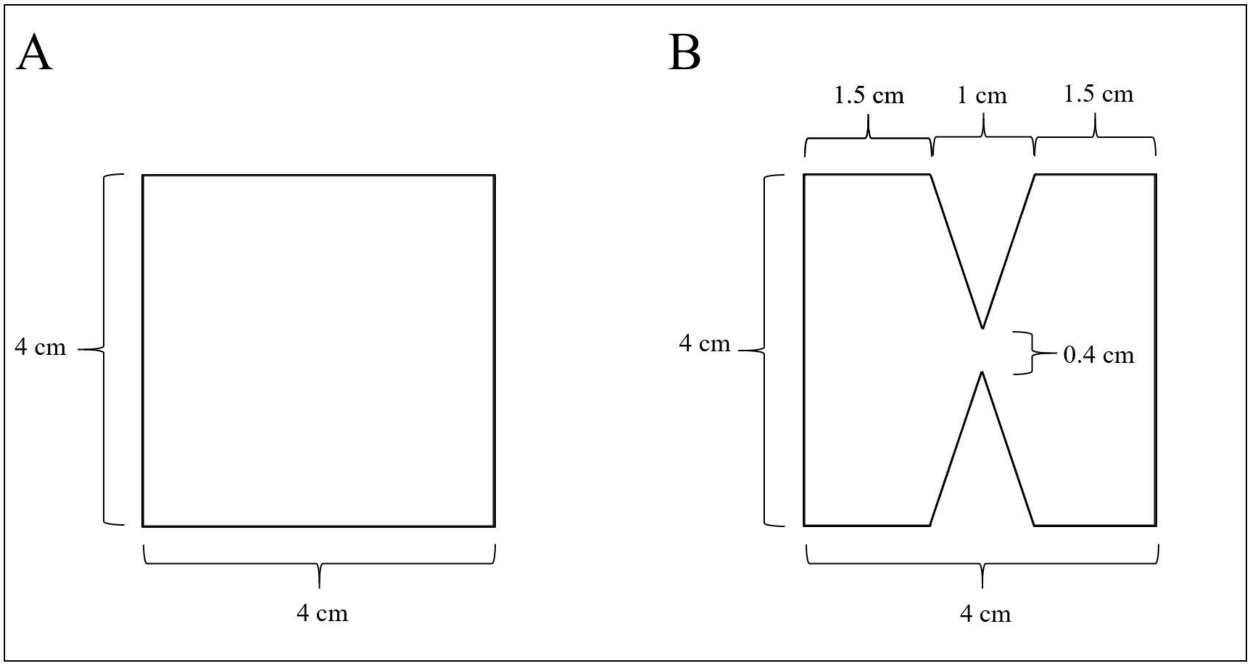
Stimuli and Materials

Participants were seated in a height-adjustable chair, 55 cm away from a Dell U2414H 24" monitor, with their head stabilized in a chin rest, ensuring their eye-level was aligned with the middle of the screen. Reaching and grasping movements were recorded using an Optotrak Certus (Northern Digital Inc., Waterloo, ON, Canada) sampled at 130 Hz. Six infrared light-emitting diodes (IREDS) were attached to the participants' right hand and wrist (2 IREDs each placed on the proximal edge of cuticle of the index finger, the proximal edge of cuticle of the thumb, and on the distal radius of the wrist). Only one IRED at each position was used to analyze the participants' movement. If there was a significant loss of data using the first IRED at one of these locations (e.g., missing or extreme values due to rotation of the hand), the second IRED would be used for analysis of that participant. An Eyelink II (SR Research Ltd., Mississauga, ON, Canada) sampled at 250 Hz was used to record binocular eye movements. Three additional IREDs were placed on the Eyelink II's headset to account for any incidental head movement during data collection. MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA) was used to integrate the motion tracking data into a common spatial and temporal frame of reference using a 7 Hz Butterworth filter, and to generate the on-screen stimuli. Both eyes were calibrated using a nine-point calibration/validation procedure. This was followed by an accuracy check that involved fixating on a centrally located dot for 8 s. The presence of an average gaze displacement error exceeding 1 cm would result in the recalibration/validation of the Eyelink II.

The 2-D computer generated virtual target stimuli consisted of either a 'Control' target, presented as a 4 x 4 cm white square with 4 uniform edges, or an 'Experimental' target, which matched the Control target in colour, size and shape, with the exception of a 1 cm notch in the middle of the top and bottom edges, leaving two 1.5 cm wide 'graspable' regions on either side (Figure 2.1). Targets were presented against a black background.

Figure 2.1

On-screen Stimuli



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

Procedure

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

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

Data Analysis

This experiment utilized a within-subject repeated measures design, and all participants were exposed to each unique trial type. Raw horizontal and vertical gaze positions were recorded for the duration of each trial, and characterized into fixations using custom algorithms developed using MATLAB (R2008a, The MathWorks Inc., Natick, Massachusetts, USA), based on a dispersion-threshold identification (I-DT) algorithm (Salvucci & Goldberg, 2000), with a minimum duration threshold of 100 ms and a maximum dispersion threshold of 1 cm. These fixations were then examined relative to the target’s center at the time participants made contact with the screen (TOC). The final horizontal and vertical coordinates of the index finger and thumb relative to the target’s center were also collected at TOC. As an additional indicator of grasp accuracy, custom programming developed using MATLAB used the final index finger and thumb positions to create an imaginary line connecting the two digits (the grasp axis) and determine the shortest absolute distance between this line and the target’s center. This distance has been used previously to indicate grasp stability when grasping 3-D objects (Goodale et al., 1994; Marotta et al., 2003). In this case, this distance was used as an additional source of information about where participants were placing their index finger and thumb in relation to the target’s center.

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

Shapiro-Wilk test was used to test the data for normality. All analyses were conducted using alpha = .05.

Multiway Frequency Analysis

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

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

The overall frequency with which all participants fixated and placed their index finger within one of these 3 regions (Count) was recorded and analyzed using R (version 3.6.1). The following Generalized Log-Linear Model (GLM; Poisson Distribution) was used to fit the data: Frequency ~ Subject*Target Position*Target Shape*Grasp Region. The deviances between the observed frequencies and the expected (no effect) frequencies were analyzed using an ANOVA (Type II Sum of Squares), run in R using the 'car' package (Fox & Weisberg, 2019). By using this method and including Frequency as the dependent variable in the model, any observed interactions involving Grasp Region (e.g., Position x Grasp Region or Shape x Grasp Region) represent a main effect (of the variable interacting with Grasp Region) on the relative frequency with which each region was chosen (Frequency). As such, the influence of each factor (i.e., the target's position and shape), on gaze and grasp position can be determined by comparing the frequency at which participants direct their gaze or place their index finger in a particular region compared to the frequency that would be expected if there were no effect. Due to an unequal number of observations across all participants, and to avoid the associated risk of committing a Type I error, the results of this analysis were interpreted using alpha = .01.

Results and Discussion

Excluded Data

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

Kinematic and Temporal Variables

Participants' average reaction time, average reach duration, average maximum wrist velocity and wrist height are provided in Table 2.1. These traditional kinematic and reaction time measures are included here to provide additional information about the way participants reached toward the targets. However, as these data have no direct relevance to our present hypotheses, formal analyses were not conducted and the results provide context only. All reach data were collected using the IREDs attached the participants' right wrist.

Table 2.1

Grasping Stationary Targets: Average Reaction Time, Reach Duration, Maximum Wrist Velocity and Wrist Height.

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

Note. Standard error of the means presented in parentheses.

Digit Placement

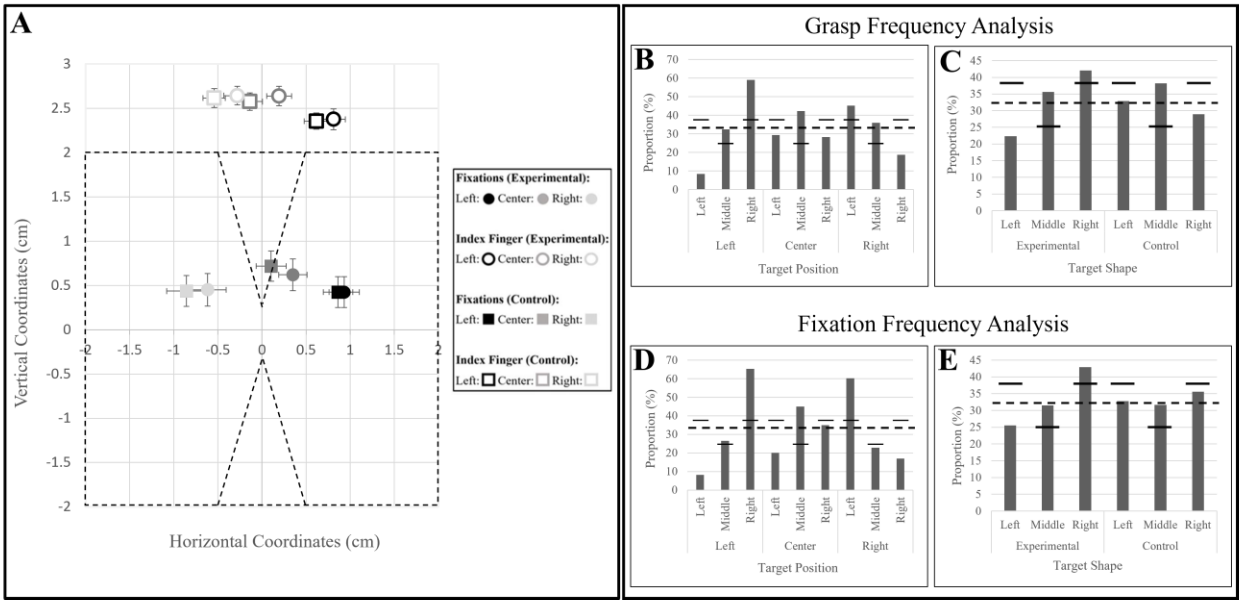
Average Horizontal Index Finger Placement

The average positions participants fixated and placed their index finger at TOC in all conditions are presented in Figure 2.2a. The 2 x 3 repeated measures ANOVA revealed a significant main effect of Position, $F(2,44) = 42.893$, $p < .001$, $\eta_p^2 = 0.672$, confirming the hypothesis that participants would minimize the amount of energy required to transport the hand to the target by grasping non-central targets on the side nearest to the reaching hand. Horizontal index finger placement was aligned with the midline when grasping Center targets ($M = 0.05$ cm to the right of the horizontal midline, $SE = 0.14$ cm). In comparison, index placement was positioned significantly more rightward when grasping Left targets ($M = 0.71$ [0.13] cm to the right of the target's horizontal midline, $p < .001$), and significantly more leftward when grasping Right targets ($M = 0.41$ [0.13] cm to the left of the horizontal midline, $p < .01$). Horizontal index finger placement when grasping Left and Right targets were significantly different ($p < .001$). Participants likely preferred to grasp the closest side of the target because digit placement on the far side of a non-central target in this task would involve exerting the unnecessary effort required to transport the fingers to a location aligned with, or past the target's midline. Despite this influence of target position however, index finger placement was always positioned relatively close to the target's horizontal midline.

Participants placed their index finger slightly farther rightward when grasping Experimental shapes (*M* = 0.26 cm to the right of the horizontal midline, *SE* = 0.12 cm) in comparison to Control shapes (*M* = 0.02 [0.12] cm to the left of the horizontal midline), as indicated by a significant main effect of Shape, $F(1,22) = 19.310$, $p < .001$, $\eta_p^2 = 0.464$. This was surprising, as it was expected that when grasping the Experimental targets with notches on the top and bottom edges of the target, digit placement would shift away from the midline in the direction of the approaching hand. While this was the case when grasping Left and Center targets, the opposite was true for Right targets, and participants still placed their digits at more rightward positions when grasping the Experimental targets. It is possible that because all participants used their right hand, grasping a more pronounced leftward position, as would be expected if participants were solely minimizing effort, would obstruct a larger portion of the target from view (Paulun et al., 2014; Maiello et al., 2019). As a result, participants shifted their digit placement rightward when grasping Experimental targets, even when positioned on the Right side of the screen.

Figure 2.2

Fixation Position and Index Finger Placement at Time of Contact



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

Grasp Region Frequency Analysis: Horizontal Index Finger Placement

When considering the frequencies at which participants placed their index finger on the Left, Middle, and Right side of the target, both Position x Grasp Region, χ^2 (4) = 457.76, $p < .001$, and Shape x Grasp Region, χ^2 (2) = 84.46, $p < .001$, interactions were significant. As can be seen in Figure 2.2b, a higher proportion of grasps occurred on the right side of the target when it was positioned on the Left side of the screen, while a higher proportion of grasps occurred in the middle of targets located in the Center of the screen, and a higher proportion of grasps occurred on the left side of targets presented on the right side of the screen. As shown in Figure 2.2c, index finger placement was positioned most frequently on the right side when grasping Experimental targets, while grasp frequency was distributed more evenly when grasping Control targets. As expected, the regions participants most frequently placed their index finger coincided with the biased direction of average horizontal index finger placement.

Distance from the Grasp Axis to the Target's COM

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

Average Vertical Index Finger Placement

A significant main effect of Position indicated that participants placed their index finger significantly lower when grasping Left targets ($M = 2.37$ cm above the target's center, $SE = 0.09$ cm) compared to when grasping Center ($M = 2.63$ [0.11], $p < .05$) or Right ($M = 2.63$ [0.10] cm, $p < 0.01$) targets¸ $F(2, 44) = 8.613$, $p < .001$, $\eta_p^2 = 0.284$. There was no significant difference between Center and Right targets ($p > .05$). As these were 2-D targets being grasped, a lowered index finger placement would not have the same repercussions as when grasping an actual 3-D square (e.g., collision with the front of the object, rather than placement on its top edge), and therefore participants may have placed their index finger lower when grasping targets presented on the left side of the screen as a result of the increased effort required to raise the hand toward a position on the contralateral side of the body.

Fixation Positions

Gaze Accuracy

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

Average Horizontal Fixations at Time of Contact

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

Fixation Region Frequency Analysis: Horizontal Fixations at Time of Contact

Similar to the frequency of index finger placement, participants fixated more frequently within regions corresponding to the final average horizontal fixation positions. As can be seen in Figure 2.2d, participants fixated more frequently on the right side of Leftward targets, the left side of Rightward targets, and toward the middle of Center targets, as confirmed by a significant Position x Grasp Region interaction, $\chi^2(4) = 765.29$, $p < .001$. Additionally, as shown in Figure 2.2e, a significant Shape x Grasp Region interaction, $\chi^2(2) = 49.63$, $p < .001$, demonstrated that participants fixated more frequently on the right side of Experimental targets, compared to Control targets, toward which fixations were distributed more evenly across regions.

Average Vertical Fixations at Time of Contact

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

Experiment 2: Grasping Horizontally Translating Targets

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

Methods

Participants

Twenty-five undergraduate psychology students (21 female; age range: 16-32 years old; *M* = 19.72 years, *SD* = 4.61) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and received course credit toward their Introductory Psychology course in exchange for participation. All participants had normal or corrected to normal vision, and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971). All procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Stimuli, Materials, and Procedure

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

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

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

Data Analysis

As in Experiment 1, a within-subject repeated measures design was utilized, and each participant's mean condition values were used for the analysis of each dependent variable. Four three-way 2 x 2 x 3 repeated measures ANOVAs (Direction x Shape x Reach Cue) were used to examine the horizontal and vertical coordinates of the fixations relative to the target's center at the following timepoints: 1) The onset of target movement (MO), and 2) Reach onset (RO), characterized as the point in time at which the participants' wrist reached a speed of 5 cm/s. Another 2 three-way 2 x 2 x 3 (Direction x Shape x Reach Cue) repeated measures ANOVAs were run using the final raw horizontal and vertical gaze coordinates to determine where participants were looking relative to the target's center at TOC. The raw gaze coordinates were used for this timepoint to account for any final eye movements not included by the I-DT algorithm occurring within the final milliseconds of the trial. Horizontal and vertical index finger placement were once again analyzed at TOC using 2 three-way (Direction x Shape x Reach Cue) repeated measures ANOVAs, and a single three-way (Direction x Shape x Reach Cue) repeated measures ANOVA was used to analyze the distance between the grasp axis and the target's center across conditions. As in Experiment 1, any violations to sphericity were corrected using a Greenhouse-Geiser correction. The data were tested for normality using the Shapiro-Wilk test. A Bonferroni correction was used to analyze all significant interactions, and all analyses were conducted using alpha = .05.

A MWF Analysis was again conducted to explore the frequency at which participants placed their index finger and directed their gaze toward each of the three Grasp Regions specified in Experiment 1. For the current experiment, these three regions were redefined as the 'trailing side', 'leading side', and 'middle' of the target. In order to analyze how the direction of target movement and the time at which the target was grasped influenced these frequencies, the previous GLM was modified to the following: Frequency ~ Subject * Direction of Target Movement * Reach Cue * Shape * Grasp Region. All other aspects of the analysis remained the same, including using alpha = .01 to determine statistical significance.

Comparison Between Stationary and Moving Targets

In order to compare digit placement when grasping stationary compared to moving targets, 2 independent-sample t-tests were conducted at each on-screen position (left, middle, and right) to compare horizontal index finger position when grasping the stationary target (Experiment 1) with index finger position when grasping the moving targets (Experiment 2) of the same shape (i.e., Control or Experimental), grasped at the same on-screen position. For example, Stationary Control Targets presented on the Left side of the screen were compared to Leftward moving Control targets grasped at Late stages of travel, and Rightward moving Control targets grasped at Early stages of travel. The result was a total of 12 independent samples t-tests (4 per each on-screen position) comparing index finger placement. Another 12 independent samples t-tests were conducted in the same manner to compare horizontal gaze positions. A Bonferroni adjusted alpha of .0125 (.05/4) was used to account for the 4 tests (2 comparing Control, and 2 comparing Experimental) occurring at each on-screen position, and Cohen's *d* was used to determine effect size.

Results and Discussion

Excluded Data

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

Kinematic and Temporal Variables

As in Experiment 1, participants' average reaction time, average reach duration, average maximum wrist velocity and wrist height are provided for additional context in Table 2.2.

Table 2.2

Grasping Moving Targets: Average Reaction Time, Reach Duration, Maximum Wrist Velocity and Wrist Height

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

Note. Standard error of the means presented in parentheses.

Digit Placement

Average Horizontal Index Finger Placement

Average index finger placement and final gaze positions when grasping rightward and leftward moving targets at TOC are presented in Figure 2.3a and 2.3b respectively. Average final horizontal index finger placement was consistently positioned behind the target's midline; participants placed their index finger to the right of the Leftward moving target's midline, and to the left of the Rightward moving target's midline. However, a significant main effect of Direction, $F(1,24) = 7.520$, $p < .05$, $\eta_p^2 = 0.239$, indicated that index finger placement was closer to the midline of Leftward moving targets ($M = 0.43$ cm behind the target's midline, $SE = 0.13$ cm) compared to Rightward moving targets ($M = 1.0$ [0.11] cm behind the target's midline).

A significant Shape by Time interaction, $F(2, 48) = 5.178$, $p < .01$, $\eta_p^2 = 0.177$, was also observed. When grasping targets at Middle stages of travel (i.e., when grasps occurred at the middle of the screen), horizontal index finger placement was positioned farther behind the midline when grasping Experimental targets ($M = 0.81$ cm behind the target's horizontal midline, $SE = 0.08$ cm) compared to when grasping Control targets at the same stage of travel ($M = 0.61$

[0.07] cm behind the midline), suggesting participants avoided the notched region, and placed their digits farther behind the target's horizontal midline compared to when grasping Control targets when the target was in the middle of the screen. There was no influence of target shape when the target was positioned at the far edges of the screen; participants consistently grasped the trailing side of the target at both Early (Experimental: $M = 0.76$ [0.11] cm behind the horizontal midline, Control: $M = 0.91$ [0.09] cm behind the midline, $p > .05$) and Late (Experimental: $M = 0.57$ [0.15] cm behind the midline, Control: $M = 0.62$ [0.12] cm behind the midline, $p > .05$) stages of travel. Final index finger placement did not significantly differ between timepoints when grasping Experimental targets. When grasping Control targets, final index finger placement was significantly farther behind the midline when grasping the target at Early stages of travel compared to at Middle stages of travel ($p < .05$).

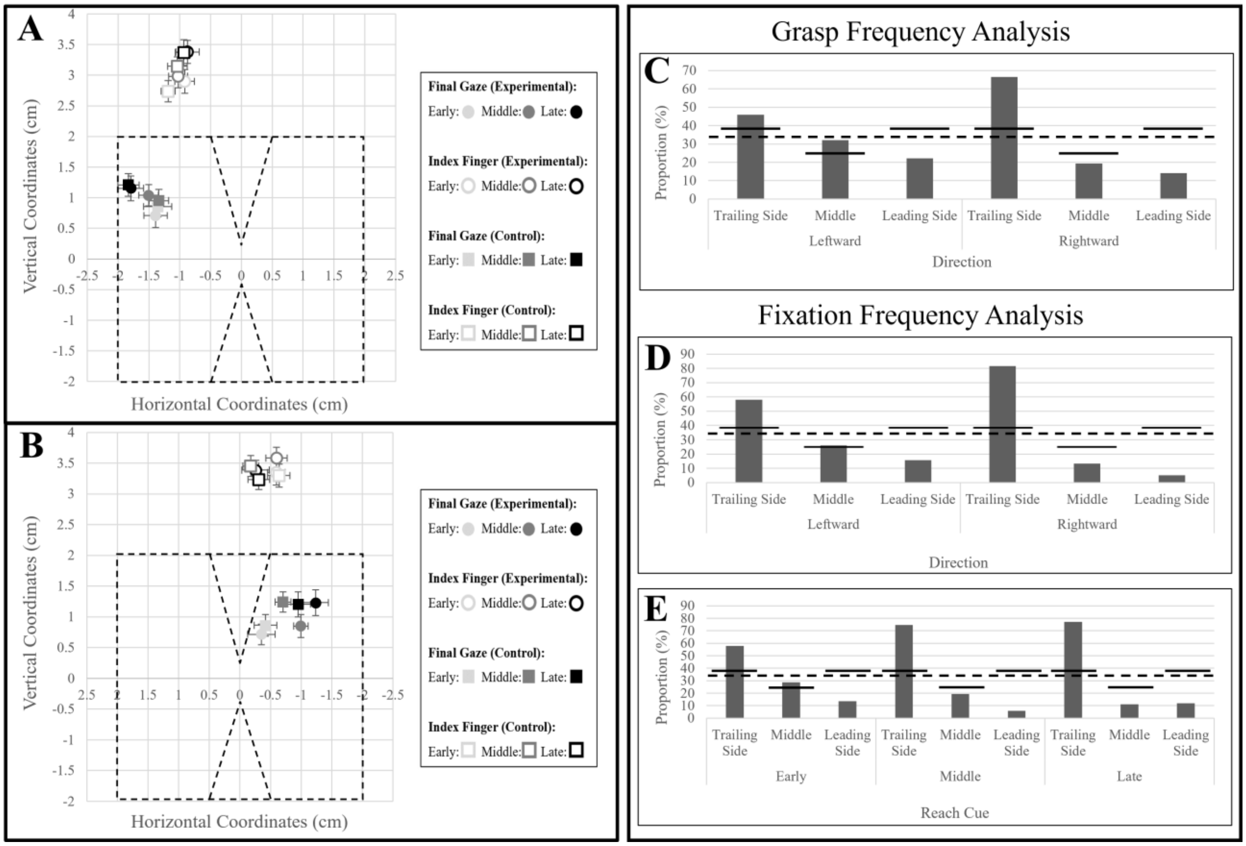
When the target was grasped at Late stages of travel, digit placement behind the midline would require less effort than reaching farther ahead to grasp the leading side as the target moved away from the reaching hand. In this sense, the current results agree with those of Experiment 1, when the targets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

Grasp Frequency Analysis: Horizontal Index Finger Placement

A significant Direction x Grasp Region interaction, χ^2 (2) = 86.01, $p < .001$, revealed that the direction of target movement influenced how often participants grasped a particular region of the target. As can be seen in Figure 2.3c, while the trailing side of the target was grasped most frequently when the target was moving either directions, a higher proportion of grasps occurred on the trailing side when the target was moving Rightward.

Figure 2.3

Gaze Position and Index Finger Placement at Time of Contact



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

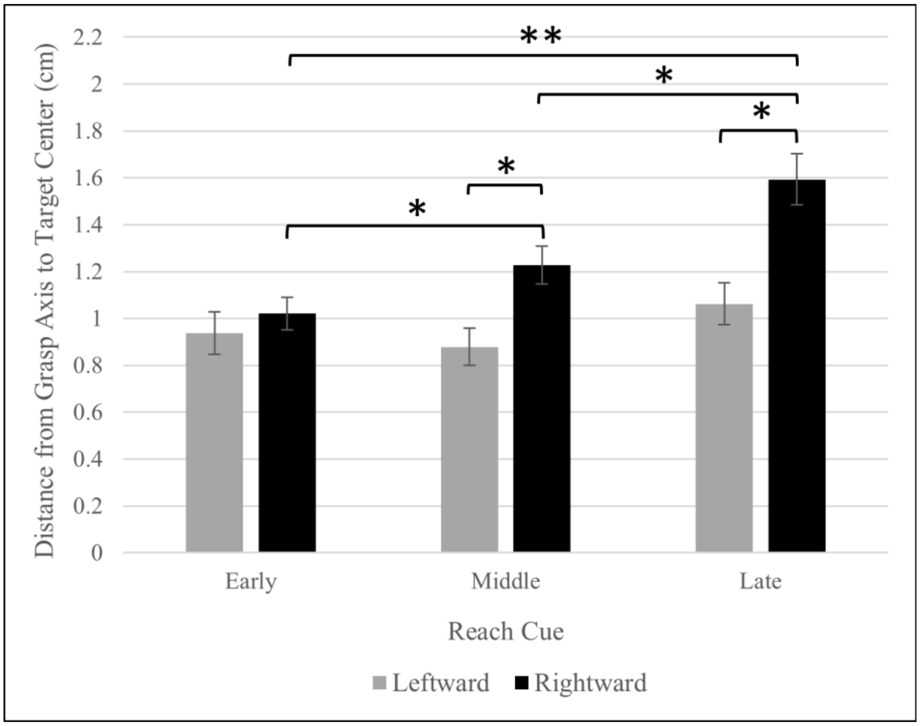
Distance from the Grasp Axis to the Target's Center

The three-way repeated measures ANOVA revealed a significant interaction between Direction and Time, $F(2,48)$, $p < .01$, $\eta_p^2 = 0.186$, displayed in Figure 2.4. Post-hoc analyses indicated that whereas there was no significant difference between Leftward and Rightward moving targets at Early stages of travel ($p > .05$), the average grasp axis was located significantly closer to the target's center when grasping Leftward moving targets at Middle ($p < .01$) and Late ($p < .01$) stages of travel compared to Rightward moving targets.

The distances between the grasp axis and the target's center did not significantly differ between any of the three stages of target travel when the target was moving leftward (all comparisons $p > .05$). However, when grasping Rightward moving targets, the distance between the grasp axis and the target's center significantly increased the farther it travelled. When grasped at Middle stages of travel, the average grasp axis was positioned significantly farther from the Rightward moving targets' center than when grasped at Early stages of travel ($p < .01$), and significantly closer to the target's center than when grasped at Late stages of travel ($p < .01$). The average grasp axis when the Rightward moving target was grasped at Late stages of travel was significantly farther from the target's center than when grasped at Early stages of travel ($p < .001$). In other words, participants placed their digits at locations that generated grasp axes positioned closer to the target's center when the Rightward moving target was approaching the grasping hand, and farther from the target's center when moving away from it. The distance between the grasp axis and the target's center remained consistent when grasping Leftward moving targets at each stage of travel, suggesting participants may have been compensating for the added difficulty of grasping a target moving toward the contralateral hemispace, and placed their digits closer to the horizontal midline regardless where the target was at the time of the grasp.

Figure 2.4

Grasp Axis Distance



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

Average Vertical Index Finger Placement

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

The stage of travel at which the target was grasped did not significantly influence the vertical placement of the index finger when the target was moving Leftward. When grasping

Rightward moving targets, average vertical index finger placement was positioned significantly lower when grasping targets at Early stages of travel compared to when grasping targets at Late stages of travel ($p < .001$).

Gaze and Fixation Positions

Gaze Accuracy

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

Visual Pursuit of the Target

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

Average Horizontal Fixations at Movement Onset

The average fixations made at the onset of Rightward and Leftward target movement are provided in Figure 2.5a and 2.5b respectively. As predicted, participants directed their gaze toward the leading edge of the target as it started moving. Bulloch et al. (2015) reported similar fixations toward the leading edge of a horizontally translating square target during pursuit. These results suggest participants prefer to visually track the leading edge of a moving target, as this side likely provides the best information about the speed, direction, and future position of the target. A significant main effect of target Shape, $F(1,24) = 16.297$, $p < .001$, $\eta_p^2 = 0.404$, indicated that average horizontal gaze was directed closer to the horizontal midline of Experimental targets (M = 0.67 cm ahead of the target's midline, SE = 0.32 cm) compared to Control targets (M = 1.13 [0.30] cm ahead of the target's midline). At this timepoint, the 'notches' at the midline of Experimental targets may have made this area more visually salient, and perhaps provided additional edges which participants could have used to obtain additional information regarding the movement of the target, not present when viewing Control targets which only had one 'leading edge'.

Fixation Frequency Analysis: Movement Onset

As seen in Figure 2.5, at the onset of target movement, participants fixated most frequently on the leading side of the target. However, a significant Shape x Grasp Region interaction was present, χ^2 (2) = 41.495, $p < .001$, indicating participants fixated more frequently on the leading side of Control targets compared to Experimental targets (Figure 2.5c). This agrees with the finding that participants fixated at an average position closer toward the midline of Experimental targets. Further, while over 50% of fixations were directed toward the leading side of Leftward moving targets, slightly less than half were directed toward the leading side of Rightward moving targets (significant Direction x Grasp Region interaction, χ^2 (2) = 17.790, $p < .001$ (Fig 5d)). This increased frequency of fixations toward the leading side of the leftward moving target suggests participants were anticipating these targets' movements to a greater degree in comparison to when the target began moving rightward, perhaps suggesting an increased motivation to efficiently track these targets. For example, anticipation of target movement would reduce the need for 'catch-up saccades' following onset of movement (De Brouwer et al., 2002), and likely contribute to overall success of the task (Mennie, Hayhoe, & Sullivan, 2007).

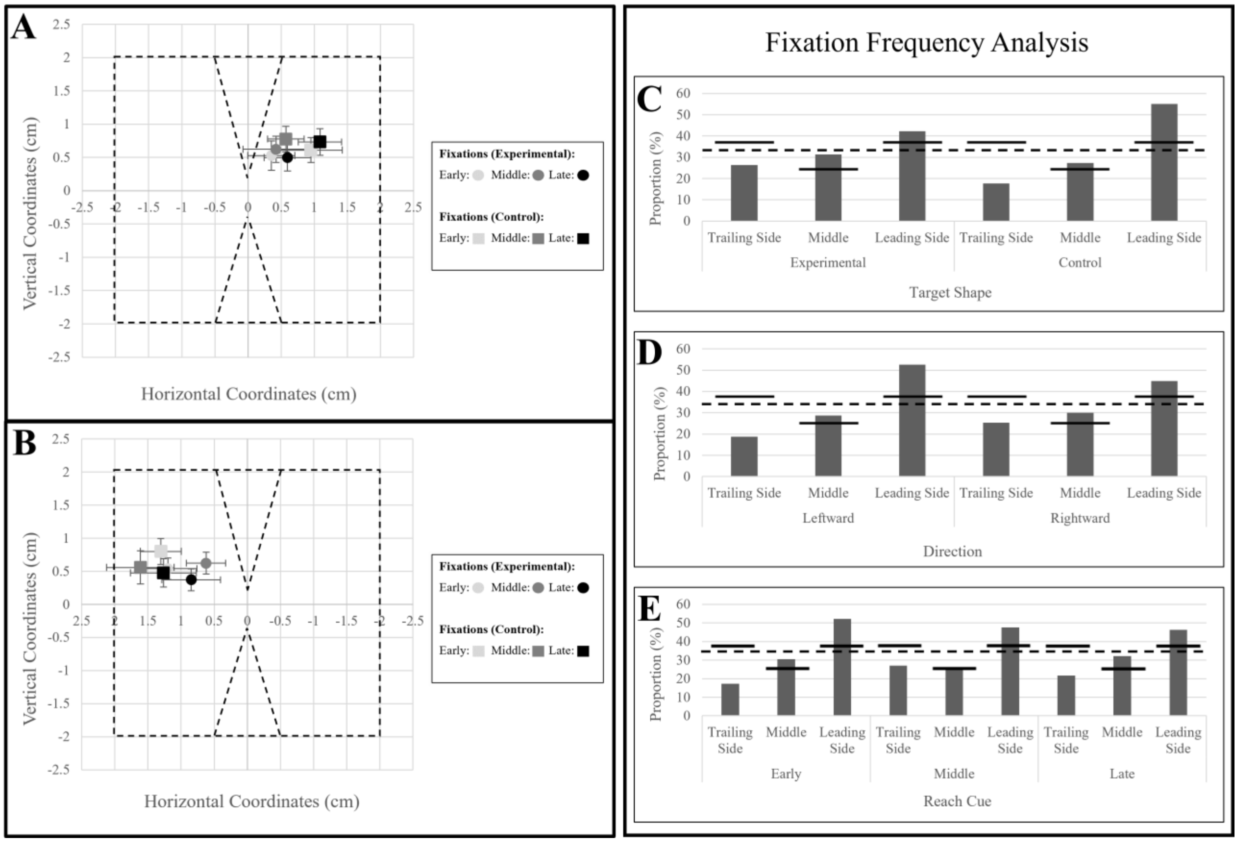
Finally, as can be seen in Figure 2.5e, a significant Reach Cue x Grasp Region interaction, χ^2 (4) = 20.943, $p < .001$, suggests that in comparison to Middle and Late stages of travel, when cued to grasp the target at Early stages of travel participants were slightly more likely to fixate toward the middle or leading side of the target compared the target's trailing side. Participants likely fixated more frequently on the leading side of these targets as a result of the simultaneous onset of target movement and presentation of the reach cue, requiring them to at once track the initial movement of the target and execute the reach-to-grasp movement.

Average Vertical Fixations at Movement Onset

On average, participants fixated 0.60 cm (SE = 0.06) above the target's center at MO. There were no significant effects of Direction, $F(1,24) = 0.322$, $p > .05$, $\eta_p^2 = 0.085$, Shape, $F(1,24) = 3.144$, $p > 0.05$, $\eta_p^2 = 0.398$, or Reach Cue, $F(2,48) = 1.793$, $p > .05$, $\eta_p^2 = 0.357$.

Figure 2.5

Fixation Position at Movement Onset



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

Average Horizontal Fixations at Reach Onset

The average fixations made at the onset of the reaching motion are provided in Figure 2.6a and 6b for rightward and leftward moving targets respectively. The three-way repeated measures ANOVA revealed a significant Direction x Shape interaction, $F(1,24) = 7.71$, $p < .05$,

$\eta_p^2 = 0.243$, at RO. Post hoc analyses revealed that average horizontal gaze was directed near the midline of Leftward moving Control targets (M = 0.16 cm ahead of the horizontal midline, SE = 0.22 cm), and behind the midline of Rightward moving Control targets (M = 0.70 [0.25] cm behind the midline), a significant difference ($p < .01$). Horizontal gaze positions did not significantly differ when reaching toward Experimental targets, and were directed toward the trailing edge of both Leftward (M = 0.65 [0.16] cm behind the midline) and Rightward (M = 0.96 [0.24] cm behind the midline, $p > .05$) moving targets.

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

Fixation Frequency Analysis: Reach Onset

Whereas participants most frequently fixated toward the leading side of the target at MO, this pattern was reversed at RO, and fixations were most frequently directed toward the trailing side of the target. Significant Direction x Grasp Region, χ^2 (2) = 13.91, $p < .001$, Shape x Grasp Region, χ^2 (2) = 67.69, $p < .001$, and Reach Cue x Grasp Region, χ^2 (4) = 43.41, $p < .001$, interactions were present (Figure 2.6c-e). Fixations were more frequently directed toward the trailing side of targets moving Rightward compared to targets moving Leftward (Figure 2.6c) and were more frequently directed toward the trailing side of Experimental targets compared to Control targets (Figure 2.6d). As seen in Figure 2.6e, whereas fixations were most frequently directed toward the trailing side of the target, these frequencies were slightly more evenly distributed when the participant was cued to grasp at Middle stages of travel.

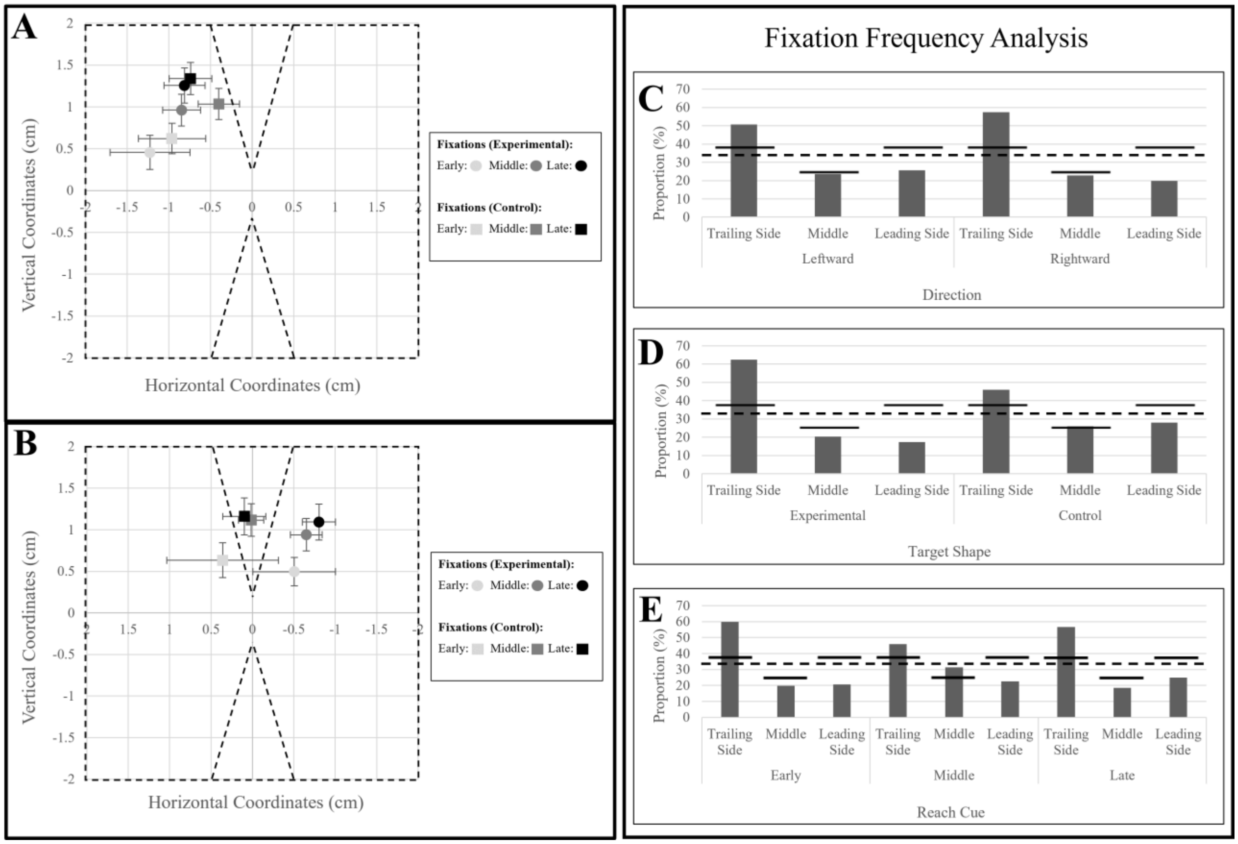
Average Vertical Fixations at Reach Onset

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

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

Figure 2.6

Fixation Position at Reach Onset



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

Average Horizontal Gaze at Time of Contact

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

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

Gaze Frequency Analysis: Time of Contact

Overall, participants most frequently directed their gaze toward the trailing side of the target when grasping, but gaze was more frequently directed toward the trailing side of Rightward moving targets compared to Leftward moving targets (Direction x Grasp Region interaction, χ^2 (2) = 139.56, $p < .001$ (Figure 2.3d). A significant Reach Cue x Grasp Region interaction was also observed, χ^2 (4) = 99.55, $p < .001$, suggesting that gaze was more distributed among the three grasp regions when grasping targets at Early stages of travel, compared to those grasped at Middle and Late stages (Fig 3e). This result agrees with the above result that average horizontal gaze was positioned closer to the target's midline when grasping targets at Early stages of travel.

Average Vertical Gaze at Time of Contact

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

Comparison of Final Horizontal Gaze and Grasp Points: Stationary versus Moving Targets

Participants' final average horizontal fixations and index finger placement when grasping stationary targets presented at the left, center, and right side of the screen (Experiment 1; Figure 2.2) were compared to participants' final gaze and index finger positions when grasping horizontally translating targets of the same shape at the same locations (Experiment 2; Figure 2.3). Table 2.3 presents the conditions being compared between the experiments, which coincide with the target being grasped on the left side, middle, and right side of the screen.

Table 2.3

Summary of Comparisons Between Experimental Conditions

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

Comparisons when the Target was on the Left Side of the Screen

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

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

Fixation Position. Participants' fixations did not significantly differ when grasping stationary and leftward moving targets grasped at Late stages of travel; gaze was directed toward the nearest (right) side of the stationary target (biased toward the approaching hand), which coincided with the trailing side of the leftward moving target, $t(46) = -1.115$, $p > .0125$, $d = 0.32$. Compared to the stationary target, gaze was directed toward the far left side of rightward moving Experimental targets grasped at Early stages of travel $t(46) = 9.008$, $p < .001$, $d = 2.61$. The same pattern was true when grasping stationary Control targets compared to leftward moving Control targets grasped at Late stages of travel, $t(46) = -.337$, $p > .0125$, $d = 0.04$, and rightward moving Control targets grasped at Early stages of travel, $t(46) = 7.742$, $p < .001$, $d = 2.38$.

Comparisons when the Target was in the Center of the Screen

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

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

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

Comparisons when the Target was on the Right Side of the Screen

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

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

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

General Discussion

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

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

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

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

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

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

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

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

Conclusion

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

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CHAPTER 3: MANIPULATION OF PHYSICAL 3-D AND VIRTUAL 2-D STIMULI: COMPARING DIGIT PLACEMENT AND FIXATION POSITION

Humans are skilled at grasping objects of varying shape and size without devoting a significant amount of cognitive effort or attention toward the task. When grasping an object, we automatically interpret the visual information available, such as its shape and position, and use this information to direct an accurate reaching movement toward the object and place the digits appropriately. The shape of the object being grasped has been known to influence various aspects of the reach-to-grasp movement, beginning as early as the planning of the grasping action (Janssen & Scherberger, 2015; Vargas-Irwin, Franquemont, Black, & Donoghue, 2015), and will predict where people direct their gaze (Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2015), the trajectory and shaping of the approaching hand during the reaching movement (Rouse & Schieber, 2015; Schettino, Adamovich, & Poizner, 2003), and the placement of the digits when grasping (Cuijpers, Smeets, & Brenner, 2004; Santello & Soechting, 1998; Schettino et al., 2013).

Another critical component influencing how a person will grasp an object is the intended manipulation of the object (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Sartori, Straulino, & Castiello, 2011). For example, when grasping an object such as a coffee cup or a pencil, we typically do so with the intention to manipulate or use the object in a pre-determined, purposeful manner; one usually grasps a coffee cup so that it can be subsequently raised and drank from, while a pencil may be picked up in a way that allows you to write. Fixations are directed toward task-relevant landmarks, such as the grasp points on the object (Belardinelli, Stepper, & Butz, 2016; Johansson, Westling, Bäckström, & Flanagan, 2001) and the particular end-goal, such as pouring from a water bottle versus simply moving it to another location, will produce unique visuomotor behaviours relevant to the particular action (Ansuini, Giosa, Turella, Altoè, & Castiello, 2008; Sartori et al., 2011). Even prior to the grasp, the intended action on an object influences the posture of the hand during the reaching phase (Ansuini et al., 2008), and in cases when the action end-goal of the grasping movement is unexpectedly changed during the reach, these postures are modified accordingly during the reaching movement to ensure the placement of the digits serves the updated goal (Hughes et al., 2012). It is therefore believed that the final posture of the hand is determined prior to the movement using feedforward modelling of the upcoming action (Elsinger & Rosenbaum, 2003;

Herbort & Butz, 2010), and is then updated accordingly by feedback mechanisms during the movement to ensure digit placement at the time of the grasp serves effective and comfortable manipulation.

Ultimately, a successful grasp is one that places the digits at comfortable locations on the object, while simultaneously generating the necessary amount of force on the object to successfully perform the intended action. When using a precision grip to grasp symmetrical objects, the index finger and thumb are typically positioned on opposite sides of the object, such that an imaginary grasp axis connecting the digits would bisect or fall close to the object's center of mass (COM), thus applying sufficient force to the COM and minimizing the amount of torque around the grasp axis (Goodale et al., 1994; Lederman & Wing, 2003). Visibility of the object being grasped will also influence how the digits are placed, as digit placement that causes the hand to obscure one's view of the object will make it difficult to grasp effectively and may interfere with future manipulation. Paulun et al. (2014) demonstrated a rightward shift in digit placement when participants grasped objects using their right hand, and a leftward shift when using the left hand regardless of the start position of the hand, suggesting grasp selection may have served to promote visibility of the object being grasped rather than minimize energy expenditure (Maiello, Paulun, Klein, & Fleming, 2019; Paulun et al., 2014). These results suggest that in order to efficiently grasp and manipulate an object, digit placement must not only ensure a stable grasp, but also minimize the extent to which the position of the hand obstructs the view of the object.

Recent work involving visually guided reaching and grasping movements toward 2-D virtual targets has indicated certain similarities in the way participants fixate their gaze and place their digits when grasping both 3-D and 2-D stimuli. For example, when using a precision grip to grasp 2-D on-screen symmetrical square targets, participants place their index finger and thumb on the top and bottom of the target respectively, at locations near the horizontal midline, suggesting participants use the shape of the stimuli to infer the location of the target's geometric center, and place their digits at locations that generate a grasp axis bisecting or falling near to this location (Bulloch, Prime, & Marotta, 2015; Thulasiram, Langridge, Abbas, & Marotta, 2020; Langridge & Marotta, 2020). Humans are naturally adept at judging the location of a flat object's COM (Bingham & Muchisky, 1993) and appear to use this information when grasping 2-D on-screen symmetrical shapes. Participants' fixations are directed toward the position of the index finger when grasping 2-D targets, as is the case when grasping 3-D objects (Belardinelli et al., 2016; Brouwer et al., 2009; Cavina-Pratesi & Hesse, 2013; Desanghere & Marotta, 2011; Voudouris, Smeets, & Brenner, 2016), suggesting a similar emphasis on index finger placement when grasping both 3-D objects and virtual 2-D targets. There is even some evidence to suggest that participants appropriately scale their grip apertures to some degree when grasping 2-D targets as they do when grasping 3-D objects (Westwood, Danckert, Servos, & Goodale, 2002).

Despite these apparent similarities, a number of studies have clearly demonstrated the differences between grasping 3-D objects compared to 'pantomimed grasps' toward 2-D stimuli, including functional (discrimination during the planning phase within key grasping regions of the brain; Freud et al., 2018) and perceptually mediated (adherence to Weber's law; Holmes & Heath, 2013; Ozana & Ganel, 2017, 2019; Ozana, Namdar, & Ganel, 2020) aspects of the grasping action. These differences are to be expected, as the action of grasping a 2-D target is inherently different from that of grasping a 3-D object, which necessarily involves more extensive processing of certain object properties such as mass, 3-D shape, surface texture, and the material from which it is made. The material properties of an object (e.g., rough versus smooth, light versus heavy) have been shown to influence primarily temporal aspects of a reach-to-grasp-movement (e.g., overall movement time, velocity, and deceleration; Weir, MacKenzie, Marteniuk, & Cargoe, 1991), and digit placement is typically directed toward positions that are lower on the object (Glowania, van Dam, Brenner, & Plaiser, 2017) and closer to the COM (Paulun, Gegenfurtner, Goodale, & Fleming, 2016) when grasping heavier objects with slippery surfaces, for which grasping is more difficult and requires more careful placement of the digits.

The fact that one's intent to manipulate an object will influence how the object is grasped highlights another critical limitation associated with the use of 2-D virtual stimuli in grasping research, namely that interaction with a 2-D stimulus does not allow for the type of physical manipulation afforded by a 3-D object. The typically available sources of information which are necessary for successful manipulation of a 3-D object (e.g., haptic feedback), are unavailable when interacting with 2-D virtual stimuli, and at best can be inferred by the visual presentation of the stimulus. Further, one does not need to consider the amount of force required to manipulate a virtual target (as there is none), nor risk mishandling or dropping such stimuli, factors which are characteristic of physical interaction with a physical 3-D object. Considering these disparities, it is difficult to compare and generalize the results of 2-D grasping studies to those involving manipulation of physical 3-D objects.

In recent years however, efforts have been made to increase the realism of 2-D virtual target interaction by introducing tasks involving active manipulation of a 2-D target, thus allowing researchers to study how this type of manipulation influences grasping behaviours. For example, in line with previous work investigating the perceptual influence on 2-D grasping (Ozana & Ganel, 2017, 2019), Ozana et al. (2020) demonstrated grip aperture trajectories adhere to Weber’s law during active manipulation of a virtual 2-D target (i.e., swiping or resizing a virtual rectangle) indicating perceptual mediation of the task, in contrast to the absolute, analytic processing involved when grasping physical objects. These results suggest the intended manipulation of a virtual target may not be sufficient to fully activate the same visuomotor processes dedicated for the visual control of action toward physical objects.

In the present study, we also introduce a task involving the manual manipulation of a virtual 2-D computer generated target. The manipulation in this study involved grasping and sliding a target from its original position to another on-screen location. The action end-goal varied to compare how the intention to move the target influenced grasping behaviours compared to when simply grasping it. An identical version of the task using a physical 3-D object was used to compare the visually guided grasping behaviours observed during interaction with each type of stimulus. While acknowledging the previously reported differences regarding actions toward 2-D and 3-D stimuli, our goal was to explore those visuomotor behaviours that have demonstrated potential similarities when grasping 3-D objects and virtual 2-D targets, namely participants’ digit placement and fixation positions in relation to the stimulus’ center.

Based on previous research demonstrating a spatial relationship between participants' gaze and index finger placement in relation to the center of a 2-D virtual target, it was hypothesized that the location of the stimulus, as well as the nature of the task being performed would influence participants’ fixation positions and digit placement to the same degree and direction when interacting with both virtual and physical stimuli. Participants were expected to fixate toward task related locations, corresponding to the placement of the index finger when interacting with both the virtual and physical stimulus as well. Observing similar task-related adjustments when grasping both types of stimulus would provide evidence for humans’ similar use of certain visuomotor strategies when grasping both virtual 2-D and physical 3-D stimuli.

The distance between the grasp axis and the stimulus' center, as well as the amount of torque generated by the horizontal placement of the digits was used to measure the stability of the grasp. These measures were included to examine if participants were grasping the virtual 2-D stimulus in a stable manner similar to the 3-D objects, despite stability not being critical in the absence of a true COM.

Methods

Participants

Forty-two undergraduate psychology students (36 female, 5 male, 1 undeclared) between the ages of 17 and 45 years (*M* = 19.36, *SD* = 4.46) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and participated for course credit toward their Introductory Psychology course. Participants were randomly sorted into two groups, and each group interacted exclusively with either a physical (*n* = 21), or virtual (*n* = 21) stimulus. All participants had normal or corrected to normal vision (e.g., wearing contact lenses, corrective eye surgery, etc.) and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix A). All participants provided informed consent prior to participation (Virtual Stimulus Condition: Appendix B; Physical Stimulus Condition: Appendix C). All procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Apparatus

Participants were seated in a height-adjustable chair with their head stabilized in a chin rest, positioned 54 cm in front of a Dell U2414H 24 in. computer monitor (resolution: 1920 x 1080, refresh rate: 60 Hz). Reaching and grasping movements were recorded using an Optotrak Certus 3-D motion tracking system (Northern Digital Inc., Waterloo, ON, Canada) sampled at 175 Hz. Six infrared light-emitting diodes (IREDS) were attached to the participants' right hand and wrist; 2 IREDS each were placed on the proximal edge of the index finger cuticle, the proximal edge of the thumb cuticle, and on the distal radius of the wrist. At each location, the IRED with the least amount of disrupted data (e.g., missing or extreme values due to rotation of the hand) was used to analyze the participant's movement. An Eyelink II (SR Research Ltd., Ottawa, ON, Canada) sampled at 250 Hz was used to record binocular eye movements. Three additional IREDs were placed on the Eyelink II's headset to account for any incidental movement of the head during data collection. MotionMonitor software (Innovative Sports

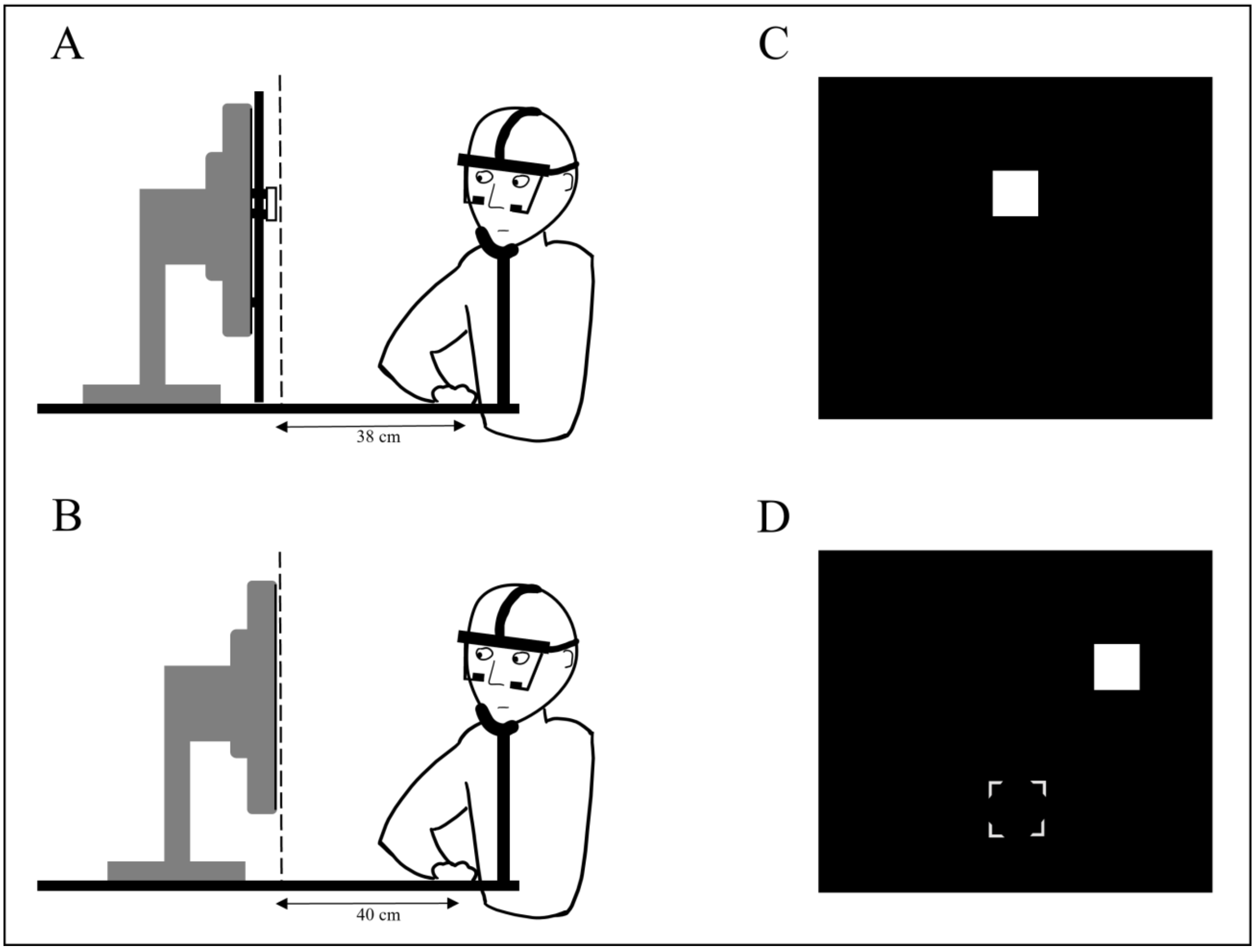
Training Inc., Chicago, IL, USA) was used to integrate the motion tracking data into a common spatial and temporal frame of reference using a 7 Hz Butterworth filter. The MotionMonitor was also used to generate the on-screen stimulus in the Virtual condition. Both eyes were calibrated using a nine-point calibration/validation procedure, followed by an accuracy check requiring participants to fixate on a dot presented in the middle of the computer screen for 8 seconds. An average gaze displacement error exceeding 0.5 cm in the horizontal axis, or 1.0 cm in the vertical axis required recalibration/validation of the Eyelink II.

Stimuli and Materials

Figure 3.1 illustrates the experimental setup for a participant in the Physical Stimulus condition (Figure 3.1a) and in the Virtual Stimulus condition (Figure 3.1b). The stimulus in the Physical condition consisted of a 3-D square block made of white foam-core board (height: 4 cm, width: 4 cm, depth: 0.5 cm). A black foam-core presentation board (height: 51 cm, width: 54 cm) was attached to the front of the computer monitor. Four low-strength organizational magnets were attached to the back side of the square block (the combined weight of the block and the magnets was 11.0 g), and additional sets of magnets were attached to the rear-facing surface of the presentation board at positions corresponding to the 3 stimulus presentation positions. During the experiment, the physical stimulus was presented at one of 3 locations: positioned either in the center of the board (aligned with the mid-sagittal axis of the participant and starting position of the hand), or 20 cm to the right or left of center, always at a vertical position of 38.5 cm above the tabletop. The stimulus in the Virtual condition consisted of a 2-D, computer-generated square, matched to the dimensions and colour of the physical stimulus and presented on the computer screen against a black background. The virtual on-screen stimulus was presented at the same horizontal and vertical positions as the 3-D stimulus in the Physical condition, so participants in both conditions were required to reach the same distance and toward the same locations.

Figure 3.1

Experimental Set-Up



Note. Illustration of the experimental setup in the Physical Stimulus condition (a) and in the Virtual Stimulus condition (b). The dotted line refers to the threshold 1 cm away from the object's surface (a) and 1 cm in front of the screen (b). The grasp was defined as the point at which the IRED on the proximal edge of the index finger cuticle reached this threshold. An example of the participant's view during an Only Grasp trial with a centrally positioned stimulus (c), and during a Slide trial with a rightward positioned stimulus (d).

Procedure

At the beginning of the experiment, participants in both conditions were given the opportunity to hold the physical stimulus. Calibration and validation of the Eyelink was then performed, followed by the first accuracy check. The experimental task ('Only Grasp' or 'Slide') order was counterbalanced, so that half the participants in each condition performed a block of

Only Grasp task trials before the block of Slide task trials, while the other half performed the tasks in the reverse order. All participants were instructed to grasp the stimulus with their index finger and thumb on the top and bottom of the stimulus respectively, and to not make contact with the stimulus using their other digits. All participants completed the task using their right hand. The time of the grasp was defined as the point at which the IRED on the participant's index finger reached within 1 cm of the object's surface (Physical condition) or the computer screen (Virtual condition). The proximal placement of the IRED on the index finger cuticle was set so this timing corresponded to the tip of the digit making contact with the stimulus.

Prior to performing each block of experimental trials, participants performed 3 practice trials (grasping the stimulus and performing the appropriate task once at each of the three stimulus positions) to familiarize themselves with the upcoming task, and to ensure data from the IREDs and Eyelink was being collected properly. Each task involved 15 experimental trials. This meant (excluding the practice trials) participants grasped the stimulus 5 times at each position. The trial-by-trial stimulus position ordering was determined randomly at the beginning of the study, and this set order was used for all participants. Participants were given a short break after completing the first task, and a second accuracy check was conducted prior to the second task practice trials.

Physical Stimulus Condition

Before each block of trials began, a stylus with 4 IREDs attached to its distal tip was used to demarcate the real-world coordinates corresponding to the three stimulus positions on the board. The dimensions of the stylus were virtually configured during the experimental set-up, prior to each experimental session. A square block (dimensions matched those of the experimental stimulus) with a mark on its surface visually displaying the stimulus' geometrical center was placed at each of the three stimulus positions, and the tip of the stylus was aligned with this marking at each location in sequence. These coordinates were recorded and used during analysis to represent the center of the physical stimulus at each of the three positions. This step was carried out each time the board was re-attached to the computer screen following removal, to ensure the virtual center of the physical stimulus used for analysis reflected the stimulus' true position on the board during the experimental trials.

Participants began each trial with the index finger and thumb of their right hand pinched together on the tabletop in the 'start position', centered 38 cm in front of the display, and aligned with the mid-sagittal plane of the body. Participants were instructed to begin each trial with their eyes closed, while the experimenter placed the physical stimulus at one of the 3 positions on the board. An auditory cue at the beginning of each trial signalled the participant to open their eyes, followed 1 s later by an auditory 'reach tone' cueing participants to grasp the stimulus on the presentation board. When performing the Only Grasp task, participants were instructed to grasp the physical stimulus using their index finger and thumb, but to not pick it up or move it. Afterward, participants returned their hand to the start position and closed their eyes. The experimenter then repositioned the stimulus as necessary before the beginning of the next trial.

The Slide task involved using a different presentation board, identical to the board used for the Only Grasp task, with the addition of a single red 4 x 4 cm square outline presented in the horizonal middle of the presentation board, 13 cm below the center stimulus' position, and 25.5 cm above the tabletop. Upon presentation of the reach tone, participants were instructed to grasp the physical stimulus with their index finger and thumb and slide it downward until it was positioned within the red square. Due to the low strength of the magnets and the stimulus' light weight, very minimal force was required to slide it. To maintain consistency with the version of the task in the Virtual condition, participants were instructed to slide the physical stimulus to the red square, rather than pick it up off the board. Magnets attached to the back of the board were used to re-secure the stimulus once aligned with the red square. Following successful relocation of the stimulus, participants returned their hand to the start position and closed their eyes.

Virtual Stimulus Condition

Participants began each trial with their right hand in the start position on the tabletop. No viewing instructions were given, and participants were allowed to freely view the monitor throughout the trial. The virtual stimulus appeared at one of the 3 on-screen positions at the beginning of each trial, followed 1 s later by the reach tone. Participants were instructed to grasp the virtual stimulus using their index finger and thumb "as if they were grasping an actual 3-D object". In the Only Grasp task, participants were only required to grasp the virtual stimulus. After making contact with the screen, participants returned their hand to the start position, and the next trial was initiated manually by the experimenter.

When performing the Slide task, a virtual red square outline appeared in the horizontal middle of the screen 13 cm below the virtual stimulus, 25.5 cm above the tabletop. As in the 3-D condition, the goal was to grasp and slide the virtual stimulus so that it was aligned with the red outline. To make this possible, user-defined formulas within the MotionMonitor were used to lock the on-screen position of the virtual stimulus to the relative position of the IRED attached to the index finger at the time the stimulus was grasped (i.e., once the IRED positioned at the proximal edge of the index finger cuticle reached a 1 cm distance from the screen). This allowed participants to grasp the stimulus by placing their index finger and thumb on the screen, and then control its movement by moving their fingers along the screen's surface as if they were in fact sliding it. For these trials, participants were instructed to first grasp the stimulus, and then slide it toward with the red outline presented at the bottom of the screen. Once the center of the stimulus was positioned within the red outline's center, the trial concluded, and participants returned their hand to the start position.

Data Analysis

Trial data for each dependent variable were averaged to create a mean value per unique condition for each participant. The horizontal placement of the index finger, as well as the horizontal and vertical fixations at the time of the grasp, distance between the grasp axis and stimulus center, and amount of torque inferred by the horizontal distance between the index finger and thumb were analyzed using five 2 (Stimulus Type: Physical versus Virtual) x 3 (Position: Left versus Center versus Right) x 2 (Task: Slide versus Only Grasp) mixed-factorial ANOVAs, with Stimulus Type as the between-subjects factor, and Position and Task as within-subject factors. The ANOVA summary tables are provided as supplementary material (Appendix D). SPSS (version 23.0) was used to analyze the data. Violations to sphericity were corrected using a Greenhouse-Geiser correction. Bonferroni adjusted *p*-values were applied to all post hoc comparisons used to analyze any significant interactions, and all analyses were conducted using alpha = .05.

Bayesian Analysis of Posterior Probabilities

Using methods described by Masson (2011), Bayesian Information Criterion approximations were calculated and used to generate posterior probabilities for the main effects, interactions, and simple effects tests of each ANOVA when appropriate. This method allowed us to calculate the probability of either a non-zero effect favouring the alternative hypothesis [$p(H_1/D)$], or a zero-effect favouring the null hypothesis [$p(H_0/D)$], being true given the data. As these probabilities sum to 1.0, only the larger of the two values are reported, thus providing evidence in favour of either the alternative or null hypothesis. The posterior probabilities are reported along with the results for each associated test and are interpreted using Raftery's (1995) grading of evidence, where .50 - .75 = '*weak*'; .75 - .95 = '*positive*'; .95 - .99 = '*strong*', and > .99 = '*very strong*'.

The dependent variables are defined as follows:

Horizontal Index Finger Placement

The horizontal distance between participants' average index finger placement and the stimulus' horizontal midline at the time of the grasp was measured and used to indicate accuracy of the grasp.

Horizontal and Vertical Fixation Positions

Participants' raw horizontal and vertical gaze positions were recorded for the duration of each trial and characterized into fixations using custom algorithms developed using MATLAB (R2016a, The MathWorks Inc., Natick, Massachusetts, USA), based on a dispersion-threshold identification (I-DT) algorithm (Salvucci & Goldberg, 2000). The horizontal and vertical distances between the participants' fixations and the stimulus' center at the time of the grasp were analyzed separately.

Absolute Distance Between Grasp Axis and Stimulus Center

Previous research has used the distance between the grasp axis and an object's COM as an indication of grasp stability when grasping 3-D objects (Goodale et al., 1994; Lederman & Wing, 2003; Marotta, Mckeeff, & Behrmann, 2003). Using custom programming developed with MATLAB, the shortest distance between the participant's grasp axis and the stimulus' center was calculated, and the average absolute distance in each condition was compared.

Horizontal Distance Between the Index Finger and Thumb

As an additional measure of grasp stability, the average horizontal distance between the index finger and thumb was used to indicate the amount of torque that would be generated by the opposing force of each digit at the time of the grasp. In this case, larger horizontal distances between the digits indicated an increased amount of torque, and decreased stability.

Results

Excluded Data

Experimental data were excluded from analysis if the participant failed to execute the task properly during an experimental trial, if visibility of the IRED on the participant's hand was compromised during execution of the task, or due to equipment failure. In total 9.5% of all experimental trials were excluded from the final analysis.

Horizontal Index Finger Placement

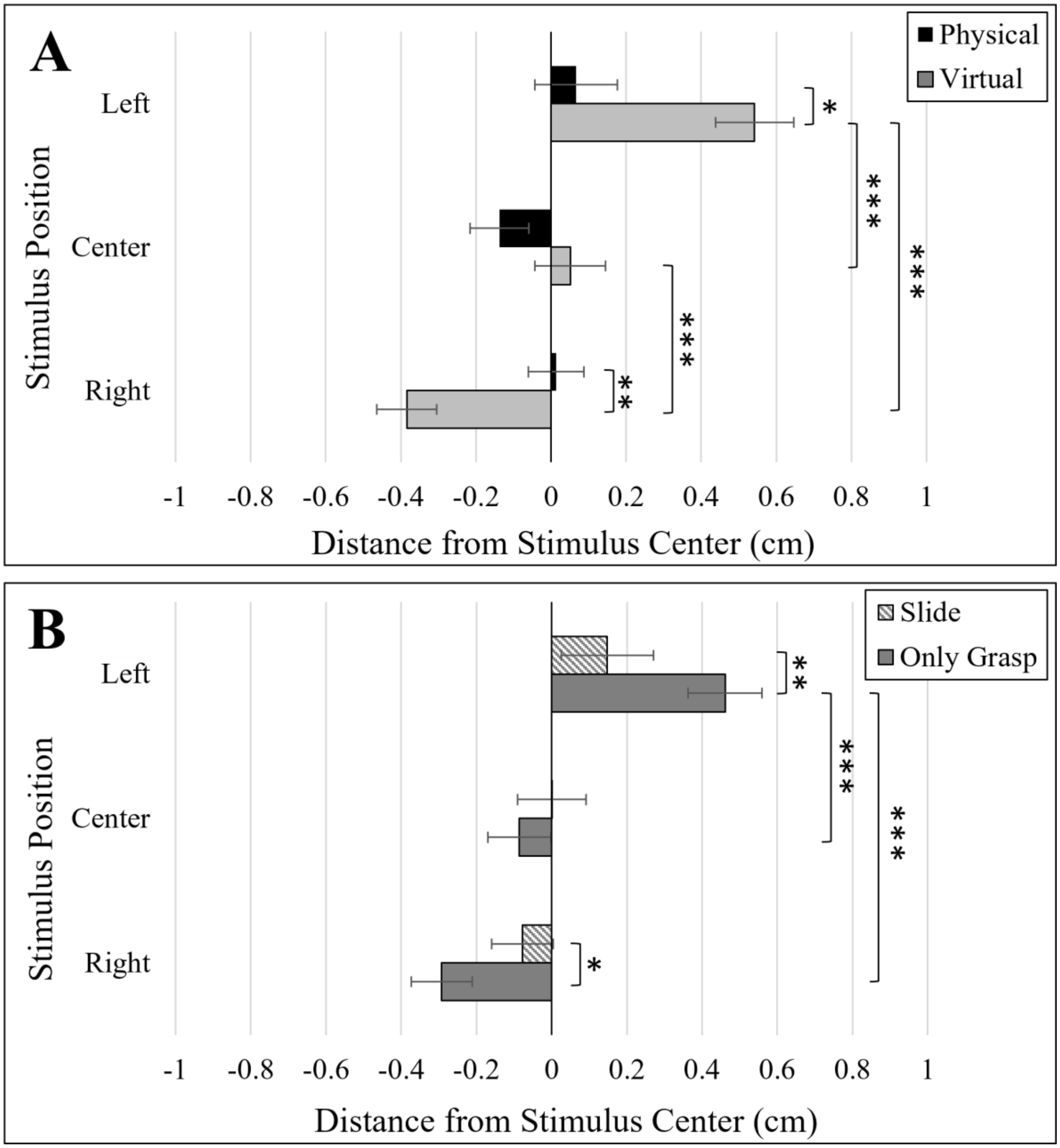
A significant Stimulus Type x Position interaction, $F(1.722, 68.865) = 15.460$, $p < .001$, $\eta_p^2 = .279$, $p(H_1/D) = .999$; Figure 3.2a, was observed, and post-hoc tests of the simple effects indicated that collapsing across Task, there were no significant differences in horizontal index finger placement when grasping the Physical stimulus at any of the three positions (all *p*s > .05), and the posterior probabilities calculated suggested only weak evidence in favour of differences between the Left and Center [$p(H_1/D) = .512$], and between the Right and Center [$p(H_1/D =$ .531], while suggesting positive evidence for the lack of difference between Left and Right [$p(H_0/D) = .800$]. In the Virtual condition however, the average placement of the index finger was shifted toward the near side of the stimulus (i.e., biased toward the center of the screen, and the starting position of the hand) when grasping non-central stimuli [Left versus Center: $p(H_1/D) = .999$; Left versus Right: $p(H_1/D) = .999$; Center versus Right: $p(H_1/D) = .987$]. Index finger placement did not significantly differ when grasping the Physical stimulus compared to the Virtual stimulus when presented in the Center [$p > .05$, $p(H_0/D) = .742$]. However, the bias toward the near side of non-central Virtual stimuli resulted in significant differences in index finger placement when grasping the Virtual stimulus compared to the Physical stimulus presented at the Left [$p(H_1/D) = .813$] and at the Right [$p(H_1/D) = .966$].

A significant Position x Task interaction was also revealed, $F(2, 80) = 10.024$, $p < .001$, $\eta_p^2 = .200$, $p(H_1/D) = .993$; Figure 3.2b, and the pairwise comparisons indicated that collapsing across Stimulus Type, participants' horizontal index finger placement was positioned closer to the near side of non-centrally located stimuli when Only Grasping, compared to a more exaggerated outward horizontal index finger placement near the horizontal midline when Sliding [Left: $p(H_1/D) = .886$; Right: $p(H_1/D) = .657$]. When the stimuli were presented in the Center, index finger placement did not significantly differ when Sliding compared to when Only Grasping [$p > .05$, $p(H_0/D) = .801$].

In fact, there were no significant differences in index finger placement between stimulus position when the task involved Sliding [Left versus Center: $p > .05$, $p(H_0/D) = .653$; Left versus Right: $p > .05$, $p(H_0/D) = .655$; Center versus Right: $p > .05$, $p(H_0/D) = .816$]. When Only Grasping the stimulus however, index finger placement was significantly different when the stimulus was presented on the Left versus presented in the Center [p(H_1/D) = .999], and when presented on the Left versus on the Right [p(H_1/D) = .999]. There was no significant difference when Only Grasping the stimulus presented in the Center compared to the stimulus presented on the Right [$p > .05$, p(H_1/D) = .541]. The Stimulus Type x Task, $F(1, 40) = 0.043$, $p > .05$, $\eta_p^2 = .001$, p(H_0/D) =.864, and Position x Task x Stimulus Type, $F(2, 80) = 0.551$, $p > .05$, $\eta_p^2 = .014$, p(H_0/D) = .980, interactions were non-significant.

Figure 3.2

Index Finger Placement



Note. Average horizontal index finger placement collapsing across Task (a) and collapsing across Stimulus Type (b). Negative values in the horizontal axis refer to distance to the left of the stimulus' horizontal midline. *Error bars* represent standard error of the means. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Fixation Positions

Accuracy Check Results

The mean absolute gaze displacement error, defined as the average absolute distance between participants' gaze and the center fixation dot during the Accuracy Checks, combined across all participants in the Virtual stimulus conditions was 0.33 cm in the horizontal axis (SE = 0.02 cm); 0.51 cm in the vertical axis (SE = 0.05 cm), and combined across all participants in the Physical stimulus condition was 0.28 cm in the horizontal axis (SE = 0.02 cm); 0.55 cm in the vertical axis (SE = 0.05 cm).

Horizontal Fixations

A significant Stimulus Type x Position interaction, $F(2, 80) = 12.696$, $p < .001$, $\eta_p^2 = .241$, $p(H_1/D) = .999$, indicated that participants' average horizontal fixations followed a similar pattern as their index finger placement. Horizontal fixations did not significantly differ when the Physical stimulus was presented on the Left (M = 0.02 cm to the left of stimulus center, SE = 0.09) compared to the Physical stimulus presented in the Center [M = 0.04 cm to the left of stimulus center, SE = 0.10 cm; $p > .05$, $p(H_0/D) = .820$], or the Physical stimulus presented on the Right [M = 0.13 cm to the left of stimulus center, SE = 0.11 cm; $p > .05$, $p(H_0/D) = .780$]. There was also no difference between the Physical stimulus presented in the Center and the Physical stimulus presented on the Right [$p > .05$, $p(H_0/D) = .792$]. However, as seen with horizontal index finger placement, horizontal fixations were shifted toward the near side of non-central Virtual stimuli. Fixations were positioned significantly farther rightward when the Virtual stimulus was on the Left (M = 0.29 cm to the right of stimulus center, SE = 0.10 cm) compared to the Virtual stimulus in the Center [M = 0.14 cm to the left of stimulus center, SE = 0.10 cm; $p = .009$, $p(H_1/D) = .956$], and compared to the Virtual Stimulus on the Right [M = 0.93 cm to the left of target center, SE = 0.11 cm; $p < .001$, $p(H_1/D) = .999$]. Average fixations also significantly differed between the Virtual stimulus presented in the Center and on the Right [$p < .001$, $p(H_1/D) = .998$].

Horizontal fixations did not significantly differ between Stimulus Type when the stimuli were presented in the Center [$p > .05$, $p(H_0/D) = .849$], or presented on the Left [$p > .05$, $p(H_0/D) = .526$]. However, fixations were positioned significantly closer to the near side of the Virtual stimulus compared to the Physical stimulus when presented on the Right [$p < .001$, $p(H_1/D) = .997$]. The main effect of Task, $F(1, 40) = 2.537$, $p > .05$, $\eta_p^2 = .060$, $p(H_0/D) = .640$, as well as the Stimulus Type x Task, $F(1, 40) = 2.576$, $p > .05$, $\eta_p^2 = .061$, $p(H_0/D) = .636$, Position x Task, $F(1.652, 66.097) = 2.272$, $p > .05$, $\eta_p^2 = .054$, $p(H_0/D) = .892$, and Stimulus Type x Position x Task, $F(1.652, 66.097) = 1.531$, $p > .05$, $\eta_p^2 = .037$, $p(H_0/D) = .946$, interactions were not significant.

Vertical Fixations

A main effect of Task, $F(1, 40) = 10.072$, $p = .003$, $\eta_p^2 = .201$, $p(H_1/D) = .945$, indicated that participants' average fixations were positioned significantly lower when Sliding the stimulus (M = 0.70 cm above stimulus center, SE = 0.16 cm) compared to when Only Grasping (M = 0.96 cm above stimulus center, SE = 0.16 cm). The main effects of Stimulus Type, $F(1,40) = 0.364$, $p > .05$, $\eta_p^2 = .009$, $p(H_0/D) = .843$, Position, $F(2, 80) = 1.152$, $p > .05$, $\eta_p^2 = .028$, $p(H_0/D) = .962$, and the Stimulus Type x Position, $F(2, 80) = 0.760$, $p > .05$, $\eta_p^2 = .019$, $p(H_0/D) =.974$, Stimulus Type x Task, $F(1, 40) = 0.180$, $p > .05$, $\eta_p^2 = .004$, $p(H_0/D) = .855$, Position x Task, $F(2, 80) = 0.086$, $p > .05$, $\eta_p^2 = .002$, $p(H_0/D) = .987$, and Stimulus Type x Position x Task, $F(2, 80) = 0.799$, $p > .05$, $\eta_p^2 = .020$, $p(H_0/D) = .973$ interactions were not significant.

Absolute Distance Between Grasp Axis and Stimulus Center

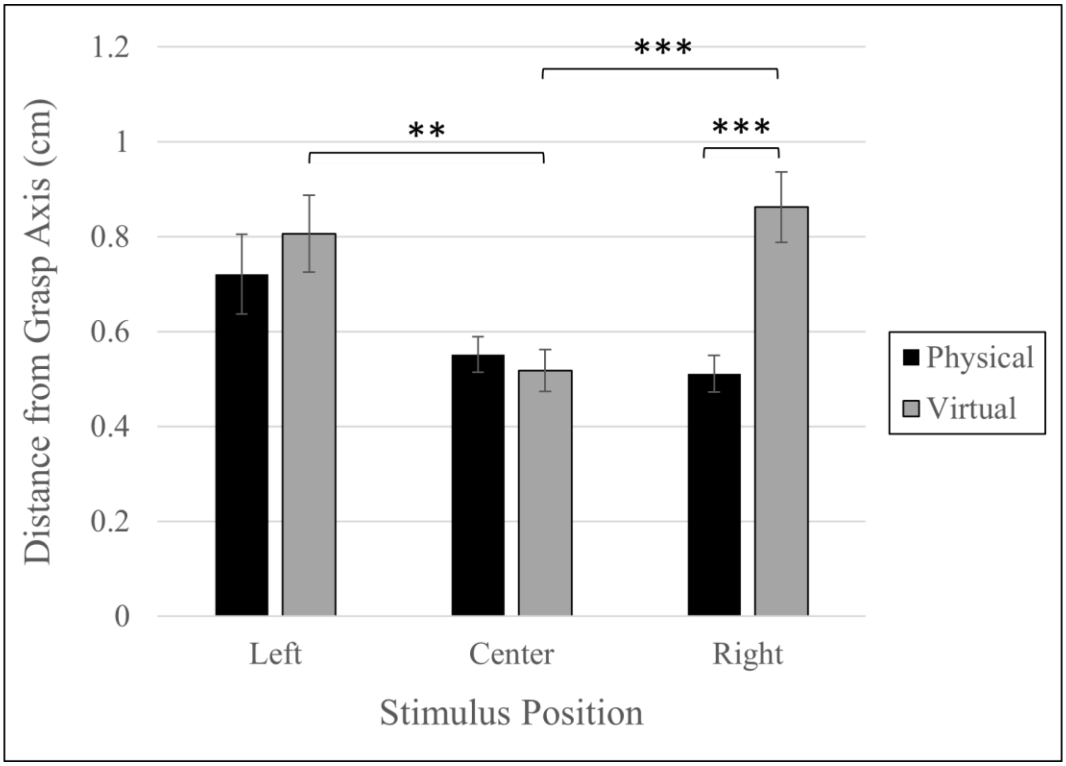
A three-way Stimulus Type x Position x Task interaction reached significance, however the posterior probabilities suggested near positive evidence in favour of the null hypothesis, $F(2, 80) = 3.327$, $p = .041$, $\eta_p^2 = .077$, $p(H_0/D) = .746$ and therefore this interaction was not analyzed further. Instead, the significant lower order Position x Stimulus Type interaction was analyzed, $F(1.720, 68.781) = 5.285$, $p = .010$, $\eta_p^2 = .117$, $p(H_1/D) = .686$; Figure 3.3. Collapsing across Task, the distance between the grasp axis and the stimulus' center did not significantly differ when interacting with the Physical stimulus presented on the Left compared to the Physical stimulus in the Center [$p > .05$, $p(H_1/D) = .665$], or compared to the Physical stimulus on the Right [$p > .05$, ($p(H_1/D) = .681$], however the posterior probabilities did suggest weak evidence in favour of these differences. There was no evidence of a significant difference between grasp axis distances when comparing the Physical stimulus when presented in the Center and on the Right [$p > .05$, $p(H_0/D) = .775$]. When interacting with the Virtual stimulus, the grasp axis distance was significantly larger when the stimulus was presented on the Left compared to in the Center [$p(H_1/D) = .965$] and was also significantly larger when the stimulus was presented on the Right compared to in the Center [$p(H_1/D) = .990$]. There was no significant difference between grasp axis distances when the Virtual stimulus was presented on the Left versus the Right [$p > .05$, $p(H_0/D) = .799$].

There were no significant differences between Physical and Virtual stimuli when the stimulus was presented on the Left [$p > .05$, $p(H_0/D) = .830$], or in the Center [$p > .05$, $p(H_0/D) = .844$]. However, the grasp axis distance was significantly larger when interacting with the Virtual stimulus compared to the Physical stimulus when presented on the Right side [$p(H_1/D) = .997$].

The main effect of Task, $F(1, 40) = 1.321$, $p > .05$, $\eta_p^2 = .032$, $p(H_0/D) = .766$, as well as the Position x Task, $F(2, 80) = 2.314$, $p > .05$, $\eta_p^2 = .055$, $p(H_0/D) = .888$, and Stimulus Type x Task, $F(1, 40) = .784$, $p > .05$, $\eta_p^2 = .019$, $p(H_0/D) = .812$, were not significant.

Figure 3.3

Grasp Axis Distance



Note. Absolute shortest distance between the grasp axis and the stimulus' center. *Error bars* represent standard error of the means. $^{**}p < .01$, $^{***}p < .001$

Horizontal Distance Between the Index Finger and Thumb

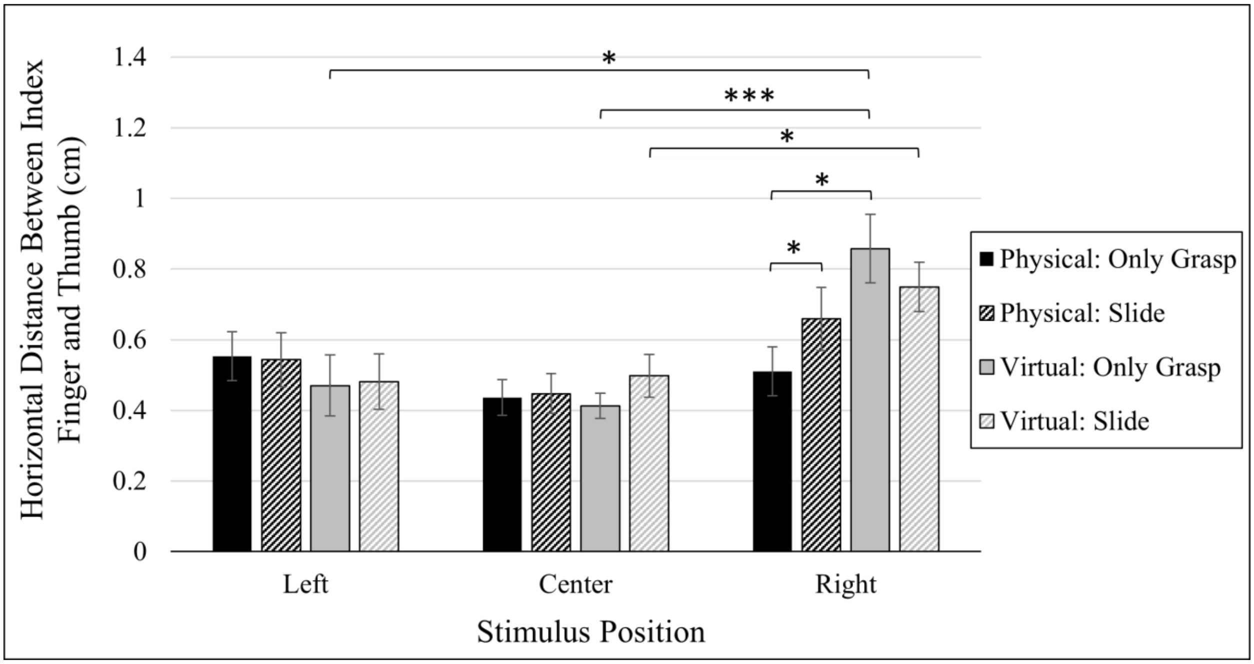
A significant three-way Stimulus Type x Position x Task interaction, $F(1.732, 69.294) = 5.310$, $p = .010$, $\eta_p^2 = .117$, $p(H_1/D) = .691$; Figure 3.4, was shown, and post-hoc tests indicated that the horizontal distance between the index finger and thumb at the time of the grasp did not significantly differ when Only Grasping the Physical stimulus presented on the Left compared to in the Center [$p > .05$, $p(H_0/D) = .555$], when Only Grasping the Physical stimulus presented on the Left compared to on the Right [$p > .05$, $p(H_0/D) = .809$], or when Only Grasping the Physical stimulus in the Center compared to on the Right [$p > .05$, $p(H_0/D) = .712$]. There were also no significant differences when Sliding the Physical stimulus presented on the Left compared to in the Center [$p > .05$, $p(H_0/D) = .735$] or on the Right [$p > .05$, $p(H_0/D) = .761$]. The post hoc comparison between Sliding the Physical stimulus presented in the Center and on the Right was deemed non-significant, however the posterior probabilities suggested positive evidence in favour of the difference [p = .052, p(H_1/D) = .802]. When Only Grasping the Virtual stimulus, the horizontal distance between the index finger and the thumb was significantly larger when the stimulus was presented on the Right compared to on the Left [p(H_1/D) = .852] and compared to in the Center [p(H_1/D) = .997]. There was no significant difference when Only Grasping the Virtual stimulus presented on the Left versus in the Center [p > .05 (p(H_0/D) = .790]. When Sliding the Virtual stimulus, there was also a significantly larger horizontal distance between the digits when the stimulus was presented on the Right in comparison to in the Center [p(H_1/D) = .898], but not in comparison to Sliding the Virtual stimulus on the Left, despite the posterior probabilities suggesting weak evidence for the difference [p > .05, p(H_1/D) = .705]. There was no significant difference when Sliding the Virtual stimulus presented on the Left compared to in the Center [p > .05, p(H_0/D) = .817].

The only significant difference between Task type occurred when interacting with the Physical stimulus presented on the Right, where the horizontal distance between the index finger and thumb was significantly larger when Sliding compared to Only Grasping, however the posterior probabilities showed little evidence of this difference [p(H_1/D) = .514]. Otherwise, there were no significant differences between Task types when interacting with the Physical stimulus presented on the Left [p > .05, p(H_0/D) = .818] and in the Center [p > .05, p(H_0/D) = .817], or when interacting with the Virtual stimulus on the Left [p > .05, p(H_0/D) = .816], in the Center [p > .05, p(H_0/D) = .652], or on the Right [p > .05, p(H_0/D) = .510].

Again, the only significant difference between Stimulus Type occurred on the Right, where the horizontal distance between the index finger and thumb was significantly larger when Only Grasping the Virtual stimulus in comparison to the Physical stimulus [p(H_1/D) = .896]. There were no significant differences between Stimulus Type when Only Grasping stimuli presented on the Left [p > .05, p(H_0/D) = .828], and in the Center [p > .05, p(H_0/D) =.857], or when Manipulating stimuli presented on the Left [p > .05, p(H_0/D) = .845], in the Center [p > .05, p(H_0/D) = .843], or on the Right [p > .05, p(H_0/D) = .823].

Figure 3.4

Torque



Note. Average horizontal distance between placement of the index finger and thumb. *Error bars* represent standard error of the means. *$p < .05$, ***$p < .001$

Discussion

The use of virtual 2-D computer-generated targets to study visually guided reaching and grasping behaviours is an attractive option for behavioural visuomotor research, as it allows the incorporation of increasingly complex experimental paradigms, in which target presentation and visual feedback can be manipulated with a higher degree of experimental control. However, a grasping action directed toward a 2-D stimulus is inherently different than a grasping action toward a 3-D object, and therefore the results of research utilizing 2-D grasping may not be immediately generalizable to the grasping of 3-D objects. This study directly compared eye-hand coordination when grasping physical and virtual stimuli, while varying the task's action end-goal to explore how the intended manipulation influenced these behaviours.

Influence of Stimulus Position

The horizontal positions participants placed their index finger and fixated their gaze, as well as the stability of the grasp and the amount of torque inferred by the placement of the digits did not significantly differ between the virtual and physical stimulus types when presented in the center of the display. However, this study demonstrated clear differences between the grasping behaviours when the stimulus was presented to the left and right of center; participants generally grasped the near side of the non-central virtual stimulus, and closer to the horizontal midline of the physical stimulus at all three positions. As hypothesized, participants' average horizontal fixations also followed these patterns, suggesting participants were fixating toward their grasp points. Similar biases in gaze and grasp position toward the near side of non-central 2-D targets have been observed when grasping the same virtual stimuli used in this study (Langridge & Marotta, 2020), and likely occur because participants are less motivated to place their digits at 'stable' positions aligned with the horizontal midline, as stability is not critical when interacting with virtual 2-D stimuli, and participants are therefore free to grasp the near side of the target, minimizing the amount of energy required to perform the task.

Paulun et al. (2014) reported digit placement shifted away from an object's COM, in the direction of the particular hand used to grasp it, suggesting participants were prioritizing visibility of the object when grasping (see also Maiello et al., 2019). Our results suggest that when grasping the virtual stimulus, participants minimized the need for increased visibility of the target in exchange for a more convenient (i.e., energy efficient) digit placement. This was apparent when the stimulus was presented on the right, which meant a grasp biased toward the near side of the stimulus would obstruct a larger portion of the stimulus from view. Even in the Physical condition, digit placement generally remained close to the stimulus' horizontal midline, rather than deviate rightward to increase visibility.

These observed differences may be related to several important methodological differences between our study and the work by Paulun et al. (2014). First, participants in Paulun et al.'s (2014) study consistently grasped a centrally located stimulus while the start point of the reach varied, whereas our study manipulated the position of the stimuli, and held the start point of the reaching movement constant. This suggests one's motivation to prioritize visibility versus energy efficiency when grasping may vary as a function of stimulus position. Second, while the manipulation of the stimulus in this study involved sliding the stimulus, Paulun et al. (2014) required participants to actually lift and move the object to another location, a movement more characteristic of the type of actions we perform every day. The different action end-goals may have placed a different emphasis on the importance of object visibility when grasping. The sliding task utilized in this study was chosen because it more closely replicates the type of action people typically perform when interacting with virtual 2-D stimuli and allowed us to make comparisons between the manipulation of the stimulus in both a physical and virtual environment. However, it is important to recognize that the eye-hand coordination behaviours observed when sliding the stimulus may not generalize to other tasks involving grasping and lifting, for which stability of the grasp and visibility of the stimulus may be more critical for success.

Digit placement was more stable and generated less torque in the Physical condition compared to the Virtual condition when the stimulus was presented on the right side of the display. When using a precision grip to grasp a rightward stimulus, participants would need to rotate their forearm inward to place their index finger and thumb at similar horizontal positions on the top and bottom of the stimulus. Although the distance participants were required to reach was not extreme, participants may have foregone the required pronation of the forearm to some degree when grasping the rightward virtual stimulus and settled on a more leftward placement of the thumb, producing a more angled grasp axis reducing stability and increasing torque. The stability of the grasp did not appear to differ as a function of stimulus type when grasping stimuli on the left or in the center of the display. Altogether, these findings suggest an overall reduction in precision when participants grasped the virtual stimulus at non-central locations, and in particular when the stimulus was presented on the right side of the display.

Influence of Task: Sliding Versus Only Grasping

Participants lowered their fixations toward more central positions when sliding both types of stimuli, which could be interpreted as an adjustment of gaze enabling participants to monitor both the index finger and thumb at the time of the grasp (Desanghere & Marotta, 2011; Belardinelli, Herbort, & Butz, 2015; Thulasiram et al., 2020). In anticipation of the intended manipulation of the stimulus, selection of each digit's contact point would need to serve both the effective execution of the grasp, and comfortable relocation of the stimulus, increasing the importance of participants' grasp point selection. The fact that similar adjustments in fixation position were made ahead of manipulation in both stimulus conditions suggests participants were also emphasizing careful digit placement when sliding the virtual stimulus.

This emphasis on precise digit placement was also reflected in the horizontal position participants placed their index finger when sliding both types of stimuli. The action of sliding the stimulus was associated with a shift in index finger placement and fixation position farther leftward when sliding the left stimulus, and farther rightward when sliding the right stimulus (i.e., away from the stimulus' near side) compared to when only grasping the stimulus these positions. This exaggerated digit placement could serve several purposes. First, digit placement closer to the horizontal midline would generate more control when manipulating the stimulus – increased control that would not be necessary when simply grasping the stimulus. Second, when the stimulus was presented on the right, a more rightward digit placement increases the amount of visual feedback of the stimulus during the subsequent manipulation (Maiello et al., 2019; Paulun et al., 2014). While an exaggerated digit placement toward the horizontal midline of a leftward stimulus in fact obstructs a larger portion of the stimulus than when only grasping, average digit placement in both the Sliding and Only Grasp conditions remained on the right side of the leftward stimulus, leaving a large region of the stimulus visible, even if slightly less so when sliding.

A third possibility is that participants may have directed their grasps farther outward in anticipation of the subsequent inward movement of the stimulus toward the center of the display. According to the 'elastic-energy hypothesis' a person may bring a limb to an exaggerated or extreme position in preparation for a subsequent movement in the opposite direction. As the manipulation in this study always involved sliding the stimulus downward to the same central location, a more extreme outward digit placement when grasping the non-central stimuli may have allowed participants to exploit the stored potential energy in the arm and facilitate the subsequent inward movement toward the center of the display. Future studies manipulating the direction participants move the stimuli once grasped may help clarify the role of elastic energy in this type of task.

These findings suggest that certain task-related adjustments were observed in both the Physical and Virtual stimulus conditions, despite these adjustments not technically being necessary when interacting with the virtual stimulus. Considering the inherent differences between physical and virtual stimuli, these adjustments might only be expected in the Physical condition, for which these aspects of the grasp are more critical to the success of the action. How than can we explain these similarities?

As the on-screen target lacked the true physical properties that would typically be used by the visuomotor system when planning and executing the grasping action, participants likely relied to some extent on their perceptual representation of the stimulus to guide their movement. When given the opportunity to manipulate the virtual stimulus (an option not typically possible with 2-D virtual stimuli), participants' perceptual representation of the target may have been updated to include features typically associated with physical object manipulation. The familiarization with the 3-D version of the virtual stimulus at the beginning of the experiment and the experimenter's instructions to 'grasp the target as if it were an actual 3-D object' may also have inspired an attribution of physical features traditionally associated with graspable objects.

Viewing 2-D images of manipulable objects is known to activate motor regions within the brain associated with physical interaction with the imaged object (Chao & Martin, 2000; Proverbio, Adorni, & D'Aniello, 2011), and manual responses are faster when participants are primed with images of those objects prior to the reach (Masson, Bub, & Breuer, 2011; Squires, Macdonald, Culham, & Snow, 2016; Tucker & Ellis, 1998). When instructed to touch images of objects as if they were lifting them, participants fixate and place their digits near the center of the imaged object, whereas these positions shift toward the object's lid when instructed to touch the object as if they were opening it (Belardinelli et al., 2015). Thus, participants can effectively incorporate their knowledge of an imaged object's physical properties and execute appropriate digit placement in response to the particular demands of the task. In the current study, presentation of the manipulable virtual stimulus may have primed the motoric response typically associated with and afforded by manipulation of a physical square 3-D object, priming participants to make responses similar to those that would be expected when grasping a physical 3-D stimulus, including adjustments accounting for a non-existent COM.

Implications, Limitations, and Future Directions

The shape of the stimulus, as well as the dependent variables measured in the current study were chosen to match those used in our previous investigations of virtual 2-D grasping, thus allowing us to interpret the results within the context of past research using similar stimuli. In this study, participants' fixations and digit placement did not significantly differ as a function of stimulus type when the grasp occurred in the center of the display. Our previous investigations have also primarily involved centrally presented stimuli (Bulloch et al., 2015; Desanghere & Marotta, 2011; Langridge & Marotta, 2017; Thulasiram et al., 2020), and the current results suggest the gaze and grasp behaviours measured in these previous studies may also generalize to the natural grasping of 3-D objects similar to the type used in this study. However, these results also question the generalizability of research measuring grasp behaviour directed toward non-central virtual 2-D stimuli (e.g., Langridge & Marotta, 2020). We also cannot assume these similarities will hold true when comparing stimuli of drastically different shape and size than those used here. It is also still unclear how stimulus motion influences the comparisons between virtual and physical stimulus interaction. Future comparisons involving increasingly complex and diverse stimuli are needed to explore the extent to which similar eye-hand coordination is maintained during interaction with virtual 2-D stimuli. Considering the advances in 3-D virtual reality and its relevant applications for visuomotor research, an interesting direction is to investigate this type of reaching and grasping behaviour in an immersive virtual reality environment, in which participants could interact with visually and haptically enriched stimuli of varying shapes and sizes, further bridging the gap between virtual and physical grasping research.

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CHAPTER 4: THE EBBINGHAUS ILLUSION INFLUENCES CURSOR MOVEMENT BUT NOT ACCURACY OR MOVEMENT TIME IN A POINT-AND-CLICK TASK

The Ebbinghaus illusion, also referred to as the Titchener circles illusion, is a well-known size-contrast illusion in which the perceived size of a central target circle is made to appear smaller or larger than its true size when surrounded by a ring of larger or smaller context circles, respectively. The strength of the illusion can be manipulated by altering the size and distance of the context circles relative to the target circle; smaller distances between the target circle and the surrounding annulus increase the perceived size of the target circle, while larger distances decrease its perceived size (Knol, Huys, Sarrazin, & Jirsa, 2015; Massaro & Anderson, 1971; Robertsô, Harris, & Yates, 2005). Visual illusions such as the Ebbinghaus illusion provide an opportunity to explore the degree of separation between a visual system dedicated specifically to the processing of a stimulus' perceptual properties, and a visual system dedicated specifically to the execution of visually guided action toward that stimulus. A functional separation of these two behavioural systems, as proposed by Goodale and Milner (1992; Milner & Goodale, 2006) suggests that a size-contrast illusion such as the Ebbinghaus illusion should primarily influence one's perceptual judgements of a stimulus' size processed within the ventral stream, while any visually guided action toward that stimulus guided by computations performed by the dorsal stream should be largely unaffected by the illusory context. The results of an early study by Aglioti, DeSouza, and Goodale (1995) appeared to demonstrate this exactly; participants' perceptual judgements of a circular disk's size were more so influenced by the size of the surrounding context circles than their grip aperture, which was scaled appropriately to the true size of the central disk. The authors interpreted these results as supporting the theory of two functionally separate visual systems, a ventral vision-for-perception stream, which uses allocentric spatial information and is susceptible to illusory effects, such as those induced by the Ebbinghaus illusion, and a dorsal vision-for-action stream, which uses metrically precise information about a stimulus' physical properties within a strictly egocentric frame of reference to guide the effector, and is therefore largely immune to illusory influences.

In the years since Aglioti et al.'s (1995) study was published, a debate surrounding the study's methodologies and the authors' interpretation of results has continued. While some subsequent studies have further supported the idea that visually-guided action is immune to illusory influences (Danckert, Sharif, Haffenden, Schiff, & Goodale, 2002; Haffenden &

Goodale, 1998; Marotta, DeSouza, Haffenden, & Goodale, 1998), others have provided evidence suggesting that both perceptual judgements and visually-guided action are influenced to some extent by visual illusions (Franz & Gegenfurtner, 2008; Franz, Gegenfurtner, Bülthoff, & Fahle, 2000; Pavani, Boscagli, Benvenuti, Rabuffetti, & Farnè, 1999). Those who argue for an 'illusion immunity' of visually guided action contend that the apparent effects of the illusion on grip aperture may be the result of an obstacle avoidance mechanism, suggesting any observed changes in grip aperture are caused by the proximity of the context circles to the target circle, rather than in response to a perceived change in target circle size. Certain studies have found evidence for this hypothesis (De Grave, Biegstraaten, Smeets, & Brenner, 2005; Gilster, Kuhtz-Buschbeck, Wiesner, & Ferstl, 2006; Haffenden & Goodale, 2000; Haffenden, Schiff, & Goodale, 2001), potentially resolving the issue of the observed changes in grip aperture despite the vision-for-action system being supposedly immune to the illusion. However, there are others who argue the positioning of the context circles is not a sufficient explanation for the observed changes in grip aperture, and therefore these changes must arise in response to a perceived change in the target circle's size (Franz, Bülthoff, & Fahle, 2003; Franz & Gegenfurtner, 2008; Kopiske, Bruno, Hesse, Schenk, & Franz, 2016).

In an attempt to reconcile these contradictory results, Glover and Dixon (2002; Glover, 2004) proposed a planning-control model of visually guided action, involving a perceptually driven 'planning stage' prior to effector movement, and a 'control stage', during which the effector is guided toward the target and on-line adjustments are made throughout the movement. According to this model, the planning stage is susceptible to visual illusions, and the effect of the illusion will decrease during the control stage as the hand approaches the target. The planning-control model is similar to the perception-action model regarding its prediction about the illusion's influence prior to and separate from movement onset: the illusory context will influence the perceived size. However, while the perception-action model suggests the dorsal stream is immune to perceptual influences, and thus the overall movement should be unaffected by the illusion, the planning-control model suggests the beginning of the movement will be observably influenced by the illusory context, and this influence will be corrected via on-line sensory control mechanisms (e.g., visual and proprioceptive feedback) during the later stages of the movement.

The separation of a visually guided action into an initial planning stage and a subsequent online control stage potentially explains why an illusion's effect on a movement is minimized when visual feedback is provided and is strongest during early stages of a movement but decreases near the end of the movement, a phenomenon referred to as the 'dynamic illusion effect' (Glover & Dixon, 2002). This model could further explain why some of the previously mentioned studies have demonstrated an apparent illusory influence on grip aperture when the perception-action model would predict none. However, a number of studies have provided evidence in direct conflict with the predictions of the planning-control model (Danckert et al., 2002; Franz, Scharnowski, & Gegenfurtner, 2005; Handlovsky, Hansen, Lee, & Elliott, 2004), leading opponents of this particular model to criticize its validity. For example, Milner and Goodale (2004) contend the planning-control model's planning stage is too vaguely defined, and argue the behavioural results used by Glover (2004) to rationalize these conclusions are in fact better explained by a perception-action dichotomy, while Franz and colleagues (Franz, 2003; Franz et al., 2005) refute the presence of a dynamic illusion effect and suggest the previously reported results were confounded by the inclusion of data points collected after the digits contacted the object. Further, Westwood (2004) questions the logic behind the proposed need for separate visual representations for the planning and control of an action in the first place. Currently, the conversation regarding the influence of illusory context on visually guided grasping is still under debate (for review, see Franz & Gegenfurtner, 2008; Smeets & Brenner, 2006).

Nevertheless, the question of illusory influence on grasping in this context is fairly specific, in the sense that the scaling of the grasp is necessarily linked to the veridical size of the target circle being grasped. This is not always the case for other types of visually guided action, where knowledge of the true size of the target is not necessarily required for successful execution of the task. The extent to which the Ebbinghaus illusion influences the precision and timing of other visually-guided actions including pointing or tapping (Alphonsa, Dai, Benham-Deal, & Zhu, 2016; Handlovsky et al., 2004; Knol, Huys, Sarrazin, Spiegler, & Jirsa, 2017; van Donkelaar, 1999) golf-putting (Chauvel & Wulf, 2015; Maquestiaux et al., 2021; Witt, Linkenauger, & Proffitt, 2012; Wood, Vine, & Wilson, 2013), and 'marble-shooting' (Cañal-bruland, Meer, & Moerman, 2016) have also been investigated. The goal of these tasks is typically to locate and direct a movement toward the center of a target, rather than scale an appropriately sized grasp based on its diameter. However, the conclusions drawn from these studies are also often contradictory. For example, van Donkelaar (1999) measured the accuracy and speed of participants' pointing movements toward the center circle of images producing the Ebbinghaus illusion when visual feedback of the hand was unavailable. While accuracy was comparable across all conditions, participants' movements were significantly slower when pointing to the perceived small target, (i.e., the version of the target surrounded by larger context circles; van Donkelaar, 1999). Fischer (2001) attempted to replicate these findings using rectangular versus circular stimuli and correcting for several potential methodological confounds in van Donkelaar's (1999) original study (e.g., visual feedback of the hand was made available, target position was randomized to avoid pre-trial response planning, and reaction time and movement amplitude were measured in addition to movement time). Contrary to van Donkelaar's results, the results of Fischer's study failed to demonstrate an influence of illusion on movement time. Interestingly, extended movement times in response to perceived smaller targets *were* observed in a second experiment conducted by Fischer in which visual feedback of the target was removed and a short (650 ms) response delay was introduced, however these differences were not significant (Fischer, 2001). This delay presumably required participants to rely on their memory of the target's position and size when completing the task, a more perceptually driven process. These results suggest that when an influence of the Ebbinghaus illusion is observed, increased movement time is associated with actions toward stimuli perceived to be smaller than their veridical size.

Increased movement time is typically associated with a more accurate movement, and therefore conditions that produce longer movement times are generally considered to require more accuracy than faster movements. This trade-off between speed and accuracy constitutes a well-known relationship referred to as Fitts' Law, which predicts that the movement time required to move to a target is a function of the ratio between the target's distance and size (Fitts, 1954). When target distance is held constant, increased movement time is required when interacting with smaller targets, for which the need for accuracy is increased. The influence of a target's perceived size on movement is often explored using adapted versions of the classic 'Fitts task', which requires participants to continuously tap between two targets of varying sizes and distances. By incorporating some form of illusory context intended to adjust the perceived size of the target, variables such as movement time and accuracy can be measured and tested for an influence of perceived target size.

Alphonsa et al. (2016) adapted a typical Fitts tapping task to include qualities of both the Ebbinghaus and the Muller-Lyer illusions. Despite the physical size and distance of the two target stimuli being identical, participants were more accurate when tapping targets in the ‘illusory easy’ condition, in which the combination of illusions increased the perceived size of the target. However, the effect of the illusion on participants’ tapping accuracy was only observed during ‘discrete’ tapping, where visual feedback of the target was removed. Further, participants’ movement times were not influenced by the illusory context in this study. More recently, the results of a study by Knol et al. (2017) demonstrated increased movement time in conditions where the target was perceived to be smaller, this time during a closed loop ‘continuous’ tapping task, where visual feedback of the target was always available. An increase in movement time when interacting with targets perceived to be smaller than their true size would be predicted by Fitts’ Law, as participants would need to increase their movement time so they can execute accurate movements to a target they perceive to be smaller (i.e., surrounded by larger context circles).

The extent to which our perceptual judgment of a target’s size is influenced by the Ebbinghaus illusion has also been used to investigate the role of perception in ballistic aiming movements, particularly golf-putting. Determining if illusory stimuli can improve skilled-aiming actions has clear implications for athletes who wish to improve their skills in this area. There is some evidence to suggest that putting performance is enhanced when the Ebbinghaus illusion is used to increase the perceived size of the hole (i.e., when surrounded by small context circles; Witt et al., 2012; Wood et al., 2013), and the improvements observed during training with the Ebbinghaus illusion may endure over time, following removal of the illusory context circles (Chauvel & Wulf, 2015). Presumably, increasing the perceived size of the hole makes the task seem easier, suggesting participants’ self-confidence may mediate their improved performance. Alternatively, the opposite could be expected to be true, and decreasing the perceived size of the hole could make participants try to be more accurate. In another ballistic task involving shooting marbles toward a target, participants who trained with a target that was made to be perceived as smaller than its true size performed better at post-test (Cañal-bruland et al., 2016). However, recent attempts to replicate these results and demonstrate an improvement in performance following training with the Ebbinghaus illusion have not always been successful (Maquestiaux et al., 2021). Thus, as is true for visually guided grasping and tapping movements, the results regarding the Ebbinghaus illusion's influence on ballistic movements and associated training applications are mixed.

Each of the studies described thus far have studied the influence of perceived target size on actions that require some form of visuomotor transformation. While the transformations required in simple reach-to-grasp or reach-to-point movements are relatively direct and natural, those required to putt a golf ball or flick a marble may be less intuitive to participants. In this study, we asked how the Ebbinghaus illusion may influence visually guided movements that require another type of common visuomotor transformation: moving an on-screen cursor using a laptop trackpad. When using a trackpad to control a cursor on a computer screen, egocentrically defined finger movements that would typically be controlled via the vision-for-action dorsal stream are used to control the position of the cursor on the vertically presented screen. Moving the cursor toward a desired location on the screen therefore requires the transformation of the egocentrically defined finger movements to the on-screen environment, where allocentric references are critical for the guidance of the cursor to the desired location. For example, when clicking on a desktop icon located in the top-left corner of a computer screen, moving the finger forward and backward along the horizontally positioned trackpad, (i.e., the proximal action), is translated into upward and downward cursor movements respectively on the vertically presented screen (i.e., the distal action). Additionally, the size of the trackpad is considerably smaller than the size of the screen, and therefore the distance one moves their finger is necessarily transformed into a farther change in on-screen cursor position. This transformation into scene-based, allocentric coordinates suggests the vision-for-perception ventral stream may exert some degree of control over the visually guided movement of the cursor (Milner & Goodale, 2006).

With sufficient practice, this transformation between coordinate systems becomes quite natural for most individuals. The ability to control the on-screen cursor using a trackpad eventually becomes a natural skill, and one rarely needs to direct their visual attention to their hand, but rather can smoothly and effectively control the on-screen cursor using visual feedback of its position alone. Cursor movements have also been shown to adhere to Fitts' Law (Sutter, Müsseler, & Bardos, 2011), suggesting the speed-accuracy trade off is present following this type of visuomotor transformation as well. Considering the population from which our participants were recruited (Introductory Psychology students at the University of Manitoba), controlling the on-screen cursor is presumed to be a practiced behaviour.

If the transformation from proximal finger movements into distal cursor movements requires some degree of perceptual control, we may expect one's cursor movements to be influenced by their perception of the onscreen stimuli being clicked on. In other words, manipulating the perceived size of an on-screen target may produce a speed-accuracy trade-off when clicking on targets perceived to be smaller or larger than they are. On the other hand, if one's cursor movements are guided primarily by a vision-for-action system, the perceptual context of the stimuli being clicked on may not demonstrate such an influence, and cursor movements would be expected to be unaffected by the perceived size of the target. The goal of this study was to investigate the influence of the Ebbinghaus illusion on the accuracy and movement time of participants' cursor movements during a simple point-and-click task. Participants were presented with a target circle, surrounded by an annulus of either small or large context circles, and were instructed to click on the center of the target circle as quickly and as accurately as possible. The accuracy of participants' click-points relative to the center of the target circle and the time it took them to complete each trial was measured. If the perceived size of the target (manipulated by the illusory context) affected participants' performance of the task, movement time was expected to increase on trials involving the perceived small target, and decrease in trials involving the perceived large target, as would be predicted by Fitts' Law. Accuracy was expected to show the reverse effect, such that participants would be more accurate (in terms of the distance from the click-point to the center of the target) when they perceived the target to be smaller than when they perceived the target to be larger. These results would suggest participants' visually guided movements were influenced by the perceived size of the target to some degree.

The number of times participants changed the direction of their cursor movement as they approached the target (number of corrective movements), and the overall curvature of their cursor trajectory (area under the curve) were also measured to examine if the illusory context influenced the trajectory of participants' cursor movements toward the target. If participants were executing their movements using a planning-control model (Glover, 2004; Glover & Dixon, 2002), we may expect to see an increased number of corrective movements and more curved trajectories on trials where the target is perceived as larger, in which case participants may make additional online corrections to increase accuracy as the cursor approaches the target. Conversely, the perception-action model (Goodale & Milner, 1992; Milner & Goodale, 2006) would suggest that if under dorsal stream control, cursor trajectories should be unaffected by the illusory context, as these movements would be predominantly guided by the vision-for-action system.

Experiment 1

Methods

Participants

Fifty undergraduate psychology students (41 female, 9 male) between the ages of 18 and 32 years old (*M* = 20.10, *SD* = 3.38) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and participated in exchange for course credit toward their Introduction to Psychology course. All participants self-reported having either normal or corrected to normal vision (e.g., wearing glasses, contact lenses, corrective eye-surgery etc.), and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix E). All participants also self-reported using their right hand to control the cursor when using a computer. All participants provided informed consent prior to participation (Appendix F), and all procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Experiment Construction

The experiment was built using lab.js (Henninger, Shevchenko, Mertens, Kieslich, & Hilbig, 2021) a free online study builder designed for the behavioural and cognitive sciences. The experiment was posted on GitHub, and participants were provided with the link to the experiment through SONA, the university's online external study management system. All participant data were saved to a secure online database (Google Firebase).

Cursor Presentation

To ensure accuracy during performance, participants' cursor was set to appear as a 'crosshair', rather than the default 'pointer'.

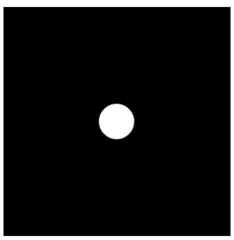
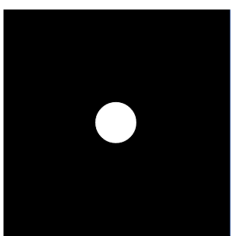
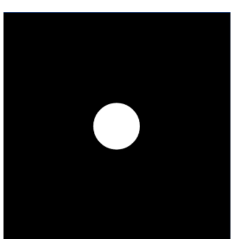
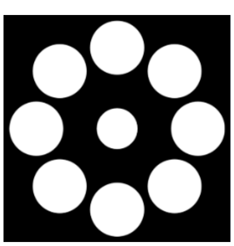
Stimuli Presentation

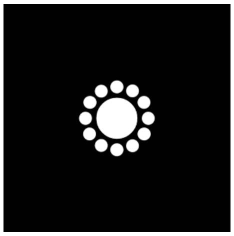
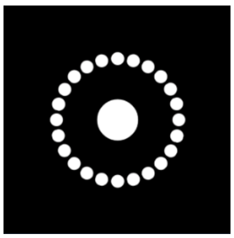
The sizes of the stimuli were measured in logical pixels (px), mapped accordingly to the physical pixels of the device's screen based on the device's screen resolution and device-pixel-ratio (DPR). Using logical pixels to design the on-screen stimuli meant the stimuli sizes remained relatively similar across devices; the DPR of devices with significantly higher screen resolutions prevented the stimuli from appearing drastically smaller than on devices with lower resolutions. Throughout this document, the term 'pixels' and the abbreviated 'px' will be used to refer to logical pixels.

The different target types used in this experiment are presented in Table 4.1. The stimuli were presented within an 800 x 600 px container, so they could be viewed on a wide range of screen sizes and resolutions. Targets appeared as white circles against a black background, and were presented either alone (Control targets), or surrounded by an annulus of context circles. The size and position of these context circles determined the direction of the illusion. In addition to the traditional variations of the Ebbinghaus illusion (small context circles positioned close to the target versus large context circles positioned far from the target) a Perceived Large (Far) target was also included, to make it possible to observe the effect of the illusion while controlling for the context circles' proximity to the target.

Table 4.1

Target Type and Dimensions

Target Type	Target Circle Diameter (px)	Context Circle Diameter (px; Proportion of Target Circle Diameter)	Distance from Edge of Target Circle to Inner Edge of Context Circle (px)
Control (Small) 	60	-	-
Control (Regular) 	70	-	-
Control (Large) 	80	-	-
Perceived Small 	70	96 (1.37)	58

Perceived Large 	70	27 (0.39)	11
Perceived Large (Far) 	70	27 (0.39)	73

Procedure

Self-Report

Once directed to the experiment website, participants were asked to confirm their use of the touchpad/trackpad of a laptop computer to complete the experiment (use of a physical mouse or touchscreen device to control the on-screen cursor was not permitted). Participants were then presented with a consent form and were required to provide consent before continuing. Next, participants reported to the best of their knowledge the type of device they were using to complete the experiment, as well as the device's screen size, and were asked to confirm once again they were using their finger on the device's touchpad/trackpad rather than a physical mouse or touchscreen device. Participants then provided demographic information regarding their vision (e.g., normal or corrected-to-normal), sex assigned at birth, and handedness. Finally, participants reported any previous involvement in eye-hand coordination sports.

Screen Set-Up

The first task involved participants using their cursor to click on 5 circular targets (diameter = 2 px) presented in sequence on their computer screen, one target each positioned in the center of the screen, 200 px to the left and right of center (these positions corresponded to the position of the targets during the experimental trials), and 150 pixels above and below the screen's center. The presentation of each target was preceded by a 200 ms mask to prevent any afterimages of the previous target. The recorded clicks at these target positions were used during analysis to confirm the metadata regarding the device's screen size and resolution were accurate, as well as to use as a reference point for the target's position during the experimental trials.

Instructions

Following the screen setup task, participants were presented with a set of instructions explaining the experiment, beginning by asking participants to maintain a distance of approximately 2 feet ('2 rulers' distance') between their head and the computer screen, in an attempt to maintain consistent viewing distance across participants. Next, participants were informed that a target circle would appear on the screen and were instructed to click on the center of the on-screen target 'AS QUICKLY AND AS ACCURATELY AS POSSIBLE'. Example images were provided to help describe the task, and to distinguish the 'target circle' from the surrounding context circles.

Experimental Task

Each trial began with a grey start button (diameter = 30 px), presented 250 px below the center of the screen. Participants were required to click the start button to initiate each experimental trial, and each experimental trial was preceded by a 200 ms mask. Each trial consisted of a target presented either 200 px to the left or right of the screen's center. Participants completed the trial by moving their cursor to the target and clicking within the target circle's boundaries, after which the target would disappear, and the start button would reappear to begin the next trial. Only clicking within the target circle's boundary ended the trial; clicks outside the boundaries were not recorded. There were no time constraints on the presentation of the stimuli, and the target remained on the screen until it was clicked.

Participants completed a set of 12 practice trials, during which each target type was presented twice, once on the left and once on the right side of the screen. Prior to the onset of the experimental trials, participants were once again reminded to 'click the center of the target circle as quickly and accurately as possible'. Participants then completed 60 randomized experimental trials (each unique combination of target type and on-screen position shuffled without replacement, then re-shuffled), such that each target type appeared 5 times on the left side of the screen, and 5 times on the right. Participants were then given an opportunity to take a break and instructed to 'Press the Continue button below to proceed to the next set of trials' before completing another 60 randomized experimental trials.

Perceptual Comparisons

After completing the 120 experimental trials, participants completed a perceptual size comparison task, in which they were presented with two different target types and were instructed to click which target they believed to be larger. These comparisons were included to check if the illusory context was effectively manipulating the perceived size of the targets. The two targets being compared were never the same type, and each target type was compared with the other 5 target types twice, appearing once on the left and once on the right side of the screen (at positions corresponding to those during the experimental trials: 200 px to the left and right of center). Participants whose responses were incorrect when comparing the three veridically different control targets were excluded from the analysis. After finishing the perceptual comparison task, all participant data were uploaded to the secure database, and participants were debriefed and directed to exit their browser.

In all three experiments, analysis of participants' perceptual comparison scores consistently indicated that the Perceived Large (Far) target was not successful in inducing the desired increase in perceived target size (participants reported an increase in the target's perceived size in as few as 32% and no more than 58% of comparisons). This is likely due to the increased distance between the context circles and the target circle. Proximity of the context circles to the target circle is known to play an important role in the direction and magnitude of the Ebbinghaus illusion's effect, with closer context circles increasing the size of the target circle, and farther context circles minimizing the size of the target circle (Knol et al., 2015; Massaro & Anderson, 1971; Robertsô et al., 2005). Based on the lack of any useful effect of the illusion, the Perceived Large (Far) target was not included in the following analyses.

Device Summary

The browser and operating system used to complete the experiment (Table G1), as well as the devices' screen resolution and DPR (Table G2), and participants' self-reported device screen size (Table G3) are provided in Appendix G.

Data Analysis

Participants' cursor movements were measured in lab.js using the Mousetrap plugin (Kieslich & Henninger, 2017), and analyzed using the mousetrap package (Kieslich, Henninger, Wulff, Haslbeck, & Schulte-Mecklenbeck, 2019) in R (R Core Team, 2020). Each trial ended once participants clicked the target, and therefore the final x and y coordinates of these cursor trajectories were used to define the position of the participants' click point on each trial. Each cursor trajectory was inspected manually, to ensure the cursor position was recorded effectively throughout the trial. Additionally, as the logging resolution (the intervals at which the cursor position was recorded throughout the movement) had the potential to vary across devices, the logging resolution of each dataset was checked. In all cases, the logging resolution was deemed satisfactory.

Each dependent variable was analyzed using a 2 (Time: Pre-Break versus Post-Break) x 2 (Position: Left versus Right) x 5 (Target Type: Control Small versus Perceived Small versus Control Regular versus Perceived Large versus Control Large) within-subjects repeated measures ANOVA. All statistical analyses were conducted using SPSS (version 23.0). A Greenhouse-Geiser correction was used to address any violations to sphericity. Violations to the assumption of normality were identified by inspecting the normality of the residual values produced by the repeated measures ANOVA. In cases where the residual values were significantly and consistently non-normal, a log transformation was applied to correct for the non-normal data. All analyses were conducted using alpha = .05, and Bonferroni adjusted p values were applied to all post hoc comparisons used to analyze any significant interactions.

Dependent Variables

Click-Point Accuracy. The radial error, calculated as the Euclidian distance (px) between the target's center and the location of the participant's click point was used to provide an absolute value representing click-point accuracy. As such, smaller values indicate click-point positions closer to the target's center and higher accuracy. These accuracy scores were then averaged within each unique condition to create a mean condition value for each participant.

Movement Time. The amount of time from the onset of cursor movement to the time at which participants clicked the target was measured in milliseconds. Movement times were averaged within each unique condition to create a mean condition value for each participant.

Area Under the Curve (AUC). Cursor trajectories were spatially normalized using 101 equidistant points (i.e., 0% to 100% of the movement distance) along the original cursor trajectory. The AUC was defined as the geometric area (px) between the trajectory and an idealized (straight) path connecting the trajectory's start and end positions. The R function polysimplify from the polyclip package (Johnson & Baddeley, 2019) was used to separate the cursor deviations from the idealized path and the polyarea function from the pracma package

(Borchers, 2021) was used to combine these deviations. Doing so produced an absolute deviation value by treating participants' deviations as additive rather than subtractive (the default method in mousetrap). AUC values were averaged within each unique condition to create a mean condition value for each participant.

Number of Corrective Movements. Using the same spatially normalized trajectories mentioned above, the frequency at which participants changed the direction of their cursor movement in either the horizontal or vertical axes during their movement toward the target in each trial was counted and averaged into a mean condition value for each participant.

Results

Excluded Data

A coding error made it possible for participants to begin their cursor movements during the 200 ms mask prior to presentation of the target, immediately after clicking the start button. This meant that any cursor movement that was executed during the 200 ms mask was not captured. In total, 1.84% of all trials involved uncaptured cursor movement during the 200 ms mask and were excluded from analysis. An additional 0.10% of all trials were removed due to missing timestamp data (timestamps: the timepoints throughout the trial at which cursor position was captured). Trials lasting longer than 5000 ms to perform the task were also removed. This cut-off was determined to be excessive based on inspection of participants' movement time data during analysis and accounted for 0.16% of the total number of trials. Finally, while the onscreen target represented the only 'clickable area' on the screen, this clickable area was defined using square boundaries, which meant that in rare cases, participants could in fact click 'outside' the circular target, in the corners of the square boundaries. This occurred in 0.02% of trials, all of which were excluded from analysis. In total, 2.12% of experimental trials were excluded from analysis.

Perceptual Comparisons

Participants' perceptual comparison scores are provided in Appendix H (Table H1). Participants' responses followed the direction of the illusion with a generally high consistency: over 75%, except for the comparisons involving the Perceived Large (Far) target. Additionally, a small portion of participants reported the Perceived Small target as being smaller than the veridically smaller Control Small target (20% when the Perceived Small target was on the left side of the screen, and 22% when it was on the right side of the screen). When comparing the

Perceived Large target on the right side of the screen with the Control Large target on the left side of the screen, 25% of participants reported the Perceived Large target as being larger, however this pronounced effect of the illusion disappeared when the target positions were reversed (0% when the Perceived Large target was on the left and the Control Large target was on the right).

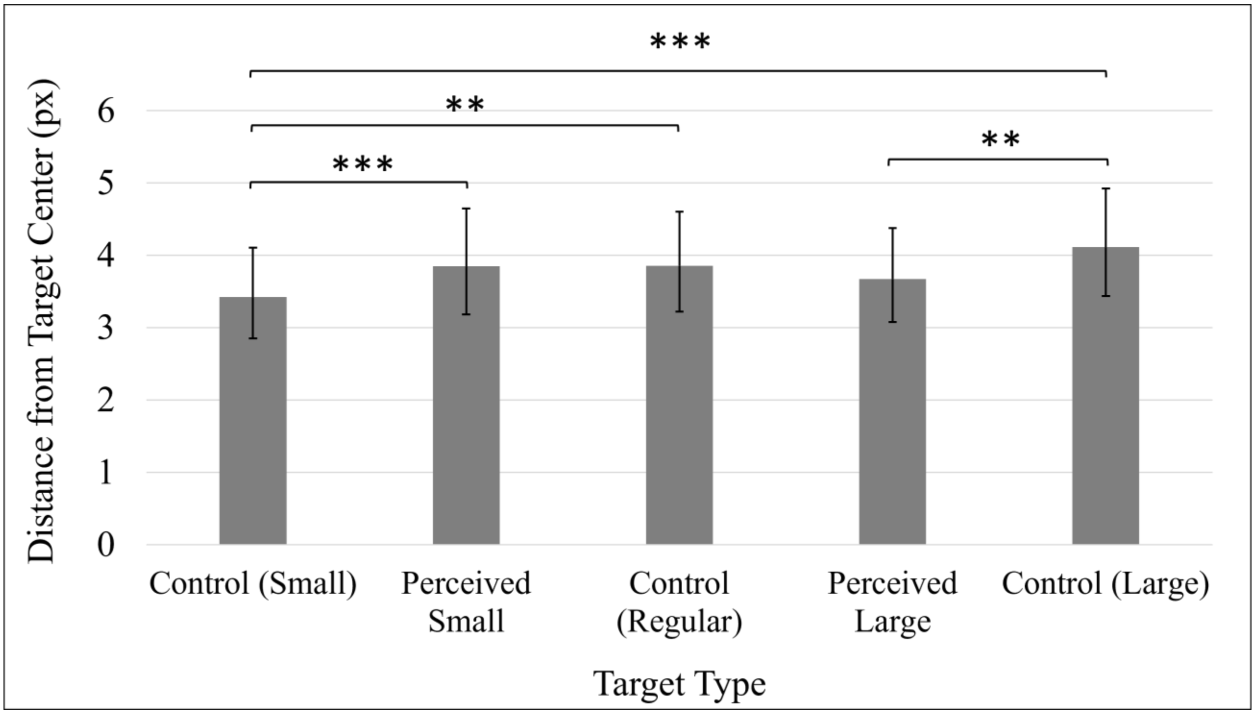
Click-Point Accuracy

Examining the distributions of participants' average accuracy scores within each condition indicated non-normal, moderately to severely positively skewed data in all conditions. To address this violation to normality, a log transformation was applied to the data. The data reported here have been back-transformed into their original units for ease of interpretation.

A significant main effect of Time, $F(1, 49) = 7.09$, $p < .05$, $\eta_p^2 = 0.126$, indicated that participants were more accurate in their click positions during the first block of trials ($M = 3.62$, 95% CI [3.04, 4.31]) compared to the second block of trials ($M = 3.94$, 95% CI [3.27, 4.73]). A significant main effect of Target, $F(4, 196) = 10.91$, $p < .001$, $\eta_p^2 = 0.182$, indicated that participants were generally most accurate when clicking on the Control Small target (Figure 4.1). However, there were no significant comparisons amongst the three same-sized targets (Perceived Small, Perceived Large and Control Regular targets), suggesting the presence of the illusion did not influence participants' clicking accuracy.

Figure 4.1

Click-Point Accuracy



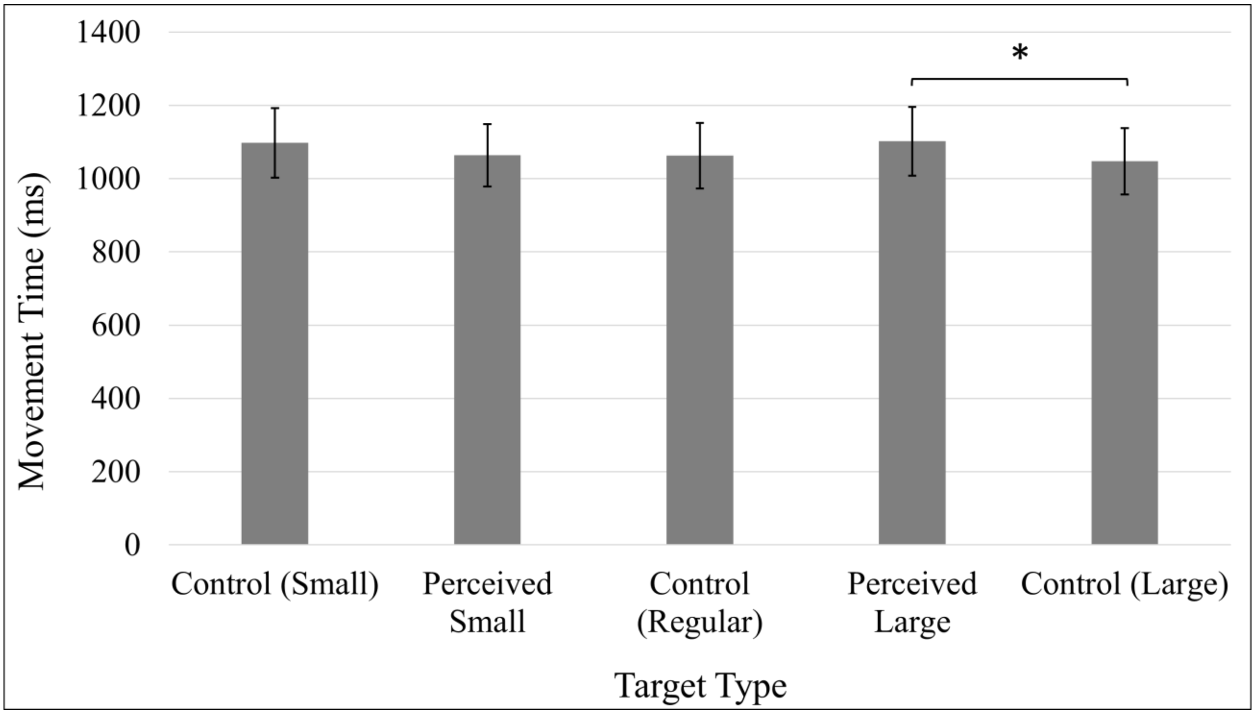
Note. Average distance from click position to target center. Values have been back-transformed into original measurement value (px). Smaller values indicate higher accuracy. Error bars represent 95% confidence intervals. $^{**}p < .01$, $^{***}p < .001$

Movement Time

A significant main effect of Target, $F(4, 196) = 4.87$, $p < .01$, $\eta_p^2 = 0.09$, suggested the type of target influenced participants' speed when performing the task (Figure 4.2). However, the only significant comparison was between the Perceived Large and the Control Large targets; movement time was significantly longer when clicking on the Perceived Large target.

Figure 4.2

Movement Time



Note. Average movement time (ms). Error bars represent 95% confidence intervals. *$p < .05$

Area Under the Curve

A significant main effect of Position, $F(1, 49) = 7.01$, $p < .05$, $\eta_p^2 = 0.125$, indicated that participants executed more curved cursor movements when the target was presented on the right side of the screen (M = 17309.72 px, 95% CI [15342.79, 19276.64]) compared to when presented on the left (M = 14608.33 px, 95% CI [12790.36, 16426.31]).

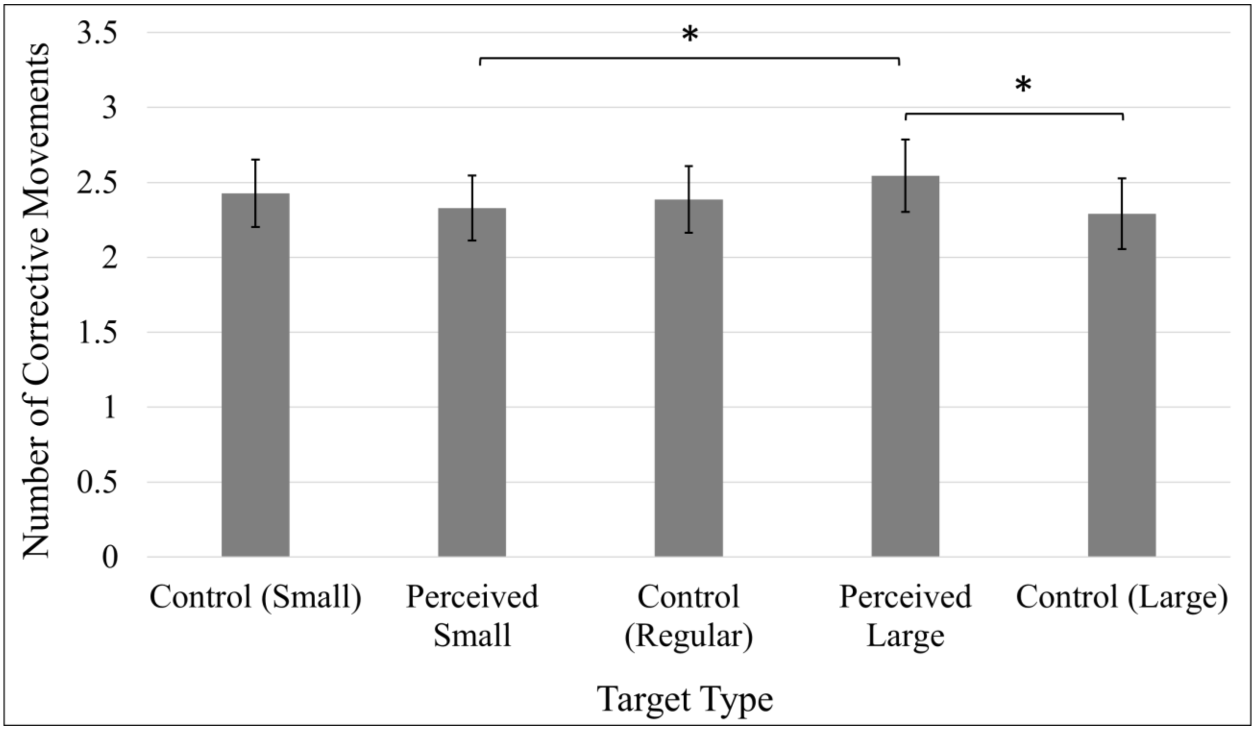
Number of Corrective Movements

A significant main effect of Target, $F(4, 196) = 3.91$, $p < .01$, $\eta_p^2 = 0.074$; Figure 4.3, showed that participants made significantly more corrective movements when clicking the Perceived Large target in comparison to the Perceived Small and Control Large targets. There were no significant differences in the number of corrective movements between any of the other target types.

An increased number of corrective movements were made when the target was positioned on the right side of the screen (M = 2.51, 95% CI [2.29, 2.73]) compared to when positioned on the left side of the screen ($M = 2.28$, 95% CI [2.05, 2.51]), as indicated by a significant main effect of Position, $F(1, 49) = 8.54$, $p < .01$), $\eta_p^2 = 0.148$.

Figure 4.3

Corrective Movements



Note. Average number of corrective movements. Error bars represent 95% confidence intervals. *$p < .05$

Discussion

In the current experiment, participants clicked on circular targets using an onscreen cursor controlled by their computer's touchpad. The Ebbinghaus illusion was used to influence participants' perception of target size when clicking. The goal was to determine if the perceived size of the circular onscreen target affected participants' cursor movements and click-point accuracy.

In a small number of cases, participants' perceptual comparison scores indicated participants judged the Perceived Small and Perceived Large targets as smaller and larger than the Control Small and Control Large targets respectively, despite the veridical sizes of these targets being different. This exaggerated effect was only produced by the Perceived Large target when positioned on the right side of the screen, opposite a leftward positioned Control Large target, however. Previous research has also demonstrated an increase in the magnitude of the Perceived Large version of the Ebbinghaus illusion when positioned rightward, suggesting the strength of the illusion may be influenced by its position within the visual field, and the hemisphere in which the visual information is processed (Saneyoshi, 2018). While the right hemisphere is traditionally credited with an advantage for global, holistic processing, the left hemisphere is associated with having an advantage for local processing of visual information (Hellige, Laeng, & Michimata, 2010) and therefore may have a pronounced role in inducing illusions requiring size-contrasts between contextual elements of a figure such as the inducers used in the Ebbinghaus illusion when the figure is presented on the right. While participants made their comparisons under free viewing conditions in this experiment, the switching of attention between the two targets may have produced certain differences in which hemisphere processed the rightward and leftward positioned targets at the time the participants made their judgement. In addition to providing confirmation that the illusory context was successful in inducing a perceived change in target size, these results suggest the magnitude of the illusion may be influenced by the position of the target.

Although participants were more likely to judge the Perceived Large target as bigger when presented on the right side of the screen, participants' click-point accuracy and movement time did not differ as a function of the target's on-screen position. However, the target's position did influence the cursor's trajectory toward the target; trajectories were overall more curved and included more corrections when targets were presented on the right side of the screen. This effect was observed regardless of the type of target being presented, and therefore the changes in cursor trajectory are more likely a result of all participants controlling the cursor with their right hand, rather than resulting from a lateralization of visuospatial processing. Using the right hand to perform a leftward movement of the cursor simply requires the extension of the digit on the touchpad, while a rightward movement requires adduction of the index finger (or rightward abduction of the middle finger), as well as a necessary adduction of the wrist. The added dexterity required to perform a rightward finger movement on the trackpad likely contributed to the increased curvature and corrective adjustments observed when guiding the cursor to rightward presented targets.

Despite participants reporting differences in the perceived size of the targets during the perceptual comparison task, click-point accuracy and movement time did not significantly differ between the three same-sized targets (i.e., the Control Regular, Perceived Small, and Perceived Large targets), suggesting the illusory context did not influence participants' performance of the task. Thus, the analysis of these performance measures appears to agree with the predictions of a perception-action theory of visually guided action. In other words, participants' judgments appear to have been driven by a perceptual system susceptible to the illusory influence during the perceptual comparison task, causing them to report differences in the perceived size of the target. During the clicking task however, participants cursor movements appear to have been guided by an action system that was immune to any perceptually mediated illusory influence and did not demonstrate any of the differences in accuracy or movement time that would be expected when acting on targets of different sizes.

Participants were most accurate when clicking the Control Small target and least accurate when clicking the Control Large target, presumably because these targets offered the smallest and largest 'clickable' areas, respectively. However, consistent differences emerged between the Control Large target and the Perceived Large target; participants were slower, more accurate, and generated more corrective movements when clicking the Perceived Large target. We present two potential explanations for these results. First, it is possible that participants' early cursor movement was influenced by the illusory context of the Perceived Large target and was therefore directed toward a target perceived to occupy a larger space than it did. An increased number of online corrections would therefore be required during the movement to accurately navigate the cursor to the center of the Perceived Large target, resulting in increased movement time, and, because of the added corrections, comparatively higher accuracy than when clicking the Control Large target. In contrast, the initial cursor movement toward the Control Large target would require less corrections during the movement, as participants' perception of the target's size matched its true size. A lesser number of corrections, paired with the target's larger physical size, would presumably result in faster, and ultimately less accurate final click positions. Significantly fewer corrective movements were also observed when clicking the Perceived Small target in comparison to the Perceived Large target, which would be expected if the opposite occurred; the illusory context caused participants to direct their initial cursor movement toward a target perceived to occupy a smaller space than it did, thus requiring less correction later in the movement. While this comparison is not easily explained by the perception-action model, as the Perceived Small and Perceived Large targets were the same metrical size, this explanation is congruent with a planning-control model in which the illusory context influences the planning stages of the movement, and online corrections during the movement are carried out in a fashion that is increasingly independent of the illusory influence (Glover, 2004; Glover & Dixon, 2002).

Alternatively, the increased accuracy, longer movement time, and higher number of corrective movements generated by the Perceived Large target may be explained by the proximity of the context circles to the target, and unrelated to a perceived difference in target size. Participants may have directed their cursors toward a larger, more general area encompassing the context circles as well as the target at the onset of the movement. When necessary (i.e., as the cursor neared the target during later stages of the movement), participants would then make the relevant differentiation between the target and context circles and execute the necessary corrections to avoid the closely positioned context circles. The larger distances between the context circles and the Perceived Small target may have promoted a more distinct separation between the annulus and target, causing participants to direct their cursors directly to the target, rather than toward an area encompassing both target and context circles. Similar reasoning has been used to possibly explain the small increases in grip aperture sometimes observed in response to the presence of small context circles (Haffenden & Goodale, 2000): participants widen their grip aperture as if to grasp the entire display (target and annulus). Unfortunately, removal of the Perceived Large (Far) target from the analysis meant we could not distinguish the illusory effect of the small inducers and their proximity to the target circle as originally intended. Currently, it remains difficult to determine which of these two explanations is more plausible.

In summary, the increased accuracy, movement time, and number of corrective movements when clicking the Perceived Large target suggests the illusory context may have influenced participants' cursor movements to some degree. However, participants' perception of the target's size did not influence their accuracy or movement time when clicking on the same-sized targets of interest, and these results are congruent with the predictions of the perception and action model (Milner & Goodale, 1994). One contributing factor may have been the relatively easy nature of the task, which may have allowed participants to successfully perform the task both quickly and accurately without much difficulty. In other words, even if the perceived size of the target did influence participants' performance, this influence may have been hidden by a 'ceiling effect'. Additionally, the perception-action model predicts that simple, practiced, and repetitive movements are more likely to be controlled by the vision-for-action dorsal stream, while novel, unpracticed tasks that require increased cognitive control are expected to require greater input from the vision-for-perception ventral stream (Milner & Goodale, 2006). Considering the relatively easy point-to-click movement required for this task and participants' assumed familiarity with laptop trackpads, participants' performance of the task may have been executed primarily under dorsal stream control, minimizing any illusory influence. Accordingly, increasing the difficulty of the task by promoting a greater emphasis on performance speed or accuracy may encourage participants to try harder. Adjusting the demands of the task may require participants to allocate more focused attention on their performance, and possibly increase the influence of the target's perceived size on the end-point measures. Experiments 2 and 3 were conducted to explore this possibility by encouraging participants to increase their speed (Experiment 2) or accuracy (Experiment 3) while performing the task.

Experiment 2

Methods

Participants

Fifty undergraduate psychology students (38 female, 12 male) between the ages of 18 and 44 years old (M = 20.02, SD = 4.40) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and participated in exchange for course credit toward their Introduction to Psychology course. Eligibility requirements were the same as in Experiment 1. All participants provided informed consent prior to participation (Appendix F), and all procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Experimental Design, Procedure, and Data Analysis

The experimental design, procedure, stimuli presentation, and analysis of the dependent variables were the same as those described in Experiment 1. The only difference involved the instructions given to participants during the break following the first set of 60 experimental trials. In this experiment participants were presented with the following message: 'Try to be faster when clicking! Remember: The goal is to click the center of the target circle AS QUICKLY AS POSSIBLE'.

Device Summary

The browser and operating system used to complete the experiment (Table G4), the devices' screen resolution and DPR (Table G5), and participants' self-reported device screen size (Table G6) are provided in Appendix G.

Results

Excluded Data

In total, 2.16% of all trials were excluded from analysis (early cursor movement during the 200 ms mask: 1.64%, unusable cursor/timestamp data: 0.38%, trial duration longer than 5000 ms: 0.10%, click-point outside target boundaries: 0.04%).

Perceptual Comparisons

Participants' perceptual comparison scores are provided in Appendix H (Table H2). As in Experiment 1, participants' perceptual comparison scores indicated the illusory context successfully influenced participants' perceptions of target size, except for the Perceived Large (Far) target, which once again had comparatively low scores. The illusion appeared to have an exaggerated effect once again in a small subset of responses, however the previously observed lateralized effect of the Perceived Large target in comparison to the Control Large target was not replicated in the current experiment; participants that judged the Perceived Large target as bigger did so as frequently on both sides of the screen.

Click-Point Accuracy

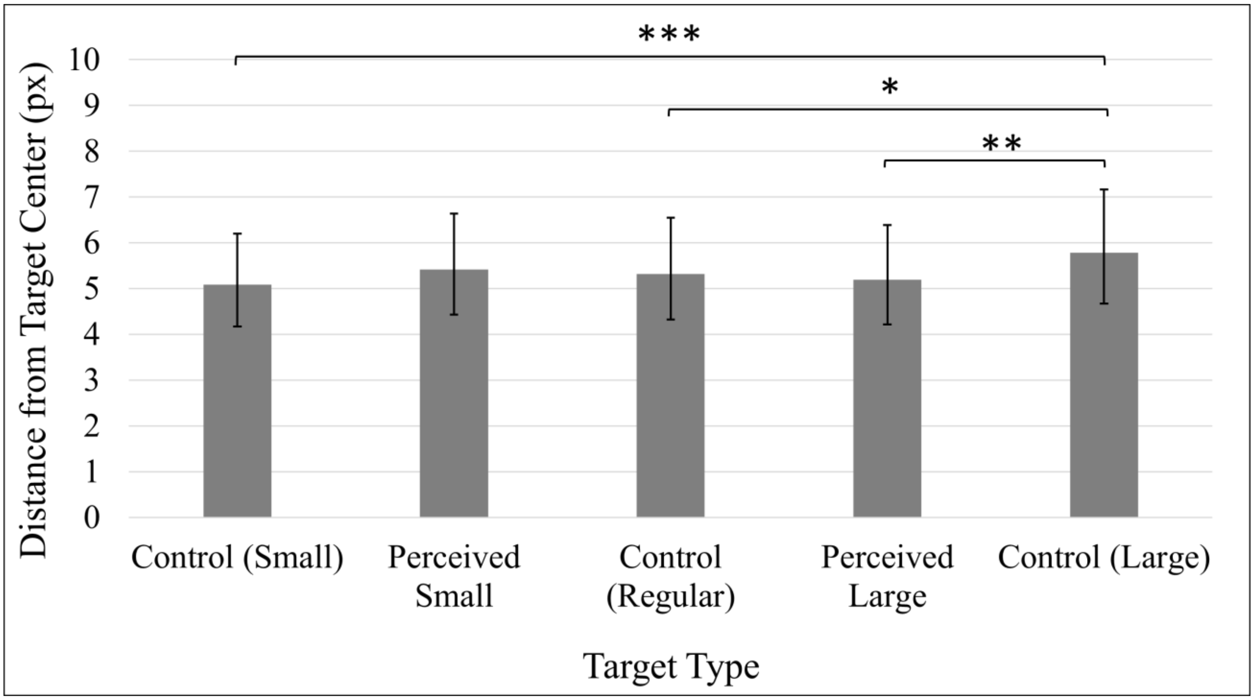
As in Experiment 1, participants' average accuracy scores violated the assumption of normality (distributions ranged from moderately to severely positively skewed on a consistent basis). A log transformation was applied to the data, and the values reported here have been back-transformed into the original units (px).

A significant main effect of Time, $F(1, 49) = 33.47$, $p < .001$, $\eta_p^2 = 0.406$, showed that participants were less accurate in the second block of trials following the manipulation ($M = 6.40$ px, 95% CI [5.15, 7.96]) compared to the first, pre-manipulation block ($M = 4.48$ px, 95% CI [3.64, 5.50]). A significant main effect of Position, $F(1, 49) = 6.92$, $p < .05$, $\eta_p^2 = 0.124$, also indicated that participants were more accurate when the target was presented on the right side of the screen ($M = 5.21$ px, 95% CI [4.23, 6.44]) than when presented on the left ($M = 5.50$ px, 95% CI [4.51, 6.68]).

Finally, a main effect of Target, $F(4, 196) = 6.915$, $p < .001$, $\eta_p^2 = 0.124$; Figure 4.4, was also found to be significant. Accuracy was worse when participants clicked on the Control Large target in comparison to all other targets except for the Perceived Small target. There were no significant comparisons amongst the same-sized targets (Perceived Small, Perceived Large, and Control Regular).

Figure 4.4

Click-Point Accuracy



Note. Average distance from click position to target center. Values have been back-transformed into original measurement value (px). Smaller values indicate higher accuracy. Error bars represent 95% confidence intervals. *$p < .01$, **$p < .01$, ***$p < .001$

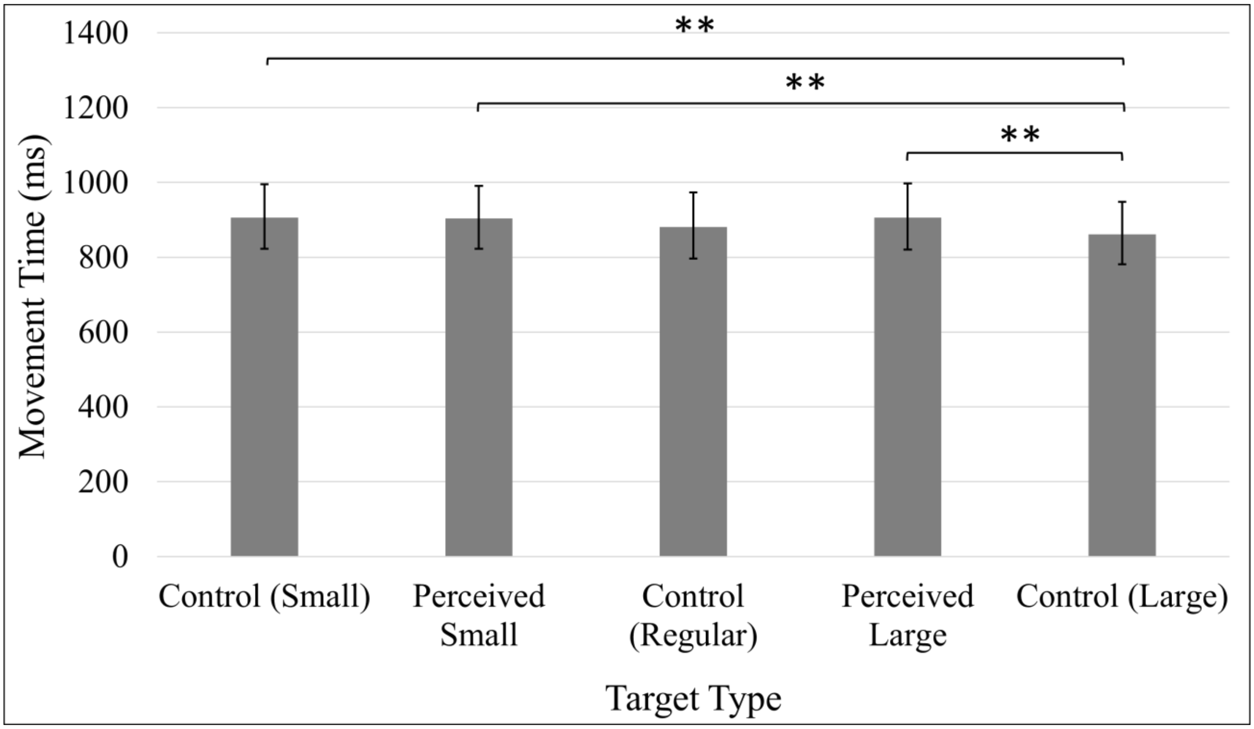
Movement Time

Participants' average movement time scores were consistently non-normal (moderately to severely positively skewed), and a log transformation was applied to the data. The values reported here have been back-transformed into the original units (ms).

Participants were significantly faster during the second block of trials following the experimental manipulation (M = 820.35 ms, 95% CI [741.31, 905.73]) compared to the first block of trials (M = 968.28 ms, 95% CI [874.98, 1069.06]), as confirmed by a significant main effect of Time, $F(1, 49) = 32.99$, $p < .001$, $\eta_p^2 = 0.402$. A main effect of Position, $F(1, 49) = 9.74$, $p < .01$, $\eta_p^2 = 0.166$, was also significant, and participants were faster when the target was presented on the left side of the screen (M = 877.00 ms, 95% CI [796.16, 968.28]) compared to targets presented on the right (M = 903.65 ms, 95% CI [822.25, 993.12]). A significant main effect of Target, $F(4, 196) = 6.63$, $p < .001$, $\eta_p^2 = 0.119$; Figure 4.5, indicated that the decreased accuracy observed when clicking on the Control Large target was also associated with a general decrease in movement time; participants were faster when clicking on the Control Large target compared to the Control Small, Perceived Small, and Perceived Large targets.

Figure 4.5

Movement Time



Note. Average movement time (ms). Error bars represent 95% confidence intervals. $^{**}p < .01$

Area Under the Curve

Cursor trajectories were significantly more curved during the second block of trials, after the manipulation (M = 17489.86 px, 95 CI [15834.25, 19145.46]) than compared to the first block of trials (M = 16131.00 px, 95% CI [14476.78, 17785.23]), as confirmed by a significant main effect of time, $F(1, 49) = 7.08$, $p < .05$, $\eta_p^2 = 0.126$. A significant main effect of Position, $F(1, 49) = 25.07$, $p < .001$, $\eta_p^2 = 0.338$, indicated that cursor trajectories were also more curved when the target was presented on the right side of the screen (M = 18914.69 px, 95% CI [16817.29, 21012.08]) than when presented on the left (M = 14706.17 px, 95% CI [13299.45, 16112.897]).

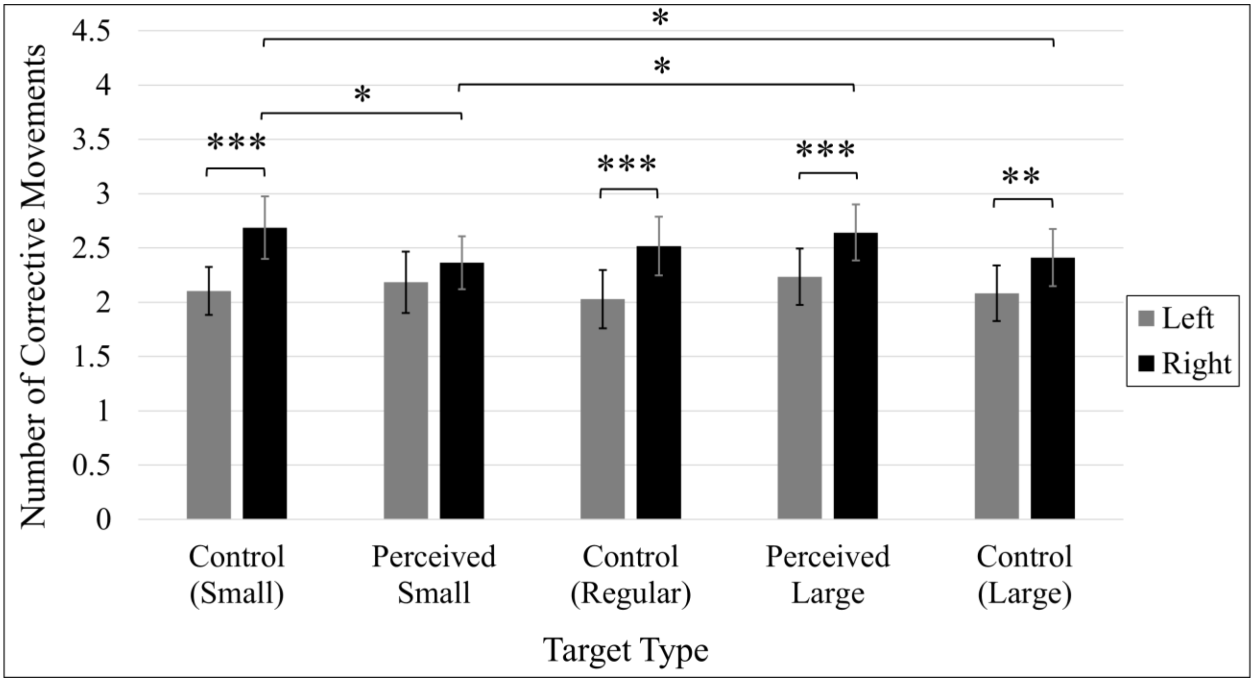
Number of Corrective Movements

A significant Position x Stimuli interaction, $F(4, 196) = 2.76$, $p < .05$, $\eta_p^2 = .053$; Figure 4.6, indicated that an increased number of corrective movements were made when clicking on each target type when positioned on the right side of the screen compared to when presented on the left side, except for the Perceived Small target, for which the number of corrective movements did not significantly differ between target positions ($p > .05$).

There were no significant differences in the number of corrective movements made by participants when clicking on targets presented on the left side of the screen (all *p*s > .05). However, significantly more corrections were made when clicking on the Control Small target in comparison to the Perceived Small target, and the Control Large target when these targets were presented on the right side of the screen. Cursor movements toward the Perceived Large target also involved more corrections in comparison to the Perceived Small target when presented on the right side of the screen.

Figure 4.6

Corrective Movements



Note. Average number of corrective movements. Error bars represent 95% confidence intervals. *$p < .05$, **$p < .01$, ***$p < .001$

Discussion

In this experiment, participants were instructed to emphasize speed when performing the task in the second block of trials. This manipulation successfully produced the expected speed/accuracy trade-off: participants performed the task faster and less accurately in the second block of trials, indicating the manipulation was successful. Cursor trajectories were also more curved following the manipulation, suggesting participants' cursor movements deviated farther from the 'ideal path' to the target when they performed the task faster.

Participants were generally less accurate and faster when clicking the Control Large target, however there were no significant comparisons in accuracy or movement time between the same-sized targets (i.e., Control Regular, Perceived Small and Perceived Large), suggesting the manipulation did not successfully induce any increased effect of the illusory context on these end-point measures. However, as in Experiment 1, analysis of the cursor path suggested the illusory context may have influenced participants' cursor movements toward the targets. Once again, more corrective movements were observed when clicking the Perceived Large target in comparison to the Perceived Small target, although this difference was only observed when these targets were presented on the right side of the screen. The Perceived Small target also generated fewer corrective movements than the Control Small target, but again this was only the case when presented on the right side of the screen. As reasoned in the Experiment 1 Discussion, this reduction in corrective movements generated by the Perceived Small target could potentially be explained by separating the movement into an early planning stage of movement, in which the perceived size of the target influences the direction of the initial cursor movement, and a late stage in which corrections are made to accurately click the center of the target (Glover, 2004; Glover & Dixon, 2002). Less corrections would be necessary when the perceived target size is smaller than its true size (i.e., the Perceived Small target), compared to when the perceived size is larger than its true size (i.e., the Perceived Large target), or when the perceived size matches the true size (i.e., the Control Small target). The fact that these comparisons were only significant when the targets were presented on the right side of the screen suggests the effect of the illusion may have been highlighted by the increased difficulty associated with a rightward movement on the trackpad. Rightward positioned targets produced more curved trajectories and longer movement times, as well as better click-point accuracy compared to targets presented on the left, and the number of corrective movements also increased on the right side for all target types except the Perceived Small target. This may suggest that while rightward movements were generally more difficult and required more corrections, an increase in corrective movements was not necessary when clicking the right-sided Perceived Small target, to which cursor movements were already more accurately guided.

The results of Experiment 2 demonstrated the expected speed/accuracy trade-off following the manipulation and produced similar differences in the number of corrective movements between the Perceived Small and Perceived Large targets that were observed in Experiment 1. However, manipulating participants' motivation to perform the task quickly did not produce any clear differences in click-point accuracy or movement time between the same-sized targets of interest, as would be expected if the perceived size of the targets was influencing their performance of the task. Experiment 3 tested the hypothesis that prioritizing participants' motivation to perform the task accurately rather than quickly may successfully induce an illusory influence on task performance.

Experiment 3

Methods

Participants

Fifty undergraduate psychology students (38 female, 11 male, 1 undeclared) between the ages of 17 and 23 years old (M = 18.96, SD = 1.59) were recruited through the Psychology Department Undergraduate Participant Pool at the University of Manitoba and participated in exchange for course credit toward their Introduction to Psychology course. Eligibility requirements were the same as in Experiments 1 and 2. All participants provided informed consent prior to participation (Appendix F), and all procedures were approved by the psychology/sociology research ethics board (PSREB) at the University of Manitoba.

Experimental Design and Procedure

The experimental design, procedure, stimuli presentation, and analysis of the dependent variables were identical to those in the first two experiments, except for the instructions provided to the participants during the break following the first 60 trials. In this experiment, participants were given the following message: 'Try to be more accurate when clicking! Remember: The goal is to click the CENTER of the target circle AS ACCURATELY AS POSSIBLE'.

Device Summary

The browser and operating system used to complete the experiment (Table G7), the devices' screen resolution and DPR (Table G8), and participants' self-reported device screen size (Table G9) are provided in Appendix G.

Results

Excluded Data

In total, 3.14% of all trials were excluded from analysis (early cursor movement during the 200 ms mask: 2.60%, unusable cursor/timestamp data: 0.10%, trial duration longer than 5000 ms: 0.44%).

Perceptual Comparisons

Participants' perceptual comparison scores are provided in Appendix H (Table H3). As in Experiments 1 and 2, the illusory context successfully influenced participants' perceptions of target size, however this was not the case for the Perceived Large (Far) target. An exaggerated influence of the illusion was observed in a small portion of participants' responses, regardless of the target's on-screen position.

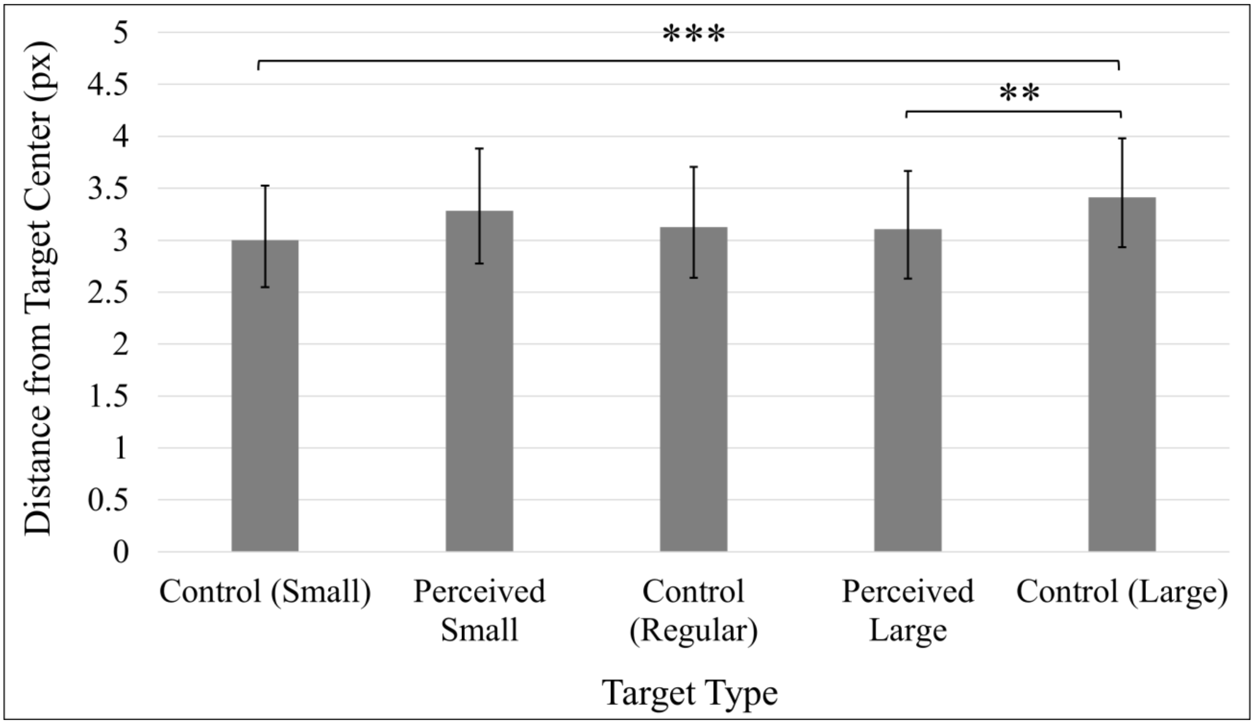
Click-Point Accuracy

As was the case for Experiments 1 and 2, participants' average accuracy scores were consistently positively skewed, and a log transformation was applied to the data. The values reported here have been back-transformed into the original units (px).

A significant main effect of Time, $F(1, 49) = 42.444$, $p < .001$, $\eta_p^2 = .464$, indicated that participants' accuracy increased following the manipulation ($M = 2.37$, 95% CI [2.05, 2.74]) compared to before the manipulation ($M = 4.27$, 95% CI [3.44, 5.29]). A significant main effect of Target, $F(4, 196) = 5.662$, $p < .001$, $\eta_p^2 = .104$; Figure 4.7, indicated the Control Large target generated significantly worse accuracy in comparison to the Control Small and Perceived Large targets. All other comparisons were non-significant (*p*s > .05).

Figure 4.7

Click-Point Accuracy



Note. Average distance from click position to target center. Values have been back-transformed into original measurement value (px). Smaller values indicate higher accuracy. Error bars represent 95% confidence intervals. $^{**}p < .01$, $^{***}p < .001$

Movement Time

A significant main effect of Time, $F(1, 49) = 61.472$, $p < .001$, $\eta_p^2 = .556$, indicated that participants were slower following the manipulation (M = 1358. 334 ms, 95% CI [1246.81, 1469.86] compared to before the manipulation (M = 1059.90 ms, 95% CI [951.28, 1168.52]).

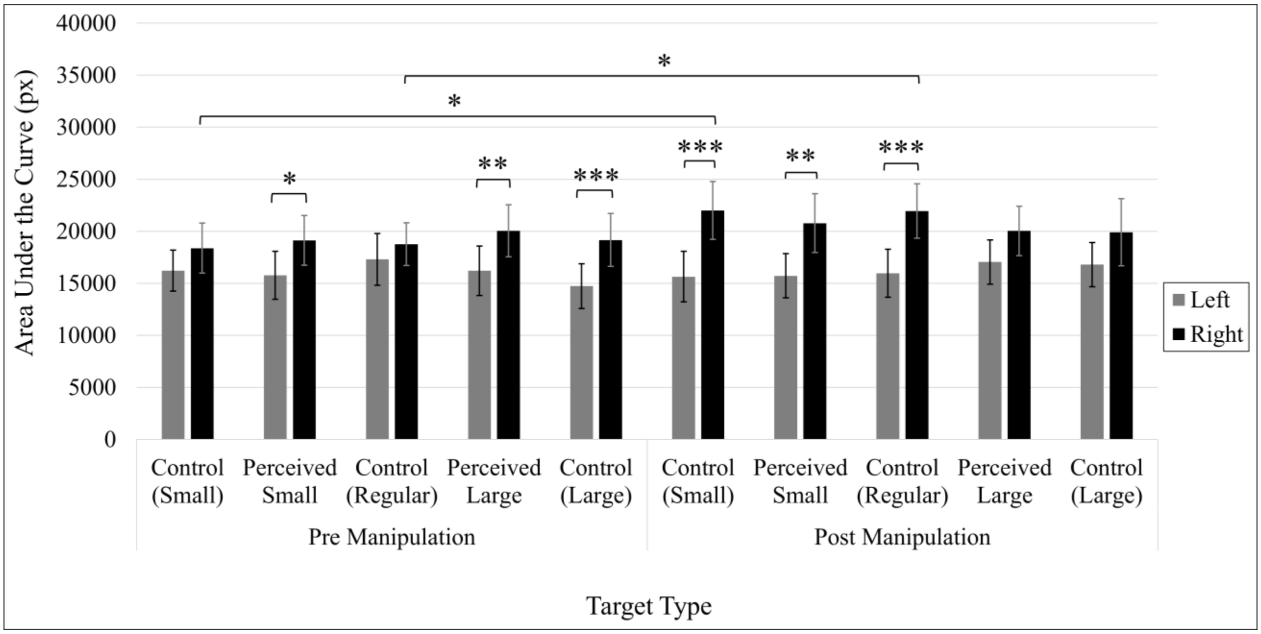
Area Under the Curve

A three-way Time x Position x Target interaction was shown to be significant, $F(4, 196) = 2.852$, $p < .05$, $\eta_p^2 = .055$; Figure 4.8. Prior to the manipulation, trajectories were more curved when the Perceived Small, Perceived Large, and Control Large targets were presented on the right side of the screen compared to the left side; the position of the target had no influence on the Control Small and Control Regular targets (ps > .05). After the manipulation, trajectories were more curved when the Control Small, Perceived Small, and Control Regular targets were presented on the right side of the screen compared to the left side; the position of the target had no influence on the Perceived Large and Control Large targets (*p*s > .05).

When clicking on Control Small and Control Regular targets presented on the right side of the screen, trajectory curvature increased following the manipulation. Otherwise, the manipulation did not influence trajectory curvature (*p*s > .05). There were no significant comparisons between any of the target types on either the left or right side of the screen, or before or after the manipulation (*p*s > .05).

Figure 4.8

Area Under the Curve



Note. Average area under the curve (px). Error bars represent 95% confidence intervals. **p < .01, ***p < .001

Number of Corrective Movements

A significant three-way Time x Position x Target interaction was observed, $F(4, 196) = 4.75$, $p < .01$, $\eta_p^2 = 0.088$; Figure 4.9.

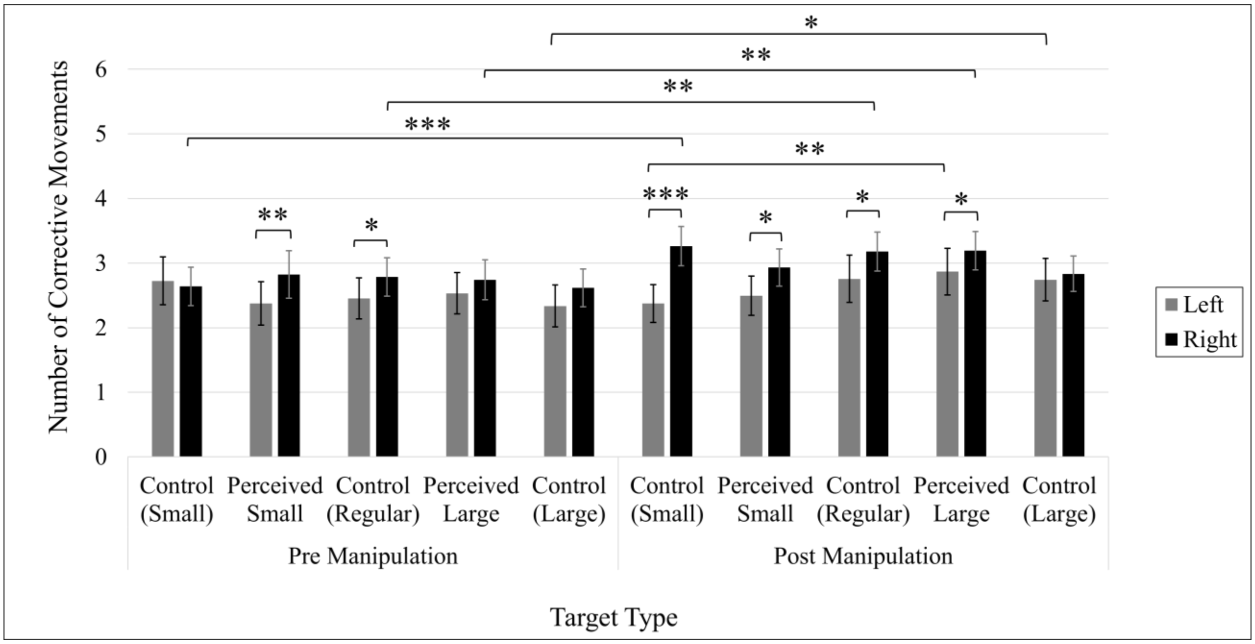
Prior to the manipulation, participants made significantly more corrective movements when clicking on rightward positioned Perceived Small and Control Regular targets in comparison to when these targets were presented on the left side of the screen. After the manipulation, more corrective movements were observed when each target was presented on the right side of the screen compared to the left side, with the exception of the Control Large target, for which the number of corrective movements did not differ between onscreen positions (p > .05).

Compared to before the manipulation, the number of corrective movements following the manipulation increased when clicking on rightward positioned Control Small, Control Regular, and Perceived Large targets. The number of corrective movements also increased post-manipulation when clicking on Control Large targets presented on the left side of the screen.

Prior to the manipulation, the number of corrective movements did not significantly differ between target types (all *p*s < .05). Following the manipulation however, participants made significantly more corrective movements when clicking on the Control Small target compared to the Perceived Large target when these targets were presented on the left side of the screen. Otherwise, there were no significant comparisons between the different targets on either the left or right side of the screen, or before or after the manipulation (*p*s > .05).

Figure 4.9

Corrective Movements



Note. Average number of corrective movements. Error bars represent 95% confidence intervals. *$p < .05$, **$p < .01$, ***$p < .001$

Discussion

As in Experiment 2, the instructions given to participants after completing the first block of trials were successful in producing a speed/accuracy trade-off. In this experiment, participants were instructed to prioritize accuracy when performing the task, and therefore this trade-off resulted in increased accuracy scores and longer movement times during the second block of trials following the manipulation. Once again, participants' click-point accuracy was worse when clicking the Control Large target in comparison to the Control Small and Perceived Large target, however unlike Experiments 1 and 2 Target Type did not demonstrate an influence on movement time in Experiment 3. As was the case in Experiments 1 and 2, the illusory context did not cause any observable differences in click-point accuracy or movement time between the three same-sized targets.

Three-way interactions were observed when examining both trajectory curvature and the number of corrective movements, suggesting the emphasis on accuracy had a different influence on participants' cursor movements depending on the type of target being clicked and its position on the screen. However, these influences also did not result in any meaningful comparisons between the three same-sized targets. In general, the number of corrective movements increased following the manipulation, particularly when the target was positioned on the right side of the screen.

In contrast to Experiment 2, an increase in trajectory curvature and the number of corrective movements was observed when the Perceived Small target was presented on the right side compared the left in this experiment. However, unlike the other same-sized target types in this experiment, this left-right difference was consistently observed prior to and following the manipulation. In contrast, when clicking the Perceived Large target, the left-right difference in trajectory curvature *disappeared* when participants were emphasizing accuracy following the manipulation, while a left-right difference in the number of corrective movements *appeared* following the manipulation. Similarly, an *increase* in trajectory curvature as well as an increase in the number of corrective movements was observed when clicking the rightward Control Regular target post manipulation. In other words, the increased emphasis on accuracy did not change the left-right difference in trajectory curvature or number of corrective movements when participants perceived the target to be smaller, however this left-right difference was influenced by the manipulation when participants perceived the target as larger (Perceived Large) or there was no illusory context (Control Regular). These results seem to suggest the cursor movements toward the Perceived Small target were not influenced by the manipulation, as was the case for cursor movements toward the other target types.

How can these results be explained in the context of a perceptual influence on participants' cursor movements? We previously hypothesized that less corrective movements may be needed when moving the cursor toward a target that is perceived to be smaller than its true size, particularly if this perceived reduction in size influenced the planning stages of the movement. If perceiving the target to be smaller than its true size already contributed to more accurate cursor movements during the early stages of movement, then we may not expect to see an exaggerated change when participants were encouraged to increase their accuracy following the manipulation in this experiment. Thus, while the illusory context may not have provided a clear influence on the performance outcomes of the task (i.e., click-point accuracy and movement time), analysis of participants' cursor movements appears to suggest that the demands of the task did not have as strong an influence on targets perceived to be smaller than their true size.

General Discussion

This study sought to examine the influence of a target's perceived size on participants' cursor movements and click-point accuracy using a simple point and click task, in which the Ebbinghaus illusion was used to manipulate the perceived size of the target. In Experiment 1, participants were simply instructed to perform the task as quickly and accurately as possible. In Experiments 2 and 3 participants' motivation to perform the task quickly or accurately was manipulated at the midway point of the experiment to test if emphasizing either of these behaviours would cause a pronounced effect of the target's perceived size on participants' cursor movements and accuracy.

Absence of Illusion Effect on Point-Click Accuracy and Movement Time

Despite participants' perceptual comparison scores consistently indicating that the presence of the illusion successfully influenced the perceived size of the targets, all three experiments failed to demonstrate an influence of perceived target size on click-point accuracy or movement time. In this sense, these results provide evidence in favour of a visually guided action system that operates separate from the influence of perception, at least in the context of the visuomotor transformation used in this study (i.e., transformation of the proximal digit movement to the distal cursor movement). The results of the current study are similar to those of a study conducted by Janczyk, Pfister, and Kunde (2013) in which participants' perceptual judgments were influenced by irrelevant stimulus dimensions during a Garner-interference speed classification task, while cursor movements directed toward these stimuli were unaffected. Thus, there appears to be increasing evidence that cursor movements are unaffected by perceptual intrusions, and compliment previous research that has failed to demonstrate an influence of perceived size on closed-loop visually guided actions such as pointing or tapping of a target (Alphonsa et al., 2016; Fischer, 2001).

As previously noted however, controlling an on-screen cursor as participants did in this study is a very different behaviour than the classic visually guided actions that have been used previously to study dissociations of perception and action, such as precision grasping or tapping. Performance of the task required participants to move their fingers on the trackpad, movements which would be defined in an egocentric reference frame and likely guided by the vision-for-action dorsal stream. However, an allocentric, scene-based reference frame would be necessary to accurately guide the onscreen cursor toward the target, suggesting participants' vision-for-perception ventral stream was potentially recruited to some degree to guide the visually guided movement. Further, the targets themselves did not have any physical object features for the action system to operate on, nor was the movement of the cursor itself a natural motor movement toward an object. However, it would be expected that as the perceptual nature of the task increases, so would the influence of the illusory context on participants' performance be expected to increase, which was not shown to be the case for the end-point measures in this study. Therefore, the lack of any apparent effect of the illusory context on participants' accuracy or movement time suggest that participants' cursor movements were not influenced by the perceptual aspects of the task, implying these movements were primarily under control of a functionally separate action system (Goodale & Milner, 1992; Milner & Goodale, 2006).

However, there are several methodological considerations that may have also contributed to the absence of an observed effect on the performance variables in this study. First, the task itself was relatively easy, simply requiring participants to move their cursors toward the target and click the center as quickly and as accurately as they could. Despite encouraging participants to perform the task faster in Experiment 2 and more accurately in Experiment 3, the task requirements did not effectively change in these experiments. Additionally, while the size of the target and the presence of the context circles varied between each trial, the target only ever appeared at one of two onscreen positions, on either the left or right side. This meant that regardless of the type of target presented, the center of the target was always located at the same leftward or rightward position. Therefore, the simple, repetitive nature of the task may have promoted a degree of dorsal stream dominance over control of the task. It is also possible that even if the perceived size of the target did in fact influence participants' performance of the task, this effect was masked by participants' overall high performance. Future versions of this experiment should involve equally distanced targets presented at a more varied range of onscreen positions, to ensure participants do not habitually move their cursor to the same locations on a trial-to-trial basis.

Second, participants performed the task in a closed-loop fashion and visual feedback of the target was always available, meaning participants had ample opportunity to refine and adjust their movements online to achieve a consistently high level of accuracy. Previous research successfully demonstrating an influence of the Ebbinghaus illusion on visually guided aiming movements has typically involved removal of visual feedback to some degree, either by removing vision of the hand (van Donkelaar, 1999), or the target (Alphonsa et al., 2016; Fischer, 2001). Both the perception-action and planning-control models predict that by removing visual feedback of the target, a greater emphasis will be placed on participants' sensorimotor memory of the target's position, therefore recruiting the perceptual system's involvement in the task, and increasing the likelihood of an illusory influence. According to the perception-action model, the action toward the target's remembered location will rely primarily on stored representations of the target within the perceptually dominated ventral stream and will therefore be more susceptible to the original illusory context of the target. Similarly, the planning-control model suggests that without visual feedback of the target facilitating the online corrections occurring during the action's 'control' phase, the movement will be primarily guided by the representation of the target's position constructed during the 'planning' phase, which is also susceptible to the illusory context prior to effector movement. Removing visual feedback of the target prior to, or at the onset of cursor movement is an intriguing option for future versions of this study.

Third, the perceptual comparison task used to confirm if the illusions effectively induced a change in perceived target size required a forced choice task between two target stimuli. Some have argued the division of attention required for this type of task may be more likely to produce an illusory effect, (Foster & Franz, 2014; Franz et al., 2000; Pavani et al., 1999) while the directed focus during an action toward a single target may reduce the influence of the illusion, making it appear as if the action was not influenced by the illusory context at all. In this study however, we were not especially interested in measuring the magnitude of the illusion, nor were we interested in comparing the effect of the illusion on perception with its effect on action, but instead included the perceptual comparison task as a manipulation check to ensure the illusory context was effective at all. Still, it is possible that the illusory stimuli used in this study were more effective during the perceptual comparison task than during the experimental trials, which could also explain the lack of any observed influence of the illusion when acting on the single target.

Finally, the online nature of this experiment meant that participation occurred remotely, using a wide range of device types, screen sizes and resolutions, and without experimenter supervision. While efforts were made to quantify the range of devices and screens used in each experiment, the presentation of the stimuli likely varied to some degree depending on the device's screen size and resolution. For example, the container in which the onscreen display was presented was set as relatively small (800 x 600 px) to accommodate the presentation of the experiment on a wide variety of screen sizes. The strength of the Ebbinghaus illusion has shown to increase as the size of the stimuli increase (Knol et al., 2015; Massaro & Anderson, 1971) and therefore the smaller display may have weakened the influence of the illusion. Each experiment was conducted using a within-subjects design in an attempt to control for the variety of stimuli presentations, however a future comparison study in which every participant completes the task using the same device and within the same testing environment would help reinforce the validity of these results.

Effect of Illusory Context on Cursor Trajectory

While the illusory context did not appear to influence participants' click-point accuracy or movement time as expected, the results demonstrated several interesting comparisons between the same-sized targets of interest that suggest the illusory context did influence participants' cursor movements toward the target. Participants generated more corrective movements toward the Perceived Large target in comparison to the Perceived Small target in Experiments 1 and 2. In Experiment 2, the Perceived Small target was the only target type to not produce an increase in the number of corrective movements when positioned on the right compared to the left side of the screen. While this left-right differentiation was observed in the trajectory curvature and number of corrective movements toward the Perceived Small target in Experiment 3, the increased emphasis on accuracy in this experiment did not influence the Perceived Small target as it did the other target types. Taken together, these results indicate participants' cursor paths were not influenced to the same degree by the on-screen position of the target or the demands of the task when clicking on the Perceived Small target in comparison to the other target types.

Whereas the perception-action model predicts participants' cursor paths will be unaffected by the illusory context, and therefore similar regardless of the type of target, a planning-control model (e.g., Glover, 2004; Glover & Dixon, 2002) might predict the number of corrections to vary as a result of the illusory context as was observed in this study. Specifically, if the illusory context decreased the perceived size of the target during the planning stage, the control stage of that movement may require less corrections than that of a movement that was planned toward a target perceived to be larger than its physical size. Further, if cursor movements toward the Perceived Small target benefited from a more accurate planning stage, these movements would likely be less influenced by the present task demands (i.e., target position or speed and accuracy of the movement), than less accurately planned movements.

Alternatively, as reasoned earlier (Experiment 1: Discussion), it is also possible that participants' cursor movements were not influenced by the effect of the illusion, but rather these differences were produced by the position of the context circles, and their varying proximities to the target circle. Previous research investigating the Ebbinghaus illusion's influence on grip aperture has suggested that participants may treat the pictorially presented context circles as obstacles or distractors when grasping a central disk or 'chip' and respond by generating wider or smaller grip apertures in response to small or large context circles respectively (Haffenden & Goodale, 2000; Haffenden et al., 2001), however there are those who argue against this as a reasonable hypothesis (Franz, Bülthoff, & Fahle, 2003; Franz & Gegenfurtner, 2008; Kopiske, Bruno, Hesse, Schenk, & Franz, 2016). It seems unlikely however that the context circles in the current experiment would elicit such obstacle avoidance mechanisms. Instead, the close proximity of the context circles surrounding the Perceived Large target may have provided participants with a larger 'general area' to direct initial cursor movements to, therefore requiring more corrective movements during later stages of the movement.

On-screen Target Position

The results of this experiment also provide valuable information regarding the nature of the target's onscreen position and its influence on participants' cursor movement, separate from any effect of illusory context. In general, participants cursor movements were slower, more curved, and consisted of a higher number of corrective movements when the target was presented on the right side of the screen than compared to when presented on the left. We propose this general effect is most likely a result of participants using their right hand to perform the task. These results suggest future investigations of trackpad-controlled cursor movement and human-computer interaction in general should consider the added mechanical constraints associated with a rightward compared to a leftward cursor movement.

Conclusion

The results of this study demonstrate that while the illusory context effectively influenced participants' perception of the target size, click-point accuracy and movement time were not influenced by the perceived size of the target. In this regard, the results provide evidence in favour of a perception-action model of visually processing (Goodale & Milner, 1992; Milner &

Goodale, 2006): participants' performance of the task was not influenced by perceptual influences such as the illusory context. However, several significant differences were observed when comparing the trajectory of the cursor movements toward the Perceived Small and Perceived Large target types. Compatible with a planning-control model (Glover, 2004; Glover & Dixon, 2002), these results suggest more corrective movements were required when the target was perceived to be larger than its physical size, while cursor movements toward a target perceived to be smaller than its physical size involved less corrections and were less likely to be affected by the particular demands of the task. As such, these results may be explained by both perception-and-action and planning-control models of visually guided action in the control of on-screen cursor movements.

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CHAPTER 5: GENERAL DISCUSSION

Despite the frequency with which vision is used to guide our everyday actions, there is still much to be learned about how the brain uses visual information to coordinate an accurate movement toward a stimulus. In this dissertation, the question of how the presentation of a 2-D stimulus influences one's visuomotor behaviour was explored in 3 studies, with the overarching goal of furthering our understanding of how the brain uses the visually available features of a 2-D stimulus during meaningful interaction. The conclusions drawn from these studies are discussed first within the perception-action framework proposed by Milner and Goodale (Goodale & Milner, 1992; Milner & Goodale, 2006), and then within the context of the behavioural gaze and grasp strategies used during task performance in general.

2-D Stimulus Interaction: The Role of Perception in Visually Guided Action

The dual stream hypothesis as proposed by Milner and Goodale describes a behavioural dissociation between a vision-for-perception ventral stream – projecting from the primary visual cortex (V1) to the inferotemporal cortex, and a vision-for-action dorsal stream – projecting from V1 to the posterior parietal cortex. Interactions between these two visual systems ensures context appropriate actions are executed successfully in each scenario, for example, grasping a hammer by the handle rather than its head. Visually guided actions toward 2-D stimuli provide an interesting context in which to study the nature of these perception-action interactions, as a virtual 2-D target does not provide the typical physical features that would normally be utilized by the dorsal stream during interaction. Rather, these properties may need to be inferred by the limited visual information provided, typically the shape of the stimulus.

It is possible that the grasping actions directed toward the 2-D stimuli used in Chapters 2 and 3 were guided exclusively by the dorsal stream without influence of the ventral stream, as is thought to be the case in simple grasping tasks toward 3-D objects. If this were the case, it would suggest the shape and position cues provided by the on-screen targets were sufficient for the execution of the grasp. Despite damage to their ventral stream and their resulting visual-form agnosia, patient D.F. has shown to be capable of scaling their grasp appropriately to 2-D images, suggesting their intact dorsal stream can use spatial information to properly scale their grasp in the absence of the volumetric information that would typically be provided by a 3-D object (Westwood, Danckert, Servos, & Goodale, 2002). However, as Westwood et al. (2002) made clear, D.F.'s ability to perform appropriately scaled grasps toward 2-D images does not necessarily prove the ventral stream is not involved in the performance of these behaviours in healthy control individuals, only that it may not be crucial.

Grasps executed exclusively under dorsal stream control would be expected to be tuned specifically to the spatial properties of the 2-D stimulus, and not influenced by any inferred volumetric properties. Interestingly, recent evidence has suggested that information about an object's weight and mass may not be processed within the ventral stream as previously believed but are in fact represented within fronto-parietal networks associated with manual interaction (Buckingham, Holler, Michelakakis, & Snow, 2018; Schwettmann, Tenenbaum, & Kanwisher, 2019). This could potentially explain some of the observed results in this study, for example why digit placement was consistently shifted toward the near side of peripherally located 2-D targets (Chapters 2 and 3), and toward the horizontal midline of 3-D objects at these locations (Chapter 3). As these 2-D stimuli did not have a true weight or distribution of mass, the dorsal stream would not consider these features when directing digit placement. When tasked with grasping the 3-D stimuli however, more detailed information regarding the 3-D objects' shape, surface contours, and COM was available to the dorsal stream, and therefore could be used to perform a more stable grasp with digit placement closer to the midline of the 3-D object. Thus, the difference in visual information made available to the dorsal stream by each stimulus type could potentially have caused the observed differences in grasp point selection when grasping these stimuli at non-central locations.

Regardless of whether the dorsal stream can perform these behaviours in isolation, there remains a consistent body of research suggesting grip scaling when grasping a 2-D stimulus is affected by perceptual influences not present when grasping physical 3-D stimuli (Holmes & Heath, 2013; Ozana & Ganel, 2017; Ozana, Namdar, & Ganel, 2020). When 'grasping' a 2-D version of a 3-D stimulus, the visual system may recruit the perceptually driven representational properties of that 3-D stimulus to supplement the impoverished visual information provided to the dorsal stream by the 2-D stimulus. After all, the ventral stream is often recruited to plan and guide context-appropriate movements executed by the dorsal stream toward 3-D objects. Therefore, it may be reasonable to predict that when required to grasp a stimulus that inherently lacks the physical properties affording an actual grasp to occur, the ventral stream is recruited to provide the ‘top-down’ information necessary to help the dorsal stream guide the grasping action.

The lateral occipital complex (LOC), a region within the ventral stream involved in the processing of visual shape and form information, as well as object perception in general (Grill-Spector, Kourtzi, & Kanwisher, 2001; Kanwisher, Chun, McDermott, & Ledden, 1996; Malach et al., 1995), is one potential source from which this representational information may be recruited and utilized to help facilitate the grasping action. While the exact mechanism through which communication between the ventral and dorsal stream is achieved is still unknown, certain pathways within the brain have been suggested as potential candidates for the exchange of this information. For example, research with non-human primates has identified neuroanatomical pathways connecting the anterior intraparietal sulcus (aIPS), a dorsal stream region critical for the planning and execution of visually guided grasping, to the inferotemporal cortex, an area believed to be a functional homologue of the LOC in humans (Borra et al., 2008). The vertical occipital fasciculus, a white matter tract running vertically between the dorsal and ventral visual cortex, has also been suggested as a potential pathway through which information regarding object properties in the ventral stream can be projected to dorsal stream processing areas responsible for planning and execution of the grasping action (Jitsuishi et al., 2020; Takemura et al., 2016).

The results of the experiment conducted in Chapter 3 failed to demonstrate any significant differences in the adjustments made to fixation position and digit placement when sliding 3-D and 2-D objects, despite the different mechanical demands required for each task (i.e., physically moving the 3-D object versus simply sliding the fingers across the screen in the 2-D condition). In Chapter 3, it was argued that the intention to manipulate the 2-D target may have recruited participants’ perceptual representation of the physical stimulus, which in turn resulted in adjusted gaze and grasp positions to account for non-existent physical object properties. The argument that the ventral stream is recruited to assign manipulatable properties to a virtual target could also explain why grip scaling adheres to Weber’s law even during active interaction with 2-D stimuli, as recently reported in a similar study by Ozana et al. (2020). Contribution of the ventral stream to the visually guided interaction with 2-D stimuli in this manner may explain why participants tend to demonstrate similar gaze and grasp behaviours, such as fixating toward the eventual point of index finger contact and placing their digits at positions that promote stability when grasping 2-D stimuli. Virtual 2-D stimuli do not necessarily require these types of behaviour when grasping, as they carry no risk of being mishandled. Nevertheless, these behaviours were observed in Chapters 2 and 3 of this dissertation, as well as previous investigations (Bulloch, Prime, & Marotta, 2015; Langridge & Marotta, 2017; Thulasiram, Langridge, Abbas, & Marotta, 2020). As previously discussed however, grasps directed toward non-central 2-D stimuli did demonstrate shifts in digit placement toward more 'convenient' positions biased toward the near side of the targets (Chapters 2 and 3), while 3-D objects located at these positions were grasped closer to their horizontal midline (Chapter 3). This may suggest the motivation to grasp the 2-D targets as if they embodied true 3-D physical properties became less crucial if the task requires a movement that is less comfortable for the individual, such as one where they reach to their left or right. However, the similar outward shift of index finger placement toward the horizontal midlines of 2-D targets and 3-D objects when participants were tasked with sliding these stimuli (Chapter 3), may suggest the intention to manipulate the targets evoked these perceptually represented object properties to some degree in response to the current task demands. In other words, the ventral stream may be recruited to ensure the targets are treated like 3-D objects when the context implies (e.g., when manipulation is involved), but will not override the preference of a comfortable grasp when simply grasping the 2-D stimuli, for which a more accurate grasp is not paramount. Thus, it's possible the degree to which participants' grasping action was guided by ventral stream may have varied as a function of participants' comfort and the nature of the task. Currently, these conclusions are speculative in nature however, and require future testing to directly explore the role of each visual stream during the grasping and manipulation of 2-D targets.

The studies reported in Chapters 2 and 3 focused on the visuomotor transformations required to reach out and grasp a stimulus, an adaptive behaviour that likely contributed to humankind's ability to interact within the immediate environment, thus serving as beneficial for our evolutionary success. The task outlined in Chapter 4 involved controlling an on-screen cursor using a computer trackpad which, despite being a relatively common action in our day-to-day life, is far removed from the type of action humans' visual system evolved to facilitate. The dual stream hypothesis predicts that as the complexities of the visuomotor transformations required to perform a task increase, so will the likelihood that top-down influences facilitated by the ventral stream will be involved when performing the task (Milner & Goodale, 2006). Therefore, actions performed within this context (i.e., the proximal movement of the digits on the trackpad to control the distal on-screen position of the target), may be more susceptible to perceptual influences, including size-contrast illusions such as the Ebbinghaus Illusion. However, the results of Chapter 4 failed to produce any differences in movement time or click-point accuracy resulting from the illusory context. This remained the case following manipulation of the task demands (i.e., prioritizing speed or accuracy) in attempts to make the task more cognitively taxing. These results could be interpreted within the perception-action framework as evidence that the task was being controlled exclusively by the dorsal stream, which remained unaffected by these scene-based, contextual influences. The relatively low level of difficulty and repetitive nature of the task, combined with participants' presumed familiarity with a laptop trackpad may have supported dorsal stream dominance over participants' cursor movements, despite the required transformation from an egocentric reference into a scene-based reference frame, which would typically involve the recruitment of the ventral stream and thus induce the illusory effect to some degree. Thus, while the results described in Chapters 2 and 3 may be interpreted as emphasizing a potential increased contribution from the ventral stream when grasping 2-D targets, the results described in Chapter 4 may conversely be interpreted as demonstrating a relinquishing of ventral stream control to the dorsal stream. However, as outlined in the Chapter 4 Discussion, there are several methodological considerations that also may have contributed to the apparent lack of perceptual influence observed in the study. It is therefore not entirely clear whether participants' actions were controlled exclusively via dorsal stream in response to the repetitive, easy nature of the task, or if the ventral stream's contribution to the task was masked by other factors, such as a 'ceiling effect' due to the relatively easy nature of the task, or presentation of the stimuli.

Interestingly, the illusory context did appear to influence participants' cursor trajectories toward the targets. Participants made more corrective movements when clicking targets perceived to be larger, despite no differences in movement time or accuracy when clicking these targets. These differences in cursor trajectory would not be predicted if the movement was being controlled exclusively by the dorsal stream, as the guidance of the cursor to the target should not have been influenced by its perceived size at any stage of the movement, but rather should be tuned to the target's veridical spatial characteristics, which remained constant. Therefore, it seems the results of this study do not fit neatly within a perception-action framework of visuomotor control. As discussed in Chapter 4, these results do however fit the predictions of the planning-control model (Glover, 2004; Glover & Dixon, 2002), which proposes an initial planning phase, susceptible to illusory influences, followed by a subsequent control phase, during which online corrections are made to correct for the inaccuracies induced by the illusory context during the planning and early stages of the movement. Unfortunately, while the results of this study contribute to the ongoing literature exploring the perceptual influence of visual illusions on visually guided actions, they do not provide any concrete conclusions in favour of either the perception-action or planning-control models.

Eye-hand Coordination during 2-D Stimulus Interaction

Visually Guided Grasping

When grasping an object, there are multiple factors that have the potential to determine where and how the digits are placed on the object at the time of contact. For example, a successful grasp may be characterized as one that places the digits at stable locations, while promoting visibility of the object, both of which are factors that will play a role in subsequent object manipulation. As the grasping action is typically guided by vision, the object features influencing grasp point selection will likely also influence how participants direct their gaze toward the to-be-grasped object.

When participants grasped virtual stationary targets aligned with their mid-sagittal axis (Chapters 2 and 3) their gaze and grasp behaviours resembled those observed when interacting with 3-D objects. This suggests there may be experimental contexts in which it is appropriate to use 2-D virtual targets as proxies for 3-D objects when studying certain aspects of eye-hand coordinated behaviour, at least in terms of the variables measured in these studies, particularly horizontal digit placement and fixation position. However, participants' gaze and grasp point selection were biased toward the near side of targets positioned to the left and right of center, a bias not shown when grasping 3-D objects located at these positions, suggesting there may be critical differences in the visuomotor behaviours directed toward peripherally positioned 2-D targets and 3-D objects.

As reasoned in Chapters 2 and 3, participants likely grasped the near side of the non-central targets because transporting the hand to these positions required less effort than grasping a more outward position, closer to the target's horizontal midline. These shifts in grasp point selection toward the near side of a 3-D object would generate an application of force to areas farther from the object's COM, thus potentially minimizing the overall stability of the grasp. A larger portion of the object may also be obstructed from view by the hand if grasped with the right hand and presented on the right side of the display. However, the potential risks that would normally present when grasping a 3-D object (e.g., mishandling or dropping the object), are not present when interacting with the 2-D target, and therefore are less likely to have influenced participants' grasp point selection during interaction. Instead, participants likely grasped the near side of the 2-D targets because these positions were closer to the reaching hand, and therefore more comfortable and required less energy (e.g., Elliott, Hansen, Mendoza, & Tremblay, 2004; Sparrow & Newell, 1998). In other words, the virtual nature of the 2-D target meant participants were not required to exert the unnecessary energy needed to grasp a more central, stable position closer to the target's horizontal midline. However, as described in Chapter 2, gaze and digit placement were consistently shifted rightward rather than leftward when grasping the notched targets, even when they were presented on the right side of the screen, and this suggests participants still prioritized visibility of the target to some degree, as is believed to be a motivating factor in digit placement when grasping 3-D objects as well (Maiello, Paulun, Klein, & Fleming, 2019), especially when a grasp region near the horizontal midline was not available.

Interestingly, participants appeared to use a different strategy when grasping targets in motion; rather than grasp the nearest side of the target, participants consistently directed their digits to locations behind the moving target's midline, even though this meant obstructing their view of rightward moving targets. This was the case regardless of whether the target was grasped at early, middle, or late stage of movement, thus contradicting the previous hypothesis that participants may try to 'catch' targets at late stages of movement by grasping their leading edge (Langridge & Marotta, 2017). It is possible that participants were again directing their grasps toward the nearest side of the moving targets, just as they did when grasping stationary targets, however their final contact points may have slipped behind the midline at the time the moving target was grasped. As reasoned in Chapter 2, an alternative explanation may be that participants preferred the trailing side of the target because it was a 'safer' location to grasp. Grasping the trailing side of a moving target avoids potential collision with the target's leading side and provides added opportunity for correction if necessary. In this sense, grasping the trailing side versus the leading side of the target may be like 'undershooting' versus 'overshooting' a target, of which the former is considered less costly (Elliott et al., 2004). Unfortunately, a comparison condition involving horizontally translating 3-D objects was not included in Chapter 2, and therefore it remains unknown whether these gaze and grasp behaviours would also be observed when grasping moving 3-D objects as well.

The locations participants fixated while visually pursuing and grasping the moving targets did suggest however that participants were in fact treating the targets as ‘graspable’. Fixations were directed toward the top edge of the targets when initiating the reach toward the targets, and these positions remained raised at the time of contact, as is typical of 3-D object grasping as well. These higher fixation positions suggest a switch in participants’ goal-directed attention from simply tracking the target’s movement to planning and guiding the grasping action, including guidance of the index finger toward the top edge of the target.

Despite participants seemingly treating the 2-D virtual targets as having physical graspable properties, the position of the stimuli (Chapter 2 and 3) and direction of movement (Chapter 2) emerged as strong predictors of how close to the target’s horizontal midline participants placed their digits, and whether these contact points matched those observed when grasping 3-D objects (Chapter 3). This was particularly evident when the targets were presented on the right side of the screen or moving rightward; grasps were generally less stable when grasping stationary 2-D targets presented on the right side (Chapter 3), and grasp stability continued to decrease the farther rightward a moving target had travelled at the time it was grasped (Chapter 2). Differences in digit placement resulting from the type of stimuli (2-D compared to 3-D) as well as the demands of the task (only grasping compared to sliding), were also more likely to be observed when grasping stimuli positioned on the right side of the display compared to in the center or on the left side of the display in Chapter 3. At first, the diminished performance when grasping rightward positioned/moving targets seems at odds with the well-established timing and accuracy advantages associated with hand movements within the ipsilateral hemispace. We attribute these differences to participants using their right hand to perform the task, and the mechanical constraints typically associated with grasping targets situated within or approaching the ipsilateral versus the contralateral hemispace. Participants were free to be more careless regarding their digit placement when grasping the virtual 2-D targets, and therefore may have been less likely to make the required kinematic adjustments (e.g., pronation of the forearm and postural adjustment of the wrist), when grasping leftward or rightward positioned virtual stimuli. As all participants performed the task using their right hand, this carelessness and prioritization of comfort over accuracy may have been more of an influencing factor when grasping stimuli presented on the right side. Participants were more likely to have made the necessary adjustments during their interaction with the 3-D stimuli, for which these adjustments were critical to the success of the grasp.

Visually Guided Cursor Control

Controlling an on-screen cursor using finger movements on a trackpad is a considerably different behaviour than a reach-to-grasp movement directed toward a target object. However, studying how vision is used to guide these types of movements can provide valuable information about how the brain is able to perform such skilled visuomotor transformations. Effectively controlling an on-screen cursor is a particularly relevant example of this type of transformation, as human-computer interaction is becoming an increasingly prevalent aspect of our daily lives.

For example, the results described in Chapter 4 demonstrated participants are faster and more accurate when clicking larger on-screen large targets compared to smaller targets, and click-point accuracy decreases as speed increases, confirming previous findings that trackpad-controlled cursor movements adhere to Fitts' Law (Sutter, Müsseler, & Bardos, 2011). Further, the current results provided consistent evidence indicating participants' curser trajectories are more curved and consist of more corrective movements when clicking on stimuli presented on the right side of the screen. Once again, we believe this to be due to participants' use of the digits on their right hand to perform the task, rather than the result of a hemispheric lateralization of visual perception. These results have implications not only for the design of future experiments measuring aspects of cursor control and on-screen target selection, for which the position and size of the on-screen stimuli should be considered, but also for the design of intuitive, easy to use on-screen environments, such as website layouts and software interfaces.

Limitations and Future Directions

Discussions regarding the limitations of each study have been included in the appropriate Chapter Discussions, however several general themes are worth summarizing. First, the square on-screen stimuli utilized in Chapters 2 and 3 were chosen to match the stimuli used in other investigations of 2-D grasping conducted by our lab (Bulloch et al., 2015; Langridge & Marotta, 2017; Thulasiram et al., 2020). While these stimuli are useful for measuring gaze and grasp behaviour toward simple, symmetrical 2-D stimuli, the results may not be generalizable to more complex shapes, and stimuli for which the inferred COM does not match the geometric center.

Future research using non-symmetrical stimuli will help clarify whether participants' grasp point selection is influenced by a 2-D stimuli's inferred COM, or its geometric center. Additionally, the use of on-screen images depicting familiar items associated with contextually relevant meanings may help differentiate the contribution from each visual stream during the type of grasping actions utilized in these studies. Advances in 3-D virtual reality technology also provide exciting opportunities to expand this line of research to incorporate the presentation of increasingly complex stimuli and experimental paradigms.

The study outlined in Chapter 4 involved data collection that occurred remotely, without experimenter supervision, and on a wide variety of devices, screen sizes, and screen resolutions. The experiments conducted in this study were designed as within-subjects designs in attempts to control for the differences in target presentation that likely occurred on a participant-to-participant, device-to-device basis. Despite these efforts, it is possible that the differences in stimulus presentation had an influence on the study results, and therefore the conclusions drawn from this data should be interpreted with caution. A follow-up study, in which all participants complete the task using the same device and under experimenter supervision would serve to improve experimental control and allow more concrete conclusions to be drawn from the observed results.

Significance

Manual interaction with virtual 2-D stimuli is an increasingly prevalent and necessary aspect of our daily lives. As each new advance in touchscreen technology continues to be adapted for personal application and consumer use, our ability to meaningfully interact with virtual 2-D stimuli is now as practical an aspect of our day-to-day operating as grasping a tool was to our ancestors. Knowledge of how our visual system processes and directs coordinated actions toward virtual stimuli has numerous beneficial applications in various contexts. For example, learning how we use vision to guide grasping movements toward stationary and moving stimuli (Chapter 2) is relevant for the development of interactive rehabilitation tools, designed to help individuals who suffer from impaired upper limb movement (e.g., following a stroke), regain these coordinated interceptive abilities. This line of research can also be incorporated into athletic training programs focused on improving eye-hand coordination and the interception of moving stimuli. Identifying the different eye-hand coordination strategies used when grasping 2-D stimuli versus 3-D objects will help determine in which contexts 2-D targets may be used in replacement of physical stimuli if desirable (Chapter 3). Finally, understanding how the visual system can perform the visuomotor transformations required to control an on-screen cursor using a device's trackpad will help promote the development of more intuitive, user-friendly graphical input devices (Chapter 4). Considering that our lifestyles are becoming increasingly dominated by human-computer interactions, it could be argued that applying a neuropsychological approach to the study of these interactions is an intuitive 'next step' in the field of perception and action research. In general, the research studies described in this dissertation contribute to the fundamental question of how the human visual system functions to processes complex visual information for the purposes of coordinating visually guided action.

Conclusion

This dissertation reports observations both novel and corroborative in nature regarding participants' visually guided interaction with 2-D stimuli and proposes several interpretations of the results regarding the interactive nature of the human visual system. Participants' fixation position and digit placement when grasping centrally located 2-D targets match those observed when grasping 3-D object (Chapter 3). However, participants appear to select convenient, nearby contact points that minimize energy expenditure when grasping non-central targets (Chapter 2 and 3), perhaps indicating the dorsal stream's control of the task in the absence of the stimulus' volumetric properties. Participants selected contact points behind the midline of moving targets (Chapter 2), possibly because the trailing side of the target carried less of a risk if the target was missed at the time of the grasp. Similar adjustments in digit placement made in response to the manipulative nature of the task when grasping both 2-D and 3-D stimuli (Chapter 3) may be suggestive of input from the ventral stream, and the embodiment of physical 3-D properties when the context implies manipulation of the 2-D target. Finally, the trajectories of participants' visually guided cursor movements were influenced by the Ebbinghaus Illusion during a task involving the transformation of proximal finger movements into distal on-screen cursor movements (Chapter 4). End-point measures such as click-point accuracy and movement time were unaffected by the illusion however, suggesting these results are perhaps better interpreted within a planning-control framework (Glover, 2004; Glover & Dixon, 2002). In conclusion, the use of virtual 2-D stimuli to measure eye-hand coordination makes it possible to measure gaze and grasp behaviours during interaction with increasingly complex stimuli while maintaining a high degree of experimental control. The current results suggest that several similar visuomotor behaviours observed during interaction with 3-D objects are reproduced when grasping 2-D virtual stimuli, however aspects such as the stimulus' position and action end-goal will influence the degree of this similarity. Research exploring visually guided action toward 2-D stimuli further provides the opportunity to investigate how humans' visual system – having evolved to facilitate interaction within the physical environment – processes and executes goal-directed actions toward stimuli lacking the physical or manipulatable features typical of 3-D objects.

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Appendix A:

Study 1 and 2 Demographics Form

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 B:

Study 1 and Study 2 (Virtual Stimulus Condition) Consent Form

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Eye-hand Coordination: 2-D Objects.

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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 computer-generated target 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. By participating in this study, you will be providing valuable data regarding how eye- and hand-movements are related during eye-hand coordination. This information is important for understanding the visuomotor strategies being utilized when grasping an object.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will receive 3 experimental credits for your participation in this study.

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.

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) by email: humanethics@umanitoba or by telephone: 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 (anticipated completion date: April 2019), please complete your mailing (or email) address below:

Mailing/Email Address: ____

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Appendix C:

Study 2 (Physical Stimulus Condition) Consent Form

UNIVERSITY OF MANITOBA | Department of Psychology

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

Eye-hand coordination: 3-D Objects.

PRINICIPAL INVESTIGATORS: Ryan Langridge, PhD Student, Psychology

University of Manitoba

Dr. Jonathan Marotta, 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 3-D object presented in front of you. 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. By participating in this study, you will be providing valuable data regarding how eye- and hand-movements are related during eye-hand coordination. This information is important for understanding the visuomotor strategies being utilized when grasping an object.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will receive 3 experimental credits for your participation in this study.

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, 2024). 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) by email: humanethics@umanitoba or by telephone: 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 D:

Study 2: ANOVA Summary Tables

Table D1.

Horizontal Index Finger Placement

Source	*SS*	*df*	*MS*	*F*	*Sig*	η_p^2
Position	10.668	1.722*	6.196	19.855	< .001	.332
Position x Stimuli Type	8.306	1.722*	4.825	15.460	< .001	.279
Error (Position)	21.491	68.865*	0.312			
Task	0.001	1	0.001	0.004	.952	< .001
Task x Stimuli Type	0.012	1	0.012	0.043	.837	.001
Error (Task)	11.545	40	0.289			
Position x Task	3.176	2	1.588	10.024	< .001	.200
Position x Task x Stimuli Type	0.174	2	0.087	0.551	.579	.014
Error (Position x Task)	12.675	80	0.158			
Intercept	0.163	1	0.163	0.178	.676	.004
Stimuli Type	0.495	1	0.495	0.538	.467	.013
Error	36.760	40	0.919			

*Greenhouse-Geisser corrected *df*

Table D2.

Horizontal Fixation Position

Source	*SS*	*df*	*MS*	*F*	*Sig*	η_p^2
Position	19.067	2	9.533	18.356	< .001	.315
Position x Stimuli Type	13.188	2	6.594	12.696	< .001	.241
Error (Position)	41.550	80	0.519			
Task	0.649	1	0.649	2.537	.119	.060
Task x Stimuli Type	0.659	1	0.659	2.576	.116	.061
Error (Task)	10.233	40	0.256			
Position x Task	0.813	1.652*	0.492	2.272	.120	.054
Position x Task x Stimuli Type	0.548	1.652*	0.331	1.531	.225	.037
Error (Position x Task)	14.311	66.097*	0.217			
Intercept	6.466	1	6.466	6.592	.014	.141
Stimuli Type	2.367	1	2.367	2.414	.128	.057
Error	39.231	40	0.981			

*Greenhouse-Geisser corrected *df*

Table D3.

Vertical Fixation Position

Source	*SS*	*df*	*MS*	*F*	*Sig*	η_p^2
Position	0.941	2	0.471	1.152	.321	.028
Position x Stimuli Type	0.621	2	0.311	0.760	.471	.019
Error (Position)	32.698	80	0.409			
Task	4.366	1	4.366	10.072	.003	.201
Task x Stimuli Type	0.078	1	0.078	0.180	.674	.004
Error (Task)	17.340	40	0.433			
Position x Task	0.018	2	0.009	0.086	.918	.002
Position x Task x Stimuli Type	0.162	2	0.081	0.799	.453	.020
Error (Position x Task)	8.127	80	0.102			
Intercept	174.075	1	174.075	29.788	<.001	.427
Stimuli Type	2.126	1	2.126	0.364	.550	.009
Error	233.751	40	5.844			

Table D4.

Absolute Distance Between Grasp Axis and Stimulus Center

Source	*SS*	*df*	*MS*	*F*	*Sig*	η_p^2
Position	2.282	1.720*	1.327	7.392	.002	.156
Position x Stimuli Type	1.632	1.720*	0.949	5.285	.010	.117
Error (Position)	12.351	68.781*	0.180			
Task	0.130	1	0.130	1.321	.257	.032
Task x Stimuli Type	0.077	1	0.077	0.784	.381	.019
Error (Task)	3.936	40	0.098			
Position x Task	0.303	2	0.151	2.314	.105	.055
Position x Task x Stimuli Type	0.435	2	0.218	3.327	.041	.077
Error (Position x Task)	5.231	80	0.065			
Intercept	110.375	1	110.375	561.415	<.001	.933
Stimuli Type	1.136	1	1.136	5.778	.021	.126
Error	7.864	40	0.197			

*Greenhouse-Geisser corrected *df*

Table D5.

Horizontal Distance Between Index Finger and Thumb

Source	*SS*	*df*	*MS*	*F*	*Sig*	η_p^2
Position	2.739	1.398*	1.959	7.365	.004	.155
Position x Stimuli Type	0.945	1.398*	0.676	2.542	.105	.060
Error (Position)	14.876	55.932*	0.266			
Task	0.033	1	0.033	0.640	.428	.016
Task x Stimuli Type	0.046	1	0.046	0.892	.351	.022
Error (Task)	2.056	40	0.051			
Position x Task	0.025	1.732*	0.014	0.404	.640	.010
Position x Task x Stimuli Type	0.329	1.732*	0.190	5.310	.010	.117
Error (Position x Task)	2.476	69.294*	0.036			
Intercept	76.632	1	76.632	459.217	<.001	.920
Stimuli Type	0.177	1	0.177	1.062	.309	.026
Error	6.675	40	0.167			

*Greenhouse-Geisser corrected *df*

Appendix E:

Study 3 Demographics Form

The following information is used to assist us in conducting our study. Please note that there is no personally identifiable information kept, and you will only be referred to by an arbitrary participant number. All information will be kept confidential, and your files will only be accessible by the investigators. You may refrain from answering any questions you choose.

Instructions

Please read each question very carefully and fill out the following information to the best of your knowledge (leave blank if you don't know the answer):

Please record the make/model and (diagonal) screen size of the device you are using to complete the experiment (e.g., macbook pro; 13.3 in):

How are you controlling the cursor on your device? (Reminder: Please only complete this experiment using a touchpad or trackpad of a laptop computer. If you are using a device that does not have a touchpad or trackpad, please exit the experiment now and contact the experimenter).

☐ Using your finger on a touch/track pad

What is your age (years)?

Vision:

○ I have normal vision

- I have corrected-to-normal vision (e.g., Wearing glasses, contact lenses, corrective eye-surgery etc.)

What is the sex you were assigned at birth?

- Male
- Female
- Prefer not to answer

Which hand do you use to do the following?

Throw a ball:

- Left
- Right

Brush your teeth:

- Left
- Right

Eat soup with a spoon:

- Left
- Right

Comb your hair:

○ Left

○ Right

Cut bread with a knife:

○ Left

○ Right

Swing a tennis/badminton racquet or bat:

○ Left

○ Right

Hammer a nail:

○ Left

○ Right

Point to something accurately:

○ Left

○ Right

Write your name:

○ Left

○ Right

Control the cursor when using a computer:

○ Left

○ Right

Do you play any eye-hand coordination sports?

○ Yes

○ No

If yes, which sports do you play?

[ ]

Appendix F:

Study 3 Consent Form

University of Manitoba

Principal Investigators:

Ryan Langridge (PhD Candidate, Psychology, University of Manitoba, langrirw@myumanitoba.ca)

Tiffany Carther-Krone (PhD Candidate, Psychology, University of Manitoba, lazart@myumanitoba.ca)

Dr. Jonathan Marotta (Professor, Psychology, University of Manitoba, Jonathan.Marotta@umanitoba.ca)

Purpose:

We are interested in how your perception of a circle affects your performance when clicking on it.

Description:

This study will last approximately 30 minutes. During the experiment you will be asked to click on circular targets as quickly and as accurately as possible. Prior to this task, you will be asked to fill out a brief questionnaire involving questions about your age, sex, handedness, vision, and the device you are currently using to complete the experiment.

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. By participating in this study you will be providing valuable data regarding how the way we perceive our visual environment affects the way we interact with it.

Costs and Payments:

There are no fees or charges to participate in this study. You will receive 1 experimental credit for your participation in this study.

Confidentiality

Your information will be kept confidential. You will be referred to by a code number. After completing the experiment, all identifying information will be saved separately from your experimental data, and will only be used to assign you participation credit. Your files will only be accessible by the investigators. Results from this study will be disseminated through conference presentations and refereed publications. Participant confidentiality will not be jeopardized.

Voluntary Consent

By selecting the 'I Consent' option below, you are indicating 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 form their legal and professional responsibilities. You are free to withdraw from the study at any time by exiting your browser (participation is completely voluntary), and/or refrain from answering any questions you prefer to omit, without prejudice or consequence. You will also still receive your participation credit if you encounter any technical difficulties, and cannot continue. This means that should you choose to withdraw at any point from the study, you will still receive 1 participation credit.

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 Research Ethics Board (REB 1) 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 (204) 474-7122 (Email: humanethics@umanitoba.ca).

Do you understand and consent to these terms?

○ I Consent

○ I Do Not Consent

If you would like to receive a general summary of the results from this study when it is completed, please provide your email address below:

Thank you for your participation!

Appendix G:

Device Summaries

Experiment 1

Table G1

Browser Identification and Operating System

Operating System	Browser	Number of Participants
Windows 10	Chrome 86	1
	Chrome 87	8
	Chrome 88	6
	Chrome 89	4
	Chrome 90	1
	Chrome 91	1
	Edge 87	3
	Edge 88	2
	Edge 89	2
	Edge 91	1
macOS (Mojave)	Chrome 77	1
	Chrome 80	1
	Chrome 87	1
	Chrome 88	1
	Chrome 91	1
	Safari 14	1
macOS(Catalina)	Chrome 85	1
	Chrome 87	3
	Chrome 88	1

	Chrome 89	1
	Safari 14	2
	Firefox 81	1
macOS(Big Sur)	Chrome 87	3
	Chrome 88	2
macOS (High Sierra)	Safari 13.1	1

Note. Browser and operating system information collected by lab.js.

Table G2

Screen Resolution (Physical Pixels) and Device Pixel Ratio (DPR).

Screen Resolution	Device Pixel Ratio (DPR)	Number of Participants
1280 x 720	1.5	6
1280 x 800	2	1
1366 x 768	1	9
1368 x 912	2	1
1440 x 900	1	5
	2	16
1500 x 1000	2	1
1504 x 1003	1.5	2
1536 x 864	1.25	8
1680 x 1050	1	1

Note. Screen resolution and DPR information collected by lab.js.

Table G3

Screen Size

Screen Size (inches)	Number of Participants
11	1
12	3
13	22
14	4
15	12
20	1
No Response	7

Note. Device screen size self-reported by participants.

Experiment 2

Table G4

Browser Identification and Operating System

Operating System	Browser	Number of Participants
Windows 8.1	Chrome 91	1
Windows 10	Chrome 87	8
	Chrome 88	2
	Chrome 91	3
	Edge 87	2
macOS (Mojave)	Chrome 87	5
	Chrome 88	1
	Safari 14	1
macOS (Catalina)	Chrome 85	1
	Chrome 87	7
	Safari 13	2
	Safari 14	3
macOS (Big Sur)	Chrome 87	4
	Chrome 88	3
macOS (High Sierra)	Chrome 87	1
	Chrome 88	2
	Safari 13	1
macOS (Yosemite)	Chrome 87	2
Chrome OS 13421	Chrome 86	1

Note. Browser and operating system information collected by lab.js.

Table G5

Screen Resolution (Physical Pixels) and Device Pixel Ratio (DPR).

Screen Resolution	Device Pixel Ratio (DPR)	Number of Participants
1280 x 720	1.5	2
1280 x 800	1	1
	2	3
1366 x 768	1	12
1368 x 912	2	1
1440 x 900	1	13
	2	14
1536 x 864	1.25	1
1600 x 900	1	1
1792 x 1120	2	2

Note. Screen resolution and DPR information collected by lab.js.

Table G6

Screen Size

Screen Size (inches)	Number of Participants
11	3
12	1
13	27
14	4
15	4
16	4
No Response	7

Note. Device screen size self-reported by participants.

Experiment 3

Table G7

Browser Identification and Operating System

Operating System	Browser	Number of Participants
Windows 10	Chrome 87	11
	Chrome 88	4
	Edge 87	1
	Edge 88	5
	Edge 91	1
macOS (Catalina)	Chrome 85	1
	Chrome 87	6
	Chrome 88	3
	Chrome 91	1
macOS (Big Sur)	Chrome 87	7
	Chrome 88	3
Mac OS X (El Capitan)	Chrome 87	1
	Safari 11	1
macOS (High Sierra)	Chrome 87	1
	Chrome 88	1
	Chrome 89	1
	Safari 13	2

Note. Browser and operating system information collected by lab.js.

Table G8

Screen Resolution (Physical Pixels) and Device Pixel Ratio (DPR).

Screen Resolution	Device Pixel Ratio (DPR)	Number of Participants
1280 x 720	1.5	5
1280 x 800	1	2
	2	2
1366 x 768	1	9
1440 x 900	1	8
	2	14
1504 x 1003	1.5	1
1536 x 864	1.25	6
1792 x 1120	2	1
1920 x 1080	1	1
1920 x 1200	2	1

Note. Screen resolution and DPR information collected by lab.js.

Table G9

Screen Size

Screen Size (inches)	Number of Participants
12	2
13	21
14	6
15	11
16	2
No Response	8

Note. Device screen size self-reported by participants.

Appendix H:

Perceptual Comparison Scores

Table H1

Experiment 1 Perceptual Comparison Scores

Onscreen Position		Right					
		Control Small	Perceived Small	Control	Perceived Large (Far)	Perceived Large	Control Large
Left	Control Small	-	20%*		90%	100%	
	Perceived Small	22%*	-	**92%**	**92%**	**94%**	96%
	Control		**88%**	**-**	**44%**	**76%**	
	Perceived Large (Far)	94%	**94%**	**32%**	**-**	**82%**	98%
	Perceived Large	100%	**96%**	**76%**	**84%**	-	0%*
	Control Large		98%		94%	24%*	-

Note. Scores represent the percent of comparisons that demonstrated the expected size ordering (Smallest to Largest): Control (Small) < Perceived Small < Control < Perceived Large (Far) < Perceived Large < Control Large. **Bolded scores represent the comparisons between the same-sized targets.** *Scores represent the percent of comparisons in which participants reported the Perceived Small target as smaller than the Control Small target, or the Perceived Large target as larger than the Control Large target (i.e., exaggerated illusory effect).

Table H2

Experiment 2 Perceptual Comparison Scores

Onscreen Position		Right					
		Control Small	Perceived Small	Control	Perceived Large (Far)	Perceived Large	Control Large
Left	Control Small	-	16%*		96%	96%	
	Perceived Small	28%*	-	**84%**	**82%**	**94%**	98%
	Control		**92%**	**-**	**44%**	**78%**	
	Perceived Large (Far)	98%	**96%**	**44%**	**-**	**76%**	90%
	Perceived Large	98%	**96%**	**88%**	**80%**	-	18%*
	Control Large		100%		96%	18%*	-

Note. Scores represent the percent of comparisons that demonstrated the expected size ordering (Smallest to Largest): Control (Small) < Perceived Small < Control < Perceived Large (Far) < Perceived Large < Control Large. **Bolded scores represent the comparisons between the same-sized targets.** *Scores represent the percent of comparisons in which participants reported the Perceived Small target as smaller than the Control Small target, or the Perceived Large target as larger than the Control Large target (i.e., exaggerated illusory effect).

Table H3

Experiment 3 Perceptual Comparison Scores

Onscreen Position		Right					
		Control Small	Perceived Small	Control	Perceived Large (Far)	Perceived Large	Control Large
Left	Control Small	-	20%*		100%	100%	
	Perceived Small	24%*	-	**88%**	**86%**	**98%**	96%
	Control		**84%**	**-**	**46%**	**82%**	
	Perceived Large (Far)	98%	**94%**	**58%**	**-**	**80%**	92%
	Perceived Large	100%	**92%**	**76%**	**76%**	-	14%*
	Control Large		94%		94%	16%*	-

Note. Scores represent the percent of comparisons that demonstrated the expected size ordering (Smallest to Largest): Control (Small) < Perceived Small < Control < Perceived Large (Far) < Perceived Large < Control Large. **Bolded scores represent the comparisons between the same-sized targets.** *Scores represent the percent of comparisons in which participants reported the Perceived Small target as smaller than the Control Small target, or the Perceived Large target as larger than the Control Large target (i.e., exaggerated illusory effect).