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RESEARCH ARTICLE

"Graspability" of objects affects gaze patterns during perception and action tasks

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Abstract When grasping an object, our gaze marks key positions to which the fingertips are directed. In contrast, eye fixations during perceptual tasks are typically concentrated on an object's centre of mass (COM). However, previous studies have typically required subjects to either grasp the object at predetermined sites or just look at computer-generated shapes "as a whole". In the current study, we investigated gaze fixations during a reaching and grasping task to symmetrical objects and compared these fixations with those made during a perceptual size estimation task using real (Experiment 1) and computer-generated objects (Experiment 2). Our results demonstrated similar gaze patterns in both perception and action to real objects. Participants first fixated a location towards the top edge of the object, consistent with index finger location during grasping, followed by a subsequent fixation towards the object's COM. In contrast, during the perceptual task to computer-generated objects, an opposite pattern in fixation locations was observed, where first fixations were closer to the COM, followed by a subsequent fixation towards the top edge. Even though differential fixation patterns were observed between studies, the area in which these fixations occurred, between the centre of the object and top edge, was the same in all tasks. These results demonstrate for the first time consistencies in fixation locations across both perception and action tasks, particularly when the same type of information (e.g. object size) is important for the completion of both tasks, with fixation locations increasing relative to the object's COM with increases in block height.

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Introduction

When you want to pick up an object, it is usually a simple matter to look where you remember leaving it, reach out to its location, and accurately pick it up. This simple task involves directing the eyes to the object and using visual information about the object's location and shape in the motor programming of the hand's reach. Generally, programming the eye movements that bring the line of sight onto a selected object requires two processing stages: selection of that object, followed by the computation of a fixation/landing position on that object (Deubel et al. 1998). When interacting with our environment, the requirements of visual analysis have been shown to be dependent on both the ongoing or planned behaviour of the individual (Hamed et al. 2002) and the cognitive demands of that task (Yarbus 1967). Indeed, when fixation locations are studied relative to ongoing behaviour, one can start to understand the function of fixation locations on task performance and completion. Although scenes can be easily identified and the 'gist' of that scene obtained very rapidly, usually within the duration of a single fixation (Biederman et al. 1982; Thorpe et al. 1996), we typically make a series of saccades and fixations to direct the foveal region of our eyes to areas of interest. Our gaze, however, is not randomly directed to objects and events around us. Gaze control is an active process wherein the viewer seeks out task-relevant information from the environment (Henderson 2003).

During scene perception, viewers tend to orient their gaze to locations that provide detailed information, rather than empty areas lacking contextual information (Helsen et al. 2000; Henderson 2003). However, when asked to view solitary stimuli, previous research suggests that the eye is drawn to the object's centre of mass (COM; He and Kowler 1991; Kowler and Blaser 1995; McGowan et al. 1998; Melcher and Kowler 1999; Vishwanath and Kowler 2003, 2004; Vishwanath et al. 2000). These results have been shown with simple forms such as circles (Kowler and Blaser 1995; Melcher and Kowler 1999), unstructured forms such as configurations of random dots (McGowan et al. 1998), and complex forms whose COM lies outside the boundaries of the shape (Vishwanath and Kowler 2003). In fact, the COM has been found to be a better predictor of where people will fixate on an object when compared to other landmarks, such as the symmetrical axis of the object (McGowan et al. 1998; Melcher and Kowler 1999). What is notable about these studies is that object size and shape are not relevant to the completion of the perceptual task as participants are just instructed to "look at the object as a whole"—instructions designed to capture what happens when we look from object to object during natural viewing.

When interacting with objects, research has shown that the relationship between eye and hand movements are intimately linked, with eye movements typically preceding hand movements in both pointing (Abrams et al. 1990; Bekkering et al. 1994; van Donkelaar et al. 2004) and object manipulation tasks (Hayhoe and Ballard 2005; Hayhoe et al. 2003; Johansson et al. 2001; Land and Hayhoe 2001; Land et al. 1999). However, less research has been devoted to investigating where on an object people are fixating during a solitary reaching and grasping movement. This issue was partially explored by de Grave et al. (2008) who were interested in fixation locations during a reaching and grasping task to objects that were either fully visible or that had the index finger, thumb, or both grasp locations partially occluded. They found that first and second fixations on the objects were above the objects COM, as well as above the visible COM (COMvis) in the case of partly occluded objects. In both instances, fixation locations were towards index finger grasp location (see also Desanghere and Marotta 2008).

Relatively few studies have explored differences in gaze strategies in the same participants while performing both a perception and action task to the same objects. Those that have clearly demonstrate that the functional demands of the task will impose distinct gaze strategies between perception and action. For example, van Doorn et al. (2009) used the Muller-Lyer illusion to investigate differences in gaze patterns during a reaching and grasping task and a perceptual size estimation task wherein the participant had to indicate the size of an object by separating their index finger and thumb. Consistent with previous findings (van Doorn et al. 2007; Otto-de Haart et al. 1999), the Muller-Lyer configuration affected perceptual estimations (judgements of the length of lines were affected by arrowheads that were surrounding the line) but not grip aperture when picking up these same objects. Similarly, differences in fixation locations during perception and action were also revealed. Fixations during estimations were concentrated symmetrically towards allocentric information (both ends of the objects), while fixations during grasping were concentrated asymmetrically towards one end (index finger landing position) and egocentric locations (the centre of the line). In a related study exploring differences in gaze strategies between perception and action to real objects, Brouwer et al. (2009) compared the fixation locations between tasks that required subjects to either reach and grasp an object or simply look at the object in the absence of any action directed towards it. They found that during first fixations on the objects, there were no differences between tasks; during both grasping and viewing, participants were looking closer to the object's COM. During second fixations however, fixations while grasping were found to be significantly higher up on the objects (towards index finger location) than those found during viewing. They suggest that first fixations on the objects are not influenced by task, but by visual features such as the COM. Second fixations, however, are more tailored to the specific task, such as towards index finger grasp location when grasping objects.

It is evident from the previous studies that differences in the visual analysis of objects emerge when generating a perceptual or motor response to an object, in terms of time spent fixating different areas of an illusory line while grasping or estimating its size (van Doorn et al. 2009) and in terms of second fixation locations when looking at or grasping shapes (Brouwer et al. 2009). Such results contribute to the large body of literature that has shown distinct differences in the processing of visual information for the purpose of perception and action (for review, see Milner and Goodale 2006). The purpose of the present study is to further explore differences in gaze patterns during perception and action. Using a similar experimental paradigm as van Doorn et al. (2009), we will ask participants to estimate the size of objects for the perceptual task and to reach out and grasp the objects for the action task (Experiment 1). By using simple symmetrical objects, where no illusory manipulations will affect our perception of object width/length, we will explore differences in gaze strategies between perception and action on real "graspable" objects in a situation where the same object properties are important for the completion of both tasks (object width). Additionally, to further investigate gaze strategies during perception, size estimations to computer-generated shapes will be explored in Experiment 2. Based on previous research, it is expected that first fixations during both perception and action tasks will be drawn towards the objects' COM so as to gain an overall representation of object shape. Subsequent fixations during grasping will be linked to index finger landing position on the objects, while subsequent fixations during estimations will be drawn to allocentric cues and directed towards both the top and bottom edges of the objects.

Experiment 1

Methods

Participants

Twenty-six undergraduate psychology students (14 women) between the ages of 18 and 38 years (mean age of 23) participated in this study. All participants were shown to be strongly right-handed as determined by a modified version of the Edinburg Handedness Inventory (Oldfield 1971) and had normal or corrected-to-normal-vision. This research was approved by the Human Research Ethics Board at the University of Manitoba.

Stimulus and procedure

Participants were required to perform a grasping task and a perceptual size estimation task, in separate blocks of trials, to centrally placed Efron Blocks. The Efron blocks differ in shape but are equal in surface area (Efron 1968) and have the following horizontal and vertical dimensions: (1) 15.2 × 4.2 cm, (2) 12.2 × 5.2 cm, (3) 10.2 × 6.2 cm, (4) 9.0 × 7.1 cm and (5) 8.0 × 8.0 cm. The Efron blocks were presented on a 20 × 20 cm vertical presentation board that was positioned 50 cm away from a chin rest, which rested on the edge of the table. Two pegs protrude from the presentation board to allow for the blocks to be suspended in such a manner that every block's vertical and horizontal centre was aligned with the board's centre. The display board was positioned beside the computer monitor that was used to calibrate the eyes, such that the blocks were suspended vertically at an equal distance from the participant as the calibration monitor. Seven infrared light-emitting diodes (IREDs) were positioned along the edge of the display board to create a rigid body, the origin of which corresponded to the centre of the board and, consequently, to the centre of each presented block (see Fig. 1 for set-up).

Reach-to-grasp movements were recorded with an Optotrak Certus 3-D recording system (150 Hz sampling rate, spatial accuracy up to 0.01 mm; Northern Digital, Waterloo, ON, Canada). Two IREDs were fastened onto the participants' index finger (positioned on the left side of the cuticle), thumb (positioned on the right side of the cuticle) and wrist (positioned on the radial portion of the wrist) of their right hand. An Eye-link II (250 Hz sampling rate, spatial resolution <0.5°; SR Research Ltd., Osgoode, ON, Canada) was used to record eye movements in both tasks. Kinematic information from both the Optotrak and the Eyelink II was integrated into a common frame of reference via Motion Monitor software (Innovative Sports technology, Chicago, IL, USA). The Motion Monitor system integrates eye, head and hand data in a common frame of reference. Both eyes were calibrated using a nine-point calibration/validation procedure on the computer monitor, after which participants were positioned in front of the display board. To ensure accurate calibrations of less than 1 degree error and reliability of binocular eye data, accuracy checks both immediately following calibration and after the completion of the experiment were taken by

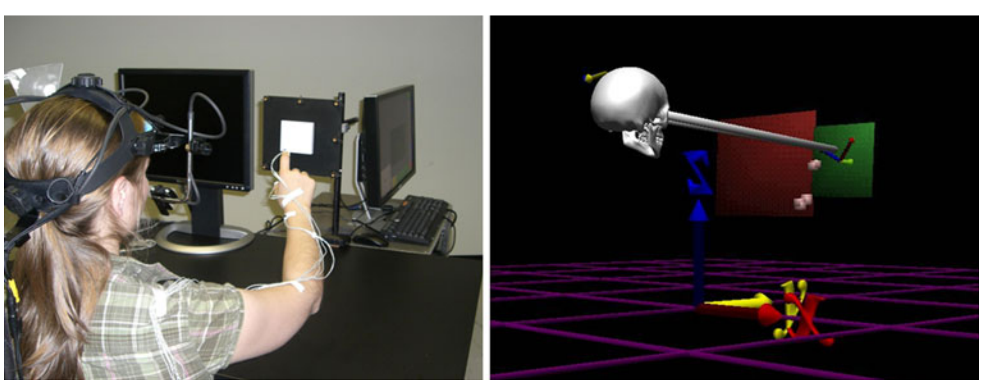

Fig. 1 Experimental set-up in real life environment (*left panel*) and in the Motion Monitor virtual environment (*right panel*)

having participants fixate a marker on the display while positional eye data were obtained.

Gaze coordinates (both horizontal X and vertical Y positions) were characterized into fixations based on a dispersion algorithm (see Salvucci and Goldberg 2000), with a minimum duration threshold of 150 ms and a maximum dispersion threshold of 1 cm. Fixations were calculated from the point when participants first opened their eyes until they either made contact with the object (in the grasping task) or finished their size estimation (indicated by a key tap made by the participant with their left hand). As pilot studies in our laboratory have shown that participants frequently look at their hand during a manual estimation task, all eye movements outside the boundaries of the display board were not included in the analysis as these values were outside of the calibration range (i.e. the eye angles were too large and accurate fixation could not detected).

A within-subject design was utilized wherein all participants performed both the grasping and estimation task. In the grasping task, participants were instructed to reach out and grasp the presented block "quickly but naturally" using only their index finger and thumb. In the estimation task, participants kept their hand stationary on the tabletop and estimated the vertical height of the presented block by moving their index finger and thumb. Task order was counterbalanced between participants. Within each task, each block was randomly presented 12 times, for a total of 60 trials per task. Sessions took approximately 1 h to complete.

Dependent variables involved in subsequent analyses include eye positions along the horizontal X- and vertical Y-axes, as well as fixation durations (ms); index and thumb positions along the horizontal X-axis of the objects; maximum opening between the index finger and thumb while grasping (maximum grip aperture: MGA); grasp axis location (distance of the joining point between index finger and thumb from the object's COM); and perceptual estimations of size (distance between index finger and thumb).

Results

Gaze data

Across all subjects, a total of 3,953 fixations were detected during grasping and 4,378 fixations during estimations. On average, participants made 2.03 and 2.32 fixations per trial during grasping and estimation tasks, respectively. Paired sample t tests revealed that the mean number of fixations elicited during each task was not statistically different ($t(25) = -1.67$, $P > 0.05$). In 94% of all experimental trials, a first fixation was detected (1,490 first fixations during grasping and 1,427 first fixations during estimations); in 85% of those trials, a subsequent (second) fixation was detected (1,337-s fixations during grasping and 1,305-s fixations during estimations). Fixations were not detected in 6% of trials due to loss of eye data (e.g. loss of corneal reflection or IRED interference), and these trials were excluded from any further analyses.

Paired sample t tests were carried out to explore any differences in position and duration of first fixations when there were multiple fixations present versus one fixation only. Analyses revealed no overall differences in fixation positions along the X- or Y-axes ($P > 0.05$) between these groups. However, differences in fixation durations were observed. Single fixation trials were found to be significantly longer in duration (P's < 0.05) than first fixations in multiple fixation trials for both grasping (single fixations trials, mean = 417 ms; multiple fixation trials, mean = 204 ms) and estimation tasks (single fixations trials, mean = 409 ms; multiple fixation trials, mean = 209 ms). Given the small number of single fixation trials (153 trials during grasping and 121 trials during estimations), and the differences in the fixation duration between groups, single fixation trials were kept separate from subsequent analyses.

For the eye data, a repeated measure analysis of variance (rmANOVA) was carried out to explore differences in fixation strategies (first fixation vs. second fixation locations for trials where multiple fixations were present) across tasks (grasping vs. estimation) and blocks (five Efron shapes). Significance levels of $P < 0.05$ were used, and for any main effects or interactions, Bonferroni-adjusted planned comparisons were carried out.

Horizontal X-axis

There were no significant main effects of task [$F(1,25) = 0.528$, $P > 0.05$], fixation [$F(1,25) = 0.370$, $P > 0.05$], or block [$F(4,100) = 1.551$, $P > 0.05$] along the horizontal axis of the objects. A task by block interaction [$F(4,100) = 9.475$, $P < 0.001$] showed that with decreases in object length, fixation locations during estimations moved from the left to the right of the object's COM (see Fig. 2b), whereas fixations during grasping moved from rightward positions towards the object's COM (except for block 4; see Fig. 2a). A cross over in fixation position was seen for the shortest block 5, that is, fixation locations during estimations were positioned more to the left of fixations during grasping on all blocks except block 5.

Vertical Y-axis

Significant main effects were found for both fixation [$F(1,25) = 14.242$, $P = 0.001$] and block [$F(4,100) = 16.694$, $P < 0.001$], including a significant interaction of task by block [$F(4,100) = 3.569$, $P < 0.05$]. The main

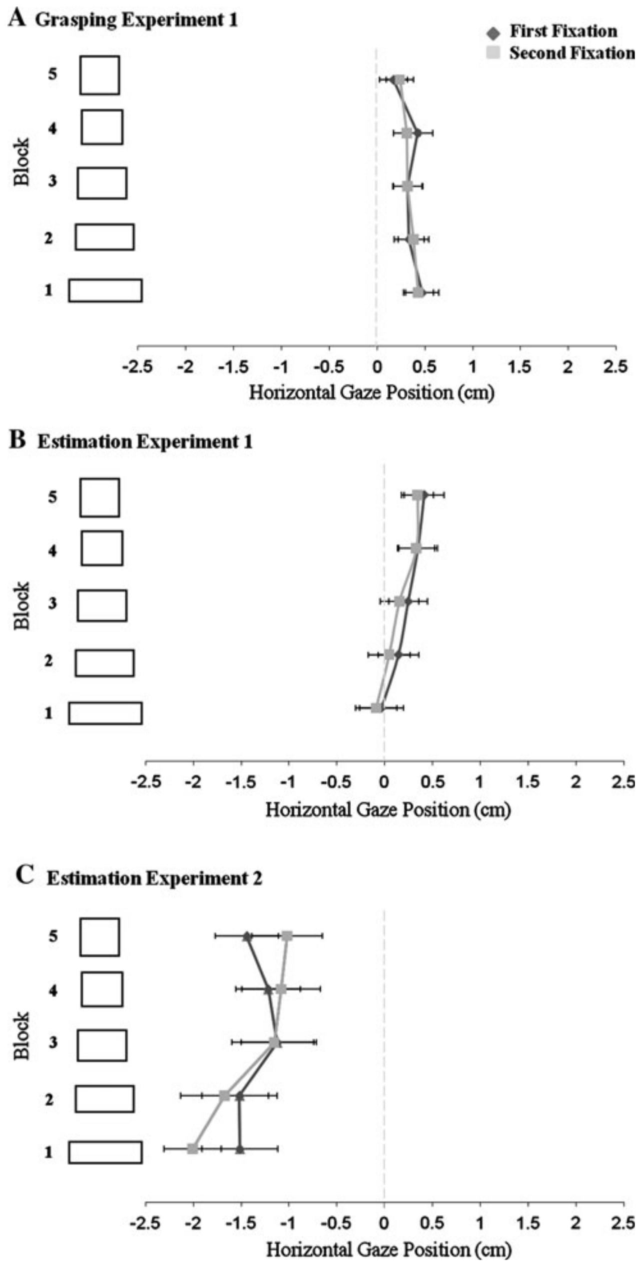

Fig. 2 The average first and second fixation locations across blocks along the horizontal *X*-axis (cm) while grasping (**a**) and making perceptual estimations (**b**) to real objects in Experiment 1 and making perceptual estimations (**c**) to computer-generated objects in Experiment 2. Positive fixation positions represent fixation locations to the right of the object's COM. *Error bars* represent the standard error of the mean

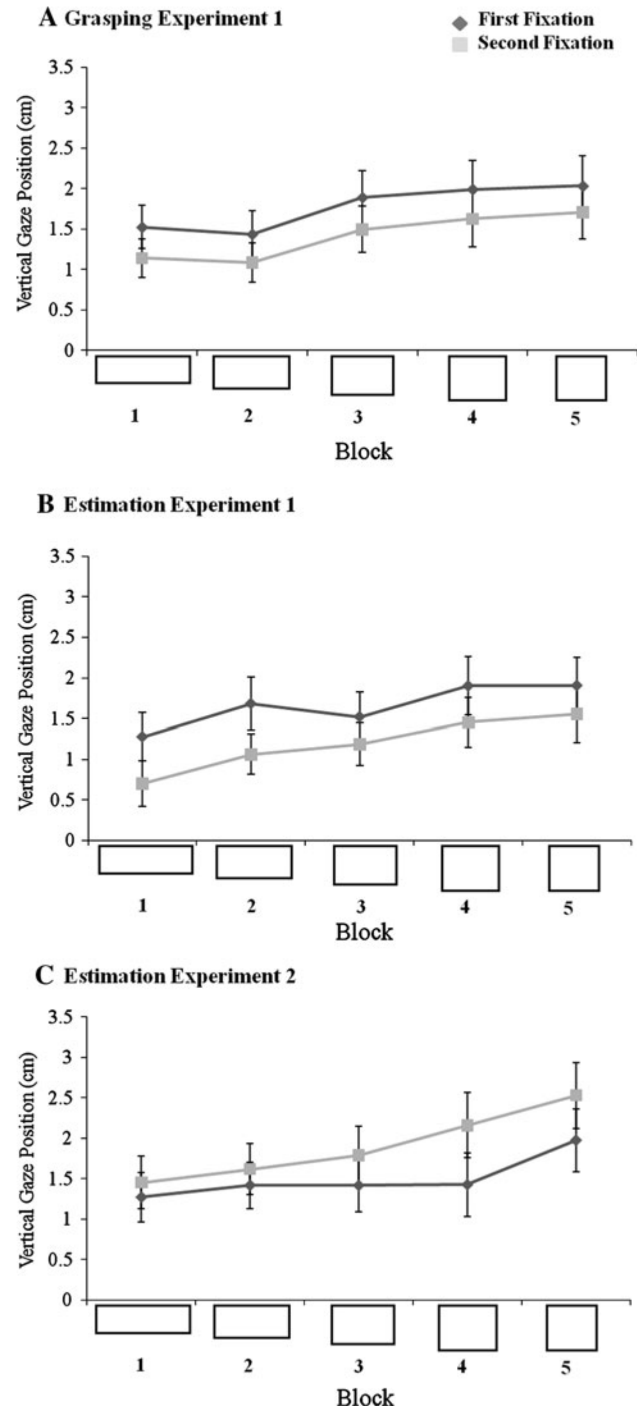

Fig. 3 The average first and second fixation locations across blocks along the vertical *Y*-axis (cm) when grasping (**a**) and making perceptual estimations (**b**) to real objects in Experiment 1 and making perceptual estimations (**c**) to computer-generated objects in Experiment 2. Positive fixation positions along the vertical axis represent fixation locations above the object's COM. *Error bars* represent the standard error of the mean

effect of fixation showed that across both tasks, second fixations were found to be significantly closer to the object's COM (mean = 1.3 cm above COM) than first fixations (mean = 1.7 cm above COM). Across blocks however, overall fixation locations (first and second fixations collapsed) were shown to move higher up on the objects with increases in block size. The task by block interaction showed that overall fixation positions were higher on all blocks during grasping when compared to estimations, except to the second smallest object (block 2; see Fig. 3).

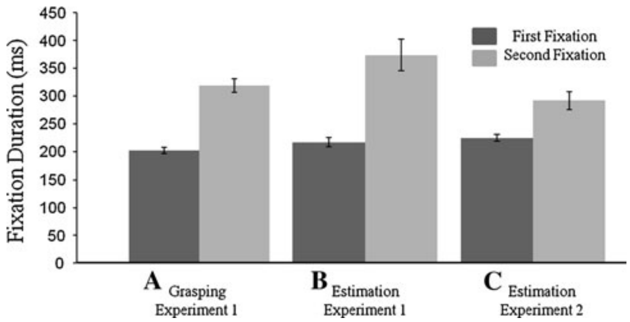

Fig. 4 The mean fixation durations (ms) for first and second fixations when grasping (**a**) and making perceptual estimations (**b**) to real objects in Experiment 1 and making perceptual estimations (**c**) to computer-generated objects in Experiment 2. *Error bars* represent the standard error of the mean

Fixation duration

A significant main effect of task [$F(1,25) = 5.345$, $P < 0.05$] and fixation [$F(1,25) = 95.339$, $P < 0.001$] was observed. Fixations during grasping were found to be significantly shorter in duration (mean = 260 ms) than fixations during estimations (mean = 395 ms; see Fig. 4a, b). Across tasks, first fixations were significantly shorter in duration (mean = 209 ms) than second fixations (mean = 346 ms).

Grasp kinematics and perceptual estimations

Perceptual estimations A one-way rmANOVA with five levels of block size was carried out on the perceptual size estimations to determine whether larger estimations occurred with increases in block size. A significant main effect of block was found [$F(4,100) = 181.87$, $P < 0.001$]. Post hoc comparisons revealed significant increases in manual estimations between all blocks (*P's* < 0.05).

Grasping data A one-way rmANOVA ran on MGA, with five levels of block size, showed a significant main effect of block [$F(4,100) = 78.43$, $P < 0.001$]. Significant increases in MGA were observed across all blocks (*P*'s < 0 .05).

To characterize grasp location along the horizontal dimension of the blocks, a one-way rmANOVA was carried out on the average grasp axis location across the five blocks. A significant main effect of block was observed [$F(4,164) = 5.745$, $P < 0.05$]. Participants' grasp axis was closer to the object's COM for the shorter blocks (4 and 5) compared with the longer blocks. These differences were significant between blocks 5 and 2. When compared with first fixation locations across blocks, a rmANOVA revealed no significant differences between grasp axis locations and first fixation locations [$F(1,4) = 2.15$, $P > 0.05$] along the *X*-axis.

Discussion

The goal of Experiment 1 was to contrast gaze locations on simple symmetrical objects during a grasping task and a perceptual size estimation task to real objects. When first fixation locations on the objects were compared, we see that across tasks fixations were drawn to the horizontal midline of the blocks, in a position between the COM and top edge. This position is consistent across blocks, with overall fixation locations moving higher up on the objects with increases in block height. Additionally, in both tasks, first fixations were found to be positioned significantly higher on the objects than second fixations, which were towards the object's COM. In contrast to the findings from Brouwer et al. (2009), our data suggest that participants in the perceptual size estimation task and the grasping task were first fixating an area towards the top edge of the object for all blocks, which we found matched index finger grasp location in the grasping task, and were then followed by a subsequent fixation towards the object's COM. This subsequent lower fixation would still allow the index finger location to be in or close to foveal view, while at the same time allowing the rest of the object to be monitored relative to the approaching hand during the grasp, perhaps to monitor both index finger and thumb placement at the same time. The main difference that emerged between tasks was fixation duration. Fixation durations were longer in the perceptual size estimation task compared with the grasping task. One possible explanation for this difference is that it might be indicative of longer processing time for visual analysis of the block during perceptual estimations. Indeed, previous research has shown that fixation duration increases with the demands of the task (De Greef et al. 2009; Just and Carpenter 1976; Van Orden et al. 2001). Even though we are well practiced in reaching out and grasping simple objects quickly and effectively, we are not well practiced in consciously estimating the size of objects for perceptual purposes. Thus, when making perceptual size estimations, participants are holding their fixations for longer periods of time to acquire the information necessary to indicate the height of that object.

Slight differences were also noted in fixation positions along the *X*- and *Y*-axes between tasks. Fixations during estimations were to the left of all fixations during grasping except on the shortest block 5, where they were positioned to the right of grasping fixations. As well, overall fixation positions during grasping were positioned higher up on all the blocks, except for block 2 (second smallest in width), when compared to estimation fixations. However, no significant differences in the overall location of these fixations were observed between tasks.

Experiment 2

Experiment 2 was designed to examine gaze strategies when looking at computer-generated objects during a perceptual task and compare these fixation locations to those elicited when interacting with real 'graspable' objects in Experiment 1. To keep the same object properties relevant across studies (object width), participants were once again required to manually estimate the size of computer-generated Efron shapes that were identical in size as those used in Experiment 1. However, there were some important differences between this Experiment and Experiment 1. Here, participants estimated object size after object presentation, requiring participants to rely on their memory of object shape. Estimations were made without visual feedback of their hand. Instead, participants made their estimations by adjusting the size of a digitized object on the computer screen until it matched the width of the previously presented block.

Participants

Eighteen undergraduate psychology students (13 women) between the ages of 18 and 23 (mean age = 19) were recruited for participation in this study. All participants were shown to be strongly right-handed as determined by a modified version of the Edinburg Handedness Inventory (Oldfield 1971) and had normal or corrected-to-normal-vision. None of the participants in this study participated in Experiment 1. This research was approved by the Human Research Ethics Board at the University of Manitoba.

Stimulus and procedure

Participants were seated approximately 50 cm away from a 19" LCD monitor (with a resolution of 1,024 × 768) with their head stabilized by a chin rest. Their hand was occluded from vision and positioned directly in front of them. An Eye-link II (250-Hz sampling rate, spatial resolution <0.5°; SR Research Ltd., Osgoode, ON, Canada) was used to record eye movements throughout the experiment. Because occluding the hand would interfere with the Optotrak's camera-based motion tracking system, we recorded finger and hand kinematic data using the Flock of Birds 'miniBIRDs' magnetic motion tracking device (up to 144-Hz sampling rate, static resolution of 0.5 mm, static accuracy 1.8 mm; Ascension Technology Corporation, USA) In this experiment, participants estimated the size of computer-generated Efron blocks that were the same size and colour as those used in Experiment 1.

At the start of each trial, participants fixated a fixation dot that randomly appeared in one of the 4 corners of the computer screen. The purpose of the fixation dot was to correct for any camera movements during the experiment (as a drift correction was performed while looking at the dot) and to ensure that participants were not starting each trial with their eyes fixated in the same spot on the computer screen. After the drift correction, a brief black and white mask was displayed (150 ms) followed by the presentation of one of the five Efron blocks positioned in the centre of the screen (white block against black background). At this point, the participant was instructed to view the object for as long as they want and then push the space bar to continue. After the presentation of another black and white mask (150 ms), participants had to make an estimation of the previously seen blocks height by adjusting the height of a white bar (1 cm wide) on the screen. The height of the white bar was programmed to change in real time in relation to the distance between miniBIRDs magnetic markers, which were attached to the participants' index finger and thumb. As such, participants could adjust this bar to a larger or smaller height by moving their index finger and thumb closer or farther apart (identical to Experiment 1). Once their estimation was complete, participants pressed the space bar to continue onto the next trial. Each participant was randomly presented with 21 trials of each block, for a total of 105 trials. Each testing session took approximately 1 h.

Results

Within this study, participants had an average of 6 fixations per trial. In 94% of all experimental trials, a first fixation was detected. In 89% of these trials, a subsequent (second) fixation was also detected. Paired sample *t* tests were carried to explore any differences in position and duration of first fixations when there were multiple fixations present versus a single fixation only. Analyses revealed no overall differences in fixation positions along the *X*- or *Y*-axes or in fixation durations (P's > 0.05). Thus, all trials where at least one fixation was detected were included in subsequent analyses. To explore differences in fixation strategies across blocks, a rmANOVA was carried out on fixation sequence (first vs. second fixation locations) across the five Efron shapes. Eye positions along the X- and *Y*-axes, as well as fixation durations (ms), were considered.

Horizontal X-axis

No significant differences between first and second fixation locations were observed [$F(1,17) = 0.012$, $P > 0.05$]. On average, fixations were located 1.4 cm to the left of the COM. There was, however, a significant main effect of block [$F(4,68) = 3.517$, $P < 0.05$]. Generally, as block size decreased in length (along the horizontal axis), fixation locations moved from leftward position closer to the object's COM. However, post hoc comparisons did not reveal any significant differences in these fixation shifts (see Fig. 2c).

Vertical Y-axis

A significant main effect of fixation [$F(1,17) = 16.795$, $P < 0.05$] revealed that first fixations were closer to the object's COM (mean = 1.5 cm above COM) than second fixations (mean = 1.9 cm above COM; see Fig. 3c). A significant main effect of block [$F(4,68) = 7.315$, $P < 0.001$] and a fixation by block interaction [$F(4,68) = 4.510$, $P < 0.05$] was also observed. As block size increased, mean vertical gaze positions across fixations moved higher up on the objects. Significantly higher fixations were observed on block 5 when compared to blocks 1, 2 and 3. The fixation by block interaction revealed that higher fixation positions were mainly mediated by changes in second fixation positions that were significantly higher up on all objects except blocks 1 and 2 (see Fig. 3c).

Fixation duration

A significant main effect of fixation duration [$F(1,17) = 23.807$, $P < 0.001$] showed that first fixations were significantly shorter in duration (mean = 224 ms) than second fixations (mean = 292 ms; see Fig. 4c).

Perceptual estimations

A one-way rmANOVA on the perceptual estimations across the five levels of block size yielded a significant main effect of block [$F(4,68) = 147.45$, $P < 0.001$]. Specifically, significant differences in size estimations were observed between all blocks (P's < 0.05), indicating larger estimations as a function of block height.

Between-group comparisons of Experiments 1 and 2

To explore differences in fixation locations between experiments, analyses were carried out comparing first and second fixation locations during the perceptual estimations to real (Experiment 1) versus computer-generated (Experiment 2) objects (estimation–estimation comparison) and between first and second fixation locations when grasping real objects (Experiment 1) versus estimating the size of computer-generated objects (Experiment 2; estimation–grasping comparison). Specifically, rmANOVAs, with the within-subject factors of fixation (first fixation, second fixation) and block (5 Efron shapes), and between-subject factor of task (Experiments 1, 2) were carried out for the *X*- and *Y*-axes and duration variables for the above-mentioned comparisons.

Between-study effects revealed significant differences in fixation locations along the horizontal *X*-axis only for both the estimation–estimation comparison [$F(1,42) = 8.861$, $P < 0.05$] and the estimation–grasping comparison [$F(1,42) = 11.75$, $P = 0.001$]. In both instances, fixations to computer-generated objects were significantly more to the left of the object's COM (mean = 1.4 cm) than those found on real objects that were located to the right of the object's COM during both grasping (mean = 0.3 cm) and estimations (mean = 0.2 cm). A fixation by block by task three-way interaction along the horizontal *X*-axis for both estimation–estimation comparisons [$F(4,168) = 3.495$, $P < 0.05$] and estimation–grasping comparisons [$F(4,168) = 3.337$, $P < 0.05$] showed significant differences between studies for first and second fixations on all five blocks with first and second fixations in Experiment 2 significantly to the left of all first and second fixations elicited in Experiment 1 (see Fig. 2).

Within-subject effects revealed a fixation by task interaction along the *Y*-axis in both the estimation–estimation comparison [$F(1,42) = 33.505$, $P = <0.001$] and the estimation–grasping comparison [$F(1,42) = 18.512$, $P = <0.001$]. When grasping or estimating the size of real objects, first fixations in both tasks were found to be significantly closer to the object top edge (means of 1.8 and 1.7 cm, respectively) than second fixations, which were closer to the objects COM (means of 1.4 and 1.2 cm, respectively; see Fig. 3a, b). When viewing computer-generated objects, an opposite pattern in fixation locations was observed. First fixations were found to be significantly closer to the object's COM (mean = 1.5 cm above COM) than second fixations, which were towards the object's top edge (mean = 1.9 cm above COM; see Fig. 3c).

A fixation by task interaction [$F(1,42) = 8.201$, $P < 0.05$] for fixation duration revealed significant differences in second fixation durations between estimations in Experiment 1 and Experiment 2 (estimation–estimation comparison), with second fixations in Experiment 1 (mean = 373 ms) significantly longer in duration than second fixations in Experiment 2 (mean = 292 ms; see Fig. 4). No differences in first fixation durations were observed. A fixation by task interaction for fixation duration was also observed between grasping fixations in Experiment 1 and estimation fixations in Experiment 2 [$F(1,42) = 7.305$, $P = 0.01$]. First fixations when grasping were found to be significantly shorter in duration (mean = 201 ms) than first fixations during estimations (mean = 224 ms; see Fig. 4). No differences in second fixation durations were observed.

Discussion

When fixations during the perceptual task to computer-generated objects were compared with fixations during the perceptual and grasping task to real objects, we found task differences with respect to fixation locations along the horizontal *X*-axis, in fixation durations, and fixation patterns. Even though information regarding object height could be obtained by looking at any point on the blocks, participants were looking significantly more to the left of the object's COM when viewing computer-generated objects when compared to estimating or grasping real objects. These leftward biases are similar to those seen in other perceptual tasks using symmetrical shapes. For example, when participants are asked to indicate the mid-point of a line (line bisection task), they place the subjective mid-point to the left of the true centre, a phenomenon known as pseudoneglect (Bowers and Heilman 1980). This leftward bias during bisection has been shown to be quite robust in a variety of stimuli such as gaps, rods, space (McCourt et al. 2001) and wedge-shaped horizontal lines (McCourt and Garlinghouse 2000), and under varying conditions such as tactile and visual bisection (Jewell and McCourt 2000). Additionally, research has shown that leftward bisection errors are accentuated with increases in object length (Jewell and McCourt 2000; McCourt et al. 1997; Werth and Poppel 1998). We found a similar effect in our perceptual estimation results in both Experiment 1 and 2 with respect to horizontal fixation position, and fixation locations are more to the left for the longest objects compared with fixation locations for the shorter blocks.

Other distinct differences between experiments were in the fixation patterns elicited in each task and in the duration of these fixations on the objects. When viewing real objects in perception and action, first fixations were located significantly closer to the objects top edge than second fixations, which were closer to the objects COM. When viewing computer-generated objects, an opposite pattern in fixation locations was observed, similar to the pattern observed in Brouwer et al. (2009). First fixations were found to be significantly closer to the object's COM than second fixations, which were towards the object's top edge. However, first and second fixation locations between experiments were not significantly different in terms of their vertical locations on the blocks. Thus, although differential *patterns* in vertical fixation positions were observed, it is along the horizontal axis that differences emerge in fixation locations when interacting with real or computer-generated objects. Finally, comparisons between tasks revealed that participants tended to look at the objects for a significantly longer duration during both first and second fixations when looking at computer-generated objects than first fixations during grasping and second fixations during estimations of real objects. It is possible that this difference in fixation duration between computer-generated and real objects in our tasks may have been due to the unique task requirements in Experiment 2 where subjects were required to view the object for the purpose of memorizing its size and shape compared to the continual moment-to-moment visual feedback of the object during grasping and estimating in Experiment 1.

Conclusion

The similarities observed in fixation locations and patterns between perception and action tasks to real objects do not seem to be a consequence of the requirements and mechanics of the manual estimation task. The perpetual estimation task to remember computer-generated objects, where the same mechanics and object properties were essential for the completion of the perceptual task in Experiment 1 to real objects, resulted in differences in fixation patterns, locations along the *X*-axis, and in fixation durations and number. Rather, the identical pattern in fixations between perception and action when interacting with real objects may be the result of interacting with the objects themselves. Behavioural evidence has suggested that our perception of an object is automatically linked to an action representation, even when we are not directly interacting with that object. For example, Tucker and Ellis (1998) demonstrated that the speed of a key press response was directly influenced by the position of an object's handle (Simon effect), although the orientation of the handle was irrelevant to the completion of the task (deciding if the object was upright or inverted). In this task, responses were faster if the orientation of the handle was congruent with the hand that was used to respond. These authors suggest that action-related information about objects is represented automatically whenever an object is viewed. In further support, Tucker and Ellis (2001) had participants view objects and make a precision or power grasp if they thought the objects were natural or manufactured. Although the grasp itself was irrelevant to the completion of the task, responses could be either congruent or incongruent with the visual object presented (i.e. a precision grasp would be used if you were to pick up a pea). Their results showed that grasp congruency influenced the speed of response, again suggesting that object perception may be automatically linked to an action representation. Results from the current study suggest that when viewing real objects, the 'graspability' of these objects may be mediating where we look—during both a perception or action task. Indeed, recent evidence suggests that ventral stream processing is not only involved in generating our perceptual representations of the world (for review, see Milner and Goodale 2006) but also contributes to initial action planning (Dijkerman et al. 2009; Van Doorn et al. 2009).

What seems to be consistent across conditions, that is, whether we are grasping an object or making a perceptual estimation to real or computer-generated objects, is the importance of the upper half of the objects, as areas below the COM are rarely fixated. Although this bias towards the top half of the object has been previously demonstrated while grasping (Desanghere and Marotta 2008; Brouwer et al. 2009), with fixation locations drawn to index finger landing position that has been shown to typically fall across the object's COM (Jeannerod 1988; Kleinholdermann et al. 2007; Lederman and Wing 2003; Marotta et al. 2003), it also holds true for perceptually mediated responses. Indeed, this study is the first to reveal consistencies in fixation locations with incremental increases in object height, demonstrated when grasping objects and making perceptual size estimations to real and computer-generated objects. However, since the objects were 'graspable' and therefore not overly large, fixations to the upper half of the objects would still permit the lower half to be maintained in vision. Size estimations or 'two-handed grasping' to very large objects might very well result in the lower edge of the objects to be fixated.

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