# EYE-HAND COORDINATION: MEMORY-GUIDED GRASPING IN A CLUTTERED ENVIRONMENT

By

Hana H. Abbas

A Thesis submitted to the faculty of Graduate Studies of

The University of Manitoba

In partial fulfillment of the requirements of the degree of

Master of Arts

Department of Psychology

University of Manitoba

Winnipeg

## Abstract

We often reach for remembered objects, such as when picking up a coffee cup from behind our laptop. In cases like this, we rely on visuospatial memory, encoded by the perceptual mechanisms of the ventral visual stream, to guide our actions, rather than on the real-time control of action by the dorsal visual stream (Milner & Goodale, 1995). Further, our motor plans must often accommodate for the messy spaces within which we act, avoiding irrelevant objects in our way. Little research has examined obstacle avoidance during memory-guided grasping, though it is likely obstacles perceived by the ventral stream as more salient will produce exacerbated avoidance maneuvers. This study examined how the availability of visual feedback altered eye-hand coordination in an obstacle avoidance paradigm. Eye and hand movements were monitored as subjects had to reach through a pair of obstacles in order to grasp a 3-D target object, under full visual feedback (visually-guided), immediately in the absence of visual feedback (memory-guided no-delay), or after a 2-s delay in the absence of visual feedback (memory-guided delay). Positions and widths of obstacles were manipulated, though their inner edges remained a constant distance apart. We expected the memory-guided delay group to exhibit exaggerated avoidance strategies due to a reliance on the perceptual mechanisms of the ventral steam. Results revealed successful obstacle avoidance and grasps of the target object in all groups, however different avoidance strategies emerged depending on the availability of visual feedback. The visually-guided and memory-guided no-delay groups used real-time visual information to alter the paths of the index finger and wrist and adjust final index finger positions on the target object, to account for positioned obstacles. Still, the no-delay group showed wider index finger paths and a failure to adjust final fixations, resulting from the inability to use visual information for the online control of action. Unexpectedly, the memory-guided delay group employed a rather moderate strategy for avoiding obstacles, in that positioned obstacles less often prompted alterations in the mechanics of the reach. In conclusion, obstacle avoidance when reaching to remembered objects adopts a more moderate, rather than exaggerative, strategy.

## Acknowledgements

I owe the completion of this work to my advisor, Dr. Jonathan Marotta, who took a chance on me and who guided me towards my fullest potential. I hope to take everything I learned in his *Perception and Action Lab* with me through my future studies. I am grateful for my advisory committee members, Dr. Tammy Ivanco and Dr. Tony Szturm, for their valuable contributions to this project. The biggest thanks go out to my peers and lab mates, particularly Ryan Langridge and Tiffany Carther-Krone, who were always keen to lend a helping hand (and eye) and without whom I would surely have been lost. Finally, much appreciation for the funds I received from the University of Manitoba's Psychology Graduate Fellowship and from the Natural Sciences and Engineering Council of Canada (NSERC).

Table of Contents

List of Figures

## Introduction

A large part of how we interact with their environment relies upon their ability to reach for and grasp objects. Reaching and grasping actions can be performed quickly and easily, without conscious planning. As such, we generally do not realize how frequently we perform goal-directed actions in our daily lives, like reaching for our coffee cups, cell phones, wallets, pencils, and the variety of other items and gadgets that make our work day go by smoothly. As basic as these actions seem, their execution relies on a sophisticated interplay between multiple information processing systems, including the visual and motor systems.

Consider the process of reaching out to grasp a cell phone from a table top. Prior to any movement occurring, the visual system receives information about the environment from the retina, which, aided by our expectations and stored representations about the nature of visual stimuli, allows for the recognition of the cell phone as *our* cell phone and not someone else's cell phone, or some other object entirely. At the same time, information about the cell phone's shape, position, and orientation in space, computed in an egocentric frame of reference (i.e. in relation to the self), is essential in planning an effective grasp in coordination with the human motor system (i.e. Graziano & Gross, 1994; Soechting & Flanders, 1992). It would be quite ineffective to approach an object without taking its shape into account, for example, in which case we may inappropriately size the aperture of our hand in order to grasp it (Verheij, Brenner, & Smeets, 2014). Additional information about the cell phone's position relative to other objects in the environment (allocentric frame of reference) contributes to how we might perceive and act upon objects in our surroundings (i.e. Fiehler, Wolf, Klinghammer, & Blohm, 2014; Neely, Binsted, & Heath, 2008). A wide range of visual information may be taken into account for planning to carry out the simple act of reaching to grasp a cell phone.

In order to form an effective movement plan for picking up the cell phone, relevant visual information must be communicated, likely via the posterior parietal cortex (PPC), to the motor, premotor, and prefrontal cortices (Buneo, Jarvis, Batista, & Andersen, 2002; Milner & Goodale, 1995; Wise, Boussaoud, Johnson, & Caminiti, 1997). Generally, planning and executing a reaching movement relies on feedforward and feedback control processes, integrating visual and proprioceptive information. During the initial ballistic phase of a reach, feedforward mechanisms may play more of a role in transforming the extrinsic motor plan (i.e. the planned trajectory of the reach, guided by vision) into an intrinsic motor plan (i.e. the specific muscle activation pattern, guided by proprioception; Medina, Jax, & Coslett, 2009). The terminal stage of the reach may rely more upon sensory feedback (Medina et al., 2009), for instance, about the hand's positioning on the object, in order to make improvements about the way that we continue to manipulate the cell phone in space and for the next time we wish to grasp our cell phone. Feedforward and feedback processes are also needed for the online control of actions, where structures such as the cerebellum and basal ganglia play a significant role in the control of visually-guided (i.e. with full visual feedback; Ebner & Fu, 1997; Doya, 2000; Glickstein, Cohen, Dixon, Gibson, Hollins, Labossiere, & Robinson, 1980; Stein & Glickstein, 1992) and memory-guided movements (i.e. without visual feedback; Doya, 2000; Ketcham, Hodgson, Kennard, & Stelmach, 2003), respectively. This brief description emphasizes the coordination required by the visual and motor systems in order to execute a seemingly effortless action as picking up a cell phone from a tabletop.

## Two Visual Streams

In the above example describing the process of reaching to grasp a cell phone, it can be seen how the visual system processes information for both understanding the visual environment and for successfully acting upon it. The *dual stream hypothesis* (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982) describes the visual system as divided into two functionally and anatomically distinct streams for processing visual information received at the primary visual cortex (V1) from the retina. The *ventral stream*, which propagates from V1 through to the inferotemporal cortex, serves to construct visual representations of the world for the recognition of objects. This stream operates in relative metrics, conveniently allowing for the recognition of an object as a cell phone, for example, regardless of its orientation in space or the luminance of the room. The *ventral stream*, interfacing with temporal and frontal memory structures (Baizer, Desimone, & Ungerleider, 1993), holds information in object working memory (Ungerleider, Courtney, & Haxby, 1998) to ultimately form long-term representational memories about what we know to be true of our visual world (vision for perception). The *dorsal stream*, on the other hand, which propagates from V1 towards the posterior parietal cortex, relies on absolute metrics of the visual scene to act upon objects in the immediate environment (vision for action). The *real-time view of action* assumes the visual representations produced by the dorsal stream are computed in real-time, immediately before an action, and are not stored, unlike the representations of the ventral stream, which can be stored and accessed over long periods of time (Milner & Goodale, 1995). According to this view, reaches to previously seen, now out-of-view, objects would not benefit from the dorsal stream’s real-time computations, and would consequently be less precise.

Despite the contrasting behavioural outputs of these two streams, there is undoubtedly a transfer of information between them (Cloutman, 2013; Farivar, 2009; Goodale & Milner, 1992; van Polanen & Davare, 2015), meaning that our perceptual representations of a given scene can certainly influence grasping behaviour (i.e. Chua, Bub, Masson, & Gauthier, 2018). Even in the simple act of reaching to grasp a cell phone, there is undoubtedly opportunity for cross-talk between perceptual representations and action strategies, though the load placed on either of the two streams varies depending on context and task demands (Carrozzo, Stratta, McIntyre, & Lacquaniti, 2002; de Grave, Brenner, & Smeets, 2004; Obhi & Goodale, 2005). Exploring the point at which our perceptual representations of a given scene influence the execution of a goal-directed action will provide insight into the interactions of perception and action.

## Visually-Guided Action

When reaching to grasp objects in the environment, vision is important for the efficient planning, execution, and online control of the movement. Movement trajectories and the ultimate contact points of the digits are planned in advance of the movement (Hesse, de Grave, Franz, Brenner, & Smeets, 2008; Rosenbaum, Vaughan, Meulenbroek, & Jansen, 2001; Voudouris, Brenner, Schot, & Smeets, 2010), utilizing visual (Hayhoe, 2000; Johansson, Westling, Bäckström, & Flanagan, 2001; Land, Mennie, & Rusted, 1999; Sarlegna & Sainburg, 2009) and proprioceptive information (Sarlegna & Sainburg, 2009) most relevant to the task at hand. A result of the effective planning of goal-directed actions is the close coupling of eye and hand movements, whereby eye movements are typically directed towards a target object before the hand. This relationship has been shown in a number of studies involving pointing (Abrams, Meyer, & Kornblum, 1990; Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Binsted, Chua, Helsen, & Elliott, 2001; Neggers & Bekkering, 2000) and grasping or object manipulation (Hayhoe & Ballard, 2005; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Johansson et al., 2001; Land & Hayhoe, 2001; Land et al., 1999). When looking at a stationary object, observers tend to fixate on the object's centre of mass (COM; Brouwer, Franz, & Gegenfurtner, 2009; Desanghere & Marotta, 2011; Mcgowan, Kowler, Sharma, & Chubb, 1998; Melcher & Kowler, 1999;

Vishwanath & Kowler, 2003; 2004; Vishwanath, Kowler, & Feldman, 2000). When planning to grasp the same object, gaze tends to be directed towards key contact points where the digits are likely to be placed (Brouwer, Franz, & Gegenfurtner, 2009; de Grave, Hesse, Brouwer, & Franz, 2008; Desanghere & Marotta, 2011; Flanagan & Johansson, 2003; Johansson et al., 2001). Specifically, gaze tends to favour the eventual contact point of the index finger (Bulloch, Prime, & Marotta, 2015; Desanghere & Marotta, 2011, 2015; Prime & Marotta, 2013; Voudouris, Smeets, & Brenner, 2016). The importance placed on the index finger's eventual location may be related to this digit's more variable movement trajectory compared to the other digits, facilitating increased precision in grasping (Brouwer et al., 2009; Galea, Castiello, & Dalwood, 2001; Land, 2009; Volcic & Domini, 2014). Grasp and gaze display these expected patterns of behaviour when visual information about the scene is continuously available. These patterns may surely be altered and the relationship between grasp and gaze weakened in the absence of visual feedback.

Actions performed with full visual feedback are more accurate than movements without vision (Carlton, 1981; Desmurget, Pélisson, Rossetti, & Prablanc, 1998; Heath & Binsted, 2007; Land, Mennie, & Rusted, 1999; Milner & Goodale, 1995; Saunders & Knill, 2004). Still, reach and grasp performance may be successful without the availability of continuous visual information about the hand, the target object, or the task environment, likely due to a reliance on other sensory information, like proprioceptive cues, for control of the action (Bagesteiro, Sarlegna, & Sainburg, 2006; Rossetti, Desmurget, & Prablanc, 1995). For instance, successful grasps may occur when reaching to remembered objects (i.e. objects viewed prior to but not during the reach), whereby the hand is appropriately moulded to accommodate differently shaped objects (Santello, Flanders, & Soechting, 2002; Winges, Weber, & Santello, 2003). Further, reaches made without vision of the arm are more accurate when visual information is available about the hand's starting position (Desmurget, Rossetti, Jordan, Meckler, & Prablanc, 1997) or about the target object's position (Prablanc, Pelisson, & Goodale, 1986). Although vision is important for effectively planning and carrying out goal-directed movements, successful reach and grasp behaviour may nonetheless occur in its absence.

Still, without continuous visual feedback, alterations in performance may be observed. Occluding portions of the reach path or of the digits causes early modifications of movement trajectories (Bozzacchi, Brenner, Smeets, Volcic, & Domini, 2018). The unavailability of visual information may produce wider grip apertures (Churchill, Hopkins, Rönnqvist, & Vogt, 2000; Fukui & Inui, 2006, 2013; Gentilucci, Toni, Chieffi, & Pavesi, 1994; Jakobson & Goodale, 1991; Rand, Lemay, Squire, Shimansky, & Stelmach, 2007; Volcic & Domini, 2016; Whitwell & Goodale, 2009), longer reach durations (Churchill et al., 2000; Connolly & Goodale, 1999) and a slowed deceleration phase of the movement (Churchill et al., 2000), ultimately causing the terminal stage of the movement to be less accurate (Carlton, 1981). It seems in the absence of visual feedback, precautionary adjustments are made at all phases of the reach-to-grasp movement, to allow a greater margin of error for ensuring an appropriate interaction with the target object (Chapman & Goodale, 2010; Keefe, Suray, & Watt, 2019). Manipulating the availability of visual feedback on performance will improve understandings about the use of vision for action compared to vision for perception in complex reaching environments.

## Grasping in Cluttered Environments

More often than not, our reaches occur in environments cluttered with task-irrelevant items. Our cell phone, for example, is hardly ever sitting alone on a bare tabletop. It is more likely that in order to pick up our cell phone, we may have to reach in between or around other objects on our desk. Humans are adept at reaching for target objects in cluttered environments, as are our primate ancestors. The kinematic similarities in reaching and grasping (Christel, & Billard, 2002; Roy, Paulignan, Farne, Jouffrais, & Boussaoud, 2000; Sartori, Camperio-Ciani, Bulgheroni, & Castiello, 2013), and action selection (Allport, Tipper, & Chmiel, 1985; Sartori, Camperio-Ciani, Bulgheroni, & Castiello, 2014), between human and non-human primates are speculated to have deep evolutionary roots in survival-related activities, such as feeding. This deep-rooted behaviour results in an apparent ease at avoiding obstacles when humans reach out to grasp an object in a cluttered environment (Chapman & Goodale, 2008, 2010). Our ability to avoid obstacles is intrinsic and automatic, suggesting the study of obstacle avoidance is actually an examination of the control of action by the unconscious dorsal stream of visual processing.

The basis of what we know about collision mitigation behaviour has been realized from investigating brain-damaged patients. In revealing the dissociations between perception and action in our visual system, patient studies have reinforced the role of the dorsal stream in visuomotor control generally (Goodale & Milner, 1992; Harvey & Milner, 1995; Perenin & Vighetto, 1988) and in automatic avoidance behaviour specifically (Schindler et al., 2004). When perception of the visual scene is incomplete, or disrupted, such as in cases of neglect (McIntosh, McClements, Dijkerman, Birchall, & Milner, 2004a; Milner & McIntosh, 2004), extinction (McIntosh et al., 2004b; Milner & McIntosh, 2004), visual form agnosia (Rice et al., 2006), and blindsight (Striemer, Chapman, & Goodale, 2009), intact obstacle avoidance behaviour can still be observed since the dorsal visual stream remains undamaged. On the other hand, impaired avoidance behaviour is observed when the dorsal stream is lesioned, such as in cases of optic ataxia (Rice et al., 2008, 2006; Schindler et al., 2004). Nearly all patients with optic ataxia fail to make automatic adjustments to their movement trajectories when obstacles are presented throughout the grasp space, reflecting a failure to integrate visual information about the task environment into a movement plan (Rice et al., 2006). Such cases of brain-lesioned patients highlight the functional and anatomical dissociation between perception and action, whereby the dorsal stream is critically responsible for the process of obstacle avoidance. The above-cited literature on this topic reveals large detriments to the visuomotor control of action, including obstacle avoidance, if the support of the dorsal stream is unavailable.

**Effect of Obstacles on Performance**

Despite the fact neurologically and physically able individuals can seamlessly maneuver through cluttered spaces, task-irrelevant objects in the environment can nonetheless influence and interfere with efficient grasping performance. The influence of non-target objects on goal-directed movements has not always been agreed upon. Early researchers claim task-irrelevant objects in the reaching environment serve as “distractors” (the *distractor perspective)*, which divert attentional resources away from the target object, in turn affecting grasping behaviour (Castiello, 1996; Howard & Tipper, 1997; Jackson, Jackson, & Rosicky, 1995; Tipper, Howard, & Jackson, 1997). Presently, the *obstacle avoidance* account is used to interpret collision mitigation events, explaining adjustments in reaches and grasps are related to the perceived risk of collision with positioned “obstacles” (Mon-Williams et al., 2001; Tresilian, 1998). This account allows for speculation that obstacles having a greater perceived consequence associated with collision may result in enhanced avoidance behaviour. For example, a collision that may result in physical pain to the subject performing the reach (i.e. a prickly cactus) or harm of another sort (i.e. risk of spilling a full glass of water) should result in modifications to the obstacle avoidance maneuver. It may be beneficial for the ventral stream to play a cooperative role in the obstacle avoidance process (de Haan, Van der Stigchel, Nijnens, & Dijkerman, 2014; Gentilucci et al., 1994; Himmelbach & Karnath, 2005; Menger, Dijkerman, & Van der Stigchel, 2013), particularly in situations where the identity of obstacles could contribute to the planning of a more efficient avoidance route.

The obstacle avoidance account proposes obstacles positioned on the same side of space as the reaching arm serve a greater risk for collision than do obstacles opposite the reaching arm (Chapman & Goodale, 2008, 2010; Dean & Brüwer, 1994; Marotta & Graham, 2016; Tresilian, 1998), influencing reach and grasp behaviour to a greater extent. Similarly, obstacles positioned close to the body or to the target object itself affect performance (Garzorz et al., 2018; Mon-Williams et al., 2001; Tresilian, 1998) as they are obtrusive to reach and grasp.

Positioned obstacles can influence reach and grasp performance, as well as gaze behaviour, in a number of ways. Reach trajectories show automatic deviations around positioned obstacles (Chapman & Goodale, 2008, 2010; Dean & Brüwer, 1994; Garzorz et al., 2018; Marotta & Graham, 2016; Mon-Williams et al., 2001; Tresilian, 1998, 1999). Dean and Brüwer (1994) have suggested the “least-minimum-distance” around obstacles is plotted by the motor system, following a speed-accuracy trade-off (i.e. Fitts Law; Fitts, 1954), planning for the shortest possible excursion around positioned obstacles while also guaranteeing a collision-free reach. The directions at which the digits set off early in the reach (Garzorz et al., 2018) and changes in the angular excursion of finger joints (the stereotypical pattern of shaping the hand when reaching to grasp and object; Ansuini, Tognin, Turella, & Castiello, 2007) have also been seen to be influenced by the presence of obstacles. Further, obstacles along the reach path tend to yield slower movement times (Castiello, 1996; Chapman & Goodale, 2008, 2010; Meegan & Tipper, 1998; Mon-Williams et al., 2001; Tipper et al., 1997; Tresilian, 1998), likely because more fine motor control is necessary when maneuvering complex environments (Mon-Williams et al., 2001). The grasp itself may be influenced by the presence of obstacles, as seen by poorer grip scaling, or, grip apertures that are inappropriately scaled to the size of target objects (Ansuini et al., 2007; Castiello, 1996; Mon-Williams et al., 2001). The maximal in-flight grip aperture tends to be smaller in the presence of obstacles, so to minimize the chance of collision by the digits (Mon-Williams et al., 2001; Tresilian, 1998). Shifts in final grasp positions may result, as if repulsed by positioned obstacles (Garzorz et al., 2018; Marotta & Graham, 2016). Similar shunts to gaze position may occur, though gaze is generally less affected by obstacles than grasp (Marotta & Graham, 2016), since there is no imminent risk for the eyes themselves to be involved in a collision event.

The anticipated likelihood of a collision, in keeping with the obstacle avoidance perspective, broadly affects goal-directed action performance. Although the distractor perspective of collision mitigation is generally discounted, it may certainly be possible for salient non-target objects to become perceptually obtrusive and attentionally captivating (Marotta & Graham, 2016; Tipper et al., 1997), influencing grasp and gaze behaviour. Obstacle avoidance relies to various degrees on the representational and contextual information provided by the ventral stream for alterations of the motor plan.

## Memory-Guided Grasping

Despite the troublesome presence of obstacles, we are often able to reach to previously seen, out-of-view objects, such as when we reach for a coffee cup from behind our laptop. In cases like this, we rely on visuospatial memory of the scene, or the stored sensory representations encoded by the perceptual ventral stream, to guide our actions (Goodale & Milner, 1992; Prime & Marotta, 2013). The obvious advantage to being able of skillfully perform actions under memory guidance is that it allows the eyes and hands be effectively involved in different tasks, simultaneously (Hayhoe & Ballard, 2005). In the current example, the eyes may remain focused on a video playing on the laptop, while the hand acts upon the remembered location of the coffee cup to take a sip. Relying on stored representations of the scene may still enable the formation of a relatively accurate, though less stable, motor plan over periods of visual delay (i.e. Heath & Binsted, 2007), which is why we are often able to successfully grasp remembered objects with little readjustment.

Still, a number of studies report kinematic differences in pointing (Elliott & Madalena, 1987; Heath & Binsted, 2007) and grasping tasks (Berthier, Clifton, Gullapalli, & McCall, 1996; Hesse & Franz, 2010; Hu, Eagleson, & Goodale, 1999; Hu & Goodale, 2000), whereby memory-guided action is generally slower, less accurate, and results in wider grip apertures when grasping. These significant changes in performance are seen even with haptic feedback provided at the end of the grasp (Hu et al., 1999). Under visual guidance, eye and hand behaviours are intimately linked (i.e. with gaze preceding grasp, and with final gaze position favouring the eventual contact point of the index finger on a target object), whereas the relationship between gaze and grasp movements becomes less robust under memory guidance (Flanagan, Terao, & Johansson, 2008; Prime & Marotta, 2013). Fundamentally, the availability of vision for action facilitates the fast and accurate execution of goal-directed movements, by allowing for efficient visuomotor planning and the activation of strategic eye-hand coordination.

According to the *perception-action theory* of Milner and Goodale (1995), in the absence of continuous visual input, grasping after a delay leads to a shift in visuomotor control from the dorsal to the ventral stream. In memory-guided grasping, the real-time motor plan of the dorsal stream is likely to be degraded with the passage of time (after 800 ms for saccades and less than 2 s for manual movements; Elliott & Madalena, 1987; Goodale, Jakobson, & Keillor, 1994; Hu & Goodale, 2000), causing a reliance on perceptual representations formed by the ventral stream.

Delay conditions that lead to a shift in visuomotor control over to the perceptual ventral network can be seen in investigations of brain-damaged patients. For instance, patients with lesions to the ventral stream (i.e. patient DF) who show intact grip scaling when interacting with objects in real-time, show impaired grasping performance when a target object is no longer visible and the reach to be performed occurs after a delay as short as two seconds (Goodale et al., 1994). As well, patients with lesions to V1 are unable to effectively avoid previously seen obstacles when a brief delay is in place, presumably because this ability would require the support of visual consciousness (Whitwell, Striemer, Nicolle, & Goodale, 2011). On the other hand, patients encumbered by parietal lesions actually show improvements when reaching to remembered objects after a delay (Milner et al., 2001; Milner, Dijkerman, McIntosh, Rossetti, & Pisella, 2003), suggestive of a relay of visuomotor control from the damaged dorsal stream to the unimpaired perceptual memory of the ventral stream (Himmelbach & Karnath, 2005). Patient studies such as these provide evidence for an exchange of visuomotor control from the dorsal to the ventral stream when action is required after the initially seen visual information is no longer accessible.

Behavioural examinations continue to support the notion that perceptual stores can influence motor actions initiated after a delay period. For example, Creem and Proffitt (1998) had subjects estimate the steepness of a hill's incline through verbal (perceptual) and motor judgements. Subjects' verbal judgements tended to greatly exaggerate the hill's slant compared to motor judgements. After a time delay, however, with the hill no longer visible, subjects' verbal and motor judgements were found to exaggerate the hill's slant to a similar degree, suggesting the motor judgements made after a delay were driven by stored perceptual representations. Along similar lines, a number of studies have indicated the effects of certain visual illusions can be induced on motor performance under delay conditions (i.e. Hu & Goodale, 2000; Westwood & Goodale, 2003; Westwood, McEachern, & Roy, 2001), overall interpreted as a shift from the mechanisms of vision for action to vision for perception.

## The Current Study

The current study sought to explore whether potential obstacles along the reach path would become more salient under memory guidance, where the perceptual mechanisms of the ventral stream would likely play a larger role in the visuomotor control of action (Milner & Goodale, 1995). For instance, a coffee cup next to our cell phone may allocate greater concern than perhaps necessary under memory-guided conditions, resulting in a more cautious obstacle avoidance approach to prevent collision. Comparisons between immediate grasps and grasps occurring after a delay, in the absence of visual feedback, are essential in confirming the effects in the delay condition are not simply due to the inability to make online corrections during movement execution but are rather because of the incapacity to effectively plan a movement using the real-time computations of the dorsal stream. Overall, the proposed research will reveal the extent to which memory-guided compared to visually-guided eye-hand coordination is impacted by the perceived interference of obstacles along a reach path, through manipulations of obstacle position and width.

## Hypotheses

Participants in this study will reach through a pair of obstacles flanking the left and right sides of the task environment in order to grasp a target object. Flanker obstacles will either both be narrow, or one of the left or right obstacles will be wide while the other remains narrow. The main hypothesis of this study is that unlike approaches undertaken when subjects are reaching with full visual feedback or immediately in the absence of visual feedback, exacerbated obstacle avoidance strategies will be observed in the memory-guided delay condition, due to a reliance on the perceptual mechanisms of the ventral stream. Memory-guided reaches after a delay are expected to incite slower movement times, increased hand deviations within the grasp space, larger grip apertures, and larger shifts in the final index finger position on the target object. Such an exaggerated avoidance strategy is expected to occur particularly in relation to obstacles that are on the same side as the reaching arm, centered in the grasp space, closer to the body, and wider in dimension.

Further, it is expected that positioned obstacles will differentially influence reach, grasp, and gaze behaviour, particularly for obstacles physically obstructing the reach path. The widths of obstacles are expected not to influence behaviour in the visually-guided or memory-guided no-delay conditions, since the physical distance between obstacles will always remain constant. In groups reaching in the absence of visual feedback, it is expected gaze will not be as influenced by the presence of obstacles as reach and grasp behaviour. Further, it is expected gaze will not be directed towards the eventual contact point of the index finger under memory guidance, as the relationship between grasp and gaze is likely to be deteriorated in the absence of visual feedback.

## Methods

### Participants

Thirty-six right-handed undergraduate students (17 male, 19 female; average age 20.9 years) were recruited from the University of Manitoba's Psychology participant research pool and received course credit for their participation. Each participant provided written consent (see Appendix A). After consent was obtained, participants verbally completed several demographics questions regarding sex, age, visual acuity, and handedness (using a modified version of the Edinburgh Handedness Inventory; Oldfield, 1971; see Appendix B). After testing, all subjects underwent debriefing (see Appendix C). This research complies with the American Psychological Association ethical standards in the treatment of participants and has been approved by the Psychology/Sociology Research Ethics Board at the University of Manitoba.

**Apparatus**

Reaching and grasping movements were recorded using an Optotrak Certus 3-D motion tracking system (Northern Digital Inc., Waterloo, ON, Canada) sampled at 100 Hz (spatial resolution .01 mm). Six infrared light emitting diodes (IREDs) were fastened to each participant's right hand and wrist (2 IREDs each placed on the left side of the cuticle of the index finger, the right side of the cuticle of the thumb, and on the radial portion of the wrist). An Eyelink II head-mounted eye tracking system (SR Research Ltd., Mississauga, ON, Canada) sampled at 250 Hz (spatial resolution $<.5°$) recorded binocular eye movements. Three additional IREDs were placed on the Eyelink II headset to account for any incidental head movement. Eye, head, and hand data were integrated into a common spatial and temporal frame of reference using MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA). The spatial frame of reference set up prior to testing was such that the origin (0, 0, 0) of the horizontal (x), vertical (z), and depth (y) axes was located at the bottom left corner of the testing surface (see Figure 1).

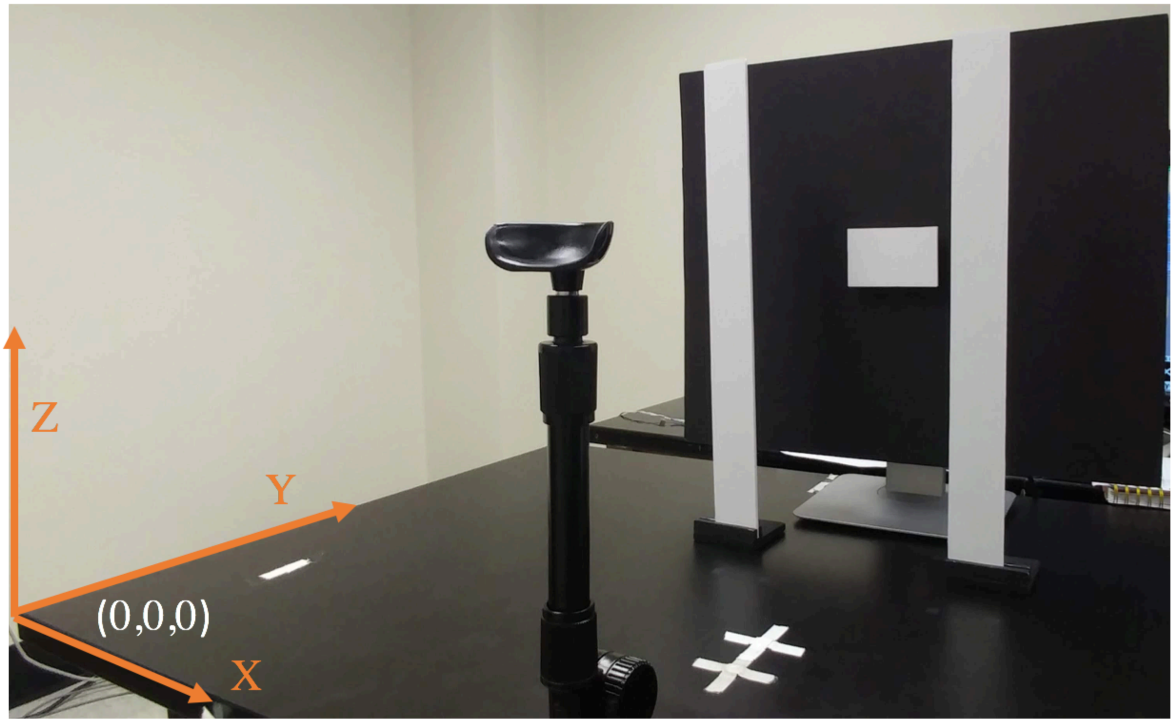


*Figure 1*. The origin of the test environment. The origin (0, 0, 0) of the horizontal (x), vertical (z), and depth (y) axes located at the bottom left corner of the testing surface.

Prior to data collection, both eyes were calibrated using a nine-point calibration/validation procedure presented on a 24-inch computer monitor. To ensure accurate calibration, an accuracy check was conducted immediately following the calibration/validation process and prior to each block of experimental trials. An accuracy check involved participants fixating on a centrally located dot for approximately 8 s, and comparing the position of their fixation to the position of the dot. The presence of an overall gaze displacement error exceeding 1 cm in either the horizontal or vertical dimension resulted in the recalibration/validation of the Eyelink II system. If these accuracy thresholds were not achieved within the time allotted for the Eyelink II set-up, the participant was excused with no penalty to them, and the session came to an end.

The availability and timing of visual feedback was controlled using a 28 × 26.5 cm "switchable glass" window (Polytronix Inc, Dallas, Texas, USA; Figure 2), housed in a 40.5 × 34.7 cm black wooden frame. Switchable glass consists of a polymer-dispersed liquid crystal film embedded within the glass that has the capacity to change between opaque and transparent states by applying a 36-volt alternating current (VAC) through the film. User defined formulas within MotionMonitor were used to generate this current and switch the window between opaque and transparent states, as well to control any auditory tones. The glass window was suspended from above, so that it did not in any way interfere with natural hand and arm movements during the reach. The window was hung ~10 cm directly in front of subjects' faces, so when opaque, it completely obstructed view of the grasp space. In order to determine the distance of the window from the subjects' face, subjects were asked whether they could see the bottom of the flanker obstacles when they were situated at the position closest to the subject. In addition, subjects were asked to fully extend their arm forward as if reaching to grasp an object from the computer screen, allowing the height of the window to be adjusted so that the forearm would not make contact with the bottom of the window's frame. Subjects sat in a height-adjustable chair that allowed their heads to be comfortably stabilized in the chin rest at its set height (30.5 cm above the table). Keeping the subjects' heads and upper bodies at the same height ensured all subjects had the same clearance under the window for making unimpeded arm movements. The experiment was conducted in a fully lit room by fluorescent lighting from the ceiling directly above the workspace.

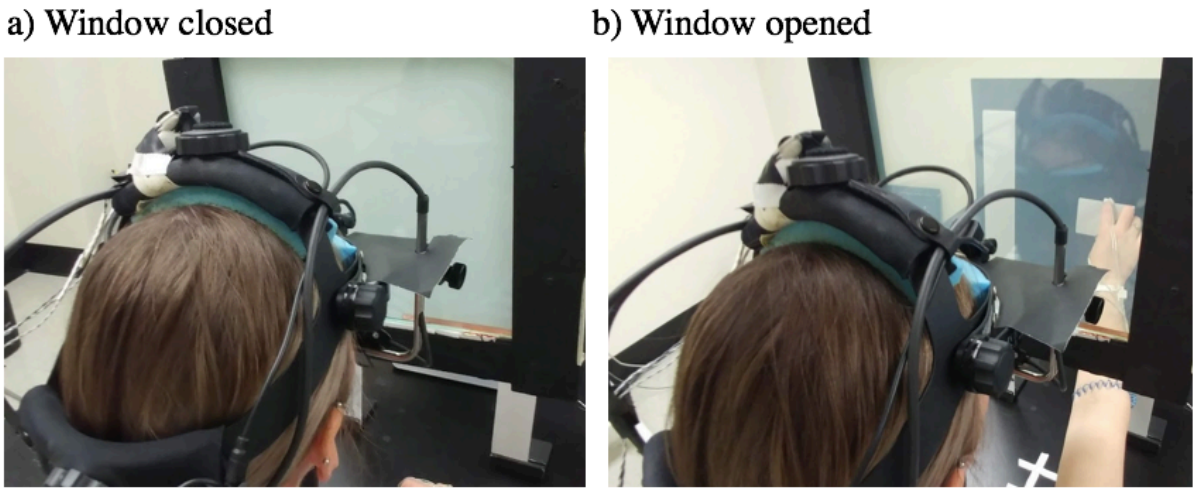


*Figure 2*. Switchable glass window. a) The window is completely opaque when it is closed so that the subject cannot see the display board, the target object, or the positioned obstacles. b) The window is transparent when opened so that the subject can see the display board, the target object, and the positioned obstacles.

**Stimuli**

Participants reached to grasp a lightweight 3-D target object on each trial, which was a white foam-core Efron shape (Efron, 1968) measuring 10 × 6.4 cm. Three distractor objects, measuring 9 × 7.1 cm, 11 × 5.8 cm, and 12 × 5.3 cm, were included to prevent subjects from “ball-parking” the size of the object to be grasped (Figure 3). This target object was mounted on a black, 54.2 × 45.8 cm vertical presentation board located 31 cm above the table, 55 cm from the subject in the chinrest, and 30 cm from the starting location of the hand. A vertically oriented magnet (2.2 × .5 cm) was fastened to the centre of the back of each Efron shape, which fit into an identical sized vertical slot of cardboard covering a steel plate, precisely in the centre of the presentation board. Thus, when a target object’s magnet was fitted into the slot, its vertical and horizontal centre was aligned with the board’s centre. The board was attached to the computer monitor that was used to calibrate the eyes with Velcro straps. Prior to the beginning of every block of trials, a cluster of IREDs attached to a stylus 20 cm in length was held to the centre of a target object positioned on the presentation board to capture the precise coordinates of the target object's COM. The presentation board was removed following the end of a block of trials to allow for an accuracy check of the eyes.

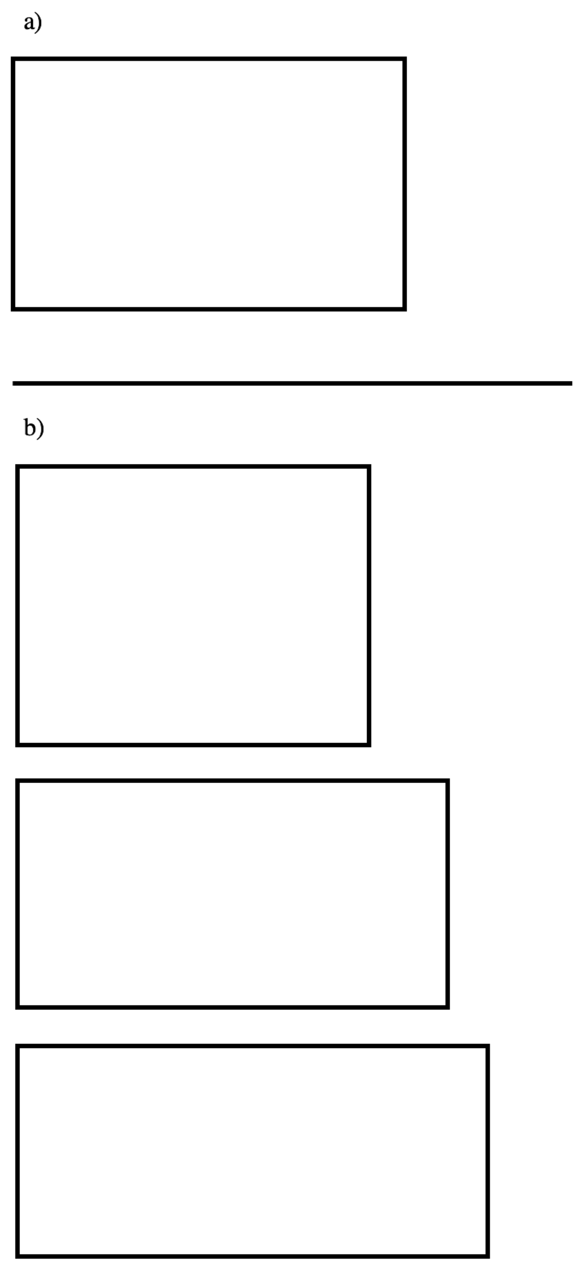


*Figure 3*. Schematic outlines of grasp stimuli. a) Target object (10 × 6.4 cm). b) Distractor objects (9 × 7.1 cm, 11 × 5.8 cm, 12 × 5.3 cm).

Within the grasp space participants reached between a pair of flanker obstacles (Figure 4), which were white foam-core rectangles measuring 50 cm in height and .5 cm in depth. For ease of switching the obstacles on a trial-by-trial basis, obstacles were slotted into a black wooden stand that added an additional .8 cm to their height. The widths of the obstacles were manipulated so that a wide (10 cm) flanker obstacle could be situated on one side of the grasp space while a narrower (5 cm) flanker obstacle could be on the other side of the grasp space, or so both flanker obstacles could be the same width (both 5 cm; Figure 5). At all times, the inner edges of the obstacles remained a constant distance apart (20 cm). On any given trial, the pair of flanker obstacles were situated in between the start position and the presentation board at any of four possible positions in the three-dimensional grasping space (Position 1 [Centre-Far]: obstacles 19 cm from the starting position and 10 cm to the left and right of the midline of the grasp space; Position 2 [Centre-Mid]: obstacles 12 cm from the starting position and 10 cm to the left and right of the midline; Position 3 [Right-Far]: obstacles 19 cm from the starting position, 5 cm to the left, and 15 cm to the right of the midline; Position 4 [Right-Mid]: obstacles 12 cm from the starting position, 5 cm to the left, and 15 cm to the right of the midline; Figure 6).

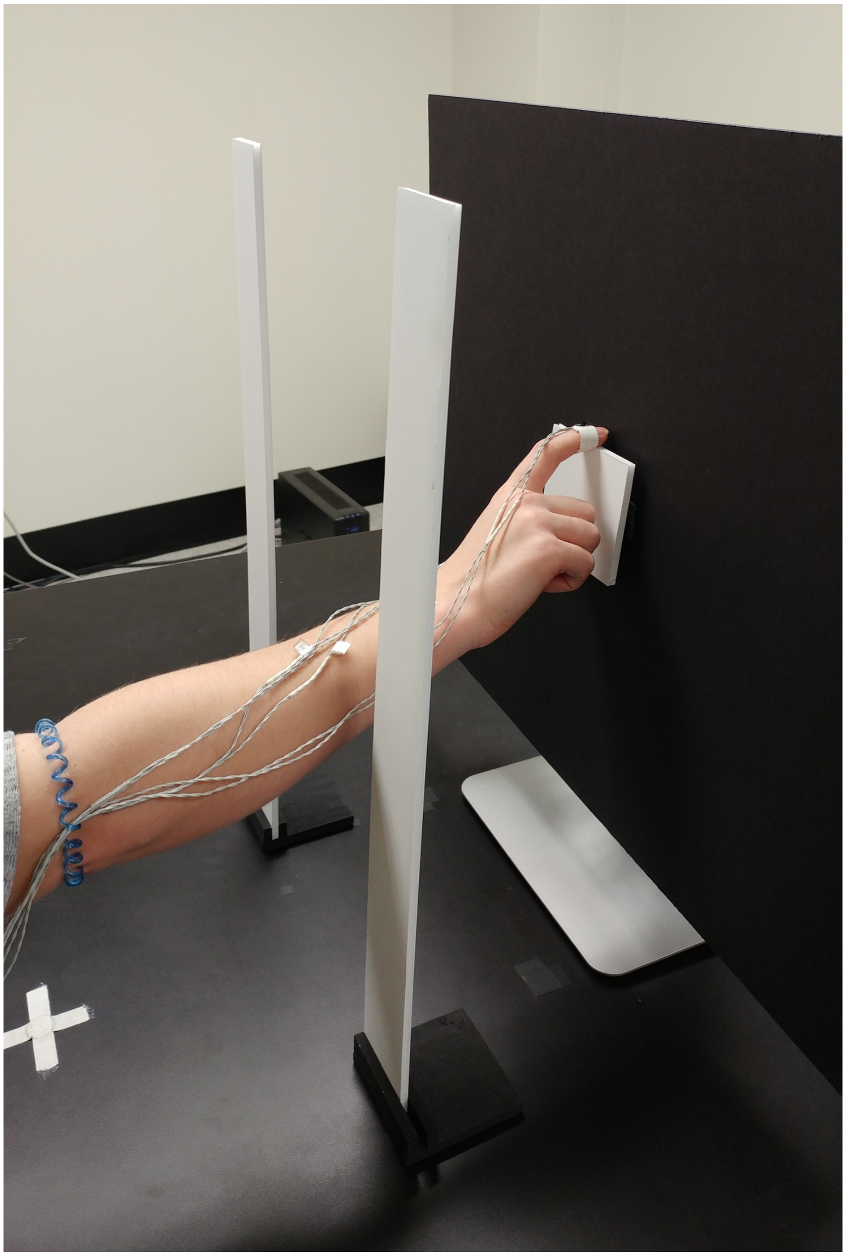

*Figure 4*. An example of a trial layout. The target is suspended on a black board directly in front of the subject. The image shows obstacles that are positioned 12 cm from the starting position, centrally positioned around the midline, with widths that are equal (5 cm).

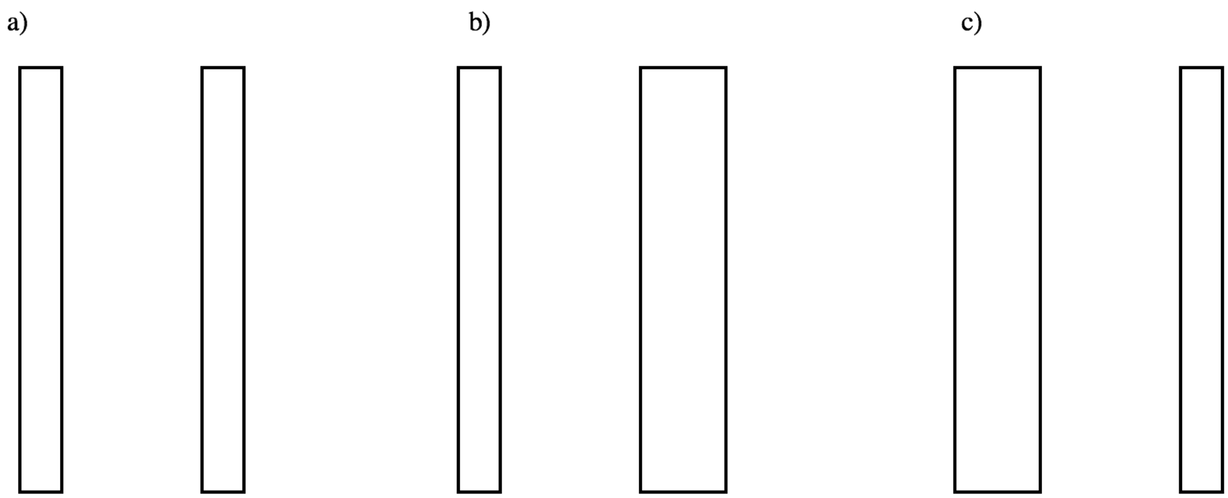


*Figure 5*. Schematic outlines of obstacle width arrangements. a) Both obstacles are narrow (5 cm each). b) The left obstacle is narrow (5 cm) and the right obstacle is wide (10 cm). c) The left obstacle is wide (10 cm) and the right obstacle is narrow (5 cm).

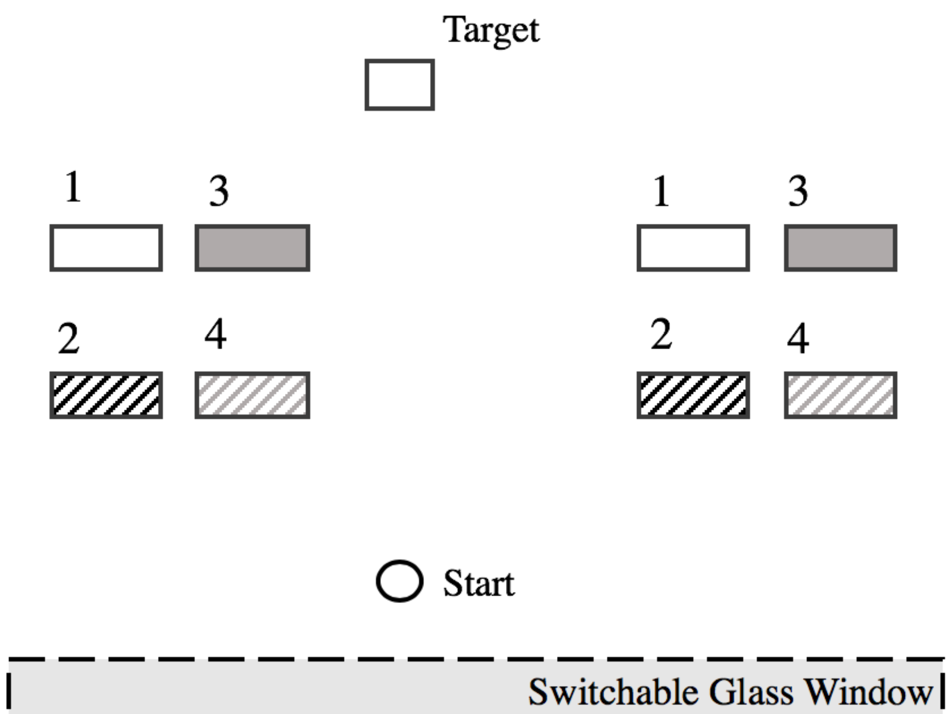


*Figure 6*. A not-to-scale schematic of potential obstacle positions. The pair of obstacles may be placed at any of four positions, with one obstacle on the left side and the other obstacle on the right side of the grasp space. The obstacle pair may be positioned either 12 cm or 19 cm from the start position, and may either be centrally placed or deviated to the right. The inner corners of the obstacles will remain a constant distance apart.

**Procedure**

A trial began with subjects holding their index finger and thumb at the starting position aligned with the chinrest and participants' midsagittal planes, with the glass window closed (i.e. opaque), completely obstructing the view. When the window was closed, the experimenter mounted a target block on the display board and positioned the pair of flanker obstacles before initiating the start of the trial. Subjects had their eyes closed between trials and opened their eyes just before initiation of the trial when the experimenter said "open". Upon initiating the trial, the window would open (becoming transparent) to reveal the grasp space for 1 s. After this initial viewing period, the window would either remain open (full-vision condition) or would close, and participants would reach to grasp the target object on the command of an auditory go-tone (350 Hz, 250 ms). On trials where the window closed after the initial viewing period, the tone would sound either immediately (memory-guided no-delay condition) or after a 2-s delay (memory-guided delay condition; Figure 7). A delay of this length was chosen based on previous literature suggesting the motor program for manual aiming and grasping movements appears to be completely degraded by 2 s (Elliott & Madalena, 1987; Goodale et al., 1994; Hu & Goodale, 2000), after which point the motor system must rely on stored perceptual representations for the guidance of action (Milner & Goodale, 1995). Subjects were instructed to reach towards and grasp the target block using a vertically oriented precision grip with the index finger and the thumb, remove the block from the display and place it on the table in front of them. A trial ceased recording when the IREDs on a subject's index finger came within a threshold of 1 cm from the target object. Four obstacle positions and 3 obstacle width arrangements resulted in 12 experimental conditions, each presented six times for a total of 72 experimental trials. The three distractor target types were presented four times each, pseudorandomly interleaved among the experimental trials for a total of 84 trials. Trials were divided evenly among 3 blocks. Due to the length of time needed to complete a typical 3-block session (~1.5 h), visually-guided, memory-guided no-delay and memory-guided delay viewing conditions were performed between-subjects, with 12 subjects per viewing condition (visually-guided condition: five males, seven females; average age 20.6 years; memory-guided no-delay condition: five males, seven females; average age 21.6 years; memory-guided delay condition: seven males, five females; average age 20.4 years). Task assignment was interleaved, such that subjects were alternately assigned a viewing condition. Participants completed four practice trials before experimentation.

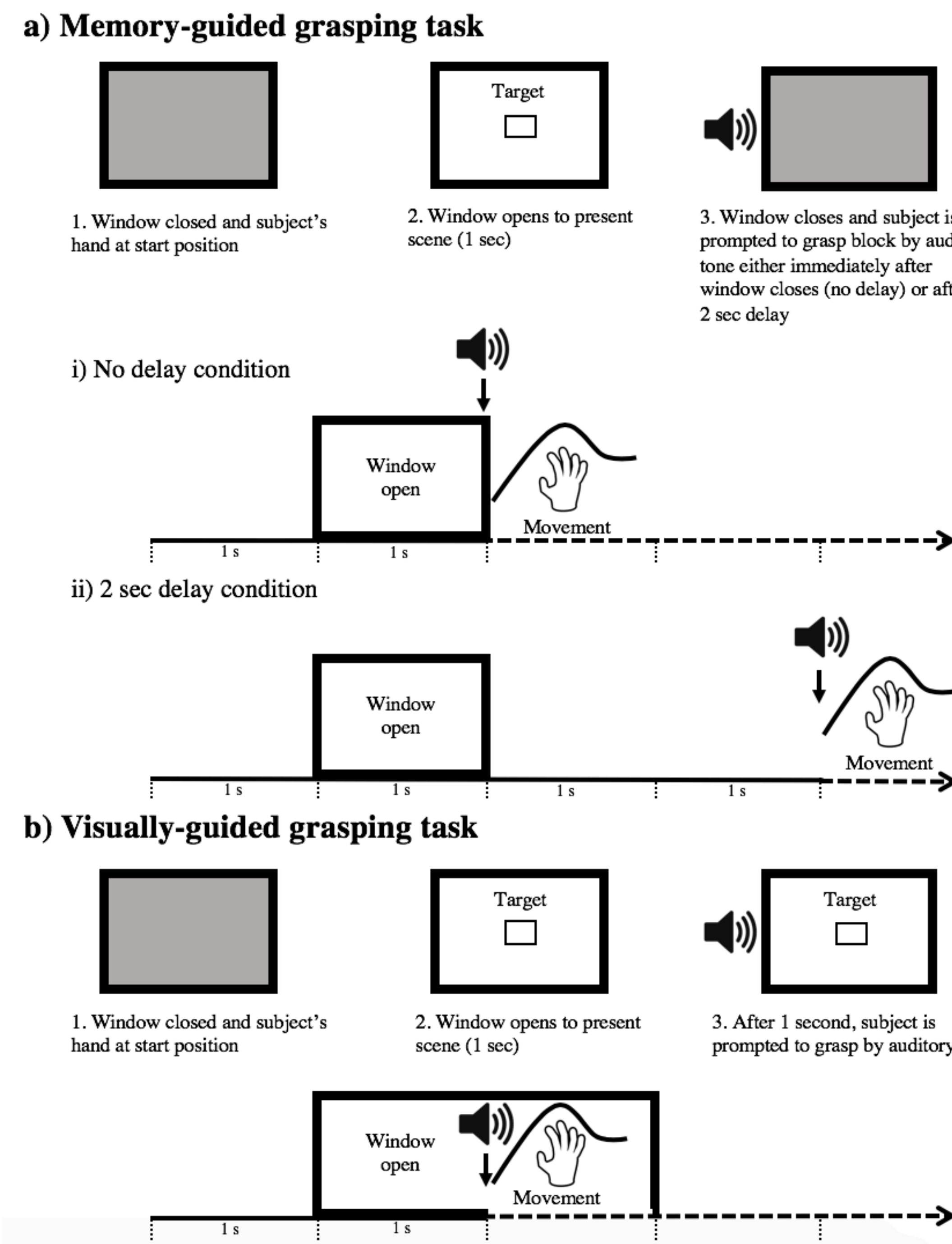


*Figure 7*. General experimental paradigm. a) In the memory-guided task, the window is closed and subjects hold their fingers at the start position on the tabletop. During the viewing phase, the window opens for 1 s to reveal the grasp space. Then, the window closes and the subject are prompted to reach for the target object by an auditory tone either immediately after window closes (no-delay condition) or after a 2-s delay has passed (2-s delay condition). b) In the visually-guided task, the trial begins with the window closed and subjects hold their fingers at the start position. The window opens and subjects view the environment for 1 s. After 1 s, an auditory tone prompts subjects to reach for the block.

## Data Collection

The goal of the present study was to examine obstacle avoidance behaviour under visually-guided or memory-guided conditions. Subjects reached in between pairs of flanker obstacles, which varied in terms of positioning and width, in order to grasp 3-D target objects. Analyses were mainly concerned with the subjects' eye positions and hand kinematic data.

### Excluded Data

Experimental trials were excluded from analysis on the basis of improper execution of the reach-to-grasp task (i.e. improper precision grip, starting to reach before the tone) or errors in the trial presentation (i.e. glitch resulting in faulty presentation of the tone, crooked target stimulus). Trials were also removed in cases where the IRED sensors on the index finger were obscured, resulting in data being extrapolated by the MotionMonitor software to reveal extreme values in terms of magnitude. This happened on occasion as participants passed their hand between the flanker obstacles or when the index finger made contact with the target obstacle and in turn ended up blocking the IREDs. These cases of extreme data were removed due to the fact that the endpoint of the trial was unclear, and therefore the data collected from all other IREDs and the eye-tracker were not reliable. Trials were not removed in cases where participants collided with an obstacle, because generally collisions only involved grazing of the forearm against obstacles, nonetheless resulting in an appropriate grasp. In total, 11.05% of all experimental trials were excluded from analysis. Within the remaining trials, data from the IREDs and from the eye-tracker were removed from the analysis of particular dependent variables if the points of interest contained crucial missing data points, physiologically impossible data or lost signals from the eye-tracker. If any IRED data point was removed from one dimension (horizontal, vertical, depth), it was removed from all dimensions for the given analysis.

**Reach Mechanics**

All data collected from the horizontal, vertical, and depth dimensions of the index, thumb, and wrist sensors was analyzed at 100 Hz. To ensure the most complete data set, comparisons between the two sensors on the index finger, thumb, and wrist were performed. The sensor that produced the fewest missing data points was used for analysis, on a participant-by-participant basis.

**Eye Data**

Eye data was collected in the horizontal and vertical planes only and was analyzed at 100 Hz. Within the horizontal and vertical dimensions, gaze location was calculated as the average between the positions of the left and right eye at the depth of the target object from the subject (54 cm). Raw horizontal and vertical eye positions were characterized into fixations based on a dispersion-threshold identification (I-DT) algorithm (Salvucci & Goldberg, 2000). Based on this algorithm, a 'fixation' was defined as the location where gaze was directed for a minimum duration of 100 ms and within a maximum dispersion of 1 cm.

**Dependent Variables**

Fixation positions were analyzed at the point in time at which the index finger made contact with the target object (the final fixation) along the vertical and horizontal axes. As well, the difference between the final fixation and the final position of the index finger along the horizontal axis was analyzed. Lastly, participants' overall gaze patterns were assessed.

Analyses of hand data were conducted on the index finger position on the target object at the time of the grasp (final index finger position) along the horizontal axis, index finger position along the horizontal axis at the point when the index finger just passed through the flanker obstacles (index finger bisection of the grasp space), maximum grip aperture (MGA) between the index finger and thumb during the reach, maximal horizontal distance traveled by the index finger during the reach (horizontal path length of the index finger), maximal horizontal distance traveled by the wrist during the reach (horizontal path length of the wrist). Wrist data was further utilized to determine the duration of the reach. Previous studies in our lab examining eye-hand coordination in cluttered environments (Marotta & Graham, 2016) have generally disregarded trials in which subjects collided with obstacles. In this study, collisions with obstacles were recorded to improve our understandings of collision mitigation under memory guidance.

For each dependent variable, a 3 (Viewing Condition; between-subjects) × 4 (obstacle Position; within-subjects) × 3 (Width arrangement; within-subjects) mixed ANOVA was performed on the mean condition values for each participant. Any violations of sphericity were tested for using Mauchly's test and were addressed using a Greenhouse-Geisser correction. ANOVAs and post hoc Bonferroni corrections were conducted using alpha = .05. Results of all pairwise comparisons can be found in Appendix E. One-sample t-tests were computed for each viewing condition, collapsing across obstacle positions and widths in order to assess whether final fixation and index finger positions deviated from the target object's horizontal COM. The Holm-Bonferroni Procedure was used to control familywise error rates for the t-tests. Adjusted alpha values and the results of the t-tests can be found in Appendix F.

## Results

### Gaze Accuracy

All participants included in this study completed an accuracy check prior to the beginning of each experimental block. The average gaze displacement error collapsed across blocks and participants was -.13 cm (*SE* = .004 cm) in the horizontal axis and .22 cm (*SE* = .004 cm) in the vertical axis.

**Overall Gaze**

Participants' overall gaze patterns were visually examined to assess whether the flanker obstacles were capturing gaze at any point during the trial for participants in the visually-guided condition, and during the 1 s viewing phase for participants in the memory-guided conditions. Throughout the reach, participants' gaze was almost exclusively directed toward the target object, with only 118 out of 2,261 total trials across all participants involving gaze directed at some point towards one of the flanker obstacles (5.22% of total trials).

Since the flanker obstacles did not appear to be an active target for gaze, we focused our efforts on the final fixations on the target objects in the vertical and horizontal planes, and how they related to the final grasp locations along the horizontal plane. Along the vertical plane, final fixations were removed from analysis if they fell 2 cm beyond the top edge or 2 cm below the bottom edge of the target object's contour. Similarly, along the horizontal plane, final fixations were removed from analysis if they fell 2 cm beyond the left or right edges of the target object's contour. Any fixation removed from analysis in the vertical plane was removed from analysis in the horizontal plane, and vice versa.

**Final Fixation in Vertical Plane**

The position of the final fixation at the time of the grasp was analyzed along the vertical plane in relation to the target object's COM (Figure 8). A Position × Width × Viewing Condition interaction was found to be significant, $F(12, 198) = 1.905$, $p < .05$, $\eta_p^2 = .104$. The position of the final fixation along the vertical plane was similar across all conditions, with the exception being participants in the memory-guided delay condition making reaches between obstacles at

Position 3 had final fixations higher from the target object's COM when both obstacles were narrow, compared to when the right obstacle was wide ($p < .05$).

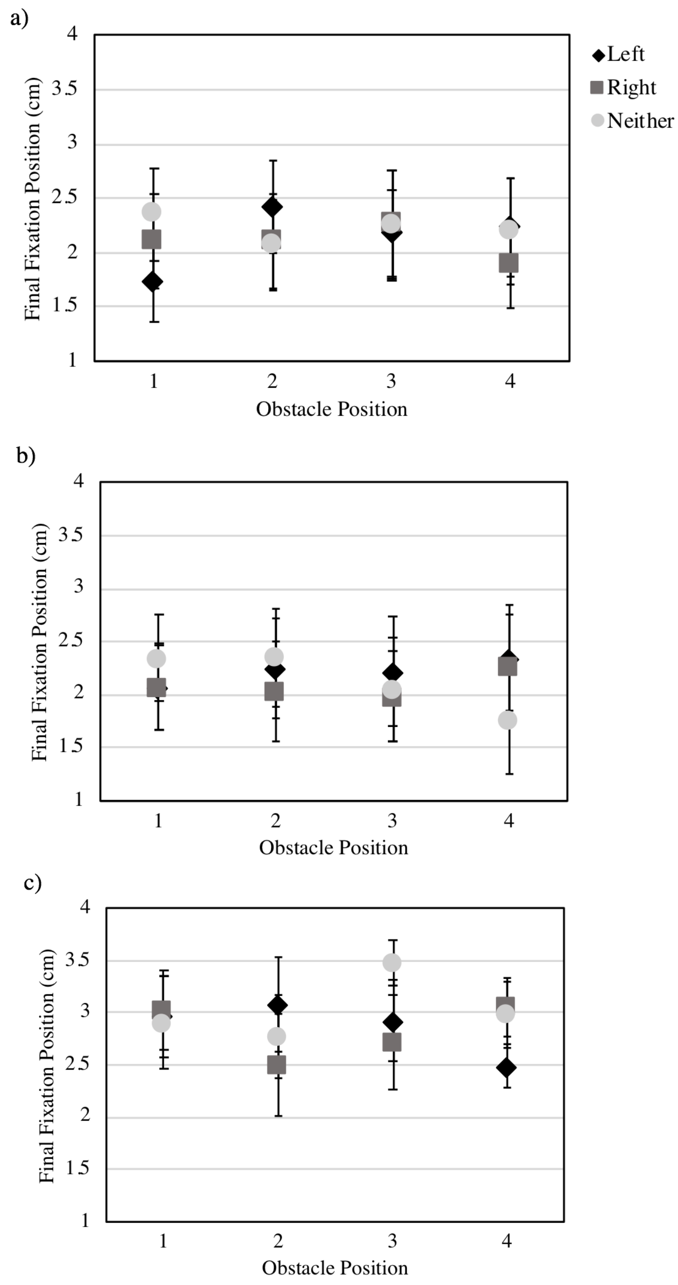


*Figure 8*. Position of the final fixation on the target object in the vertical plane in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Positive values denote coordinates above the target object's COM. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Final Fixation in Horizontal Plane**

The position of the final fixation at the time of the grasp was analyzed along the horizontal plane in relation to the target object's COM (Figure 9). The ANOVA revealed a significant Position × Viewing Condition interaction, $F(6, 99) = 7.443$, $p < .001$, $\eta_p^2 = .311$. For participants reaching with full visual feedback, the effect of obstacle position was apparent in producing final fixations on the target object that landed further to the left when the obstacles were at centrally located Positions 1 and 2, compared to when the obstacles were at right-deviated Positions 3 and 4 (all $p < .001$). No significant differences between the final fixations on the target object along the horizontal plane are apparent for either of the memory-guided conditions. The results of the t-tests revealed final fixations were not significantly different from the target object's COM in visually-guided, $t(11) = .214$, p > .0083, memory-guided no-delay, $t(11) = -.15$, p > .01, and memory-guided no-delay conditions, $t(11) = 1.654$, p > .0125.

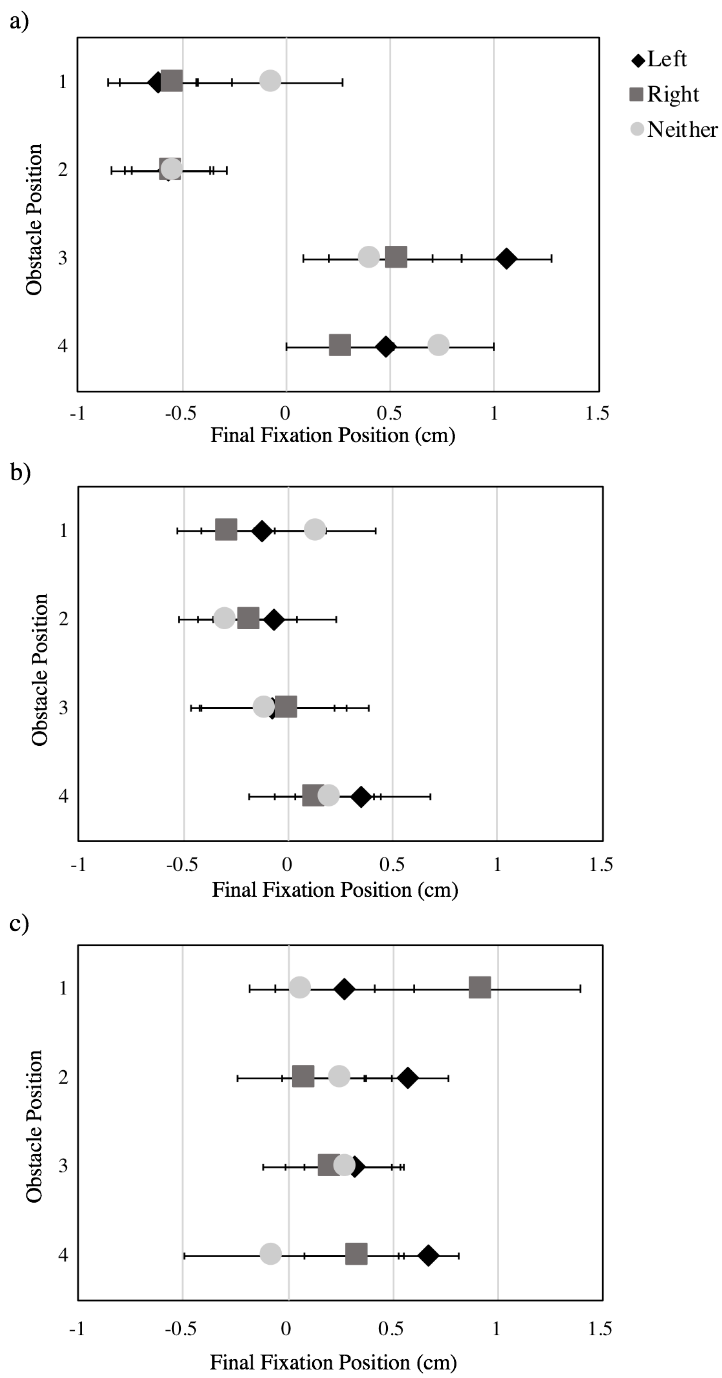


*Figure 9*. Position of the final fixation on the target object in the horizontal plane in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Negative values denote coordinates to the left of the target's COM, whereas positive values denote coordinates to the right of the target object's COM. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Final Index Finger Position in Horizontal Plane**

The contact position of the index finger on the target object relative to its horizontal COM was calculated to be an indicator of grasp performance (Figure 10). Final index finger positions were removed from analysis if they fell 2 cm beyond the left or right edges of the target object's contour. The ANOVA revealed a significant interaction of obstacle Position × Width × Viewing Condition, $F(12, 99) = 2.158$, $p < .05$, $\eta_p^2 = .116$. Participants in the visually-guided condition showed final index finger positions further to the left with obstacles at Positions 1 and 2, compared to Positions 3 and 4, when either the left flanker obstacle was wide (all, $p < .001$) or when both were narrow (1 vs 3, 2 vs 3, and 2 vs 4, $p < .01$; 1 vs 4, $p < .001$). When the right flanker obstacle was wide, participants in this condition also showed more leftward final index finger placement with obstacles at Position 1 compared to Position 3 ($p < .05$) and Position 2 compared to Positions 3 and 4 (1 vs 3 and 2 vs 4, $p < .05$; 2 vs 3, $p < .01$). Participants in the memory-guided no-delay condition showed final index finger positions further to the left with obstacles at Position 1 compared to Positions 3 and 4 when the left flanker obstacle was wide (all, $p < .01$). When the right flanker obstacle was wide, participants in this condition showed more leftward final index finger placement with obstacles at Position 1 compared to Positions 3 and 4 (1 vs 4, $p < .05$; 1 vs 3, $p < .01$) and Position 2 compared to Position 3 ($p < .05$). When both flanker obstacles were narrow, participants showed more leftward final index finger placement with obstacles at Positions 1 and 2, compared to Positions 3 and 4 (1 vs 3, 1 vs 4, and 2 vs 3, $p < .01$; 2 vs 4, $p < .001$). Participants in the memory-guided delay condition showed final index finger positions further to the left with obstacles at Positions 2 and 4 compared to Position 3, when the left flanker obstacle was wide (3 vs 4, $p < .05$; 2 vs 3, $p < .01$). No significant differences in final index finger were observed between the different positions of obstacles for participants in the memory-guided delay condition, when the right flanker obstacle was wide or when both obstacles were narrow. The results of the t-tests revealed final index finger placements landing significantly to the left of the target's COM in visually-guided, $t(11) = -4.654$, $p < .0167$, and memory-guided delay grasps, $t(11) = -4.791$, $p < .05$. Final index finger placements were not significantly different from the target's horizontal COM for grasps occurring in the memory-guided no-delay condition, $t(11) = -2.028$, $p > .025$.

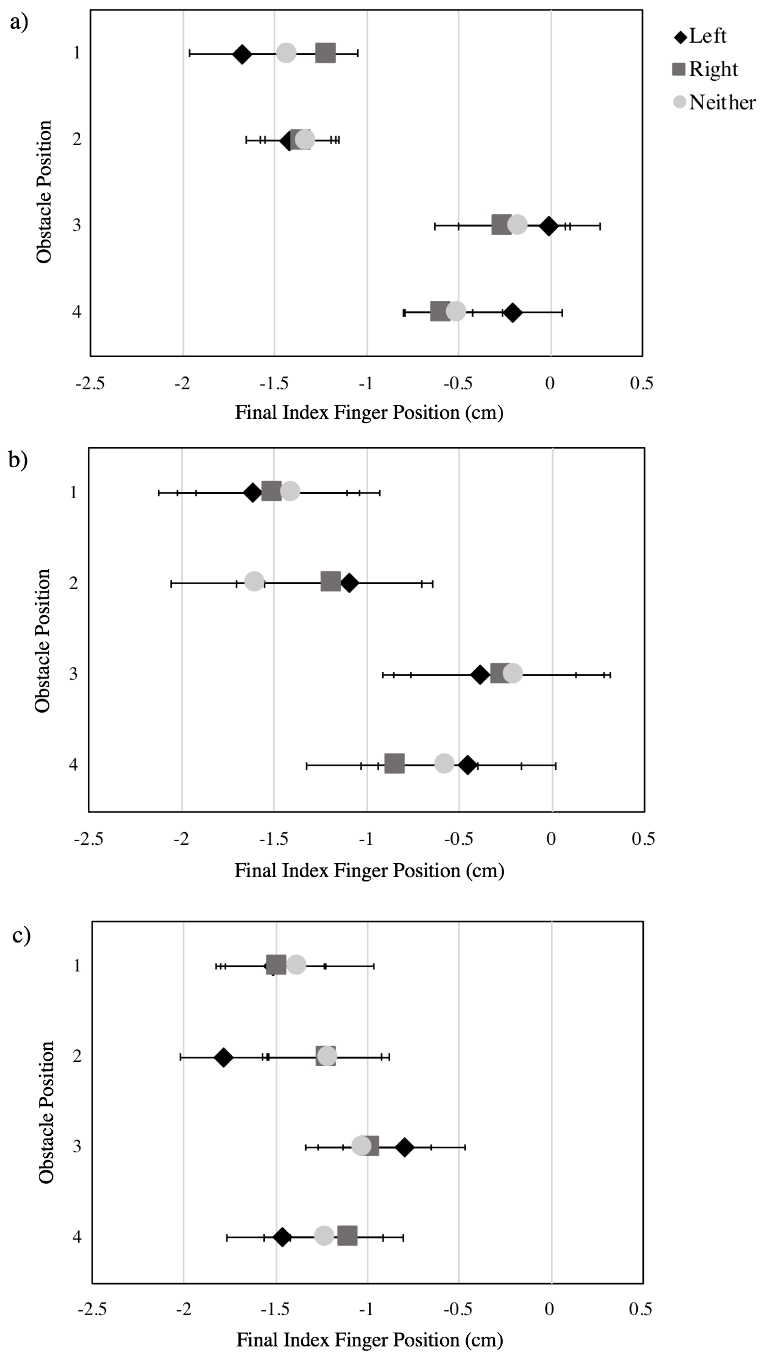


*Figure 10*. Position of the index finger on the target object in the horizontal plane in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Negative values denote coordinates to the left of the target's COM, whereas positive values denote coordinates to the right of the target object's COM. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Distance Between Final Fixation and Final Index Finger Positions on the Target in Horizontal Plane**

This variable is a measure of the distance between the index grasp point and the final fixation along the horizontal plane (Figure 11). This measure is useful in determining the relationship between grasp and gaze under the different viewing conditions. An obstacle Position × Width × Viewing Condition interaction was found to be significant, $F(12, 198) = 2.057$, $p < .05$, $\eta_p^2 = .111$. No significant differences between final index finger and final fixation placements were observed at any of the position or width arrangements for participants reaching under full visual feedback. Participants reaching in the memory-guided no-delay condition displayed increased separation between final index finger and final fixation placements when reaching between obstacles at Position 1 compared to Position 3, when the left flanker was wide ($p < .05$) and when both obstacles were narrow ($p < .01$). Participants in the memory-guided delay condition displayed increased separation between final index finger and final fixation placements when reaching between obstacles at Position 2, when the left flanker was wide, compared to participants reaching under full visual feedback ($p < .05$). Further, participants reaching in the memory-guided delay condition displayed increased separation between final index finger and final fixation placements when reaching between obstacles at Position 2 compared to Position 3, when the left flanker was wide ($p < .05$). Participants in this viewing condition also displayed increased separation between final index finger and final fixation placements when reaching between obstacles at Position 1 compared to Positions 2 and 3, when the right obstacle was wide (all $p < .05$).

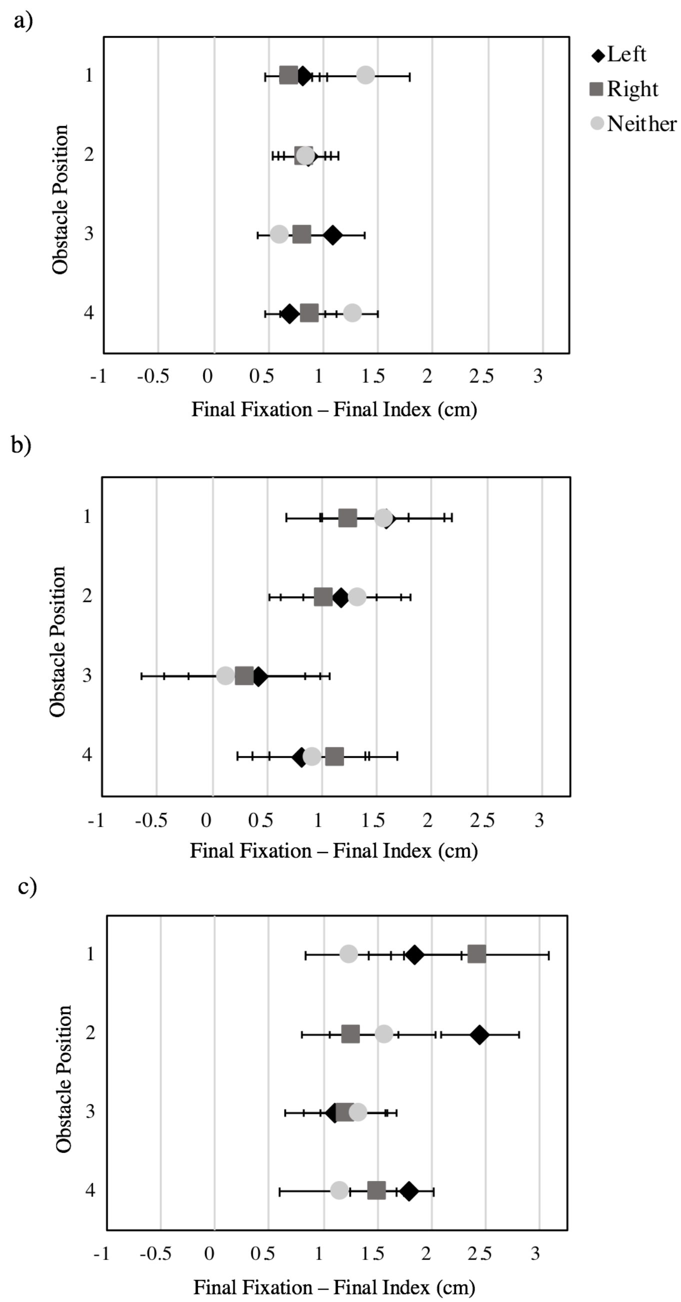


*Figure 11*. Distance between final fixation and final index finger positions on the target in the horizontal plane in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Negative values represent final fixation positions that landed further left than final index finger positions, whereas positive values represent final fixation positions that landed further right than final index finger positions. A value of zero would indicate that final fixation and final index finger positions are perfectly aligned. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Index Finger Bisection of the Grasp Space**

The horizontal position of the index finger relative to the inner edge of the left flanker obstacle was extracted at the point at which the index finger just passed the depth coordinate of the pair of flanker obstacles, to inform about the bisection of the grasp space (Figure 12). A main effect of obstacle position was found, $F(3, 99) = 95.661$, $p < .001$, $\eta_p^2 = .744$. Subjects tended to bisect the grasp space closer to the left flanker obstacle when the obstacles were at right-deviated Positions 3 and 4 compared to when the obstacles were at centrally located Positions 1 and 2 (all $p < .001$). Bisections closer to the left flanker obstacle also occurred when obstacles were located at Position 2 compared to Position 1 ($p < .05$).

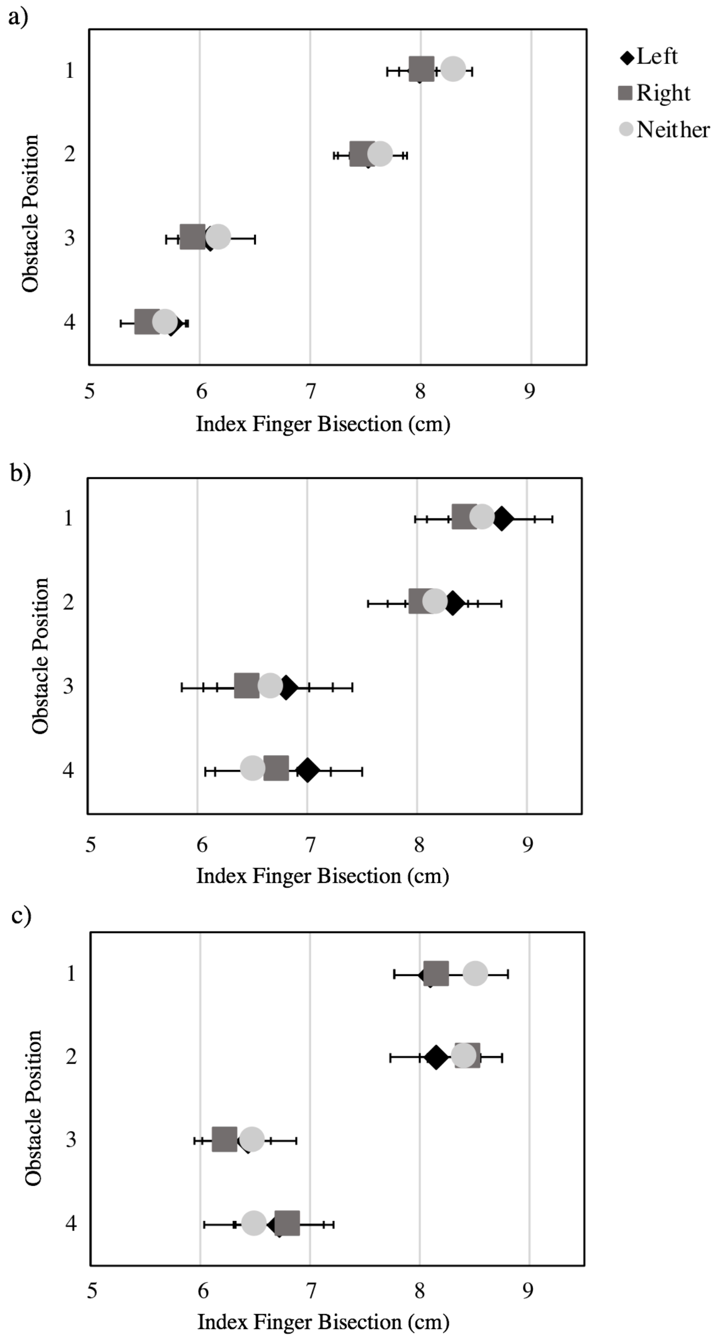


*Figure 12*. Horizontal bisection of the space between obstacles by the index finger in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Smaller values indicate a closeness of the index finger to the inner edge of the left flanker obstacle, whereas larger values indicate a closeness of the index finger to the inner edge of the right flanker obstacle. A value of 10 cm would indicate the index finger bisected the grasp space precisely at the midpoint between obstacles, although this never occurred. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Maximum Grip Aperture (MGA)**

The MGA represents the maximal distance between the index finger and thumb during the reach as an indicator of grasp performance, specifically related to grip scaling (Figure 13). An obstacle Position x Width interaction was found to be significant, $F(2.42, 79.92) = 3.005$, $p < .05$, $\eta_p^2 = .083$. With flanker obstacles situated at Position 2, grip aperture was slightly larger when the right obstacle was wide, compared to when the left obstacle was wide ($p < .05$). For all other comparisons, MGA was not significantly different, although a trend in the data hints towards the visually-guided viewing condition having smaller MGAs than memory-guided no-delay ($p = .189$) and delay ($p = .142$) conditions, $F(2, 33) = 2.656$, $p = .085$.

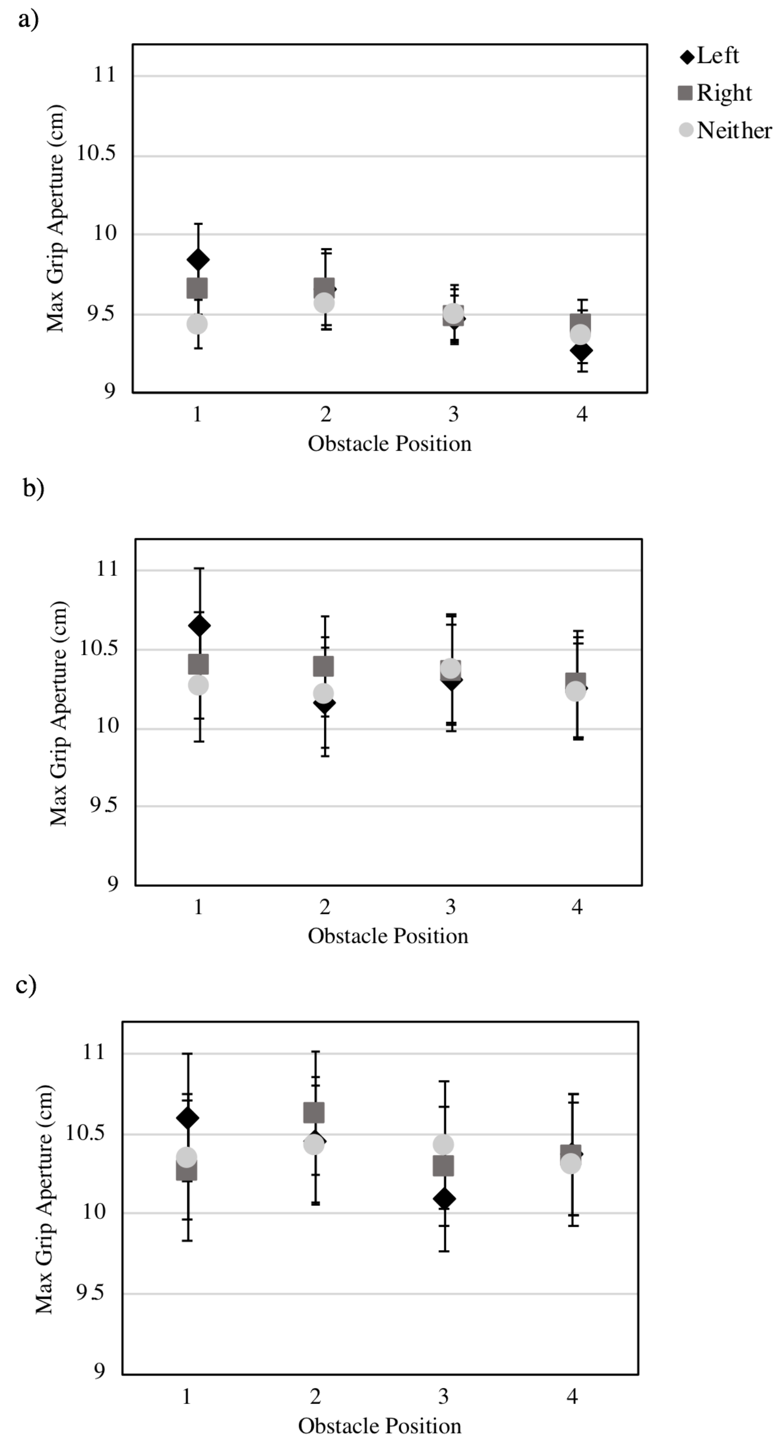


*Figure 13*. Maximum grip aperture in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Horizontal Path Length of Index Finger**

The total distance moved by the index finger in the horizontal plane during the reach was calculated to inform about deviations around obstacles (Figure 14). Main effects of obstacle position, $F(3, 99) = 16.617$, $p < .001$, $\eta_p^2 = .335$, and viewing condition, $F(2, 33) = 3.782$, $p < .05$, $\eta_p^2 = .186$, were found. The effect of obstacle position was evident in the greater horizontal path lengths of the index finger when the obstacles were at right-deviated Positions 3 and 4 compared to when the obstacles were at centrally located Positions 1 and 2 (2 vs 4, $p < .05$; 2 vs 3, $p < .01$; 1 vs 3 and 1 vs 4, $p < .001$). A longer horizontal path length was also apparent when obstacles were located at Position 2 compared to Position 1 ($p < .05$). Participants in the memory-guided no-delay condition showed greater horizontal path lengths of the index finger than participants reaching in the visually-guided condition ($p < .05$).

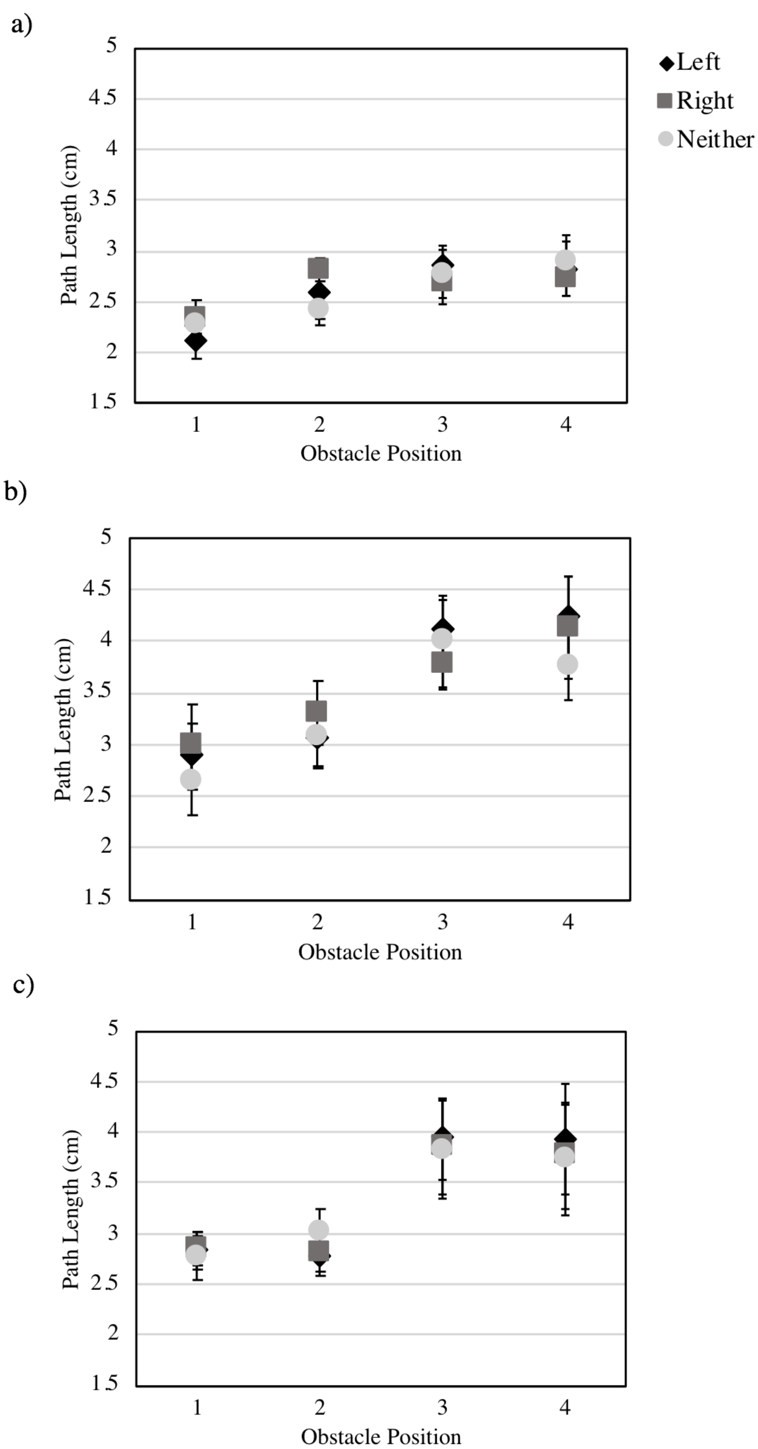


*Figure 14*. Horizontal path length of the index finger in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Horizontal Path Length of Wrist**

The total distance moved by the wrist in the horizontal plane during the reach was calculated to inform about deviations around obstacles (Figure 15). Interactions of obstacle Position × Width, $F(3.659, 117.102) = 2.596, p < .05, \eta_p^2 = .075$, and Position × Viewing Condition, $F(6, 99) = 2.685, p < .05, \eta_p^2 = .144$, were found to be significant. Participants in the visually-guided and memory-guided no-delay conditions showed greater horizontal path lengths of the wrist when reaching in between obstacles at Position 2 over Positions 1, 3, and 4 and Positions 1 and 4 over Position 3 (visually-guided: 1 vs 2, $p < .01$; 1 vs 3, 2 vs 3, 2 vs 4, and 3 vs 4, $p < .001$; memory-guided no-delay: 1 vs 2 and 3 vs 4, $p < .01$; 1 vs 3, 2 vs 3, and 2 vs 4, $p < .001$). Participants in the memory-guided delay condition showed greater horizontal path lengths of the wrist when reaching in between obstacles at Positions 1, 2, and 4 over Position 3 (all $p < .001$). Across viewing conditions, larger horizontal path lengths of the wrist were evident when the left flanker obstacle was wide compared to when both obstacles were narrow, for obstacles situated at Position 4 ($p < .05$). Further, when the right flanker obstacle was wide, or when both obstacles were narrow, the greatest horizontal path lengths of the wrist were apparent with obstacles at Position 2, followed by Position 1, followed by Position 4, with the smallest path lengths resulting from obstacles at Position 3 (wide right obstacle: 1 vs 4, $p < .05$; 1 vs 2, 1 vs 3, 2 vs 3, 2 vs 4, and 3 vs 4, $p < .001$; both obstacles narrow: 1 vs 2 and 3 vs 4, $p < .05$; 1 vs 3, 1 vs 4, 2 vs 3, and 2 vs 4, $p < .001$). When the left flanker obstacle was wide, larger horizontal path lengths of the wrist were apparent when reaching in between obstacles at Positions 1, 2, and 4 over Position 3 (all $p < .001$).

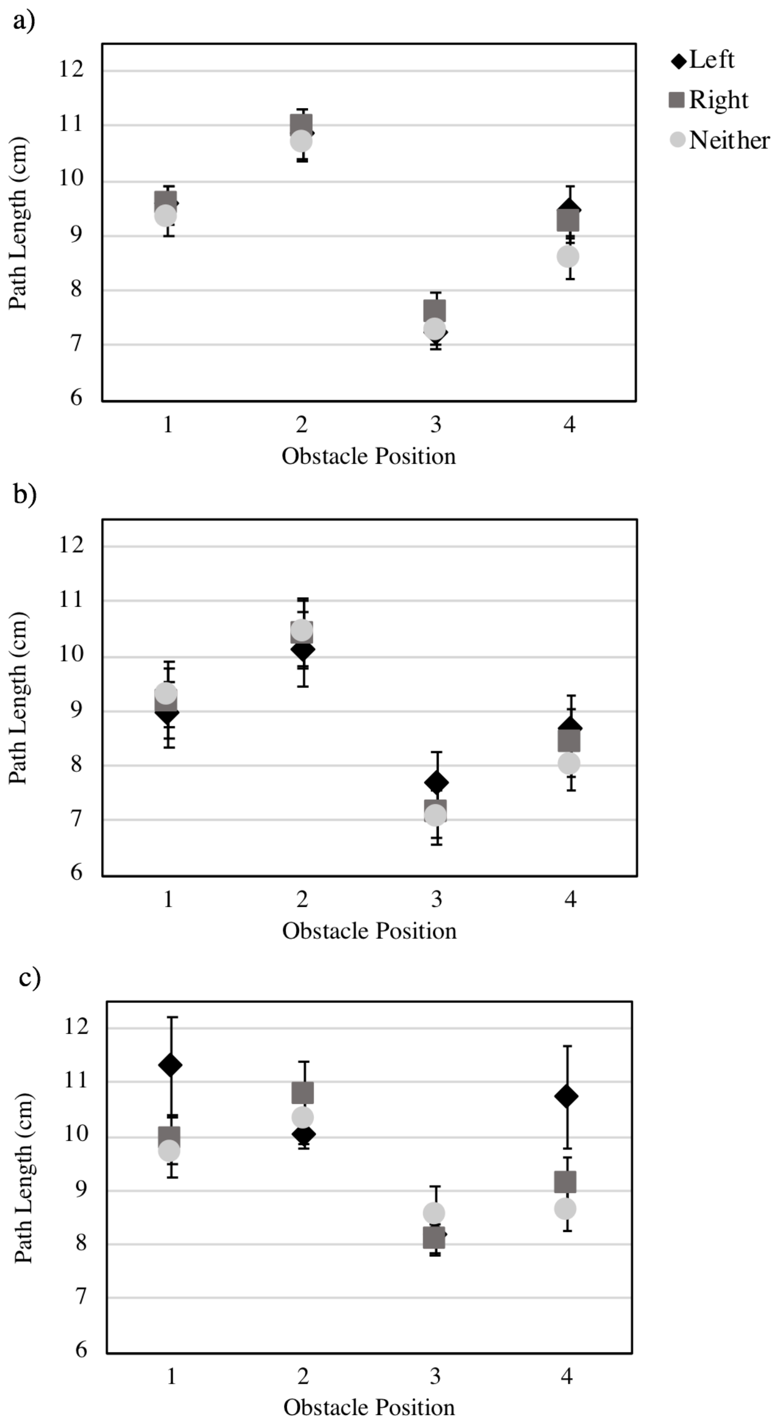


*Figure 15*. Horizontal path length of the wrist in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Data for one participant in the memory-guided no delay condition was not available, due to significant drops in data from the wrist sensors. Error bars represent standard error of the mean.

**Reach Duration**

The time from the start to the end of the reach was recorded (Figure 16). Reach onset was defined by a formula in MotionMonitor, as the point at which the velocity of the wrist became greater than 5 cm/s. The end of the reach was considered the point at which the index finger came within a threshold of 1 cm from the target object in the depth dimension. A main effect of obstacle position was found, $F(3, 99) = 3.503$, $p < .05$, $\eta_p^2 = .096$. Reach durations were fairly consistent, with the exception being obstacles at Position 4 producing slightly longer reaches than obstacles at Position 3 ($p < .05$). Nonetheless, a trend of reach duration was apparent between viewing conditions, $F(2, 33) = 3.182$, $p = .054$, suggesting reaches in the visually-guided condition having shorter durations than reaches in the memory-guided no-delay ($p = .181$) and delay conditions ($p = .072$).

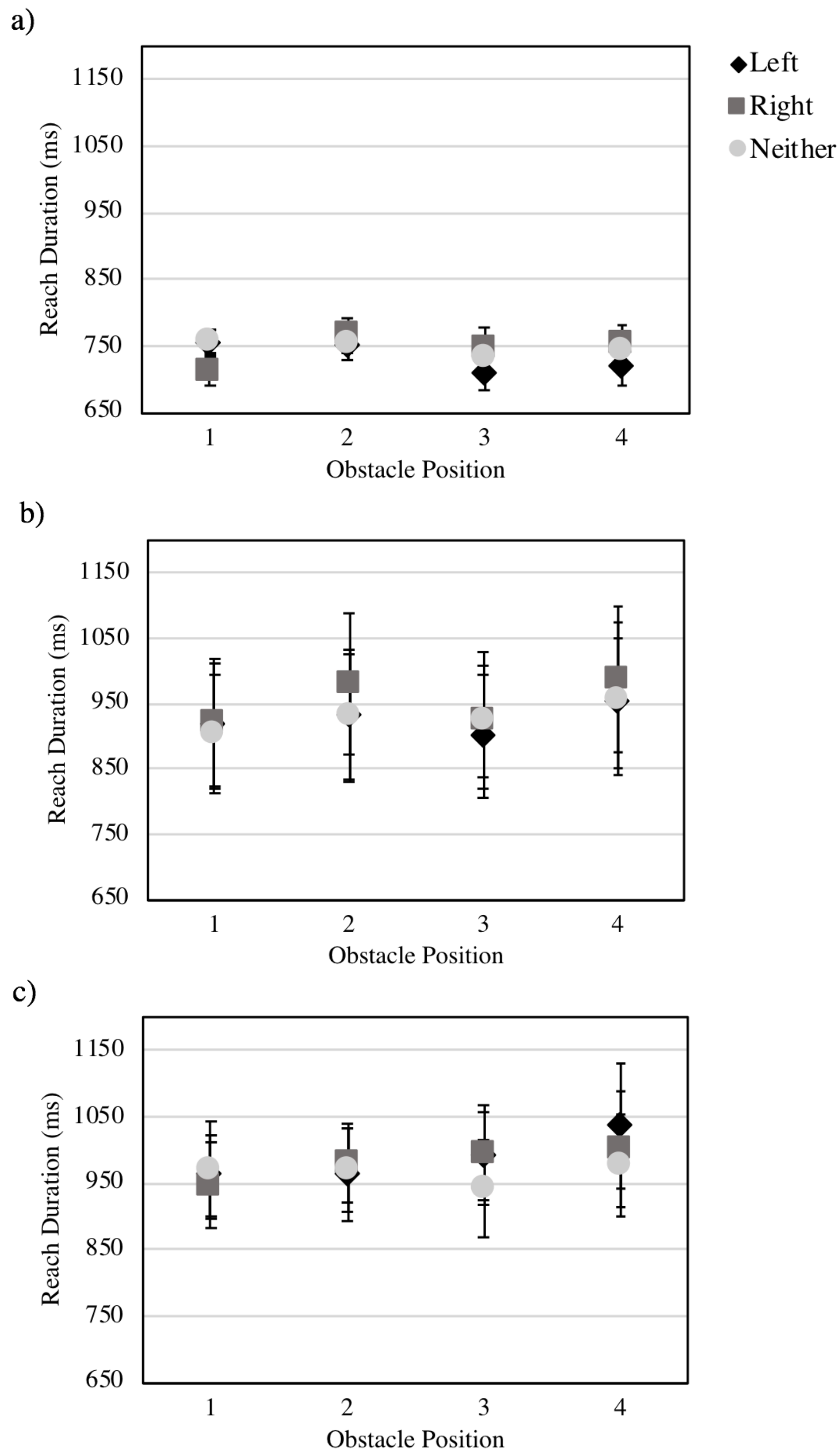


*Figure 16*. Reach duration in a) visually-guided, b) memory-guided no-delay, and c) memory-guided delay conditions. Shapes in the legend refer to the obstacle width arrangements, with the *black diamond* representing conditions where the left obstacle was wide, the *dark grey square* representing conditions where the right obstacle was wide, and the *light grey circle* representing conditions where both obstacles were narrow. Error bars represent standard error of the mean.

**Number of Collisions**

The total number of times that a participant collided with any of the positioned obstacles was recorded. Specifically, it was recorded whether the left or the right flanker obstacle was collided with, and whether the obstacle was wide or narrow. Overall, participants rarely collided with obstacles (.004% of trials for the visually-guided condition, .03% of trials for the memory-guided no-delay condition, and .04% of trials for the memory-guided delay condition), and so this variable was not further analyzed. When collisions did occur, subjects predominantly collided with the right obstacle of the pair, particularly when situated at Position 2. This position is the most mechanically constraining, as it is closest to the body, and there is a need to orient the elbow in order for the forearm to clear the obstacles. It is not surprising that collisions predominantly occurred with the right obstacle, since participants were reaching with their right hands.

## Discussion

The aim of the present study was to explore obstacle avoidance behaviour as subjects reached out and grasped 3-D target objects under visually-guided or memory-guided conditions. Subjects in the visually-guided condition performed with full vision of the task environment, whereas in the memory-guided conditions, subjects were briefly presented with the visual scene (for 1 s) before making a reach towards the target object either immediately or after a 2-s delay without visual feedback. On any given trial, subjects had to maneuver their reaching arm through a pair of flanker obstacles in order to get to the target object. The positions and widths of the obstacles were manipulated, though their inner edges remained a constant distance apart. Analyses focused on a number of eye and hand variables throughout the reach-to-grasp movement. Generally, obstacle avoidance behaviours occurred in a manner consistent with the obstacle avoidance account of collision mitigation (Tresilian, 1998), although several variables were seemingly less affected by the experimental manipulations. Altogether, our main results show distinctive avoidance approaches were undertaken depending on the availability of visual information. Specifically, contrary to expectation, under the perceptual control of the ventral stream, obstacle avoidance in the memory-guided delay condition followed a more moderate, rather than exaggerative, strategy.

Several of the variables analysed, including MGA, reach duration, and the position of the final fixation along the vertical axis were not affected greatly either by obstacle properties or by the availability of visual information during the reach-to-grasp movement. A consistent MGA was revealed, with the exception of wide right obstacles inciting slightly larger MGAs compared to wide left obstacles at the centre-mid position. No further comparisons were seen to be significant across obstacle positions, width arrangements, or viewing conditions, likely because all experimental grasps occurred with one size of target object. Still, a trend in the data suggests smaller MGAs occurred in the visually-guided compared to memory-guided viewing conditions. Reach durations were not significantly different between viewing conditions, though a trend in the data indicates reaches without visual feedback might actually be slower than reaches with full vision, consistent with previous literature (i.e. Churchill et al., 2000; Connolly & Goodale, 1999). The reason significant differences in reach duration did not emerge could be related to the fact that slower movement speeds tend to be associated with increased uncertainty throughout the reach, allowing for a greater margin of error to complete effective goal-directed movements (Chapman & Goodale, 2010). Likely, the uncertainty involved with the paradigm degenerated quickly after experimentation as subjects became comfortable with the task, realizing the target object would remain in the same location and that flanker obstacles were not inherently dangerous. Lastly, participants generally maintained final fixations at comparable positions along the vertical axis, across obstacle positions, widths, and viewing conditions. This may relate to the central positioning of the target object, directly in subjects' line of sight. Overall, MGA, reach duration, and the position of the final fixation in the vertical plane were not found to be particularly affected by the characteristics of obstacles within the task environment, nor the availability of visual information, resulting mainly from methodological factors.

**General Obstacle Avoidance Approaches**

Before discussing the distinctive strategies adopted within each of the viewing conditions, the obstacle avoidance behaviours present in all viewing conditions will be examined. To begin with, subjects' index finger grasp locations tended to land at or to the left of the target object's COM in the horizontal plane, despite obstacle position or width. While this finding could have been caused in part by the placement of the recording IREDs on the left side of the index finger, it is more likely that the position of obstacles resulted in a general repulsion of the index finger away from obstacles on the same side as the reaching arm, as in previous literature (Chapman & Goodale, 2008, 2010; Dean & Brüwer, 1994; Garzorz et al., 2018; Marotta & Graham, 2016; Tresilian, 1998). The effect of positioned obstacles on index finger grasp site is further strengthened if we consider previous literature revealing final index finger placements landing to the right of the COM when grasping symmetrical 3-D objects (Desanghere & Marotta, 2015; Paulun, Kleinholdermann, Gegenfurtner, Smeets, & Brenner, 2014). Such a rightward bias in grasping symmetrical objects is indicative of an effect of handedness on grasp point selection, allowing increased visibility of the target object when grasping with the right hand (Paulun et al., 2014). Hence, the leftward bias we are seeing in index finger grasp site seems to result from a repulsion of the index finger away from obstacles positioned on the same side as the reaching arm.

Across all obstacle positions and width arrangements, participants' index finger bisections were similarly biased to the left, never actually travelling right of the midpoint between obstacles. This leftward bias could have resulted from the index finger being situated on the left side of the hand as it passed through the pair of obstacles, though it is more likely that the trajectory of the index finger was set to avoid obstacles on the right side of the grasp space. Further, obstacles at the centre-mid position elicited greater leftward bisection compared to obstacles at the centre-far position, supporting claims that obstacles positioned closer to the body are more obtrusive than obstacles further out (Garzorz et al., 2018; Tresilian, 1998). Besides this, participants' index fingers tended to bisect the space between obstacles furthest to the left when the obstacles were right-deviated, compared to centered, likely since the position of the target object was in close proximity to the left flanker obstacle when the pair was deviated to the right.

Evidence for the effect of positioned obstacles emerged in the horizontal path lengths of participants' index fingers, with larger path lengths in the presence of right-deviated obstacles, compared to centered obstacles. Although right-deviated obstacles allow greater clearance for the forearm during the reach, associated with a reduced risk of collision with the right obstacle of the pair, there is a need to maneuver the index finger around the left obstacle to make a stable grasp on the target object. With centered obstacles, the index finger would simply need to project forward from the start position to reach the centre of the target, ultimately requiring little variability in index finger trajectory. Further, greater horizontal path lengths of the index finger were observed at the centre-mid compared to the centre-far obstacle position, indicating a greater need to orient the hand around obstacles close to the body. Along similar lines, obstacles positioned close to the body posed the greatest mechanical challenge for the horizontal path lengths of participants' wrists, with obstacles at the centre-mid position eliciting the greatest horizontal deviation while the least deviation was observed with obstacles at the right-far position. Unlike the index finger, less deviation was needed for the wrist to maneuver around obstacles in the right-far position, likely because this position allowed the hand easy clearance when passing through. The larger path lengths of the index finger with right-deviated obstacles imply although the wrist is easier able to clear obstacles at this position, adjustments in the trajectory of the index finger are necessary for executing a stable grasp of the target object. This is consistent with previous literature (Brouwer et al., 2009; Galea, Castiello, & Dalwood, 2001; Land, 2009; Volcic & Domini, 2014) showing the more variable path of the index finger facilitates increased precision in grasping.

Lastly, overall gaze was generally directed at the target object rather than towards either of the flanker obstacles, consistent with the results of a previous investigation in our lab showing obstacles affected reach mechanics more than gaze behaviour (Marotta & Graham, 2016). The motor system needs to be sensitive to environmental characteristics to effectively complete goal-directed actions. However, the eyes are never in any physical danger of colliding with objects so can be less sensitive to the physical properties of the reaching space, to the extent that movement plans can be computed using peripheral vision exclusively (Chapman & Goodale, 2008). Nonetheless, further investigations manipulating the saliency of obstacles will increase understandings about the types of obstacles that can capture gaze.

Despite the effects of obstacles on performance, performance in all groups was quite good, showing successful grasps of the target object, minimal instances of collision, and final fixations that did not significantly differ from the target object's horizontal COM. In keeping with a previous study in our lab (Marotta & Graham, 2016), positioned obstacles tended not to capture the attention of subjects' gaze. Across viewing conditions, obstacle avoidance behaviours occurred in a manner consistent with the obstacle avoidance account of collision mitigation (Tresilian, 1998), whereby subjects' index fingers bisected the grasp space furthest to the left and greater horizontal path lengths of the index finger and wrist occurred when obstacles were at the most obtrusive position (close to the body and centered in the grasp space). Even still, distinctive obstacle avoidance strategies emerged depending on the availability of visual feedback throughout the reach-to-grasp movement.

**Obstacle Avoidance Strategy in the Visually-Guided Condition**

The results of the visually-guided condition provide evidence for the use of real-time visual information for the effective programming and online control of goal-directed actions, presumably by the dorsal stream (Milner & Goodale, 1995). Participants' final fixations and index finger locations on the target object along the horizontal axis were precisely adjusted to accommodate obstacle positions, with fixations and index finger placements pushed furthest left particularly when reaching between centrally-positioned obstacles. These results support the increased avoidance of particularly obtrusive obstacles along the reach path (Tresilian, 1998). Further, given any significant differences in the position of final fixations with respect to positioned obstacles were not apparent within either memory-guided condition, suggests it would be inefficient to attempt to tailor gaze to the task environment in the absence of continuous visual feedback. Our results provide further evidence for the coupling of eye and hand movements when visual information is available throughout the reach-to-grasp movement (Brouwer, Franz, & Gegenfurtner, 2009; de Grave, Hesse, Brouwer, & Franz, 2008; Desanghere & Marotta, 2011; Flanagan & Johansson, 2003; Johansson et al., 2001), as the difference between final fixation and final index finger positions on the target object remained consistent across all obstacle positions and width arrangements. Deviations around obstacles were "efficient", with the smallest horizontal path lengths of the index finger occurring in the visually-guided condition compared to memory-guided conditions. The horizontal paths of the wrist in the visually-guided condition appeared to be effectively adjusted to accommodate positioned obstacles, indicating visual information was utilized for the effective planning of the obstacle avoidance maneuver. Overall, the results of this group are consistent with the previous literature examining obstacle avoidance behavior under full visual feedback, supporting the role of the dorsal stream in the real-time control of action.

**Obstacle Avoidance Strategy in the Memory-Guided No-Delay Condition**

Results of the memory-guided no-delay condition are consistent with the real-time view of action whereby visual information may be used by the dorsal stream for action on a moment-to-moment basis but is not stored for use over time (Milner & Goodale, 1995). The memory-guided no-delay results differ from the results of the visually-guided group, as although visual information was available for computing an effective motor plan, only proprioceptive sensory feedback would have been available for making in-flight adjustments to the obstacle avoidance maneuver. Overall, the results are consistent with expectations that the obstacle avoidance strategy in the memory-guided no-delay condition relies on the real-time computations of the dorsal stream, though falls short due to the unavailability of visual information during movement execution.

Subjects in this group were able to sufficiently modify final index finger positions on the target object to account for obstacles positioned in the grasp space, similar to the visually-guided condition, although index finger placement was more variable in this condition, compared to visually-guided and memory-guided delay conditions. Without visual information to guide eye movements, final fixations on the target object were not affected by positioned obstacles in the horizonal plane. In other words, without vision throughout the reach-to-grasp movement, final fixations tended to consistently land at one general location on the target object despite the positions and widths of obstacles. Accordingly, the relationship between the final index finger and fixation positions on the target object along the horizontal axis was degraded, resulting from inadequate adjustments of final fixation positions in addition to increased variability in final index finger placement in response to positioned obstacles. In deviating around obstacles, the widest horizontal paths of the index finger were observed in this condition, compared to the visually-guided and memory-guided delay conditions, indicating an attempt to follow a similar obstacle avoidance trajectory as in the visually-guided group relying only on proprioceptive feedback to guide the movement in-flight. Likewise, the horizontal paths of the wrist in the memory-guided no-delay condition appeared to be effectively adjusted to accommodate positioned obstacles, indicating visual information was utilized for the effective planning of the obstacle avoidance maneuver. Ultimately, reaches occurring immediately without visual feedback seemingly rely on the action-based strategies of the dorsal stream (Milner & Goodale, 1995), with suboptimal execution in the absence of visual feedback for the online control of action.

**Obstacle Avoidance Strategy in the Memory-Guided Delay Condition**

The memory-guided delay group employed a more moderate, perceptual strategy for avoiding obstacles, in that positioned obstacles less often prompted alterations in the mechanics of the reach. Although positioned obstacles did not elicit the expected exaggerated avoidance responses in this group, results nonetheless provide evidence for a reliance on the stored perceptual representations of the ventral stream in delayed grasping (Milner & Goodale, 1995). In the absence of continuous visual information, reaches to remembered objects after a brief delay seemed to follow a "good enough" approach for avoiding obstacles. Presumably, without the availability of real-time visual information, attempting to adapt motor plans to account for the specific properties of obstacles would be inefficient and effortful.

Results of the memory-guided delay group mirrored the no-delay group in that final fixations were not modified according to positioned obstacles along the horizontal axis. It seems when acting upon remembered objects, final fixations need not be adjusted to precisely account for the positions or widths of obstacles. In the memory-guided grasping conditions, the eyes appear to take on a predominant role in maintaining the position of the target object irrespective of positioned obstacles, while the hand takes on the role of avoiding obstacles, relying largely on the guidance of proprioceptive sensory feedback. Previous studies support the use of such an oculomotor strategy as a way to reduce the load on internal cognitive resources when performing spatial memory tasks (Clark, 1997; Hodgson, Bajwa, Owen, & Kennard, 2000; Ketcham et al., 2003; Kirsch & Maglio, 1994).

Subjects in this group showed fewer instances of altered final index finger positions on the target object, accounting for obstacles in the grasp space, compared to the visually-guided and memory-guided no-delay conditions. That is to say, the index finger landed more often in one general location, to the left of the target object's COM, regardless of obstacle position or width. Likely, participants positioned their index finger at a location on the target object that they found to be "safe" early on during experimentation and continued to output a motor plan that would allow them to end up at that position. A moderate strategy such as this is indicative of subjects relying on behavioural heuristics, where formulating a unique motor plan to accommodate the characteristics of the task environment on every single trial is computationally costly in the absence of accurate visual information. This result is somewhat unexpected given the hypothesis that the interference of flanker obstacles should be exacerbated under memory guidance, although it provides unique insight into the type of perceptual strategy utilized when acting after a brief time delay in the absence of visual information. Moreover, the widths of obstacles did not result in exaggerated avoidance maneuvers. It seems the perceptual mechanisms of the ventral stream do not necessarily cause wider obstacles to be judged as more salient under memory guidance, at least in the context of our experimental paradigm. Although a gap space of 20 cm between obstacles proved challenging enough, with a number of collision events recorded, it is possible wider obstacles would incite more exaggerated avoidance strategies had the gap distance also been manipulated, increasing the necessity to steer clear of positioned obstacles. Potentially, intermittently inserting narrower gap distances might provoke exaggerated avoidance behavior, as this would demand adjustments to the motor plan, utilizing accurate information about the visual scene, on a trial-by-trial basis. Along similar lines, it is possible that manipulations of the density or stability of obstacles might induce differential avoidance strategies under memory guidance, such that more care is taken to avoid knocking over a less stable obstacle or bumping one's hand into a very stiff obstacle on the way to the target object. Regardless, it seems the deterioration of eye-hand coordination at the time of grasp resulted from the inadequate adjustment in final fixation and index finger positions in response to positioned obstacles.

In deviating around positioned obstacles, subjects in this viewing condition revealed horizontal path lengths of the index finger that did not significantly differ from those in the visually-guided and memory-guided no-delay conditions, indicating a more moderate route of avoidance. Similar to the placement of the index finger on the target object, participants seem to be deviating around obstacles such that they can effectively clear them, but so that they do not have to compute exact trajectories based upon the characteristics of the task environment. Moreover, reaches in the memory-guided delay condition appeared to elicit fewer instances of adjustment in the horizontal path of the wrist to accommodate positioned obstacles, indicating visual information about the scene was not utilized effectively for planning the obstacle avoidance maneuver. Overall, the results of the memory-guided delay condition are consistent with presumptions that delayed actions should not be able to benefit from the real-time computations of the dorsal stream (Milner & Goodale, 1995). However, contrary to expectation, subjects reaching in the absence of visual feedback after a brief delay resorted to a more moderate strategy in guiding an effective grasp through a cluttered environment.

**Summary**

In conclusion, this study provides novel evidence for the obstacle avoidance strategies utilized during memory-guided conditions, supportive of a shift in the visuomotor control of action from the dorsal to the ventral visual stream when grasping after a brief 2-s delay in the absence of visual feedback (Milner & Goodale, 1995). It appears obstacle avoidance under the memory-guided delay condition adopts a more moderate, rather than exaggerative, strategy. Future investigations are needed to examine how the properties of obstacles and the difficulty of the task might influence avoidance strategies under memory-guided conditions, pushing the boundaries of ventral stream control in obstacle avoidance paradigms. This research is significant in improving our understandings as to the roles of perception and action in our interactions with our surroundings, specifically, in considering the point at which perception might influence a forthcoming action. Realizing how healthy young adults perform in the context of the current experimental paradigm has the potential to advance efforts in improving the performance of individuals afflicted by sensory or motor impairment. Finally, knowledge as to the processes involved in natural human operations (i.e. reaching and grasping) may be beneficial in prompting modifications of gaming, robotics and user control systems to allow for more efficient manipulations of objects within real or virtual cluttered environments.

References

Abrams, R. A., Meyer, D. E., & Kornblum, S. (1990). Eye-hand coordination: oculomotor control in rapid aimed limb movements. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(2), 248–267. https://doi.org/10.1037/0096-1523.16.2.248

Allport, D. A., Tipper, S. P. & Chmiel, N. R. J. (1985). *Attention and Performance*. Cambridge, MA: MIT Press.

Ansuini, C., Tognin, V., Turella, L., & Castiello, U. (2007). Distractor objects affect fingers' angular distances but not fingers' shaping during grasping. *Experimental Brain Research*, *178*(2), 194–205. https://doi.org/10.1007/s00221-006-0723-0

Bagesteiro, L. B., Sarlegna, F. R., & Sainburg, R. L. (2006). Differential influence of vision and proprioception on control of movement distance. *Experimental Brain Research*, *171*(3), 358–370. https://doi.org/10.1007/s00221-005-0272-y

Bekkering, H., Adam, J. J., Kingma, H., Huson, A., & Whiting, H. T. A. (1994). Reaction time latencies of eye and hand movements in single- and dual-task conditions. *Experimental Brain Research*, *97*(3), 471–476.

Berthier, N., Clifton, R., Gullapalli, V., & McCall, D. (1996). Visual information and object size in the control of reaching. *Journal of Motor Behavior*, *28*(3), 187–197. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=pubmed&cmd=Retrieve&dopt=AbstractPlus&list_uids=16628151009069567648related:oA4lNz4Pw-YJ%5Cnpapers3://publication/uuid/530C1FCF-B4A0-42E3-BD11-CD11E19FB423

Binsted, G., Chua, R., Helsen, W., & Elliott, D. (2001). Eye ± hand coordination in goal-directed aiming. *Human Movement Science*, *20*, 563–585.

Bozzacchi, C., Brenner, E., Smeets, J. B., Volcic, R., & Domini, F. (2018). How removing visual information affects grasping movements. *Experimental Brain Research*, *236*(4), 985–995.

https://doi.org/10.1007/s00221-018-5186-6

Brouwer, A., Franz, V. H., & Gegenfurtner, K. R. (2009). Differences in fixations between grasping and viewing objects. *Journal of Vision*, *9(1)*(18), 1–24. https://doi.org/10.1167/9.1.18.Introduction

Bulloch, M. C., Prime, S. L., & Marotta, J. J. (2015). Anticipatory gaze strategies when grasping moving objects. *Experimental Brain Research*, *233*(12), 3413–3423. https://doi.org/10.1007/s00221-015-4413-7

Buneo, C. A., Jarvis, M. R., Batista, A. P., & Andersen, R. A. (2002). Direct visuomotor transformations for reaching. *Nature*, *416*(6881), 632–636.

Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology. Human Perception and Performance*, *7*(5), 1019–1030. https://doi.org/10.1037/0096-1523.7.5.1019

Carrozzo, M., Stratta, F., McIntyre, J., & Lacquaniti, F. (2002). Cognitive allocentric representations of visual space shape pointing errors. *Experimental Brain Research*, *147*(4), 426–436. https://doi.org/10.1007/s00221-002-1232-4

Castiello, U. (1996). Grasping a Fruit: Selection for Action. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(3), 582–603. https://doi.org/10.1037/0096-1523.22.3.582

Chapman, C. S., & Goodale, M. A. (2008). Missing in action: The effect of obstacle position and size on avoidance while reaching. *Experimental Brain Research*, *191*(1), 83–97. https://doi.org/10.1007/s00221-008-1499-1

Chapman, C. S., & Goodale, M. A. (2010). Seeing all the obstacles in your way: The effect of visual feedback and visual feedback schedule on obstacle avoidance while reaching. *Experimental Brain Research*, *202*(2), 363–375. https://doi.org/10.1007/s00221-009-2140-7

Christel, M. I., & Billard, A. (2002). Comparison between macaques' and humans' kinematics of prehension: the role of morphological differences and control mechanisms. *Behav. Brain Res., 131*, 169–184.

Chua, K. W., Bub, D. N., Masson, M. E. J., & Gauthier, I. (2018). Grasp representations depend on knowledge and attention. *Journal of Experimental Psychology: Learning Memory and Cognition*, *44*(2), 268–279. https://doi.org/10.1037/xlm0000453

Churchill, A., Hopkins, B., Rönnqvist, L., & Vogt, S. (2000). Vision of the hand and environmental context in human prehension. *Experimental Brain Research*, *134*(1), 81–89. https://doi.org/10.1007/s002210000444

Clark, A. (1997). *Being there: Putting brain, body and world together again*. Cambridge, MA: MIT Press.

Cloutman, L. L. (2013). Interaction between dorsal and ventral processing streams: Where, when and how? *Brain and Language*, *127*(2), 251–263. https://doi.org/10.1016/j.bandl.2012.08.003

Connolly, J. D., & Goodale, M. A. (1999). The role of visual feedback of hand position in the control of manual prehension. *Experimental Brain Research*, *125*(3), 281–286. https://doi.org/10.1007/s002210050684

Creem, S. H., & Proffitt, D. R. (1998). Two memories for geographical slant: Separation and interdependence of action and awareness. *Psychonomic Bulletin and Review*, *5*(1), 22–36. https://doi.org/10.3758/BF03209455

de Grave, D. D. J., Brenner, E., & Smeets, J. B. J. (2004). Illusions as a tool to study the coding of pointing movements. *Experimental Brain Research*, *155*(1), 56–62. https://doi.org/10.1007/s00221-003-1708-x

de Grave, D. D. J., Hesse, C., Brouwer, A.-M., & Franz, V. H. (2008). Fixation locations when grasping partly occluded objects. *Journal of Vision*, *8*(7), 1–11. https://doi.org/10.1167/8.7.5

de Haan, A. M., Van der Stigchel, S., Nijnens, C. M., & Dijkerman, H. C. (2014). The influence of object identity on obstacle avoidance reaching behaviour. *Acta Psychologica*, *150*, 94–99. https://doi.org/10.1016/j.actpsy.2014.04.007

Dean, J., & Brüwer, M. (1994). Control of human arm movements in two dimensions: paths and joint control in avoiding simple linear obstacles. *Experimental Brain Research*, 497–514.

Desanghere, L., & Marotta, J. J. (2011). "Graspability" of objects affects gaze patterns during perception and action tasks. *Experimental Brain Research*, *212*(2), 177–187. https://doi.org/10.1007/s00221-011-2716-x

Desanghere, L., & Marotta, J. J. (2015). The influence of object shape and center of mass on grasp and gaze. *Frontiers in Psychology*, *6*(OCT). https://doi.org/10.3389/fpsyg.2015.01537

Desmurget, M., Pélisson, D., Rossetti, Y., & Prablanc, C. (1998). From eye to hand: Planning goal-directed movements. *Neuroscience and Biobehavioral Reviews*, *22*(6), 761–788. https://doi.org/10.1016/S0149-7634(98)00004-9

Desmurget, M., Rossetti, Y., Jordan, M., Meckler, C., & Prablanc, C. (1997). Viewing the hand prior to movement improves accuracy of pointing performed toward the unseen contralateral hand. *Experimental Brain Research*, *115*(1), 180–186. https://doi.org/10.1007/PL00005680

Doya, K. (2000). Complementary roles of basal ganglia and cerebellum in learning and motor control. *Current Opinion in Neurobiology*, *10*(6), 732–739. https://doi.org/10.1016/S0959-4388(00)00153-7

Elliott, D., & Madalena, J. (1987). The influence of uncertainty and premovement visual information on manual aiming. *The Quarterly Journal of Experimental Psychology*, *39*(A), 541–559. https://doi.org/10.1037/h0084263

Farivar, R. (2009). Dorsal-ventral integration in object recognition. *Brain Research Reviews*, *61*(2), 144–153. https://doi.org/10.1016/j.brainresrev.2009.05.006

Fiehler, K., Wolf, C., Klinghammer, M., & Blohm, G. (2014). Integration of egocentric and allocentric information during memory-guided reaching to images of a natural environment. *Frontiers in Human Neuroscience*, *8*(August), 1–12. https://doi.org/10.3389/fnhum.2014.00636

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. *Nature*, *424*(6950), 769–771. https://doi.org/10.1038/nature01861

Flanagan, J. R., Terao, Y., & Johansson, R. S. (2008). Gaze Behavior When Reaching to Remembered Targets. *Journal of Neurophysiology*, *100*(3), 1533–1543. https://doi.org/10.1152/jn.90518.2008

Fukui, T., & Inui, T. (2006). The effect of viewing the moving limb and target object during the early phase of movement on the online control of grasping. *Human Movement Science*, *25*(3), 349–371. https://doi.org/10.1016/j.humov.2006.02.002

Fukui, T., & Inui, T. (2013). Utilization of visual feedback of the hand according to target view availability in the online control of prehension movements. *Human Movement Science*, *32*(4), 580–595. https://doi.org/10.1016/j.humov.2013.03.004

Galea, M. P., Castiello, U., & Dalwood, N. (2001). Thumb invariance during prehension movement: Effects of object orientation. *NeuroReport*, *12*(10), 2185–2187. https://doi.org/10.1097/00001756-200107200-00028

Garzorz, I. T., Knorr, A. G., Gilster, R., & Deubel, H. (2018). The influence of obstacles on grasp planning. *Experimental Brain Research*, *0*(0), 1–10. https://doi.org/10.1007/s00221-018-5321-4

Gentilucci, M., Toni, I., Chieffi, S., & Pavesi, G. (1994). The role of proprioception in the control of prehension movements: a kinematic study in a peripherally deafferented patient and in normal subjects. *Experimental Brain Research*, *99*(3), 483–500. https://doi.org/10.1007/BF00228985

Goodale, M. A., Jakobson, L. S., & Keillor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, *32*(10), 1159–1178. https://doi.org/10.1016/0028-3932(94)90100-7

Goodale, M. a., & Milner, a. D. (1992). Separate visual pathways for perception and action. [Review] [61 refs]. *Trends in Neurosciences*, *15*(1), 20–25. https://doi.org/10.1016/0166-2236(92)90344-8

Graziano, M. S. A., & Gross, C. G. (1994). Mapping Space With Neurons. *Current Directions in Psychological Science*, *3*(5), 164–167. https://doi.org/10.1111/1467-8721.ep10770670

Hayhoe, M. (2000). Vision using routines: A functional account of vision. *Visual Cognition*, *7*(1–3), 43–64. https://doi.org/10.1080/135062800394676

Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in Cognitive Sciences*, *9*(4), 188–194. https://doi.org/10.1016/j.tics.2005.02.009

Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B. (2003). Visual memory and motor planning in a natural task. *Journal of Vision*, *3*(1), 6. https://doi.org/10.1167/3.1.6

Heath, M., & Binsted, G. (2007). Visuomotor memory for target location in near and far reaching spaces. *Journal of Motor Behavior*, *39*(3), 169–177. https://doi.org/10.3200/JMBR.39.3.169-178

Hesse, C., de Grave, D., Franz, V. H., Brenner, E., & Smeets, J. B. J. (2008). Planning movements well in advance. *Cognitive Neuropsychology*, *25*(7–8), 985–995. https://doi.org/10.1080/02643290701862399

Hesse, C., & Franz, V. H. (2010). Grasping remembered objects: Exponential decay of the visual memory. *Vision Research*, *50*(24), 2642–2650. https://doi.org/10.1016/j.visres.2010.07.026

Himmelbach, M., & Karnath, H. O. (2005). Dorsal and ventral stream interaction: Contributions from optic ataxia. *Journal of Cognitive Neuroscience*, *17*(4), 632–640. https://doi.org/10.1162/0898929053467514

Hodgson, T. L., Bajwa, A., Owen, A. M., & Kennard, C. (2000). Strategic control of gaze direction during the Tower of London task. *J Cogn Neurosci, 12*, 894–907.

Howard, L. A., & Tipper, S. P. (1997). Hand deviations away from visual cues: Indirect evidence for inhibition. *Experimental Brain Research*, *113*(1), 144–152. https://doi.org/10.1007/BF02454150

Hu, Y., Eagleson, R., & Goodale, M. A. (1999). The effects of delay on the kinematics of grasping. *Experimental Brain Research*, *126*(1), 109–116. https://doi.org/10.1007/s002210050720

Hu, Y., & Goodale, M. A. (2000). Grasping after a delay shifts size-scaling from absolute to relative metrics. *Journal of Cognitive Neuroscience*, *12*(5), 856–868. https://doi.org/10.1162/089892900562462

Jackson, S. R., Jackson, G. M., & Rosicky, J. (1995). Are non-relevant objects represented in working memory? The effect of non-target objects on reach and grasp kinematics. *Experimental Brain Research*, *102*(3), 519–530. https://doi.org/10.1007/BF00230656

Jakobson, L. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: a kinematic analysis of human prehension. *Experimental Brain Research*, *86*(1), 199–208. https://doi.org/10.1007/BF00231054

Johansson, R. S., Westling, G., Bäckström, A., & Flanagan, J. R. (2001). Eye–Hand Coordination in Object Manipulation. *Journal of Neuroscience*, *21*(17), 6917–6932.

https://doi.org/10.1523/JNEUROSCI.21-17-06917.2001

Keefe, B. D., Suray, P.-A., & Watt, S. J. (2019). A margin for error in grasping: hand pre-shaping takes into account task-dependent changes in the probability of errors. *Experimental Brain Research*, *237*(4), 1063–1075. https://doi.org/10.1007/s00221-019-05489-z

Ketcham, C. J., Hodgson, T. L., Kennard, C., & Stelmach, G. E. (2003). Memory-motor transformations are impaired in Parkinson's disease. *Experimental Brain Research*, *149*(1), 30–39. https://doi.org/10.1007/s00221-002-1332-1

Kirsh, D., & Maglio, P. (1994). On distinguishing between epistemic and pragmatic action. *Cogn Sci, 18*, 513–549.

Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience*, *26*(1), 51–62. https://doi.org/10.1017/S0952523808080899

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research*, *41*(25–26), 3559–3565. https://doi.org/10.1016/S0042-6989(01)00102-X

Land, M., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception*, *28*(11), 1311–1328. https://doi.org/10.1068/p2935

Marotta, J. J., & Graham, T. J. (2016). Cluttered environments: Differential effects of obstacle position on grasp and gaze locations. *Canadian Journal of Experimental Psychology*, *70*(3), 242–247. https://doi.org/10.1037/cep0000079

Mcgowan, J. W., Kowler, E., Sharma, A., & Chubb, C. (1998). Saccadic localization of random dot targets. *Vision Research*, *38*(6), 895–909. https://doi.org/10.1016/S0042-6989(97)00232-0

McIntosh, R. D., McClements, K. I., Dijkerman, H. C., Birchall, D., & Milner, A. D. (2004).

Preserved obstacle avoidance during reaching in patients with left visual neglect. *Neuropsychologia*, *42*(8), 1107–1117. https://doi.org/10.1016/j.neuropsychologia.2003.11.023

McIntosh, R. D., McClements, K. I., Schindler, I., Cassidy, T. P., Birchall, D., & Milner, A. D. (2004). Avoidance of obstacles in the absence of visual awareness. *Proceedings of the Royal Society B: Biological Sciences*, *271*(1534), 15–20. https://doi.org/10.1098/rspb.2003.2545

Medina, J., Jax, S. A., & Coslett, H. B. (2009). Two-component models of reaching: Evidence from deafferentation in a Fitts' law task. *Neuroscience Letters*, *451*(3), 222–226. https://doi.org/10.1016/j.neulet.2009.01.002

Meegan, D. V., & Tipper, S. P. (1998). Reaching into Cluttered Visual Environments: Spatial and Temporal Influences of Distracting Objects. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, *51*(2), 225–249. https://doi.org/10.1080/027249898391611

Melcher, D., & Kowler, E. (1999). Shapes, surfaces and saccades. *Vision Research*, *39*(17), 2929–2946. https://doi.org/10.1016/S0042-6989(99)00029-2

Menger, R., Dijkerman, H. C., & Van der Stigchel, S. (2013). The Effect of Similarity: Non-Spatial Features Modulate Obstacle Avoidance. *PLoS ONE*, *8*(4). https://doi.org/10.1371/journal.pone.0059294

Milner, A. D., Dijkerman, H. C., Pisella, L., McIntosh, R. D., Tilikete, C., Vighetto, A., & Rossetti, Y. (2001). Grasping the past: Delay can improve visuomotor performance. *Current Biology*, *11*(23), 1896–1901. https://doi.org/10.1016/S0960-9822(01)00591-7

Mon-Williams, M., Tresilian, J. R., Coppard, V. L., & Carson, R. G. (2001). The effect of obstacle position on reach-to-grasp movements. *Experimental Brain Research*, *137*(3–4), 497–501. https://doi.org/10.1007/s002210100684

Neely, K. A., Binsted, G., & Heath, M. (2008). Egocentric and allocentric visual cues influence the specification of movement distance and direction. *Journal of Motor Behavior*, *40*(3), 203–213. https://doi.org/10.3200/JMBR.40.3.203-213

Neggers, S. F. W., & Bekkering, H. (2000). Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology*, *83*(1995), 639–651.

Obhi, S. S., & Goodale, M. A. (2005). The effects of landmarks on the performance of delayed and real-time pointing movements. *Experimental Brain Research*, *167*(3), 335–344. https://doi.org/10.1007/s00221-005-0055-5

Paul M. Fitts. (1954). the Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology*, *47*(6), 381–391. Retrieved from http://www2.psychology.uiowa.edu/faculty/mordkoff/InfoProc/pdfs/Fitts 1954.pdf

Paulun, V. C., Kleinholdermann, U., Gegenfurtner, K. R., Smeets, J. B. J., & Brenner, E. (2014). Center or side: Biases in selecting grasp points on small bars. *Experimental Brain Research*, *232*(7), 2061–2072. https://doi.org/10.1007/s00221-014-3895-z

Prablanc, C., Pelisson, D., & Goodale, M. A. (1986). Visual control of reaching movements without vision of the limb. *Experimental Brain Research*, *62*(2), 293–302. https://doi.org/10.1007/bf00238849

Prime, S. L., & Marotta, J. J. (2013). Gaze strategies during visually-guided versus memory-guided grasping. *Experimental Brain Research*, *225*(2), 291–305. https://doi.org/10.1007/s00221-012-3358-3

Rand, M. K., Lemay, M., Squire, L. M., Shimansky, Y. P., & Stelmach, G. E. (2007). Role of vision in aperture closure control during reach-to-grasp movements. *Experimental Brain Research*, *181*(3), 447–460. https://doi.org/10.1007/s00221-007-0945-9

Rice, N. J., Edwards, M. G., Schindler, I., Punt, T. D., McIntosh, R. D., Humphreys, G. W., … Milner, A. D. (2008). Delay abolishes the obstacle avoidance deficit in unilateral optic ataxia. *Neuropsychologia*, *46*(5), 1549–1557. https://doi.org/10.1016/j.neuropsychologia.2008.01.012

Rice, N. J., McIntosh, R. D., Schindler, I., Mon-Williams, M., Démonet, J. F., & Milner, A. D. (2006). Intact automatic avoidance of obstacles in patients with visual form agnosia. *Experimental Brain Research*, *174*(1), 176–188. https://doi.org/10.1007/s00221-006-0435-5

Rosenbaum, D. A., Vaughan, J., Meulenbroek, R. J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review*, *108*(4), 709–734. https://doi.org/10.1037/0033-295X.108.4.709

Roy, A. C., Paulignan, Y., Farne, A., Jouffrais, C. & Boussaoud, D. (2000). Hand kinematics during reaching and grasping in the macaque monkey. *Behav. Brain Res., 117*, 75–78.

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying Fixations and Saccades in Eye-Tracking Protocols, 71–78. Retrieved from https://www.cs.drexel.edu/~salvucci/publications/Salvucci-ETRA00.pdf

Santello, M., Flanders, M., & Soechting, J. F. (2002). Patterns of Hand Motion during Grasping and the Influence of Sensory Guidance. *The Journal of Neuroscience*, *22*(4), 1426–1435. https://doi.org/22/4/1426 [pii]

Sarlegna, F. R., & Sainburg, R. L. (2009). The roles of vision and proprioception in the planning of reaching movements. *Adv Exp Med Biol*, *629*, 317–335. https://doi.org/10.1007/978-3-319-47313-0

Sartori, L., Camperio Ciani, A., Bulgheroni, M. & Castiello, U. (2013). Reaching and grasping behaviour in Macaca fascicularis: a kinematic study. *Exp. Brain Res., 224*, 119–124.

Sartori, L., Camperio-Ciani, A., Bulgheroni, M., & Castiello, U. (2014). Monkey see, Monkey reach: Action selection of reaching movements in the macaque monkey. *Scientific Reports*, *4*, 1–6. https://doi.org/10.1038/srep04019

Saunders, J. A., & Knill, D. C. (2004). Visual Feedback Control of Hand Movements. *Journal of Neuroscience*, *24*(13), 3223–3234. https://doi.org/10.1523/JNEUROSCI.4319-03.2004

Schindler, I., Rice, N. J., McIntosh, R. D., Rossetti, Y., Vighetto, A., & Milner, A. D. (2004). Automatic avoidance of obstacles is a dorsal stream function: Evidence from optic ataxia. *Nature Neuroscience*, *7*(7), 779–784. https://doi.org/10.1038/nn1273

Soechting, J. F., & Flanders, M. (1992). Moving in three-dimensional space: Frames of reference, vectors, and coordinate systems. *Annual Review of Neuroscience*, *15*, 167–191.

Striemer, C. L., Chapman, C. S., & Goodale, M. A. (2009). “Real-time” obstacle avoidance in the absence of primary visual cortex. *Proceedings of the National Academy of Sciences*, *106*(37), 15996–16001. https://doi.org/10.1073/pnas.0905549106

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance*, *9*(3), 427–443. https://doi.org/10.1037/0096-1523.9.3.427

Tipper, S. P., Howard, L. A., & Jackson, S. R. (1997). Selective reaching to grasp: Evidence for distractor interference effects. *Visual Cognition*, *4*(1), 1–38. https://doi.org/10.1080/713756749

Tresilian, J. R. (1999). Selective attention in reaching: When is an object not a distractor? *Trends in Cognitive Sciences*, *3*(11), 407–408. https://doi.org/10.1016/S1364-6613(99)01390-X

Tresilian, James R. (1998). Attention in action or obstructin of movement? A kinematic analysis of avoidance behavior in prehension. *Experimental Brain Research*, *120*(3), 352–368. https://doi.org/10.1007/s002210050409

Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Sciences*, *95*(February), 883–890. https://doi.org/10.1073/pnas.95.3.883

van Polanen, V., & Davare, M. (2015). Interactions between dorsal and ventral streams for controlling skilled grasp. *Neuropsychologia*, *79*, 186–191. https://doi.org/10.1016/j.neuropsychologia.2015.07.010

Verheij, R., Brenner, E., & Smeets, J. B. J. (2014). The influence of target object shape on maximum grip aperture in human grasping movements. *Experimental Brain Research*, *232*(11), 3569–3578. https://doi.org/10.1007/s00221-014-4046-2

Vishwanath, D., & Kowler, E. (2004). Saccadic localization in the presence of cues to three-dimensional shape. *Journal of Vision*, *4*(6), 445–458. https://doi.org/10.1167/4.6.4

Vishwanath, Dhanraj, & Kowler, E. (2003). Localization of shapes: Eye movements and perception compared. *Vision Research*, *43*(15), 1637–1653. https://doi.org/10.1016/S0042-6989(03)00168-8

Vishwanath, Dhanraj, Kowler, E., & Feldman, J. (2000). Saccadic localization of occluded targets. *Vision Research*, *40*(20), 2797–2811. https://doi.org/10.1016/S0042-6989(00)00118-8

Volcic, R., & Domini, F. (2014). The visibility of contact points influences grasping movements. *Experimental Brain Research*, *232*(9), 2997–3005. https://doi.org/10.1007/s00221-014-3978-x

Volcic, R., & Domini, F. (2016). On-line visual control of grasping movements. *Experimental Brain Research*, *234*(8), 2165–2177. https://doi.org/10.1007/s00221-016-4620-x

Voudouris, D., Brenner, E., Schot, W. D., & Smeets, J. B. J. (2010). Does planning a different trajectory influence the choice of grasping points? *Experimental Brain Research*, *206*(1), 15–24. https://doi.org/10.1007/s00221-010-2382-4

Voudouris, D., Smeets, J. B. J., & Brenner, E. (2016). Fixation biases towards the index finger in almost-natural grasping. *PLoS ONE*, *11*(1), e0146864. https://doi.org/10.1371/journal.pone.0146864

Westwood, D. A., & Goodale, M. A. (2003). Perceptual illusion and the real-time control of action.

Westwood, D. A., Heath, M., & Roy, E. A. (2003). No evidence for accurate visuomotor memory: Systematic and variable error in memory-guided reaching. *Journal of Motor Behavior*, *35*(2), 127–133. https://doi.org/10.1080/00222890309602128

Westwood, D. A., McEachern, T., & Roy, E. A. (2001). Delayed grasping of a Müller-Lyer figure. *Experimental Brain Research*, *141*(2), 166–173. https://doi.org/10.1007/s002210100865

Whitwell, R. L., & Goodale, M. A. (2009). Updating the programming of a precision grip is a function of recent history of available feedback. *Experimental Brain Research*, *194*(4), 619–629. https://doi.org/10.1007/s00221-009-1737-1

Whitwell, R. L., Striemer, C. L., Nicolle, D. A., & Goodale, M. A. (2011). Grasping the non-conscious: Preserved grip scaling to unseen objects for immediate but not delayed grasping following a unilateral lesion to primary visual cortex. *Vision Research*, *51*(8), 908–924. https://doi.org/10.1016/j.visres.2011.02.005

Winges, S. A., Weber, D. J., & Santello, M. (2003). The role of vision on hand preshaping during reach to grasp. *Experimental Brain Research*, *152*(4), 489–498. https://doi.org/10.1007/s00221-003-1571-9

Wise, S. P., Boussaoud, D., Johnson, P. B., & Caminiti, R. (1997). PREMOTOR AND PARIETAL CORTEX: Corticocortical Connectivity and Combinatorial Computations. *Annual Review of Neuroscience*, *20*(1), 25–42.

Appendix A

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:**
Dr. Jonathan Marotta, Professor
Ryan Langridge, PhD Student
Hana Abbas, MA Student
Aneet Saran, Honours Student

Department of Psychology
University of Manitoba

**SOURCE OF SUPPORT: NSERC CGSM and 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, 2022). 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 B

Modified Edinburgh Handedness Assessment

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 soup with a spoon. L/R
4. Comb your hair. L/R
5. Cut bread with a knife. L/R
6. Swing tennis/badminton racquet or bat. L/R
7. Hammer a nail. L/R
8. Point to something accurately. L/R
9. Write your name. L/R

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

IPD: __________

Appendix C

Debriefing Form

**INVESTIGATORS:** Dr. Jonathan Marotta (Professor)
Ryan Langridge (PhD Student)
Hana Abbas (MA Student)
Aneet Saran (Honours Student)

Department of Psychology
University of Manitoba

---

Thank you for participating in this study. In this study we were interested in where on the object you were looking when grasping it. Despite the co-occurrence of both vision and visuomotor processes, vision and motor functioning are typically studied independently, so their critical interactions are poorly understood. What is currently lacking in this area is a clear understanding of where people are looking while grasping objects of varying complexity. Specifically, this study sought to expand current understandings of visual and visuomotor interactions by characterizing the location of eye-movements made to visually presented objects. If you have any questions later on, please feel free to contact me – my contact information is on your consent form. Thank-you again for participating, and have a great day.

Appendix D

Initial Ethics Approval

UNIVERSITY OF MANITOBA | Research Ethics and Compliance

Human Ethics
208-194 Dafoe Road
Winnipeg, MB
Canada R3T 2N2
Phone +204-474-7122
Email: humanethics@umanitoba.ca

**PROTOCOL APPROVAL**

**TO:** **Ryan Langridge**
**Jonathan Marotta**
Principal Investigators

**FROM:** **Kelley Main, Chair**
Psychology/Sociology Research Ethics Board (PSREB)

**Re:** **Protocol #P2017:050 (HS20735)**
**"Eye-Hand Coordination: 3-D Objects"**

---

**Effective:** April 25, 2017 **Expiry:** April 25, 2018

**Psychology/Sociology Research Ethics Board (PSREB)** has reviewed and approved the above research. PSREB is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.*

This approval is subject to the following conditions:

1. Approval is granted only for the research and purposes described in the application.
2. Any modification to the research must be submitted to PSREB for approval before implementation.
3. Any deviations to the research or adverse events must be submitted to PSREB as soon as possible.
4. This approval is valid for one year only and a Renewal Request must be submitted and approved by the above expiry date.
5. A Study Closure form must be submitted to PSREB when the research is complete or terminated.
6. The University of Manitoba may request to review research documentation from this project to demonstrate compliance with this approved protocol and the University of Manitoba *Ethics of Research Involving Humans.*

**Funded Protocols:**

- **Please mail/e-mail a copy of this Approval, identifying the related UM Project Number, to the Research Grants Officer in ORS.**

Research Ethics and Compliance is a part of the Office of the Vice-President (Research and International)
umanitoba.ca/research

# Appendix E

## Significant Bonferroni Pairwise Comparisons

Table 1

*Final Fixation along the Vertical Plane (cm)*

| Position × Width × Viewing Condition | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Viewing Condition | Position | Width | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
| Delay | 3 | Right vs Same | 2.7 | .5 | 3.5 | .4 | .016 | -.014 | -.001 |

*Note*. Negative values denote coordinates below the target object's COM, while positive values denote coordinates above the target object's COM.

Table 2

*Final Fixation along the Horizontal Plane (cm)*

| Position × Viewing Condition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Viewing Condition | Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
| Vision | 1 vs 3 | -.4 | .2 | .7 | .3 | .000 | -.016 | -.005 |
| Vision | 1 vs 4 | -.4 | .2 | .7 | .3 | .000 | -.015 | -.004 |
| Vision | 2 vs 3 | -.6 | .2 | .5 | .2 | .000 | -.018 | -.006 |
| Vision | 2 vs 4 | -.6 | .2 | .5 | .2 | .000 | -.015 | -.006 |

*Note*. Negative values denote coordinates to the left of the target object's COM, while positive values denote coordinates to the right of the target object's COM.

Table 3

*Final Index Finger Position in the Horizontal Plane (cm)*

| Position × Width × Viewing Condition | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Viewing Condition | Width | Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
| Vision | Left | 1 vs 3 | -1.7 | .4 | 0 | .4 | .000 | -.025 | -.008 |
| Vision | Left | 1 vs 4 | -1.7 | .4 | -.2 | .4 | .000 | -.023 | -.006 |
| Vision | Left | 2 vs 3 | -1.4 | .3 | 0 | .4 | .000 | -.022 | -.006 |
| Vision | Left | 2 vs 4 | -1.4 | .3 | -.2 | .4 | .000 | -.019 | -.005 |
| Vision | Right | 1 vs 3 | -1.2 | .3 | -.3 | .4 | .031 | -.019 | -.001 |
| Vision | Right | 2 vs 3 | -1.4 | .4 | -.3 | .4 | .006 | -.019 | -.002 |
| Vision | Right | 2 vs 4 | -1.4 | .4 | -.6 | .3 | .029 | -.015 | -.001 |
| Vision | Same | 1 vs 3 | -1.5 | .4 | -.2 | .4 | .002 | -.021 | -.004 |
| Vision | Same | 1 vs 4 | -1.5 | .4 | -.5 | .3 | .000 | -.015 | -.004 |
| Vision | Same | 2 vs 3 | -1.4 | .3 | -.2 | .4 | .006 | -.021 | -.003 |
| Vision | Same | 2 vs 4 | -1.4 | .3 | -.5 | .3 | .003 | -.014 | -.002 |
| No-Delay | Left | 1 vs 3 | -1.6 | .4 | -.4 | .4 | .001 | -.02 | -.004 |
| No-Delay | Left | 1 vs 4 | -1.6 | .4 | -.5 | .4 | .003 | -.02 | -.003 |
| No-Delay | Right | 1 vs 3 | -1.5 | .3 | -.3 | .4 | .003 | -.021 | -.003 |
| No-Delay | Right | 1 vs 4 | -1.5 | .3 | -.9 | .3 | .044 | -.013 | .0 |
| No-Delay | Right | 2 vs 3 | -1.2 | .4 | -.3 | .4 | .028 | -.018 | -.001 |
| No-Delay | Same | 1 vs 3 | -1.4 | .4 | -.2 | .4 | .003 | -.021 | -.003 |
| No-Delay | Same | 1 vs 4 | -1.4 | .4 | -.6 | .3 | .001 | -.014 | -.003 |
| No-Delay | Same | 2 vs 3 | -1.6 | .3 | -.2 | .4 | .001 | -.023 | -.005 |
| No-Delay | Same | 2 vs 4 | -1.6 | .3 | -.6 | .3 | .000 | -.016 | -.004 |
| Delay | Left | 2 vs 3 | -1.8 | .3 | -.8 | .4 | .007 | -.018 | -.002 |
| Delay | Left | 3 vs 4 | -.8 | .4 | -1.5 | .4 | .039 | .0 | .013 |

*Note*. Negative values denote coordinates to the left of the target object's COM, while positive values denote coordinates to the right of the target object's COM.

Table 4

*Distance between the Final Fixation and the Final Index Finger Positions on the Target along the Horizontal Plane (cm)*

| Position × Width × Viewing Condition | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Viewing Condition | Position | Width | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
| Vision vs Delay | 2 | Left | .9 | .4 | 2.4 | .4 | .031 | -.031 | -.001 |
| No-Delay | 1 vs 3 | Left | 1.6 | .4 | .4 | .5 | .012 | .002 | .021 |
| No-Delay | 1 vs 3 | Same | 1.6 | .5 | .1 | .5 | .004 | .004 | .025 |
| Delay | 2 vs 3 | Left | 2.4 | .4 | 1.1 | .5 | .010 | .002 | .024 |
| Delay | 1 vs 2 | Right | 2.4 | .4 | 1.3 | .4 | .022 | .001 | .022 |
| Delay | 1 vs 3 | Right | 2.4 | .4 | 1.2 | .5 | .033 | .001 | .024 |

*Note*. Negative values represent final fixation positions that landed further left than final index finger positions, while positive values represent final fixation positions that landed further right than final index finger positions.

Table 5

*Index Finger Bisection of the Grasp Space (cm)*

| Position | | | | | | | |
|---|---|---|---|---|---|---|---|
| Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
| 1 vs 2 | 8.3 | .2 | 6.3 | .2 | .042 | 7.5E-05 | .006 |
| 1 vs 3 | 8.3 | .2 | 6.3 | .2 | .000 | .015 | .024 |
| 1 vs 4 | 8.3 | .2 | 6.3 | .2 | .000 | .015 | .024 |
| 2 vs 3 | 8.0 | .2 | 6.3 | .2 | .000 | .011 | .022 |
| 2 vs 4 | 8.0 | .2 | 6.3 | .2 | .000 | .013 | .021 |

*Note*. Smaller values indicate a closeness of the index finger to the inner edge of the left flanker obstacle, while larger values indicate a closeness of the index finger to the inner edge of the right flanker obstacle.

Table 6

*Maximum Grip Aperture (cm)*

| Viewing Condition | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| **Viewing Condition** | | | | | | | |
| Vision vs No-Delay | 9.5 | .3 | 10.3 | .3 | 0.189 | -.019 | .002 |
| Vision vs Delay | 9.5 | .3 | 10.4 | .3 | 0.142 | -.019 | .002 |
| No-Delay vs Delay | 10.3 | .3 | 10.4 | .3 | 1.000 | -.011 | .01 |

| Position | Width | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|---|
| **Obstacle Position × Width** | | | | | | | | |
| 2 | Left vs Right | 10.1 | .2 | 10.2 | .2 | .037 | -.003 | -6.4E-05 |

Table 7

*Horizontal Path Length of the Index Finger (cm)*

| Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| **Position** | | | | | | | |
| 1 vs 2 | 2.6 | .1 | 2.9 | .1 | .044 | -.005 | -4.6E-05 |
| 1 vs 3 | 2.6 | .1 | 3.5 | .2 | .000 | -.014 | -.005 |
| 1 vs 4 | 2.6 | .1 | 3.6 | .2 | .000 | -.014 | -.004 |
| 2 vs 3 | 2.9 | .1 | 3.5 | .2 | .007 | -.012 | -.001 |
| 2 vs 4 | 2.9 | .1 | 3.6 | .2 | .024 | -.013 | -.001 |

| Viewing Condition | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| **Viewing Condition** | | | | | | | |
| Vision vs No-Delay | 2.6 | .2 | 3.5 | .2 | .044 | -.017 | .0 |

Table 8

*Horizontal Path Length of the Wrist (cm)*

Position × Viewing Condition

| Viewing Condition | Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|---|
| Vision | 1 vs 2 | 9.5 | .4 | 10.8 | .4 | .001 | -.022 | -.005 |
| Vision | 1 vs 3 | 9.5 | .4 | 7.3 | .4 | .000 | .013 | .029 |
| Vision | 2 vs 3 | 10.8 | .4 | 7.3 | .4 | .000 | .026 | .044 |
| Vision | 2 vs 4 | 10.8 | .4 | 9.1 | .4 | .000 | .009 | .026 |
| Vision | 3 vs 4 | 7.3 | .4 | 9.1 | .4 | .000 | -.024 | -.01 |
| No-Delay | 1 vs 2 | 9.1 | .4 | 10.3 | .5 | .007 | -.021 | -.003 |
| No-Delay | 1 vs 3 | 9.1 | .4 | 7.3 | .4 | .000 | .01 | .026 |
| No-Delay | 2 vs 3 | 10.3 | .5 | 7.3 | .4 | .000 | .02 | .039 |
| No-Delay | 2 vs 4 | 10.3 | .5 | 8.3 | .5 | .000 | .011 | .029 |
| No-Delay | 3 vs 4 | 7.3 | .4 | 8.3 | .5 | .003 | -.017 | -.003 |
| Delay | 1 vs 3 | 10.3 | .4 | 8.3 | .4 | .000 | .012 | .028 |
| Delay | 2 vs 3 | 10.4 | .4 | 8.3 | .4 | .000 | .012 | .03 |
| Delay | 3 vs 4 | 8.3 | .4 | 9.5 | .4 | .000 | -.019 | -.005 |

Position × Width

| Position | Width | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|---|
| 4 | Left vs Same | 9.6 | .4 | 8.4 | .2 | .021 | -.022 | -.001 |
| 1 vs 3 | Left | 9.9 | .4 | 7.7 | .2 | .000 | .012 | .032 |
| 2 vs 3 | Left | 10.3 | .3 | 7.7 | .2 | .000 | .018 | .034 |
| 3 vs 4 | Left | 7.7 | .2 | 9.6 | .4 | .000 | -.029 | -.009 |
| 1 vs 2 | Right | 9.5 | .3 | 10.7 | .3 | .000 | -.017 | -.006 |
| 1 vs 3 | Right | 9.5 | .3 | 7.6 | .2 | .000 | .013 | .026 |
| 1 vs 4 | Right | 9.5 | .3 | 8.9 | .3 | .015 | .001 | .012 |
| 2 vs 3 | Right | 10.7 | .3 | 7.6 | .2 | .000 | .024 | .038 |
| 2 vs 4 | Right | 10.7 | .3 | 8.9 | .3 | .000 | .013 | .023 |
| 3 vs 4 | Right | 7.6 | .2 | 8.9 | .3 | .000 | -.019 | -.007 |
| 1 vs 2 | Same | 9.4 | .3 | 10.5 | .3 | .001 | -.017 | -.003 |
| 1 vs 3 | Same | 9.4 | .3 | 7.6 | .3 | .000 | .011 | .025 |
| 1 vs 4 | Same | 9.4 | .3 | 8.4 | .2 | .000 | .005 | .016 |
| 2 vs 3 | Same | 10.5 | .3 | 7.6 | .3 | .000 | .022 | .035 |
| 2 vs 4 | Same | 10.5 | .3 | 8.4 | .2 | .000 | .014 | .028 |
| 3 vs 4 | Same | 7.6 | .3 | 8.4 | .2 | .020 | -.015 | -.001 |

*Note*. Data for one participant in the memory-guided no delay condition was not available, due to significant drops in data from the wrist sensors.

Table 9

*Reach Duration (ms)*

| Viewing Condition | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| Vision vs No-Delay | 741.07 | 70.55 | 934.99 | 70.55 | .181 | -44.56 | 5.77 |
| Vision vs Delay | 741.07 | 70.55 | 976.97 | 70.55 | .072 | -48.75 | 1.57 |
| No-Delay vs Delay | 934.99 | 70.55 | 976.97 | 70.55 | 1.000 | -29.361 | 20.97 |

| Position | *M1* | *SEM1* | *M2* | *SEM2* | *p* | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| 3 vs 4 | 872.98 | 40.07 | 902.20 | 46.40 | .032 | -5.67 | -.017 |

*Note*. The comparisons depicted for the effect of viewing condition were not of significance but are used to exemplify a trend.

Appendix F

One Sample T-Tests

Table 10

*Final Fixation Position Compared to Target's Horizontal COM*

| Viewing Condition | *t* | *df* | *p* | Holm-Bonferroni *p*-value | Mean difference | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| Vision | .214 | 11 | .835 | .0083 | .00043 | -.004 | .0048 |
| No-Delay | -.15 | 11 | .883 | .01 | -.00035 | -.0055 | .0048 |
| Delay | 1.654 | 11 | .126 | .0125 | .0031 | -.001 | .0072 |

*significant at corrected Holm-Bonferroni p-value

Table 11

*Final Index Finger Position Compared to Target's Horizontal COM*

| Viewing Condition | *t* | *df* | *p* | Holm-Bonferroni *p*-value | Mean difference | 95% CI Lower | 95% CI Upper |
|---|---|---|---|---|---|---|---|
| Vision | -4.654 | 11 | .001* | .0167 | -.0087 | -.013 | -.0046 |
| No-Delay | -2.028 | 11 | .067 | .025 | -.0094 | -.02 | .0008 |
| Delay | -4.791 | 11 | .001* | .05 | -.013 | -.019 | -.0069 |

*significant at corrected Holm-Bonferroni p-value