EYE-HAND COORDINATION DURING REACHES AROUND AN OBJECT

by

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Abstract

Studies into reaching have typically looked at the reaching arm or the eyes alone, ranging from single actions performed in controlled lab settings to a series of actions completed in natural environments. The current experiment looked at measures of the hand, arm and eyes as a right-handed subject performed a single reach and grasp action among real objects with their right hand. Specifically, this experiment was designed to investigate the impact of a potential non-target object (NTO) in the reach space on eye-hand coordination. Results showed that NTOs contralateral to the reaching arm produced almost no effects, whereas those ipsilateral became more “invasive” as they were located nearer a subject. Ipsilateral NTOs also produced a shift away from their location in fixation and grasp location on a target. These results suggest the brain used an “attention-for-action” system that highlighted locations as they became more relevant to the task.

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Introduction

Reaching to grasp objects is the fundamental way that humans interact with their environment. It facilitates the use of tools and the manipulation of our environment. Reaching is so ubiquitous to the human experience that, although we perform the action frequently, it requires almost no conscious planning to execute. However, the ease and efficiency in making a reach hides what must be a sophisticated interaction between multiple information processing systems in the brain. Visual information about the environment is communicated to the motor-system as it is needed to produce optimal trajectories for the hand through space. Visual information about a reach target is used to generate accurate and stable grasp mechanics. Vision also informs about areas of potential collision, ensuring that a busy researcher doesn't knock over their coffee while reaching through their papers. The coordination between the visual and motor systems additionally is prepared to respond almost instantly if they do knock the coffee over, so that their work isn't ruined in the spill.

The past 20 years have seen an improvement in the theoretical understanding of prehension, along with maturation in the technology used to measure its components. Because of this, modern paradigms can now integrate a range of measures typically utilized separately in the prior literature. In other words, it is now possible to combine data derived from measures of both the eyes and hand to better understand the dynamics of eye-hand coordination. It is also possible to begin work on new models and heuristics of human reach. With the maturation in technology, models complementary to those of Fitts' law (Fitts, 1954) of reach timing can be generated that incorporate information about the eyes as well as the hand. This allows us to now begin answering Berenstein's (1967) degrees of freedom problem, providing some understanding of why, of the infinite possible ways an action could be performed, people select the methods they do.

Features of the Gaze System

Humans direct their gaze through space to gather visual information about the world around them, bringing a point in space into the center of vision. Gaze therefore provides the most detailed and featurally rich information about the environment to the brain. Studies of the movements and fixations of the eyes across a visual scene is a robust field of investigation. However, gaze deployment during action is often studied using two-dimensional displays, with small and localized targets. For instance, Binsted, Chua, Helsen and Elliott (2001) developed a pointing task that utilized small LED lights to recreate the ends of the Müller-Lyer illusion (a neutral X, or half an X to produce the semi-triangular < or > shape), in order to influence subject's perception of target location, measured by saccadic deployment. Though Binsted et al. (2001) have provided an essential stepping-stone for the investigation of visuomotor behaviour, modern technology allows us to move into settings where real objects can be used in place of LED lights or other artificial stimuli.

More real world attempts to examine gaze have come from complex sequences of actions. Land, Mennie and Rusted (1999) tracked the deployment of gaze while subjects prepared tea in a kitchen. Though this environment is highly ecologically valid, the complexity of the task sequence requires the deployment of gaze during multiple motor plans. Forester, Carbone, Koesling and Schneider (2011) have additionally measured the deployment of gaze in the more novel context of competitive cup stacking, where cups must be stacked in a specific order as fast as possible. Even though this paradigm again utilized a highly ecologically valid setting, it combined many motor plans together and employed paradigm that investigates gaze only during complex sequences of movements. These previous paradigms have left less complex real-world movement relatively uninvestigated.

Exceptions to this are rare but existent. De Grave, Hesse, Brouwer and Franz (2008) had subjects reach to a target that was occluded by an object placed directly in front of it while recording data from the eyes and hand. However, de Grave et al. (2008) were concerned with what grasp locations would be selected on the object when a participant had only limited information about object shape. Even though this is an important avenue of research, it involves the contribution of memory to reach rather than investigating the mechanisms behind gaze deployment in a setting where memory is unnecessary (no relevant information is being occluded from the subject). An additional exception comes from the work of Johansson, Westling, Backstrom and Flanagan (2001). In their study, subjects reached and grasped an object, which they subsequently manipulated around an obstacle in order to hit a target switch. They found subjects commonly fixated landmarks in the scene, such as the grasp location on the bar and the target switch, but never the hand or bar as it was in transit. They concluded that gaze facilitated reach by marking specific landmarks before the arrival of the hand. In fact, all of the above mentioned studies found that, in both automatic tasks like making tea and novel tasks like cup stacking, gaze fixations preceded the arrival of the hand to a specific point in space. Therefore, gaze can be seen to facilitate reach through the investigation of task-relevant landmarks or targets to ensure proper execution. For instance, Johansson et al. (2001) suggest gaze selects a target on the bar that represents a handle, as the bar must be lifted in their paradigm.

Features of the Prehension System

The motor system plans actions in a “functional” manner, such that items in the world are evaluated for their relevance to the task. When encoding obstacles, those which are most relevant to the task, produce greater behavioural results – they are more “functionally” relevant to the reach. One example of this was observed by Dean and Bruwer (1994), who had subjects move a pointer to a target location while avoiding a single obstacle. Subjects consistently plotted trajectories further away from obstacles located on the same side of the workspace as their reaching arm. Building on these results, Tresilian (1998) found that subjects reached further around obstacles closer to themselves or the target. These observations are explained by the fact that an object ipsilateral to the reaching arm is much more likely to cause a collision, as not only the hand, but the elbow and shoulder must be navigated around it. Similarly, obstacles closer to the subject or target cause greater avoidance trajectories than those at middle distances because they are more likely to obstruct the action. In line with this interpretation, obstacles placed beyond the target are seen to have no impact on reach at all. Mon-Williams, Tresilian, Coppard and Carson (2001) had subjects reach to a target with an obstacle either in front of, adjacent to, or beyond it. Obstacles beyond that target, which were unlikely to cause collisions during the reach, had no observable impact on reaching or grasping mechanics.

Obstacle avoidance is coordinated in such a way that a complex collision minimization system is developed, such that the greater the deviations in hand trajectory around an obstacle, the greater the risk of collision with that obstacle, as interpreted by the visuomotor system. For instance, Dean and Bruwer (1994) found that reaches made at greater velocities also avoided obstacles at larger distances. This is again similar to the "functional" ipsilateral bias, in that reaches at greater speeds are more likely to contain variance in trajectory, thus increasing the likelihood of a collision with the obstacle. By navigating further from the obstacle, the probability of collision is reduced. The authors proposed that the motor system plotted a "least-minimum-distance" around obstacles that reduced the likelihood of collision while accomplishing the task goal with the least expenditure of energy. This formed the core of "obstacle avoidance" theory, which explains obstacle avoidance trajectories as representing the degree to which an obstacle is seen to obstruct the reach task. Mon Williams et al. (2001) provided additional evidence that highlights the imperative of avoidance in coordinating the hand through a workspace: in the presence of an obstacle, reach velocity is reduced because more fine motor control is necessary. Therefore the motor system reduces reach velocity to ensure there is no collision due to increased reach variability.

Minimizing the probability of obstacle collision appears to be a defining principle of visuomotor coordination during a reach. Chapman and Goodale (2008), in a paradigm where subjects were instructed to reach through two obstacles, found that participants would bisect the obstacles, such that their arm and hand maximized the distance between both obstacles (with an ipsilateral bias), rather than optimizing the shortest reach trajectory or avoiding the most physically obstructing obstacle. This collision minimization settles what might have been a conflict between Tresilian (1998) and Chapman and Goodale's (2008) work: rather than determining the distance at which to avoid the most obstructing obstacle, the visuomotor system appears to plot a least-minimum-distance around all places of potential collision.

These optimal avoidance trajectories may be plotted using a series of via-points (Dean &

Bruwer, 1994), where sequences of movements necessary to complete a goal are combined to form a single motor plan. At each via-point within a movement, the necessary posture to achieve the desired trajectory through that point is encoded; the posture required at the final via-point encoded first, as the optimal trajectory at any via-point is dependent on the postural requirements of the point immediately following it (Vaughan, Rosenbaum & Meulenbroek, 2001).

Conceptualizing via-points as the postural arrangements of joints, employed to complete a reach, translates well onto the mechanisms of the skeletomuscular system. As Rosenbaum, Loukopoulos, Meulenbroek, Vaughan and Engelbrecht (1995) explain: As one moves their elbow from a bent to straight posture, the bicep (front of the arm) expands and the triceps (back of the arm) contract. This creates a balance of tensions between the two muscles focused at the elbow. Control of the prehension system during a reach may then be thought of as the transition between the muscle tensions required at each via-point, relative to the posture needed at the following point.

Coordination Between Gaze and Reach

Visuospatial information from the environment itself is highly informative to the motor system in plotting an effective reach. Subjects are able to use the relationship between objects around them as “landmarks” that can aide in the judgment of distance. Obhi and Goodale (2005) found that the presence of landmarks during the encoding of target position reduced variance in measures of reach mechanisms (endpoint variability, for instance), even though the landmarks were removed before the reach began. Krigolson, Clark, Heath and Binsted (2007) additionally showed that task-irrelevant backgrounds that appeared at a close or medium distance from the subject also reduced end-point error in reaches compared to those done in the presence of distant backgrounds or no backgrounds at all. Because vision is so beneficial to action, it is necessary to understand how vision is used to influence motor planning.

Hayhoe (2000), in a review aimed at demonstrating the functional use of vision, describes gaze as arriving at a location as it becomes relevant to completing a task. This “just-in-time” deployment of vision across a workspace has been described in previously mentioned studies (Binsted et al., 2001; Forster et al., 2011; Johansson et al., 2001), where the eyes are seen as gathering task relevant information from the environment just as it becomes necessary for action. Further evidence for this comes from Chapman and Goodale (2010) who had subjects point to a target in the presence of either one or two obstacles, with or without visual feedback from their hand. While differences in performance between the vision and no-vision groups did emerge (such as greater end-point deviation when the hand is not visible), of particular relevance here is the fact that performance with no visual feedback was still comparable to conditions where visual feedback was available. Trajectories used by the subjects to complete the task did not differ significantly between the vision and no-vision groups, suggesting that vision is optimized to provide the motor system with information it requires for the next immediate phase of the reach, as opposed to monitoring the status of the hand as it acts.

The “just-in-time” deployment of vision allows features of reach targets to be extracted when they are needed, such as the target’s center-of-mass. While performing a stable precision grip, described as an object being enclosed from opposite directions by the thumb and forefinger (Kleinholdermann, Brenner, Franz & Smeets, 2007), subjects grasp falls across or close to the object’s horizontal center-of-mass, ensuring maximal stability while grasping (Goodale, Meenan, Bulthoff, Nicolle, Murphy & Racicot, 1994; Lederman & Wing, 2003; Paulun et al., 2013).

Gaze appears to be directly tied to the forefinger of the reaching hand during prehension, facilitating the optimal grasp site. Desanghere and Marotta (2011) had subjects reach to objects of various sizes, demonstrating that the location of forefinger grasp serves as a fixation point for the reach. This coupling of grasp location and gaze is also found in the vertical deployment of the eyes, which shifts toward the forefinger grasp-point as the target gets larger, fixating closer to the top edge of the object.

The use of gaze to guide action appears intrinsic to motor-planning. Building upon research that showed people were able to use either tactile or visual information to make reach movements, Jones, Cressman and Henriques (2010), showed subjects consistently used visual cues to plan action, even when doing so resulted in less efficient arm movements than would be performed if the subject were able to prioritize other sensory modalities.

Attention-for-Action

This complex coordination between visual signals and behaviour may be mediated by visual attention. In a series of studies, Castiello (1998, 1999) found grip aperture could be manipulated by drawing attention to a distractor with different dimensions than the target. For example, when attention is drawn to a distractor larger than the target object, grip apertures generated for the target increase relative to control. Conversely, a distractor smaller than the target reduces grip aperture. This was expanded by Ansuini, Tognin, Turella and Castiello (2007), who found that not only were the primary grip-relevant digits (thumb and forefinger) impacted by distractor size, so too were the remaining fingers. Therefore, even though coordination between visual, attentional and motor systems can produce sophisticated trajectories that avoid obstacles in a workspace, it does not ensure a “foolproof” deployment of the motor system. Given that the current content of attention is able to interfere with motor signals, it emphasizes the functional use of gaze in drawing the eyes to task-relevant locations just as that visual information is necessary for successful actions.

Attention’s role in coordinating between visual and motor systems is more intrinsic than simply prioritizing visual information for the deployment of action. Aivar, Brenner and Smeets (2008) ran a series of experiments where subjects performed a reach task in the presence of an obstacle. In one condition, the obstacle began moving as the subject performed the reach task. The earliest response from the subject to this movement occurred at roughly 120ms. However, this response was non-corrective. Rather than moving their hand around the new obstacle location, they briefly deviate their trajectory toward the location of the movement. It took roughly 200ms from motion onset of the obstacle before the subject was able to deploy a new motor-plan that brought the hand around the new obstacle location. Though Aivar et al. (2008) did not monitor eye-data, there is a robust literature that highlights the ability of motion onset to capture attention (Abrams & Christ, 2006; Guo, Abrams, Moscovitch & Pratt, 2010). Interpreted in this way, movement toward the motion onset in Aivar et al.'s (2008) study is the consequence of attentional capture by the obstacle’s motion, whereas the correction at 200ms represents the ability of the visuomotor system to coordinate the appropriate response to the changes in reaching environment. Rather than attention influencing actions, these results suggest that attentional and motor signals may share encoding at early stages of information processing. Though it does appear there is a strong tie between attentional processing and motor planning, Sailer, Eggert, Ditterich and Straube (2002) demonstrated that these systems process information independent of one another. The authors had participants point to a target while fixating another location, in the presence or absence of a distractor. Their results were consistent with independent encoding of the target in both visual and motor systems as the pointing hand demonstrated a different pattern of distractor influence than did gaze. They warn about taking the overlap between these systems too literally, as each of the attentional, motor and visual systems have their own independent, but interactive, processing streams that together coordinate action.

Results from psychophysical investigations of “visual marking” (Watson & Humphreys, 1997) provide a valuable foundation for the study of attention in eye-hand coordination – particularly in cluttered environments. In a visual search task, if the onset of some distractors precedes that of the target and remaining distractors, the visual system is said to “mark” the locations of the initially displayed items, as they are known not to be the target. This marking inhibits the amplitude of the signal from the marked space during the subsequent search task, reducing the spatial area and number of objects that need to be searched in order to locate the target. If there is such a strong overlap in the attentional and motor-planning systems, it would be unsurprising to see mechanisms responsible for target selection in visual search tasks also play a role in target selection for a visuomotor task. In this way, areas of the workspace that are not task-relevant may be “marked” in the same way as the initial distractors in a visual search task. By “marking” these spaces, processing in the motor and occulomotor systems may be biased away from these marked locations, as is seen in the visual search paradigm. Therefore, an obstacle’s location may be “marked” by the attentional system, allowing this marking to cascade through the motor systems, drawing the hand and the eyes away from the obstacle.

Neuroarchitecture

Goodale et al. (1994) first provided evidence of physically distinct and independent visual processing streams. Subject DF, a patient with visual form agnosia due to damage to her ventral ("perceptual") processing system, running from primary visual cortex to the inferotemporal lobe, was unable to distinguish objects on the basis of their shape but was still able to perform a grasping task due to an intact dorsal ("action") stream, running from primary visual cortex to the posterior parietal lobe. This implied that, even without perceptual awareness of object size, the visuomotor system is able to access relevant size data when performing a visually guided action. Since DF was never explicitly aware of the size of the target, it is seemingly impossible that she was using deliberate, top-down mechanisms to determine accurate grip aperture. An automatic system, independent of explicit perceptual awareness, must then be responsible for such behaviours. Further evidence of this comes from the investigations of a patient with optic ataxia, RV, who had a damaged dorsal stream but intact ventral stream (Goodale et al., 1994). Even though RV was able to perceive the size of an object, she was not able to reach out and interact with it, showing a clear role of the dorsal processing pathway in reaching that the ventral stream cannot compensate for.

In a later investigation of optic ataxia and prehension, Schindler, Rice, McIntosh, Rossetti, Vigheto and Milner (2004) presented participants with a more "natural" grasping task where a target object was accompanied by an obstacle in the reach space, better simulating the environment in which most actions occur. They found that without an intact visuomotor system, the subjects with optic ataxia were unable to compensate for the presence of the obstacle; their reach trajectories were invariant regardless of obstacle location. To complete the double-dissociation, Rice, McIntosh, Schindler, Mon-Williams, Demonet and Milner (2006) had patient DF and another patient with visual form agnosia, SB, perform the same task. Even though the patients were unable to perform a perceptual bisection task (they couldn't tell the center-point of an object), they were able to perform reaches that compensated and navigated around obstacles present in the reach-space. This confirmed Goodale et al.'s (1994) contentions about dual processing streams. Further, the double-dissociation presented in these two experiments suggests that the ventral processing stream plays little, if any role in coordinating a reach around an obstacles. However, this point may be overstated. Even though it seems the brain is able to use exclusively dorsal processing to reach around an obstacle, it wouldn't be unexpected that the identity of the obstacle would influence trajectories. A subject is likely to reach around a cactus at a greater distance than a wooden block (Chapman & Goodale, 2008).

While it has been proposed that these same dorsal processing areas in the parietal cortex play a role in visual marking (Humphreys, Owen & Yoon 2006); marking may, in fact, occur earlier than the parietal lobe. Sylvester, Jack, Corbetta and Shulman (2008) recorded activity in the visual cortex while subjects were given either a valid or invalid cue orienting them to the location of a potential target. They found that there was a reduction of activity in areas of the visual cortex associated with processing the uncued area of space. Similarly, Chapman and Goodale (2011), in a task that had subjects reach around an obstacle while undergoing fMRI, found location based inhibition in the intraparietal sulcus and early visual cortex in a reaching experiment for locations occupied by obstacles. The attentional marking of areas to-be-avoided by the eyes or the hand occurs very early in the visual system, and share locations of encoding. This not only displays the intrinsic tying of visual and motor signals through attentional inhibition, it suggests that such a distinction between motor and visual signals has not developed at such early visual areas.

The Ventral System

Though some have argued that obstacle avoidance is coordinated using exclusively dorsal processing systems (Rice et al., 2006), there is reason to believe the ventral stream may also play a role in prehension. Johansson et al. (2001) found that subjects frequently fixated and reached toward the handle of an object that needed to be manipulated. This result highlights that object-identity information is used by the prehension system to guide reaching. Understanding the handle as a target for the visuomotor systems requires perceptually encoding the identity of the handle in the first place. It has also been shown that there is a strong tying of signals between target items that are encoded in terms of dorsal vision-for-action and ventral vision-for-perception (Deubel & Schneider, 1996; Deubel, Schneider & Paprotta, 1998). Deubel et al. (1998) found that target discrimination is superior when the item being discriminated is also the target of a pointing task whereas performance deteriorates when trying to discriminate one item while pointing to another, suggesting an obligatory coupling of attention-for-perception and attention-for-action in the visual system.

The purpose of this thesis is to extend this previous research into an investigation of the deployment of gaze while reaching around an obstacle. Given the maturation in the technology available to measure eye and hand coordination, we are able to examine the role attention plays in coordinating visual and motor systems during an action. This study manipulated the location of an obstacle located either ipsilateral or contralateral to the subjects reaching hand. The obstacle was positioned at one of 6 possible locations, and subjects were instructed to reach for a target while avoiding the obstacle.

Hypotheses

It is hypothesized that reaches made in the presence of obstacles will be slower than those without (Mon Williams et al., 2001). Obstacles on the ipsilateral side the work-space to the reaching arm will produce greater avoidance distances than those contralateral, as will those closer to the target or the subject (Chapman & Goodale, 2008; 2010). Obstacles that physically obstruct the reach to a greater degree are also expected to cause greater avoidance trajectories.

Gaze is expected to be drawn and anchored to the target (Neggers & Bekkering, 2000). However, the presence of clutter in the reach space is expected to modify the pattern of gaze deployment such that a greater number of fixations are expected away from the location of the obstacle (Watson & Humphreys, 1997; Chapman & Goodale, 2011). However, obstacles may be encoded as salient distractors when coordinating reach actions (Tipper, Howard & Jackson, 1997).

Methods

Experimental Task

Participants. 20 right-handed undergraduate students (7 male, 13 female; average age 21.1 years), were recruited from the University of Manitoba's psychology subject research pool. Each participant provided written consent (Appendix A). Subjects were screened for handedness using a modified self-report version of the Edinburg Handedness Inventory (Oldfield, 1971; Appendix B). After the testing session, all subjects underwent debriefing (Appendix C). This research was approved by the Research Ethics Board of the University of Manitoba (Appendix D).

Materials and Equipment. Reaches were recorded using an Optotrak Certus 3-D recording system (130 Hz sampling rate, spatial accuracy up to 0.01 mm; Northern Digital, Waterloo, ON, Canada). Two infrared light emitting diodes (IREDS) were fastened to each of the subject's index finger (positioned on the left side of the cuticle) and thumb (positioned on the right side of the cuticle). A Velcro watchband was attached to the subject's wrist, which held two IREDS 5cm above the subject's wrist (Figure 1a). An Eye-link II (250 Hz sampling rate, spatial resolution < 0.5 degrees; SR Research Ltd., Osgoode, ON, Canada) was fitted to each subject's head (Figure 1b) and calibrated using a computer-displayed 9-point calibration to an accuracy of 1^{o} visual angle. Positional data from both the Optotrak and the Eyelink II were integrated into a common coordinate frame using MotionMonitor software (Innovative Sports technology, Chicago, IL, USA).

The target object on each trial was one of three white foam-core Efron shapes (Efron, 1968) (8x8cm, 10x6.5cm, 15x4.5cm; figure 2a), mounted on a black board 40cm above the table and 55cm from the subject and 35cm from the starting location of the hand. (Figure 3). Two additional blocks (9x7cm, 12x5.5cm; Figure 2b) also serve as potential target objects, but act as distractors to prevent participant's from "ballparking" the size of the target. No analysis is performed on reaches where a distractor object serves as the target. Obstacles are white foam-core rectangles, 50cm in height, 5cm in width and 0.5cm in depth (Figure 3).

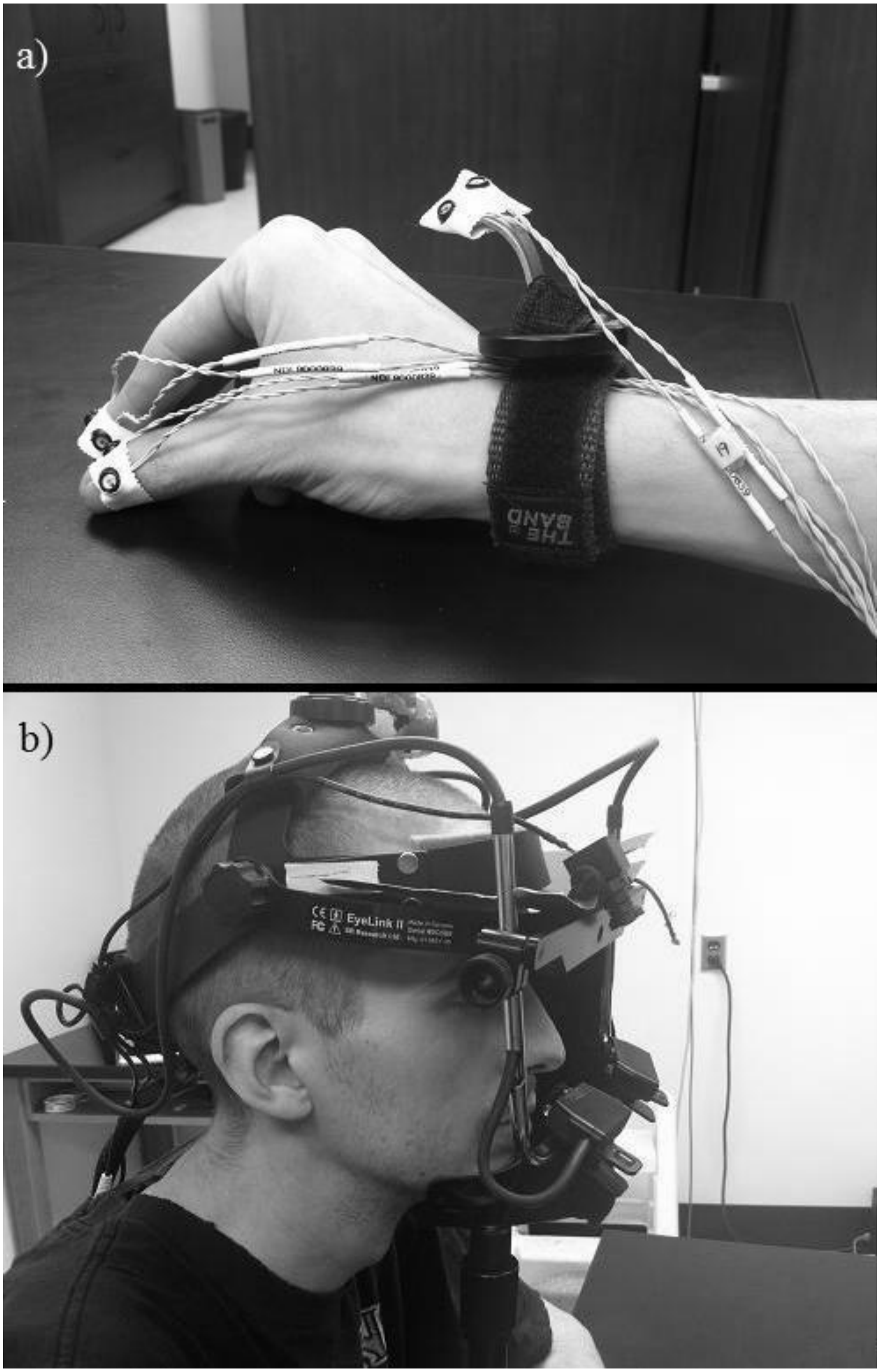

Figure 1: a) Author TG’s hand in the starting posture equipped with index, thumb and wrist infrared sensors; b) Author TG set-up in the eye-tracker and chin rest.

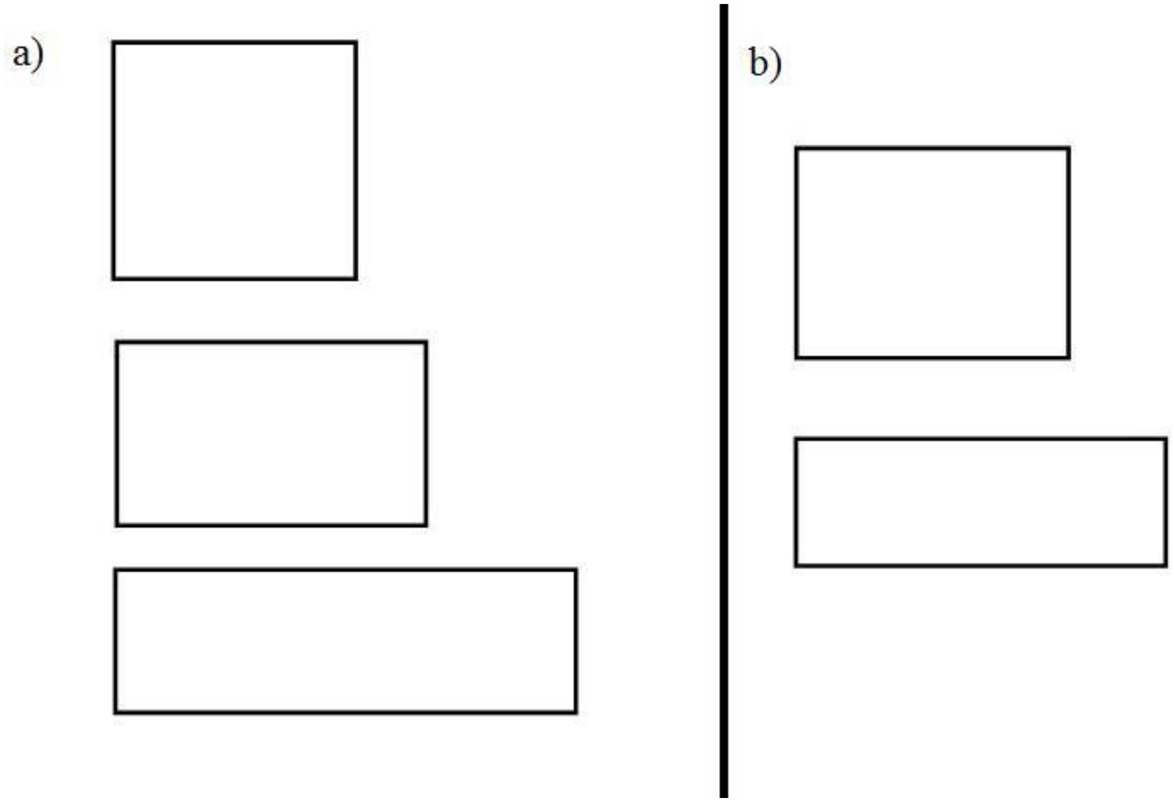

Figure 2: a) Reach targets A (top), B (middle) and C (bottom); b) Distractor targets.

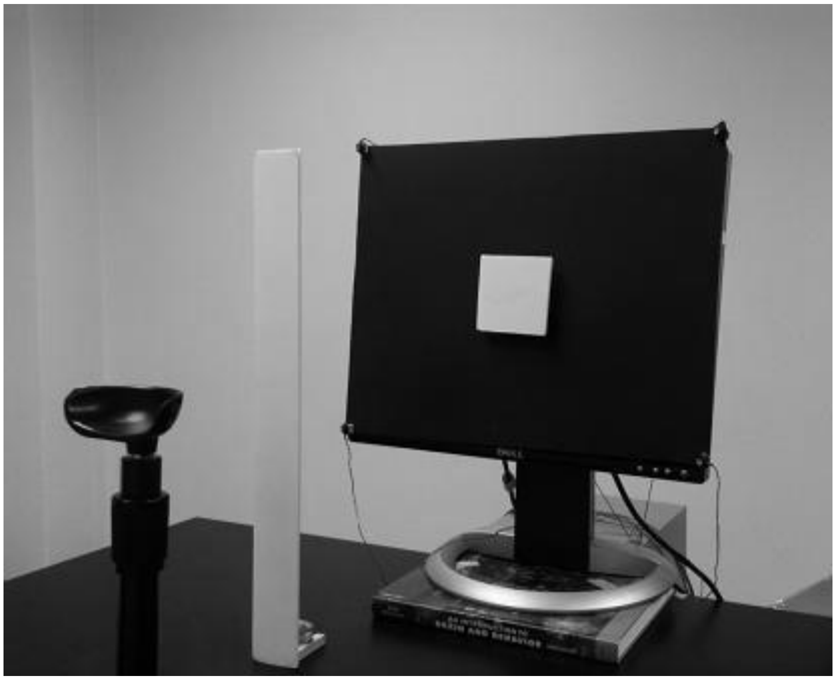

Figure 3: An example of a typical trial with the NTO placed on the left.

Procedure. Subjects were instructed to reach out and grasp the target-object displayed in front of them as quickly but accurately as possible with their right hand, while avoiding collision with the obstacle. Subjects were additionally instructed to grasp the object along its vertical axis between their index finger and thumb, remove it from the board and place it on the table in front of them. Before each trial, subjects were instructed to close their eyes so the materials for the forthcoming reach could be prepared. Subjects were instructed to open their eyes and begin their reach with the auditory cue “and open”.

Most reaches were in the presence of a single obstacle, the only exception being obstacle-free control trials. For each subject, obstacles appeared only ipsilateral or contralateral to their right hand. On any trial, an obstacle could be located at any one of 6 possible positions defined as the conjunction points between three depths from the starting position (close, middle or far; 10cm, 17cm, 24cm) and two horizontal positions from the midline between the starting position of the hand and the target (in or out; 7cm, 10cm) (Figure 4). On some trials the obstacle was not present; these trials acted as a control condition. Participants were instructed to begin each trial with their index finger and thumb resting on a taped start position 20cm in front of them (35cm from the target), with their remaining fingers tucked under their hand (hand position demonstrated in Figure 1a, see Figure 3 for a typical trial set-up).

Experimental trials were randomly divided into four blocks. In a full experiment, a subject would reach four times to each of the three target-objects, in each obstacle condition (six positions and one control) and once to each of the two distractor-objects, in each obstacle condition for a total of 98 trials. Accuracy tests, performed within the MotionMonitor’s coordinate system, were conducted at the beginning and end of each block of trials. If the error between the point-to-fixate and the subject's measured fixation-point was greater than 1cm in

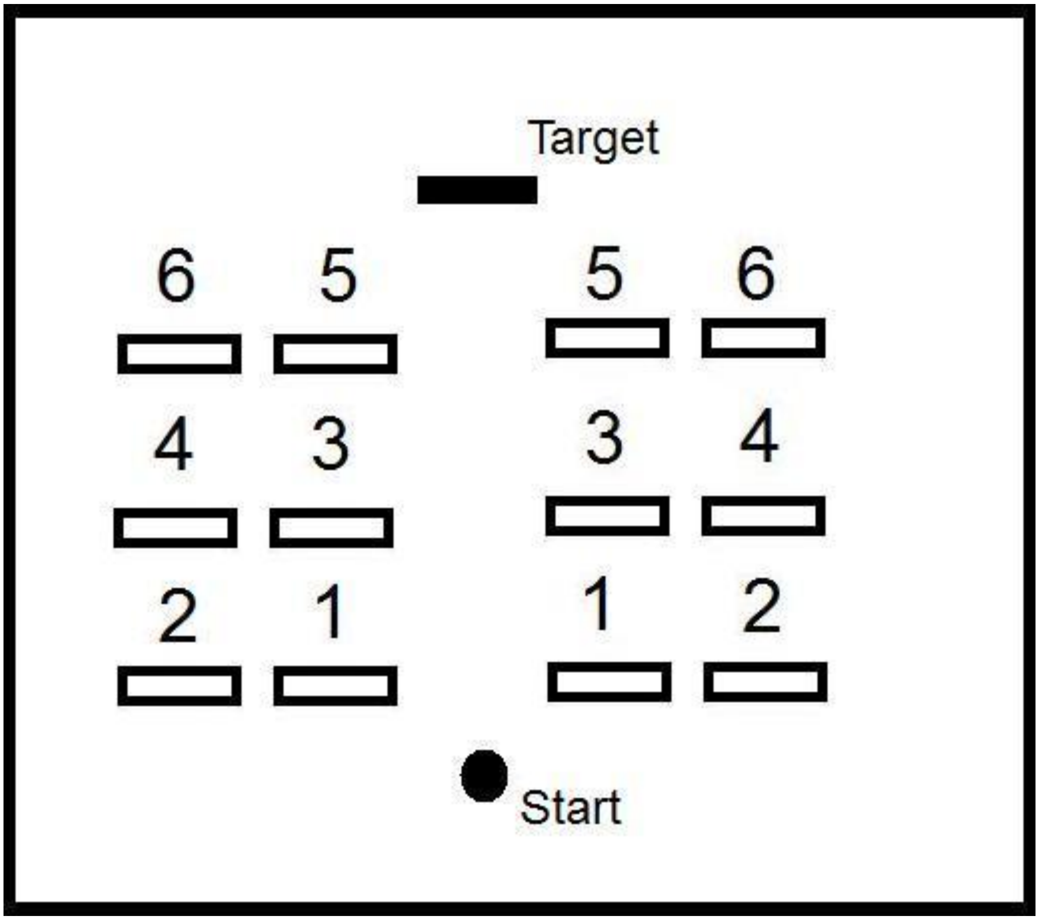

Figure 4: Possible NTO locations arranged to the right or the left of the subject's reaching hand.

either the horizontal or vertical dimension, the eye-tracker was recalibrated.

Analysis

Reach Mechanics. All data was collected from the index, thumb and wrist at 130Hz and analyzed within the MotionMonitor software. Data points were lost during the reach if the camera's view of an infrared sensor was obscured. This was most common when obstacles were contralateral to the subject's reaching hand – on the left hand side. To ensure analysis was performed on the most complete data, comparisons between the two sensors on the index, thumb and wrist were performed. The sensor that produced the most complete data set, or had the fewest missing data points, was used for analysis.

When the Optotrak is obstructed by an obstacle and misreads or cannot read an infrared sensor, it often reports an erroneous location rather than no location. In order to eliminate these erroneous data points, data from these sensors was filtered first by coordinate. In the horizontal dimension, any data point found beyond 27.5cm from the start location was eliminated. In the vertical and depth dimensions, any data points below 0cm or above 60cm were removed. These coordinates fall well outside of the reach area and constitute artifacts or misreading of the sensors.

Even though the coordinate sensor does much to eliminate this erroneous data, a velocity filter was also used to reduce noise. For the index, thumb and wrist, any point that was greater than two standard deviations from the mean velocity on a given trial was removed. After both the coordinate and velocity filters, if a data point had been removed from one dimension (horizontal, vertical, depth), it was removed from all dimensions. All remaining infrared sensor data was interpolated non-linearly using a cubic spline program (Advanced Systems Design and Development, 2005) in Microsoft Excel (Microsoft Co., Redmond, WA, USA). Trial start and end points were determined using the interpolated wrist sensor data. The trial began when the velocity of the wrist reached 10cm/s and ended when the velocity slowed to under 8cm/s.

Dependent variables analyzed from infrared sensors on the wrist were: The duration of the reach (time, in milliseconds, between the start and end point of the reach) and average wrist velocity. In addition, a measure of the total horizontal distance moved by the wrist during each trial was collected to inform about deviations around obstacles. The final position of the index finger on the target relative to its horizontal center-of-mass was calculated along with maximum grip aperture (MGA), the maximal difference between the index and thumb during the reach.

Eye Data. Eye data was analyzed at 130Hz in the MotionMonitor software. Data from the eye-tracker was measured in the horizontal and vertical planes only. Measures of depth from the EyeLink system, even in optimal conditions, can be unreliable at times. To accommodate this, horizontal and vertical gaze position was calculated at an assumed distance equal to that of the distance between the subject and the target object (55cm). For both the horizontal and vertical dimension, gaze location was calculated as the average between the position of the left and right eye at the depth of the target.

For each eye, if a data point was missing in either the vertical or horizontal dimension, it was removed for both dimensions as well as from the opposite eye's data. Eye data was then filtered according to methods outlined in Nystrom and Holmqvist (2010). Using a least-squares method outlined by Savitzky and Golay (1964) data was smoothed using a span of 53.85ms and a degree of 3. Even though Nystrom and Holmqvist (2010) suggest a filter with a degree of 2 and a span of 20ms, a longer span with greater degree is more appropriate for the equipment used in our paradigm. Following data smoothing, a coordinate filter similar to the one used for infrared sensor data was employed, eliminating any data points falling beyond 27.5cm from the horizontal dimension's midpoint or any points below 0cm or above 60cm in the vertical dimension.

Following Nystrom and Holmqvist's (2010) procedure, eye data was then filtered for both velocity and acceleration, with data points greater than 1000º/s or $100{,}000^{\circ}/s^2$ removed, as they represent physically impossible eye movements normally associated with measurement error (Nystrom & Holmqvist, 2010; Duchowski, 2003). Data was converted between centimeters and degrees of visual angle using a program developed by the Affect and Cognition Lab Knowledgebase (2011). If a data point was removed for being above one of these thresholds, the preceding and following data points were additionally removed until velocity or acceleration returned to trial median. Data points that, when combined, represented data shorter than 38.46ms were also removed, as it is unlikely this represented meaningful eye-opening but rather some artifact detected by the EyeLink, while the participant's eyes were closed or during a blink. Additionally, any data points in the vertical dimension that were 10.98cm (15º visual angle) above or below the center-of-mass of the target object were removed. Data beyond 10.98cm reflected errors associated with the uncovering of the pupil by the eyelid or artifacts produced while the eyes were closed.

Blinks were calculated as any period lasting over 53.85ms where no eye-data was recorded. Finally, any period of missing data less than 53.85ms was linearly interpolated. This prevented artifacts from disrupting the method of saccade and fixation detection described below.

Eye-Movements. Detection of saccades and glissades was completed according to Nystrom and Holmqvist's (2010) method. Glissades are short, corrective eye-movements made directly after a saccade to fix overshoot or undershoot of the saccade target. Even though saccades and glissades are not a specific part of the current hypotheses, a procedure that separates them from other eye data is preferable to one that does not. The current procedure used velocity measures within a trial to determine thresholds for saccade detection on a trial-by-trial basis.

Fixations. Fixations were determined once data points belonging to saccades and glissades were removed. The current method, a distribution method, defined fixations as any period of data where the position of gaze remained within 1cm along the horizontal and vertical plane lasting at least 61.54ms.

If a fixation was beyond the edge of the target object nearest the obstacle, the subject was considered to be fixating the obstacle. The obstacle was always at least 7cm from the midline between the starting location and target, and though the largest target width extends 7.5cm from its horizontal midline, the viewing angle of the subject during reach prevents occlusion of this edge by the obstacle. Given subjects primarily fixate a target’s top edge, in order to facilitate accurate grasping, rather than its extremities (Desanghere & Marotta, 2011) it is safe to say that any deployment of gaze beyond the edge nearest the obstacle was directed at the obstacle itself and not a blank or functionally unimportant region of space.

Dependent variables analyzed from fixation data are the duration, horizontal and vertical position of gaze for the first, second and final fixations within a trial. A tally of the total number of fixations was recorded for each trial. Finally, a measure of the difference between the final fixation point in the horizontal dimension and the horizontal position of the index finger as it grasps the target object was recorded.

Results

Data Removed

Accuracy tests, performed immediately following each block of trials, were used to assess the accuracy of eye-data for each particular block of trials. If the test demonstrated above-tolerance error values (greater than 1cm), that block of trials was removed from analysis. If two blocks of trials were removed for a single participant, that participant's data was excluded from analysis. In total, a single block of trials was removed from 14 of 20 participants, 5 of 10 for participants with left side NTOs, 9 of 10 for those with right side.

All trials were checked by-eye after filtering and data interpolation for irregularities: Crucial missing data points, physiologically impossible data or lost signals from infrared sensors or the eye-tracker. All of these trials were removed, in addition to trials where subjects collided with the NTO or moved their wrist back toward themselves prior to grasping the object. In total, 145 of 1386 trials, roughly 10%, were removed, 106 when the NTO was to the left of the subject and 39 when it was to the right.

For each participant, if there were any NTO-Location x Target conditions without a single observation, that participant was eliminated from analysis, which occurred for a single subject. In total, after all necessary data removal, 629 trials remained for reaches with a left side NTO (51% of total) and 612 (49%) remained for those on the right. Participants who reached with left side NTOs lost more trials due to difficulty cleaning the data and sensor occlusion during the reach task; participants who reached with right side NTOs lost more trial blocks due to losses in eye-tracker accuracy, possibly due to increased body movement during right side NTO trials impacting the calibrated accuracy of the eye-tracker.

Data Analysis

For each dependent variable, a 2 x 7 x 3 Mixed Model RM-ANOVA was performed investigating the main effects of the between-subject variable NTO-side (2), and of the within-subject variables of potential NTO-location (7) and target-object (3). In addition to the six labeled potential NTO-locations, an additional control condition, in which no NTO was present, was included in the design. All tests of significance were based on an alpha level of 0.05. Violations of sphericity, determined using Mauchly's test, were corrected with Hyunh-Feldt adjustments. Posthoc Tukey's HSD were performed where necessary. During the posthoc analyses, particular attention was paid to the impact of NTOs closer to the reaching hand by comparing inner locations with outer ones (1 v 2, 3 v 4, 5 v 6). Similarly, the effects of NTOs near the subject were investigated (1 v 3, 1 v 5, 3 v 5, 2 v 4, 2 v 6, 4 v 6). Results of all significant pairwise comparisons can be found in Appendix E.

Reach Mechanics

Reach Duration. A main effect of NTO-Location [$F(3.93, 70.68) = 17.69, p < .001$] was found. The NTO-Side x Location [$F(3.93, 70.68) = 14.99, p < .001$] and NTO-Location x Target [$F(7.19, 129.44) = 2.307, p = .029$] interactions were also found to be significant (see Figure 5 and 6, respectively). In all cases, when the NTO was on the left-side, there were no differences in subject performance between conditions. In contrast, the presence of an NTO on the right-side produced reaches of greater duration than the control condition. An effect of NTO proximity to the participant was also seen, with longer durations observed when the NTO was in the closest location, 1, over farther locations 3 or 5 and location 4 over 6. The effect of object proximity to the reach path was demonstrated with reaches of longer duration when the NTO was in location 1 over location 2. Similar patterns of results were seen when investigating the NTO-Location main effect or the Location x Target interaction; however, these results appear to be primarily driven by reaches with a right-sided NTO present. The effect of NTO locations on the right side was so strong that it persisted when averaged across the null effect found from left side NTOs, producing a significant main effect and interaction. An unpredicted effect was seen in the comparison between NTOs on the right-side at locations 3 and 4. The more lateral location 4 actually produced greater reach durations than the more inward location 3.

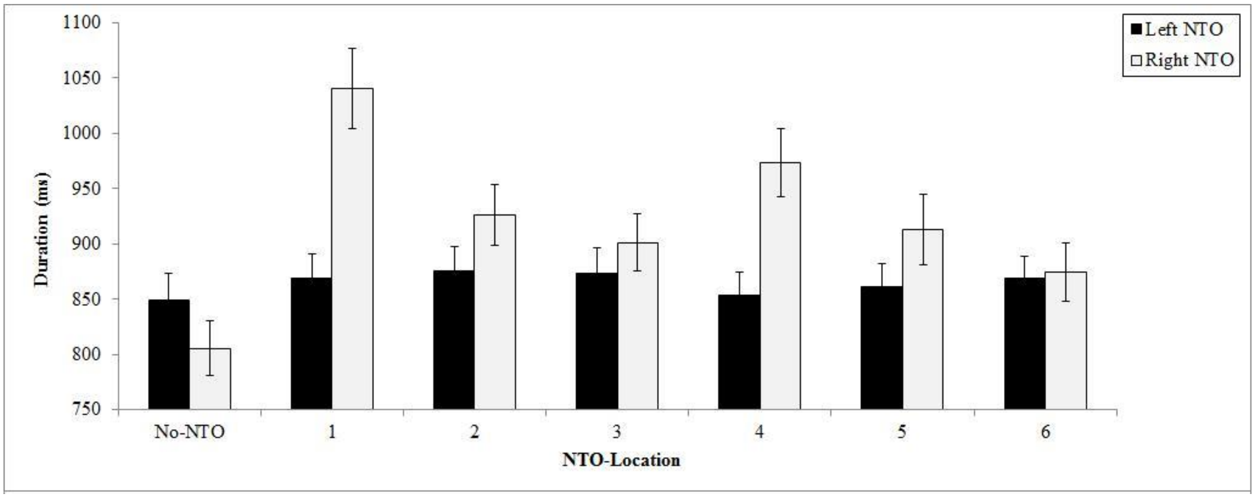

Figure 5: NTO-Side x Location interaction shows the effect of proximity to a subject increasing the duration of a reach for right side NTOs.

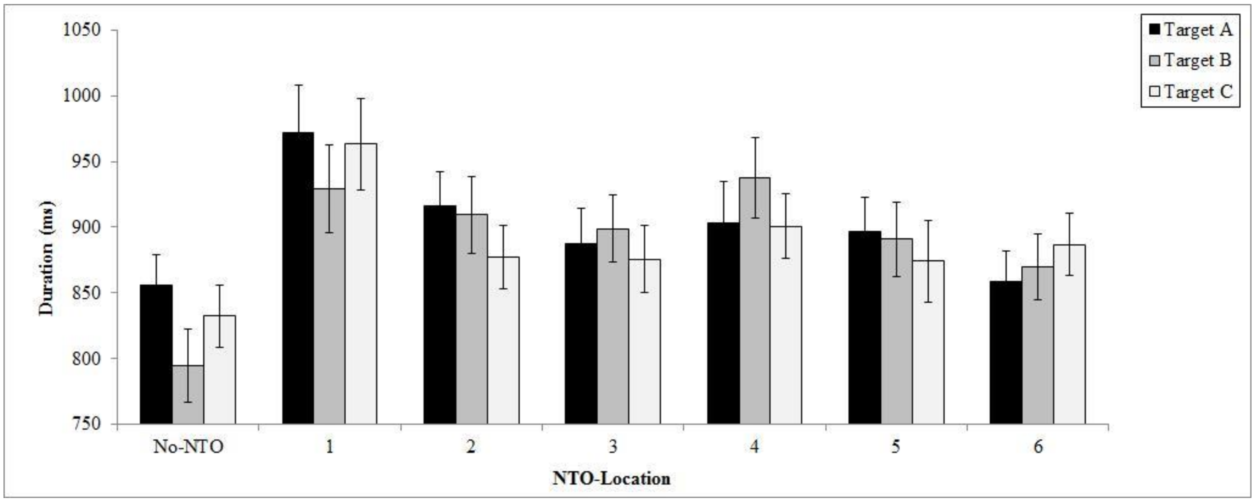

Figure 6: NTO-Location x Target interaction shows greater durations in the presence of an NTO, however, this is likely a result of the differences among NTO locations on the right side.

Wrist Deviation. Wrist deviation is a variable that compares the movement a subject's wrist makes in the horizontal plane while reaching. Main Effects of NTO-Side [*F*(1, 18) = 12.21, $p = .003$], NTO-Location [*F*(4.76, 85.43) = 67.07, $p < .001$] and Target [*F*(2, 36) = 5.48, $p = .008$] were found. The NTO-Side x Location [*F*(4.76, 85.43) = 33.17, $p < .001$] interaction was also found to be significant (see Figure 7).

When the NTO was on the left side, there were no differences in subject performance with two exceptions: NTOs in location 1 on the left-side produce greater wrist movement than did the control condition or NTOs in location 5. This is the only dependent variable where differences between locations on the left-side were found. In all cases, the presence of an NTO on the right-side produced reaches that deviated a greater distance than the control condition. The effect of NTO proximity to the subject was evident in the greater deviation present when the NTO was closest to the reaching hand, location 1, over further locations 3 or 5, location 2 over locations 4 and 6 and location 4 over location 6. The effect of object proximity to the reach path was demonstrated with reaches that deviated a greater distance when the NTO was in location 1 over location 2. Greater deviations in reach trajectory were seen in every NTO location condition on the right-side compared to the left, including the control condition.

Akin to results found for the reach duration variable, similar effects to those found in the Side x Location interaction were seen within the comparisons made for the NTO-Location main effect. These again seem to reflect the differences found among right-side locations in the Side x Location interaction. Additionally, the Target main effect suggests that participants made reaches with more deviation when reaching to the taller target A over shorter and wider targets B and C [Target A: $M = -0.94$, $SD = 1.18$; B: $M = -0.48$, $SD = 1.43$; C: $M = -0.29$, $SD = 2.05$].

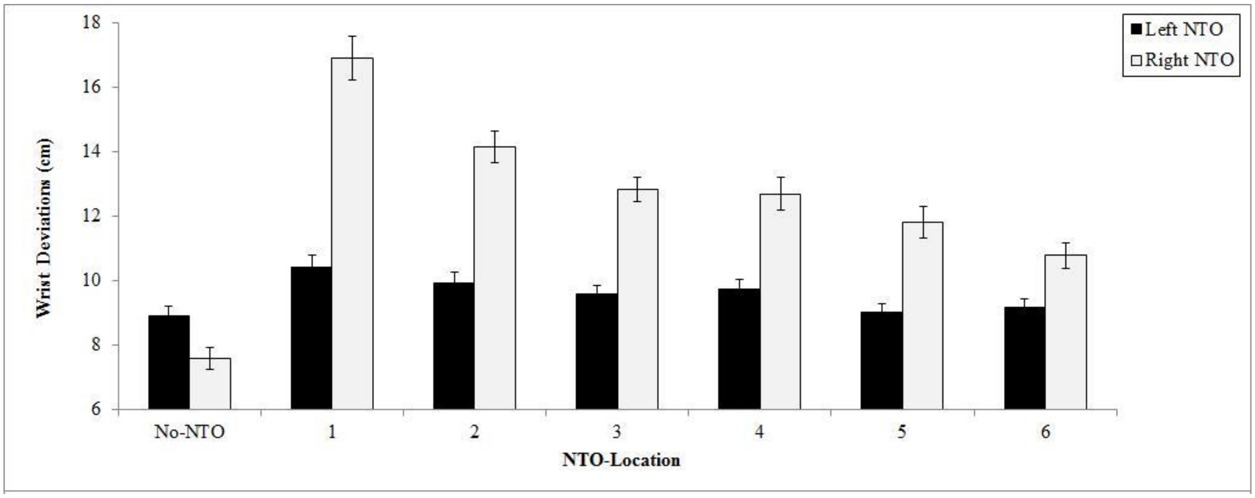

Figure 7: NTO-Side x Location interaction shows the effect of proximity to a subject increasing the trajectory deviations of a reach for right side NTOs. Only the closest NTO location, position 1, was significantly different among left side NTOs.

Average Reach Velocity. Average reach velocity refers to a measure, in centimeters per second, of the average velocity of wrist movement during a reach. A main effect of NTO-Location [$F(4.59, 82.58) = 6.802, p < .001$] was found. The NTO-Side x Location [$F(4.59, 82.58) = 5.55, p < .001$] and NTO-Location x Target [$F(8.13, 146.35) = 2.44, p = .016$] interactions were also found to be significant (see Figure 8 and 9, respectively). In all cases, when the NTO was on the left side, no differences in average reach velocity were found. Comparisons made among NTO-Locations on the right side followed the same pattern demonstrated among previous dependent variables. All NTO-present conditions produced slower average velocities than did the control condition. Additionally, participants who reached in the presence of right-side NTOs were able to take greater advantage of the NTO-absent control condition, reaching with a greater average velocity than did those who reached in the presence of left-side NTOs. NTO-Location 4 on the right side again demonstrated an unexpected effect. When the NTO was in this position, reach velocity was slower than in the closer location 2. Investigating the NTO-Location x Target interaction showed that reaches made to the B block in the control condition were faster than at all other locations.

Maximum Grip Aperture. A main effect of Target [$F(2, 36) = 483.59, p < .001$] was found. The NTO-Side x Location [$F(5.21, 93.69) = 2.757, p = .021$] and NTO-Location x Target [$F(12, 216) = 2.43, p = .006$] interactions were also found to be significant (see Figure 10 and 11, respectively). Subjects demonstrated typical grip scaling, using nearly identical steps in aperture size as the block grew, as seen with larger apertures for block A [$M = 11.12, SD = 0.65$], followed by B [$M = 9.88, SD = 0.83$] and then C [$M = 8.62, SD = 0.89$]. A significantly smaller aperture was seen when the NTO is in locations 1, 2 and 4 on the left-side than on the right, showing a

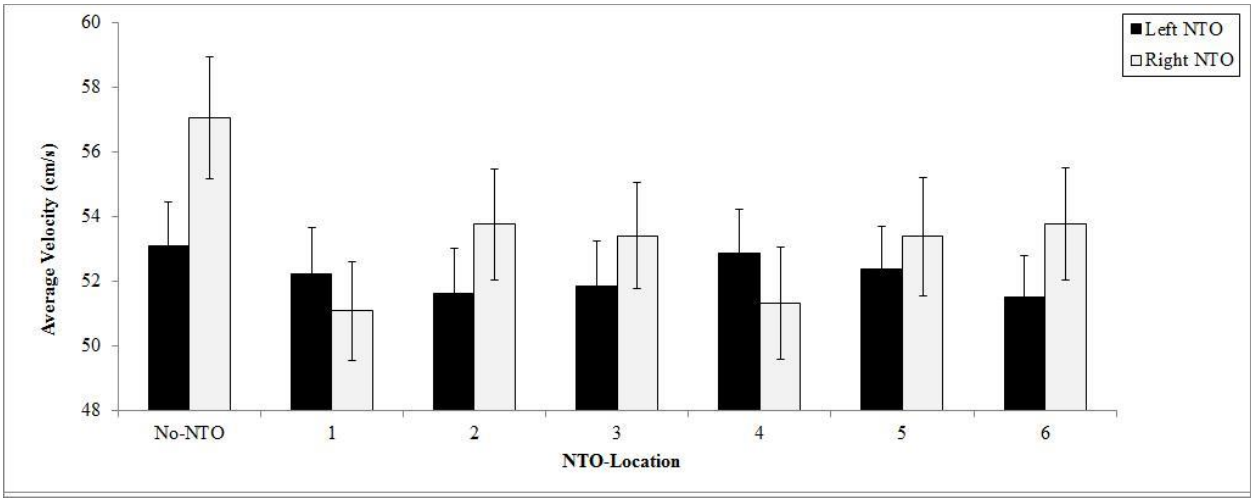

Figure 8: NTO-Side x Location interaction shows greater average velocities for subjects who saw right side NTOs in the control condition.

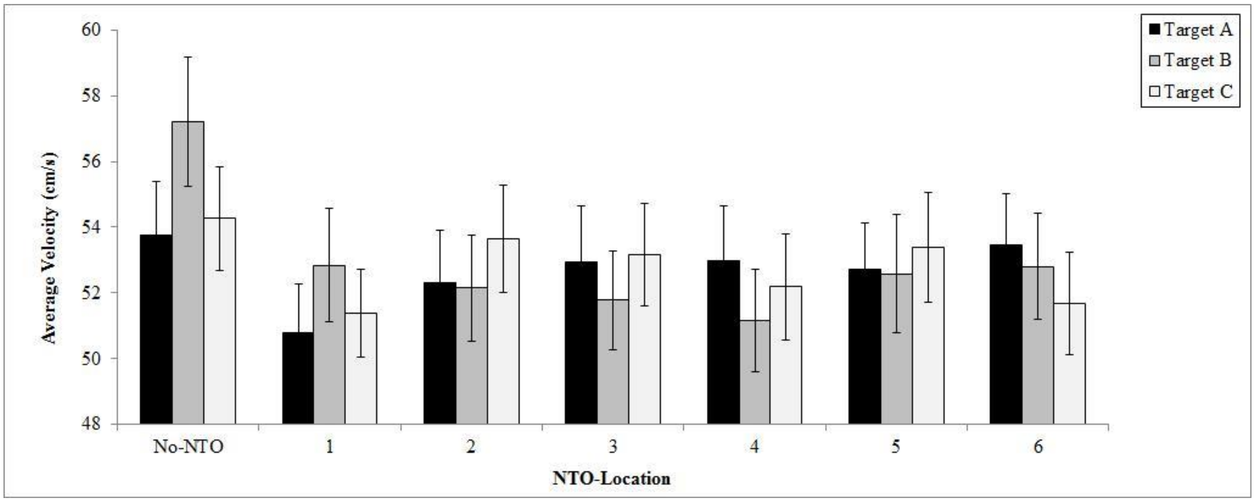

Figure 9: NTO-Location x Target interaction shows slower average velocity in the presence of an NTO, however, this is likely a result of the differences among NTO locations on the right side.

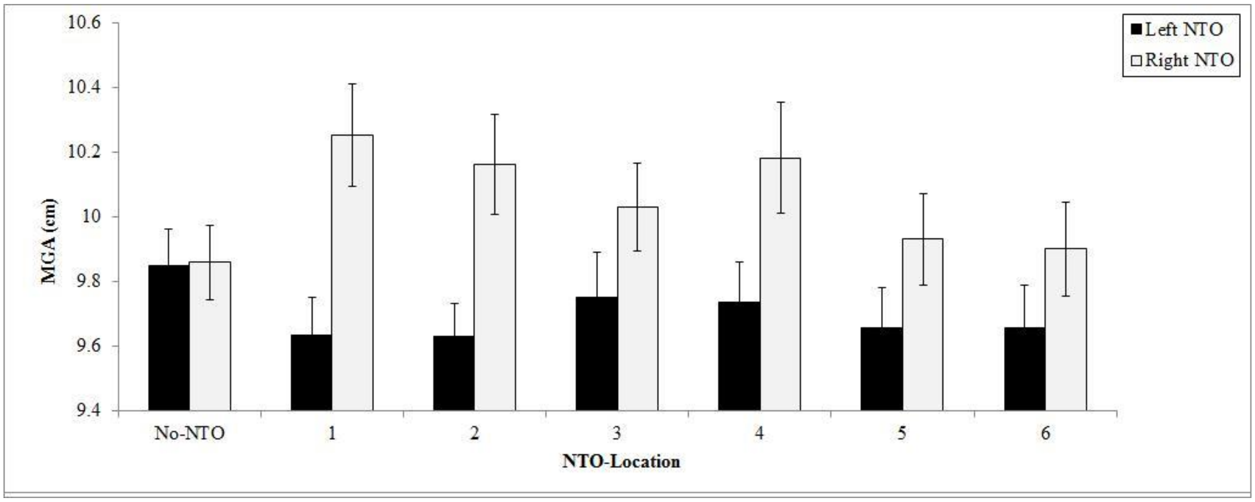

Figure 10: NTO-Side x Location interaction shows larger MGA when a subject had an NTO to the right in positions 1, 2 and 4.

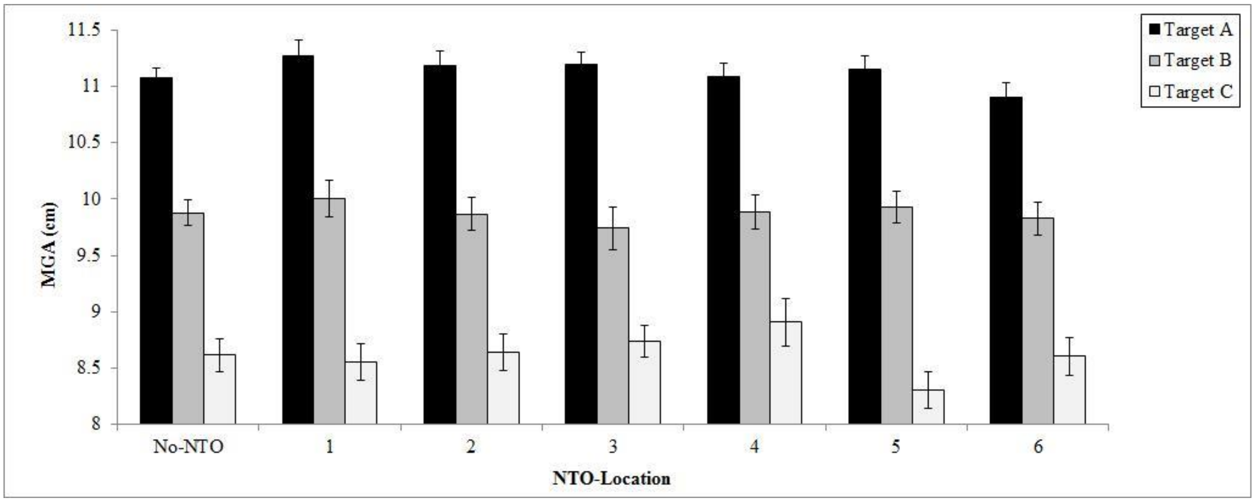

Figure 11: NTO-Location x Target interaction shows typical grip scaling at all NTO locations.

more controlled reach when the NTO is on the left. Only the comparison between NTO-locations 3 and 5 when participants reached for target C was significant in the Location x Target interaction.

Horizontal Index Grasp Location. The horizontal index grasp location refers to the location on the target where a subject's index grasped the object compared to its horizontal midpoint. Main effects of NTO-Side [$F(1, 18) = 15.46$, $p = .001$], NTO-Location [$F(3.32, 59.82) = 8.59$, $p < .001$] and Target [$F(1.19, 21.36) = 11.15$, $p = .002$] were found. The NTO-Side x Location [$F(3.32, 59.82) = 7.96$, $p < .001$] and NTO-Side x Target [$F(1.19, 21.36) = 7.65$, $p = .009$] interactions were also found to be significant (see Figure 12). In all cases, when the NTO was on the left side, there were no differences in grasp location between NTO locations. In all cases, the presence of an NTO on the right side produced leftward shifts of grasp location on the target greater than the control condition. NTOs in the closer location 2 on the right produced a greater shift in grasp position than did those in position 6, the position furthest from the subject. Leftward shifts in grasp location were seen in every NTO location condition on the right-side, compared to the left, with the exception of the control condition, which did not differ based on NTO-side.

For the NTO-Side x Target interaction, when the NTO was on the left side, participants showed a difference in grasp location as the target became wider and shorter. Wider objects produced a more rightward grasp location, such that the grasp location on target C [$M = 0.92$, $SD = 1.45$] was further right than it was on B [$M = 0.36$, $SD = 1$], which was further right than A [$M = -0.27$, $SD = 0.81$]. This effect was not seen when the NTO was on the right side, suggesting the presence of the NTO on the right anchors grasp location to a particular stable grasp-point

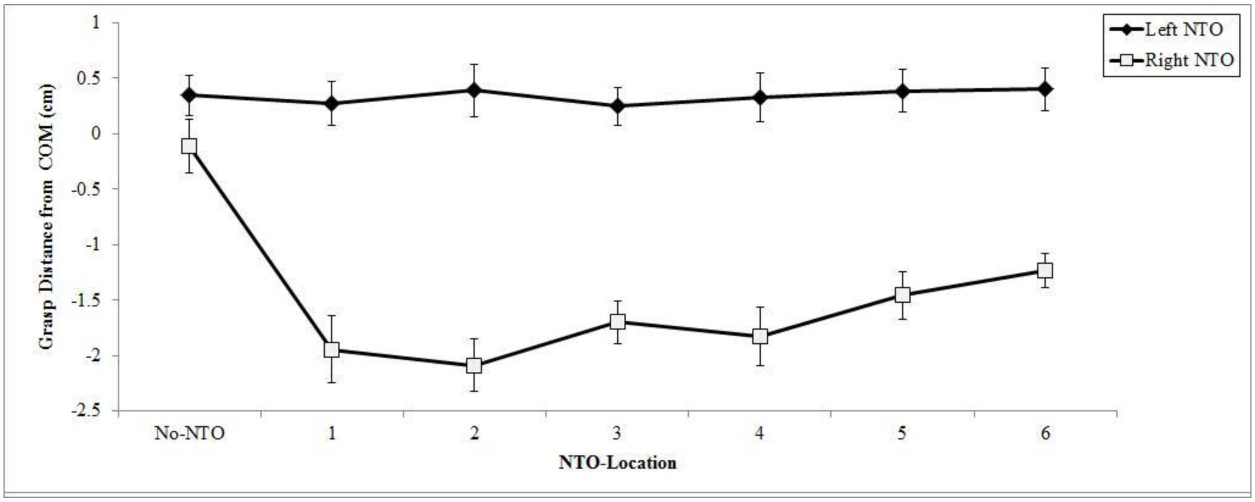

Figure 12: NTO-Side x Location interaction shows the leftward shift in grasp point when there is a NTO to the right.

regardless of target shape.

A series of one-sample t-tests was performed to further analyze final grasp location to determine if it differed significantly from the horizontal center of mass of the target among the various target objects. Looking at each target individually, when the NTO was on the left side, grasp location was significantly different from the target's horizontal midline on each target object, although grasp location was to the left of the target's midline when it was object A [Left-A: $t(69) = -2.63, p < .05$; Left-B: $t(69) = 2.97, p < .01$; Left-C: $t(69) = 5.22, p < .01$]. Grasp locations when the NTO was on the right side did not differ between target objects, but were significantly to the left of target center of mass [Right side: $M = -1.48$, $SD = 1.02$; $t(209) = -21.02, p < .01$].

Gaze Mechanics

Fixation Number and Duration. Fixations occur when gaze is held in a particular location in space for an extended period or duration. Subjects almost never fixated the NTO. Of 1241 trials only 19 contained a fixation toward the NTO (1.53%) and of 3847 total fixations across all subjects, only 19 were toward the NTO (0.49%) For fixation number, a main effect of Target [$F(2, 36) = 3.45, p = .043$] was found [Target A: $M = 3.21$, $SD = 0.98$; B: $M = 2.99$, $SD = 0.96$; C: $M = 3.11$, $SD = 1.1$]. At first and second fixation, no main effects or interactions were found for fixation duration. For the final fixation, a main effect of Target [$F(2, 36) = 4.24, p = .022$] was found [Target A: $M = 455.69$, $SD = 234.72$; B: $M = 480$, $SD = 257.58$; C: $M = 440.47$, $SD = 234.83$].

Horizontal Position. This variable refers to the location of a fixation in the horizontal plane when compared to the horizontal midpoint of the target object. For the first fixation, no main effects were found to be significant. The NTO-Side x Location [*F*(6, 108) = 3.24, *p* = .006], NTO-Side x Target [*F*(2, 36) = 3.48, *p* = .042], and NTO-Side x Location x Target [*F*(8, 140.31) = 2.04, *p* = .048] interactions were also found to be significant (see Figure 13, 14 and Table 1, respectively). Pairwise comparisons do suggest a pattern of results similar to those found with grasp location, however at the first fixation participants have not yet demonstrated the same structure in their behaviour, as few relevant comparisons are significant. As the target became wider and shorter, the first fixation was seen more rightward when NTOs were to the left, and more leftward when NTOs were to the right.

For the second fixation, main effects of NTO-Side [*F*(1, 18) = 4.88, *p* = .040] and NTO-Location [*F*(6, 108) = 2.34, *p* = .037] were found. The NTO-Side x Location [*F*(6, 108) = 2.67, *p* = .019] interaction was also found to be significant (see Figure 15). The leftward push from right-side NTOs, as seen with grasp location, is beginning to be demonstrated. Several right-side NTO-locations are seen to push location of gaze to the left compared to the right-side control condition, and all locations, except 1, push the location of gaze leftward when compared to its left-side analog.

Analysis of the final fixation revealed main effects of NTO-Side [*F*(1, 18) = 9.89, *p* = .006] and NTO-Location [*F*(4.1, 73.86) = 3.46, *p* = .011]. The NTO-Side x Location [*F*(4.1, 73.86) = 2.51, *p* = .048] and NTO-Side x Target [*F*(1.54, 27.64) = 5.05, *p* = .020] interactions were also found to be significant (see Figure 16). In all cases, when the NTO was on the left-side, there were no differences in subject performance. In all cases, the presence of an NTO on the right-side produced shifts leftward in the location of the final fixation when compared to the

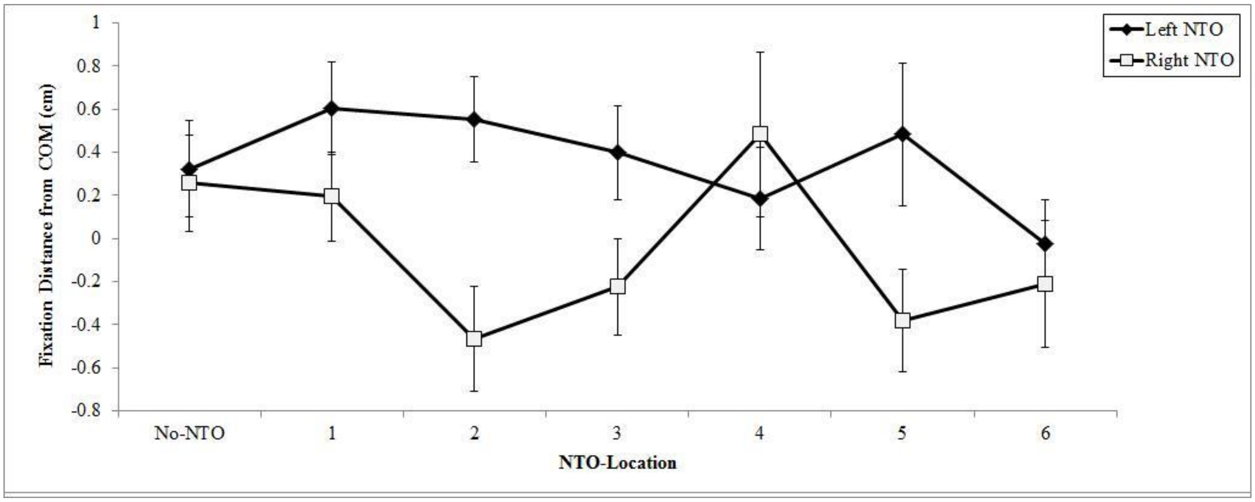

Figure 13: NTO-Side x Location interaction, at the first fixation there is little pattern to the data broken down over NTO position.

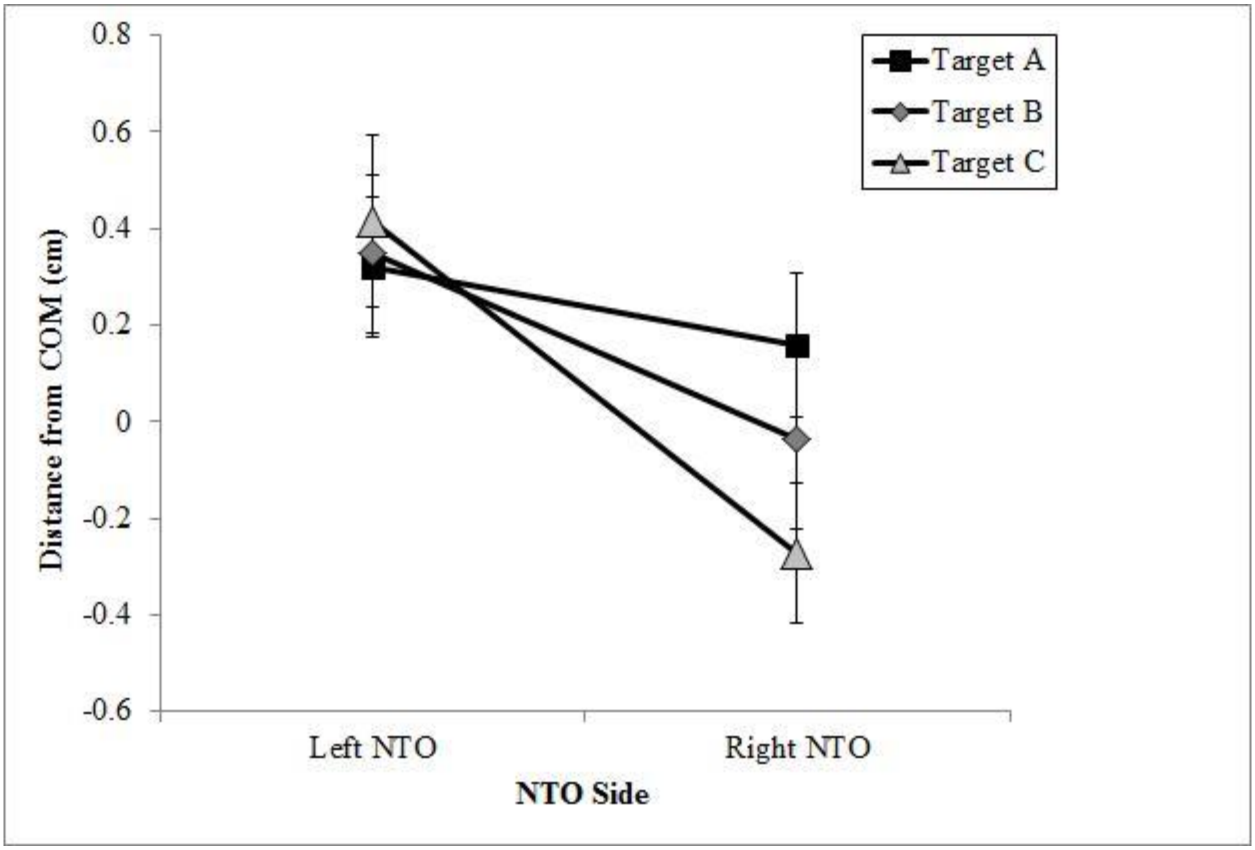

Figure 14: NTO-Side x Target interaction, at first fixation, a subject who sees left NTOs does not differ in horizontal gaze position between targets, but a subject who sees right NTOs does.

First Fixation Horizontal Position (cm)

NTO-Side x Location x Target Tukey Pairwise Comparisons

Comparison	M1	M2	q	Sig
Left 0A v Right 0A	0.26	-0.15	1.17	>.05
Left 0B v Right 0B	0.25	0.59	-0.96	>.05
Left 0C v Right 0C	0.45	0.33	0.36	>.05
Left 1A v Right 1A	0.66	0.36	0.87	>.05
Left 1B v Right 1B	0.37	0.23	0.40	>.05
Left 1C v Right 1C	0.78	0.00	2.23	>.05
Left 2A v Right 2A	0.13	0.12	0.02	>.05
Left 2B v Right 2B	0.50	-0.51	2.90	>.05
Left 2C v Right 2C	**1.03**	**-1.01**	**5.80**	**<.01***
Left 3A v Right 3A	0.34	-0.13	1.35	>.05
Left 3B v Right 3B	0.55	0.11	1.25	>.05
Left 3C v Right 3C	0.31	-0.65	2.73	>.05
Left 4A v Right 4A	-0.38	1.21	-4.54	>.05
Left 4B v Right 4B	0.57	-0.23	2.26	>.05
Left 4C v Right 4C	0.37	0.47	-0.28	>.05
Left 5A v Right 5A	1.00	-0.61	4.58	>.05
Left 5B v Right 5B	0.34	0.25	0.27	>.05
Left 5C v Right 5C	0.11	-0.79	2.56	>.05
Left 6A v Right 6A	0.22	0.30	-0.23	>.05
Left 6B v Right 6B	-0.15	-0.70	1.56	>.05
Left 6C v Right 6C	-0.14	-0.24	0.30	>.05

Table 1: All NTO-Side x Location x Target Tukey pairwise comparisons for the horizontal position of gaze during the first fixation of a trial with the only significant comparison highlighted.

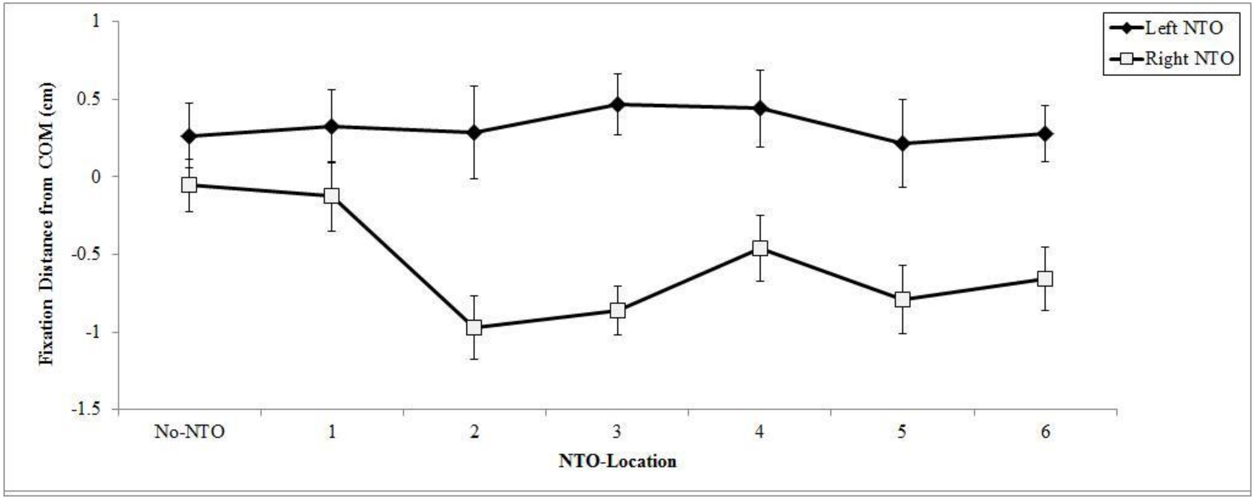

Figure 15: NTO-Side x Location interaction, at second fixation the leftward “push” from right side NTOs begins to emerge.

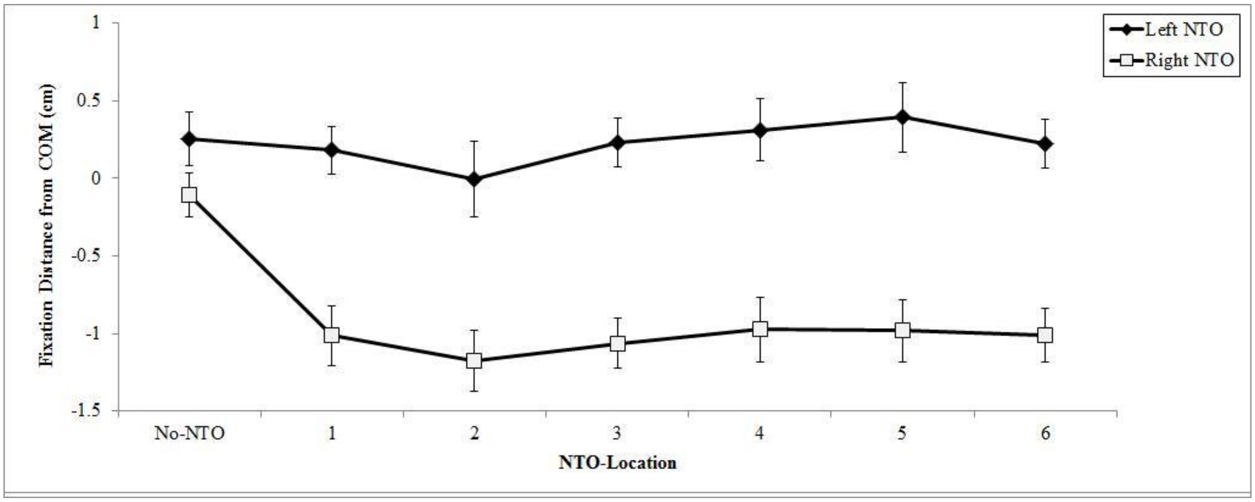

Figure 16: NTO-Side x Location interaction, the point of final fixation has been pushed left by right NTOs. The control conditions do not differ between NTO side.

control condition. No effects of NTO proximity to the reach or participant are seen. Leftward shifts in fixation location are seen in every NTO location condition on the right-side compared to the left with the exception of the control condition which did not differ based on NTO side. This pattern of results is nearly identical to the effect seen on grasp location from ride-side NTOs. Additionally in line with the findings from grasp location are the effects of the target object's shape. As the object became shorter and wider, final gaze position shifted to the right, however only in the presence of left-side NTOs [Left-A: *M* = -0.03, *SD* = 0.9; Left-B: *M* = 0.15, *SD* = 0.97; Left-C: *M* = 0.55, *SD* = 1.2].

A series of one-sample t-tests was performed to further analyze whether the horizontal position of the final fixation differed from the target object's center of mass. When the NTO was on the left-side, gaze position was only significantly different from the target's horizontal center of mass for target block C [Left-A: *t*(69) = -0.29, *p* > .05; Left-B: *t*(69) = 1.25, *p* > .05; Left-C: *t*(69) = 3.66, *p* < .01]. Gaze position when the NTO was on the right side, which did not differ between target objects, was significantly to the left of target center of mass, [Right side: *M* = -0.9, *SD* = 0.84; *t*(209) = -15.56, *p* < .01].

Vertical Position. This variable refers to the location of a fixation in the vertical plane when compared to the vertical midpoint of the target object. No main effects or interactions were found to be significant for the first fixation. For the second fixation, only a main effect of Target [Target A: *M* = 2.05, *SD* = 2.03; B: *M* = 1.41, *SD* = 1.75; C: *M* = 1.44, *SD* = 2.27; *F*(2, 36) = 7.02, *p* = .003] was found, demonstrating that on trials with taller targets, subjects will look higher on the object. Similar results were seen with the final fixation, where a main effect of Target [Target A: *M* = 1.8, *SD* = 1.36; B: *M* = 1.25, *SD* = 1.37; C: *M* = 1.01, *SD* = 1.52; *F*(1.36, 24.51) = 9.19, *p* = .003] was found again demonstrating that on trials with taller targets, subjects will look higher on the object.

Distance between Horizontal Index Grasp Point and Final Fixation. This variable is a measure of the distance between the index grasp point and the final fixation location in the horizontal plane. A main effect of Target [Target A: *M* = -0.5, *SD* = 1.34; B: *M* = -0.12, *SD* = 1.39; C: *M* = -0.07, *SD* = 1.55; *F*(1.63, 29.33) = 10.62, *p* = .001] was found. The NTO-Side x Location [*F*(6, 108) = 2.29, *p* = .041] interaction was also found to be significant (see Figure 17). These results demonstrate that, when the target is on the right side and positioned at the locations our results suggest are the most impactful on reach (1, 2 and 4) grasp location is further to the left of final fixation. No difference in the distance between final fixation and grasp location are found between NTOs on the left.

A series of t-tests was performed to determine if final fixation location was ever significantly different from grasp position. When NTOs appeared on the left side, including the control condition, grasp location was significantly to the right of fixation [*t*(209) = 2.15, *p* < .05]. Conversely, NTOs on the right-side, control condition included, produced grasp locations to the left of fixation [Left side: *M* = 0.11, *SD* = 0.77; Right side: *M* = -0.58, *SD* = 1.02; *t*(209) = -8.15, *p* < .01]. This is consistent with the previous results and suggests fixations may be less sensitive to shifts resulting from the presence of NTOs than is grasp location on the target.

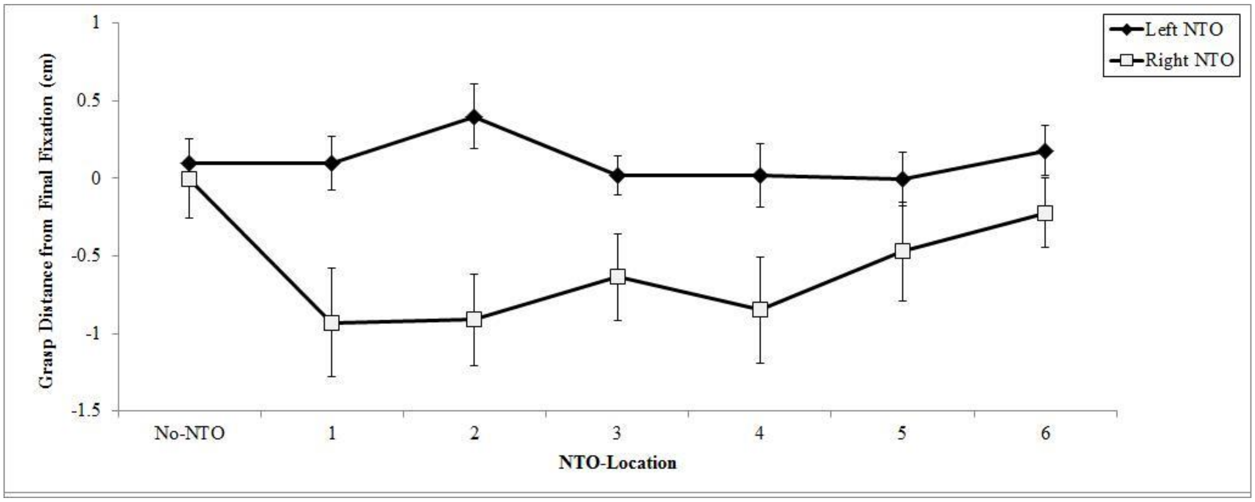

Figure 17: NTO-Side x Location interaction, when the NTO is in the most “invasive” positions on the right side, grasp point is pushed further left of fixation.

Discussion

Studies on reaching have tended to focus on data obtained from the reaching hand and arm or from the eyes exclusively. Advances in methods and technology have allowed us to investigate measures the effects of non-target objects (NTOs) on reach in both modalities in order to describe the mechanisms of eye-hand coordination. In line with our first hypotheses, reaches with an NTO on the right side were slower in average velocity, took longer to complete and demonstrated more trajectory deviation than did those with an NTO on the left side. When the NTO was on the right, positions closer to the subject were more intrusive, producing greater response times, slower average velocity and greater deviations in reach trajectory. With left side NTOs, the only such effect was seen when comparing trajectory deviations produced by NTOs in the closest position, with those in the position furthest from the subject and the NTO-free control. Though it was hypothesized that NTOs closer to the target would also be intrusive to reach, this was not the case. It may be that the NTOs close to the target did not obstruct the grasping phase of the reach enough to produce dramatic changes in reach mechanics – in contrast to previous studies that did find such effects (Tresilian, 1998).

Regarding our second set of hypotheses, gaze was directed at the target and anchored there nearly exclusively, as only 0.5% of fixations fell toward the NTOs (or 1.53% of trials). We did not see any patterns in eye-tracker data that suggested NTOs were treated as salient distractors. NTOs to the right of the subject produced leftward shifts of final fixation from the target's COM, whereas those to the left produced a shift to the right, though only to a significantly different degree when the target was its longest and shortest (Target C). Though this does support out hypothesis, comparing these results with a similar pattern found in the investigation of index grasp location suggests that shifts in fixation left or right from the target's COM may originate from separate mechanisms; shifts in fixations to the right may be caused by something different than are those to the left.

When the NTO was to the left, final index grasp point was also shifted right of the target's COM and of the final gaze fixation. This position did not vary based on NTO location, including comparisons made to the NTO-free control, but did differ based on target shape; moving further to the right as the target became wider and shorter. This pattern of results replicates previous research where NTOs were never present during reaches (Desanghere and Marotta, 2011; Paulun et al., 2013) and suggests the shift rightward in grasp and gaze is not due to left side NTOs at all. When the NTO was to the right, the grasp location was shifted to the left of both the target's COM and final gaze fixation, with the NTOs in the most invasive positions shifting the grasp point the furthest. Unlike left side NTOs, the shift in grasp position did not differ based on target shape. Subjects' grasp and gaze in the NTO-free control condition did not differ based on the side the NTOs were presented. We conclude that the shift in position of gaze and grasp demonstrated in the presence of right side NTOs was from a "push" from the presence of an NTO.

Interestingly, our hypotheses were only supported when the NTO was to the right of the subject; when it was to the left, reaches were undifferentiated on almost every measure. Though it is known ipsilateral NTOs generally produce greater effects on reaches (Dean and Bruwer, 1994), our results do not suggest a continuum of impact based on the nearness of the NTO to the reaching arm. Rather, subjects in the right and left side NTO groups were approaching the task in an entirely different manner. When the NTO was to the left, the risk of collision was so low that it seems subjects developed a set reach plan that was repeated nearly identically for each condition. When the NTO was to the right, however, the intrusiveness of the NTOs appears to have forced subjects to appraise the scene to develop a plan for each trial that would bring the hand and arm around the NTO to the target.

The most convincing evidence of this difference in strategies comes when comparing reaches performed in the NTO-free control condition between subjects in the left and right side NTO groups. If subjects in the left side NTO group were performing the same trial-by-trial appraisal as those in the right side group, it would be expected that performance would not only be indistinguishable between the control and NTO locations on the left, but also that performance between the two control conditions would be identical, as all conditions would be seen as posing little threat of collision. This is not the case; subjects in the right side NTO group produced more "efficient" movements in the control condition (with greater velocities and smaller trajectory deviations) than those produced by the left side group. The trial-by-trial appraisal of the scene employed by subjects in the right side NTO group appears to have produced benefits. Since the subject was more attentive to the scene, when the opportunity to make a more efficient reach appeared, they were ready to take it.

Even though we did observe the results we expected in terms of shifts in gaze and grasp location from right side NTOs, it may be premature to suggest this is the same attentional effect that is seen in visual marking (Watson & Humphreys, 1997). In this view of our results, the spatial location occupied by the NTO would have its attentional salience inhibited by early visual and parietal areas (Chapman & Goodale, 2011). This deprioritization of non-target relevant space produced a shift in attention away from the NTO, with greater shifts produced from NTOs that were found to be more "invasive". An NTO's "invasiveness" in this way acts as a measure of attentional salience; therefore the additional deprioritization needed to reduce the salience of more “invasive” NTO positions produced the greater shifts seen in grasp location.

Though it is true that an explanation focusing on the mechanisms of attention pushing the motor system from task irrelevant locations in space is congruent with our findings, so is one that suggests the motor system pulls attention toward the places that are most relevant to the reach. This explanation is reflected best by the theory of “least-minimum-distance” (Dean and Bruwer, 1994); a subject plotted their reach, according to the configuration of the reach space, using via-points that brought the hand and arm to the target with the smallest chance of collision with the NTO. To accomplish this, via-points further away from the NTO were planned by the motor system as the NTO increased in “invasiveness”, which is reflected in the shifting of grasp location further left on the target. As gaze facilitated the anchoring of grasp to the target by providing relevant information as it became necessary (Desanghere and Marotta, 2011; Hayhoe, 2000), attentional and gaze mechanisms were shifted to the left to provide the most up to date information at the location the index would land.

It may be that either view is too reductionist when talking about reaches being made in increasingly complex experimental settings. Rather than framing reaching behaviour as either the motor system informing attention or attention informing the motor system, it may be better to imagine the mechanism driving eye-hand coordination during reach as being part of an attention-for-action system, where the items or features determined to be salient to attention are based on the task specific priorities of an action. Though there is little doubt these systems could be isolated physiologically or behaviourally, the value of narrative perspectives that focus on one over the other will likely be limited to strict experimental designs.

Demonstrating this cohesion between motor and attentional processing, our results also showed that measures of reach mechanics were more sensitive to the attentional relevance of an

NTO than were measures of gaze. This was seen primarily in the comparison between index grasp location and final gaze fixation. The “push” from right side NTOs was of greater magnitude for grasp location than for fixation and when looking at the difference between grasp and final fixation, the most invasive positions pushed grasp further to the left from the final fixation, while the final fixation location was not altered by NTO position. Functionally, this makes sense; because the task was relatively the same from trial-to-trial, the information that perception and attention needed to provide the motor system was identical on each reach, resulting in a clustering of results across conditions. Conversely, the motor system needed to be sensitive to changes in the environment in order to accurately execute the reach; put bluntly, the eye is never at risk of colliding with the NTO and therefore can afford to be less sensitive to the layout of the reaching space. As a consequence, the motor system accomplished path planning using exclusively peripheral vision (Goodale et al., 1994; Chapman & Goodale, 2008).

The clustering of eye positions over trials also lends support to Hayhoe’s (2000) “just-in-time” theory. The information necessary for reach was provided via the fixation of reach relevant locations; yet, the pattern of effects on gaze does not appear until the final fixation, with much greater variance in the position of first and second fixations. This shows that, though the visual system will highlight task relevant locations, it does so as that information becomes most relevant; in this case, later in the reach as the hand approaches the target. Not only is the attention system task and strategy dependent, but is also sensitive to the temporal relevance of objects when determining locations necessary to fixate for task completion.

One unexpected pattern of results was found with regard to NTOs in position 4 on the right side. In terms of reach duration, trajectory deviations, MGA, average velocity and the leftward “push” of grasp location from final fixation, NTOs in position 4 produced impacts on reaches equal to or greater than those found for NTOs at locations closer to the subject. Though the NTO may have been closer to a subject's hand in positions 2 or 3, it may be the extra constraint of having to plot a trajectory around position 4, with the elbow as the focal point of contact, which contributes to the positions "invasiveness". At the closer positions, once the hand had deviated around the NTO, the arm could generally follow the same path to complete the reach. When the NTO was in position 4, this was not the case; the hand could reach the target with relatively little deviation from an ideal path, whereas the elbow risked collision with the NTO. Because subjects had less fine motor control over their elbow than hand, the motor system may have planned reaches that overcompensated for the NTO at that position. The NTO became more invasive not because it was closer to the subject, but because it impacted a part of the arm that is less controlled during reach than is the hand.

Looking to the future, this exploratory research offers insights into potential research programmes that could utilize hand and eye data to further how we understand the coordination of vision and action. Specifically, this research was designed with the intent to investigate possible ventral contributions to reaching, as current theories tend to downplay the ventral system's role in directing action (Schindler et al., 2004; Rice et al., 2006). NTOs of different colour, shape or pattern would activate attentional mechanisms associated with perceptual, or ventral, visual processing (Goodale et al., 1994). If reach or gaze mechanics are impacted by such ventral pictorial features, this would provide powerful evidence of ventral contributions to reach. Further, this paradigm could be used beyond testing ventral feature processing, but to also test the impact of NTO identity. For instance, can a cactus produce greater impacts on reach than an NTO that shares certain features with it? If so, this would provide insight into the cross-talk between the dorsal and ventral visual systems, among other things. More pure tests of dorsal attention could also be accomplished through this paradigm. The introduction of moving NTOs, those defined by contrasts in luminosity or those containing black and white patterns could provide more direct tests of dorsal attentional mechanisms without the contribution of ventral perceptual processing.

In summation, we found that NTOs to the right of the subject (ipsilateral to a subject's reaching arm) produced reaches of a longer duration, slower velocity and with greater trajectory deviations than do those left (contralateral) of the subject. The impact of the NTO on reach was increased as it was moved into positions that were of greater obstruction to the hand and arm. When the NTO was to the left, almost no differences were found between NTO locations. This right-left (ipsilateral-contralateral) effect is likely due to different strategies employed by subjects resulting in both costs and benefits to reach when the NTO is to the right and a single pattern of reaching when the NTO is to the left. Right side NTOs were additionally found to "push" both gaze fixations and index grasp locations to the away from their position, whereas left side NTOs produced reaches identical to those performed in the absence of NTOs. This may have been due to an attention-for-action system that prioritized stimuli in the environment based on the subject's goals and strategies.

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Appendix A

Informed Consent

INVESTIGATORS:	Loni Desanghere Timothy Graham Dr. Steve Prime Department of Psychology University of Manitoba (204) 480-1248	Dr. Jonathan Marotta Department of Psychology University of Manitoba (204) 474-7057

SOURCE OF SUPPORT: NSERC and CIHR
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 pick up objects.

DESCRIPTION: During this study you will be asked to either reach out and pick up objects that are placed in front of you or to perform a perceptual task. In some conditions you may be asked to reach for the object while avoiding foam-core obstacles either with feedback or without. An eye tracker will be used to record your eye movements when performing these tasks and an OPTOTRAK 3-D 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. 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 evident risks inherent in the tasks you will perform but some of the tests may be difficult. While this may be frustrating to you, there will always be an investigator with you to assist you and support you.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will not receive any payment for your participation. For your participation, you will receive course credits towards your introductory psychology course.

CONFIDENTIALITY: Your information will be kept confidential. You will be referred to by a code number. Your files will only be accessible by the investigators and will be destroyed 5 years after the completion of the study.

VOLUNTARY CONSENT: If you do not wish to participate in the study, you are free to leave without consequence and we thank you for your consideration. 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. 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.

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 Secretariat at 474-7122, or e-mail Margaret_bowman@umanitoba.ca. 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 a general summary of the results from this study when it is completed, please leave contact information below.

____

____

____

Appendix B

Demographics Questionnaire

ID_______

Sex:_________

Age:_________

Do you have normal or corrected to normal vision? __________________________

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

1. Throw a ball. L/R
2. Brush your teeth. L/R
3. Eat 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? ________________________

Appendix C

Debriefing Form

INVESTIGATORS: Loni Desanghere
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Timothy Graham
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University of Manitoba
(204) 480-1248

Dr. Jonathan Marotta
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University of Manitoba
(204) 474-7057

Thank you for participating in this study. In this study we were interested in where on the object or in the environment you were looking when reaching, picking up the object or when performing perceptual task. 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 reaching for or grasping objects that differ in shape, size, symmetry and location and how these fixations differ when doing perceptual tasks. 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 or obstacles. 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

RENEWAL APPROVAL

10 July 2009

TO: **Loni Desanghere**
Jonathan Marotta
Principal Investigators

FROM: **Bruce Tefft, Chair**
Psychology/Sociology Research Ethics Board (PSREB)

Re: **Protocol #P2007:073**
"Eye Movements and Grasping: Where do we Look when Picking up Objects?"

Please be advised that your above-referenced protocol has received approval for renewal by the **Psychology/Sociology Research Ethics Board**. This approval is valid for one year only.

Any significant changes of the protocol and/or informed consent form should be reported to the Human Ethics Secretariat in advance of implementation of such changes.

Appendix E

Significant Tukey Pairwise Comparisons

Reach Duration (ms)

	NTO-Location			
Comparison	M1	M2	q	Sig.
0 v 1	827.57	954.9	-13.74	<.01
0 v 2	827.57	900.83	-7.9	<.01
0 v 3	827.57	887.4	-6.45	<.01
0 v 4	827.57	913.78	-9.3	<.01
0 v 5	827.57	887.21	-6.43	<.01
0 v 6	827.57	871.71	-4.76	<.05
1 v 3	954.9	887.4	7.28	<.01
1 v 5	954.9	887.21	7.3	<.01
4 v 6	913.78	871.71	4.54	<.05
1 v 2	954.9	900.83	5.83	<.01

	NTO-Side x Location			
Comparison	M1	M2	q	Sig.
Right 0 v 1	805.6	1040.71	-17.94	<.01
Right 0 v 2	805.6	926.2	-9.2	<.01
Right 0 v 3	805.6	901.18	-7.29	<.01
Right 0 v 4	805.6	973.89	-12.84	<.01
Right 0 v 5	805.6	912.76	-8.18	<.01
Right 0 v 6	805.6	874.36	-5.25	<.01
Right 1 v 3	1040.71	901.18	10.64	<.01
Right 1 v 5	1040.71	912.76	9.76	<.01
Right 4 v 6	973.89	874.36	7.59	<.01
Right 1 v 2	1040.71	926.2	8.74	<.01
Right 3 v 4	901.18	973.89	-5.55	<.01
Left 1 v Right 1	869.1	1040.71	-13.09	<.01
Left 4 v Right 4	853.68	973.89	-9.17	<.01

	NTO-Location x Target			
Comparison	M1	M2	q	Sig.
0A v 1A	855.48	972.31	-10.56	<.01
0A v 2A	855.48	916.22	-5.49	<.05
1A v 3A	972.31	887.66	7.65	<.01
1A v 3A	972.31	896.67	6.84	<.01
2A v 6A	916.22	858.75	5.19	<.05
1A v 2A	972.31	916.22	5.07	<.05
0B v 1B	794.87	929.23	-12.15	<.01
0B v 2B	794.87	909.33	-10.35	<.01
0B v 3B	794.87	898.72	-9.39	<.01
0B v 4B	794.87	937.76	-12.92	<.01
0B v 5B	794.87	890.8	-8.67	<.01
0B v 6B	794.87	869.71	-6.77	<.01
4B v 6B	937.76	869.71	6.15	<.01
0C v 1C	832.37	963.17	-11.82	<.01
0C v 4C	832.37	900.77	-6.18	<.01
0C v 6C	832.37	886.67	-4.91	<.05
1C v 3C	963.17	875.83	7.89	<.01
1C v 3C	963.17	874.17	8.05	<.01
1C v 2C	963.17	876.96	7.79	<.01

Wrist Deviation (cm)

	NTO-Location			
Comparison	M1	M2	q	Sig.
0 v 1	8.26	13.66	-26.16	<.01
0 v 2	8.26	12.04	-18.31	<.01
0 v 3	8.26	11.21	-14.27	<.01
0 v 4	8.26	11.22	-14.36	<.01
0 v 5	8.26	10.41	-10.44	<.01
0 v 6	8.26	9.97	-8.31	<.01
1 v 3	13.66	11.21	11.89	<.01
1 v 5	13.66	10.41	15.72	<.01
2 v 6	12.04	9.97	10	<.01
4 v 6	11.22	9.97	6.05	<.01
1 v 2	13.66	12.04	7.85	<.01

Target

Comparison	M1	M2	q	Sig.
A v B	11.33	10.87	3.28	<.05
A v C	11.33	10.7	4.54	<.01

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Left 0 v 1	8.92	10.44	-5.2	<.01
Left 1 v 5	10.44	9.01	4.86	<.05
Right 0 v 1	7.59	16.89	-31.8	<.01
Right 0 v 2	7.59	14.16	-22.45	<.01
Right 0 v 3	7.59	12.84	-17.93	<.01
Right 0 v 4	7.59	12.7	-17.45	<.01
Right 0 v 5	7.59	11.81	-14.43	<.01
Right 0 v 6	7.59	10.78	-10.9	<.01
Right 1 v 3	16.89	12.84	13.88	<.01
Right 1 v 5	16.89	11.81	17.38	<.01
Right 2 v 4	14.16	12.7	4.99	<.01
Right 2 v 6	14.16	10.78	11.55	<.01
Right 4 v 6	12.7	10.78	6.55	<.01
Right 1 v 2	16.89	14.16	9.36	<.01
Left 0 v Right 0	8.92	7.59	4.52	<.05
Left 1 v Right 1	10.44	16.89	-22.08	<.01
Left 2 v Right 2	9.92	14.16	-14.48	<.01
Left 3 v Right 3	9.58	12.84	-11.15	<.01
Left 4 v Right 4	9.75	12.7	-10.08	<.01
Left 5 v Right 5	9.01	11.81	-9.57	<.01
Left 6 v Right 6	9.16	10.78	-5.53	<.01

Average Velocity (cm/s)

NTO-Location

Comparison	M1	M2	q	Sig.
0 v 1	55.08	51.67	8.22	<.01
0 v 2	55.08	52.7	5.72	<.01
0 v 3	55.08	52.63	5.89	<.01
0 v 4	55.08	52.11	7.17	<.01
0 v 5	55.08	52.89	5.26	<.01
0 v 6	55.08	52.65	5.86	<.01

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 1	57.06	51.09	10.18	<.01
Right 0 v 2	57.06	53.76	5.62	<.01
Right 0 v 3	57.06	53.41	6.21	<.01
Right 0 v 4	57.06	51.33	9.77	<.01
Right 0 v 5	57.06	53.4	6.24	<.01
Right 0 v 6	57.06	53.78	5.59	<.01
Right 2 v 4	53.76	51.33	4.15	<.05
Right 4 v 6	51.33	53.78	-4.18	<.05
Right 1 v 2	51.09	53.76	-4.56	<.05
Left 0 v Right 0	53.1	57.06	-6.75	<.01

NTO-Location x Target

Comparison	M1	M2	q	Sig.
0A v 1A	53.74	50.78	5.04	<.05
0B v 1B	57.22	52.84	7.46	<.01
0B v 2B	57.22	52.16	8.61	<.01
0B v 3B	57.22	51.78	9.26	<.01
0B v 4B	57.22	51.16	10.3	<.01
0B v 5B	57.22	52.58	7.89	<.01
0B v 6B	57.22	52.81	7.5	<.01
0C v 1C	54.27	51.39	4.9	<.05

MGA (cm)

Target

Comparison	M1	M2	q	Sig.
A v B	11.12	9.88	21.97	<.01
A v C	11.12	8.62	43.98	<.01
B v C	9.88	8.62	22.01	<.01

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 1	9.86	10.25	-4.5	<.05
Left 1 v Right 1	9.64	10.25	-7.07	<.01
Left 2 v Right 2	9.63	10.16	-6.1	<.01
Left 4 v Right 4	9.74	10.18	-5.09	<.01

NTO-Location x Target

Comparison	M1	M2	q	Sig.
3C v 5C	8.74	8.3	5.91	<.01

Final Index Grasp Location (cm)

NTO-Location

Comparison	M1	M2	q	Sig.
0 v 1	0.12	-0.83	8.17	<.01
0 v 2	0.12	-0.85	8.28	<.01
0 v 3	0.12	-0.73	7.24	<.01
0 v 4	0.12	-0.75	7.42	<.01
0 v 5	0.12	-0.53	5.6	<.01
0 v 6	0.12	-0.42	4.6	<.05

Target

Comparison	M1	M2	q	Sig.
A v B	-0.94	-0.48	-4.58	<.01
A v C	-0.94	-0.29	-6.5	<.01

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 1	-0.11	-1.94	11.11	<.01
Right 0 v 2	-0.11	-2.09	11.96	<.01
Right 0 v 3	-0.11	-1.7	9.63	<.01
Right 0 v 4	-0.11	-1.82	10.38	<.01
Right 0 v 5	-0.11	-1.45	8.14	<.01
Right 0 v 6	-0.11	-1.24	6.81	<.01
Right 2 v 6	-2.09	-1.24	-5.15	<.01
Left 1 v Right 1	0.28	-1.94	13.45	<.01
Left 2 v Right 2	0.39	-2.09	15	<.01
Left 3 v Right 3	0.25	-1.7	11.8	<.01
Left 4 v Right 4	0.33	-1.82	13.05	<.01
Left 5 v Right 5	0.39	-1.45	11.15	<.01
Left 6 v Right 6	0.4	-1.24	9.91	<.01

NTO-Side x Target

Comparison	M1	M2	q	Sig.
Left A v B	-0.27	0.36	-4.47	<.01
Left A v C	-0.27	0.92	-8.42	<.01
Left B v C	0.36	0.92	-3.96	<.01
Left A v Right A	-0.27	-1.61	9.5	<.01
Left B v Right B	0.36	-1.33	11.95	<.01
Left C v Right C	0.92	-1.5	17.16	<.01

Number of Fixations

Target

Comparison	M1	M2	q	Sig.
A v B	3.21	2.99	3.71	<.05

Final Fixation Duration (ms)

Target

Comparison	M1	M2	q	Sig.
B v C	480	440.47	4.08	<.01

First Fixation Horizontal Position (cm)

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 2 v 4	-0.47	0.48	-5.2	<.01
Left 2 v Right 2	0.55	-0.47	5.59	<.01
Left 5 v Right 5	0.48	-0.38	4.75	<.05

NTO-Side x Target

Comparison	M1	M2	q	Sig.
Right A v C	0.16	-0.27	4.3	<.01
Left B v Right B	0.35	-0.04	3.85	<.05
Left C v Right C	0.42	-0.27	6.87	<.01

NTO-Side x Location x Target

Comparison	M1	M2	q	Sig
Left 2C v Right 2C	1.03	-1.01	5.8	<.01

Second Fixation Horizontal Position (cm)

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 2	-0.05	-0.97	5.33	<.01
Right 0 v 3	-0.05	-0.86	4.69	<.05
Right 0 v 5	-0.05	-0.79	4.27	<.05
Right 1 v 3	-0.13	-0.86	4.27	<.05
Right 1 v 2	-0.13	-0.97	4.91	<.01
Left 2 v Right 2	0.29	-0.97	7.31	<.01
Left 3 v Right 3	0.46	-0.86	7.7	<.01
Left 4 v Right 4	0.44	-0.46	5.24	<.01
Left 5 v Right 5	0.21	-0.79	5.84	<.01
Left 6 v Right 6	0.28	-0.66	5.45	<.01

Final Fixation Horizontal Position (cm)

NTO-Location

Comparison	M1	M2	q	Sig.
0 v 1	0.07	-0.42	4.47	<.05
0 v 2	0.07	-0.59	6.04	<.01
0 v 3	0.07	-0.42	4.46	<.05
0 v 6	0.07	-0.39	4.25	<.05

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 1	-0.11	-1.02	5.86	<.01
Right 0 v 2	-0.11	-1.17	6.89	<.01
Right 0 v 3	-0.11	-1.06	6.17	<.01
Right 0 v 4	-0.11	-0.98	5.6	<.01
Right 0 v 5	-0.11	-0.98	5.65	<.01
Right 0 v 6	-0.11	-1.01	5.83	<.01
Left 1 v Right 1	0.18	-1.02	7.71	<.01
Left 2 v Right 2	-0.01	-1.17	7.54	<.01
Left 3 v Right 3	0.23	-1.06	8.35	<.01
Left 4 v Right 4	0.31	-0.98	8.3	<.01
Left 5 v Right 5	0.39	-0.98	8.87	<.01
Left 6 v Right 6	0.22	-1.01	7.95	<.01

NTO-Side x Target

Comparison	M1	M2	q	Sig.
Left A v C	-0.03	0.56	-4.82	<.01
Left B v C	0.15	0.56	-3.29	<.05
Left A v Right A	-0.03	-0.84	6.56	<.01
Left B v Right B	0.15	-0.87	8.34	<.01
Left C v Right C	0.56	-1	12.73	<.01

Second Fixation Vertical Position (cm)

Target

Comparison	M1	M2	q	Sig.
A v B	2.05	1.41	4.71	<.01
A v C	2.05	1.44	4.45	<.01

Final Fixation Vertical Position (cm)

Target

Comparison	M1	M2	q	Sig.
A v B	1.8	1.25	4.11	<.01
A v C	1.8	1.01	5.92	<.01

Grasp Distance from Final Fixation (cm)

Target

Comparison	M1	M2	q	Sig.
A v B	-0.5	-0.12	-5.21	<.01
A v C	-0.5	-0.07	-6	<.01

NTO-Side x Location

Comparison	M1	M2	q	Sig.
Right 0 v 1	0	-0.93	4.84	<.05
Right 0 v 2	0	-0.91	4.74	<.05
Right 0 v 4	0	-0.85	4.42	<.05
Left 1 v Right 1	0.1	-0.93	5.35	<.01
Left 2 v Right 2	0.4	-0.91	6.83	<.01
Left 4 v Right 4	0.02	-0.85	4.54	<.05