Fixation locations when grasping partly occluded objects

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When grasping an object, subjects tend to look at the contact positions of the digits (A. M. Brouwer, V. H. Franz, D. Kerzel, & K. R. Gegenfurtner, 2005; R. S. Johansson, G. Westling, A. Bäckström, & J. R. Flanagan, 2001). However, these contact positions are not always visible due to occlusion. Subjects might look at occluded parts to determine the location of the contact positions based on extrapolated information. On the other hand, subjects might avoid looking at occluded parts since no object information can be gathered there. To find out where subjects fixate when grasping occluded objects, we let them grasp flat shapes with the index finger and thumb at predefined contact positions. Either the contact position of the thumb or the finger or both was occluded. In a control condition, a part of the object that does not involve the contact positions was occluded. The results showed that subjects did look at occluded object parts, suggesting that they used extrapolated object information for grasping. Additionally, they preferred to look in the direction of the index finger. When the contact position of the index finger was occluded, this tendency was inhibited. Thus, an occluder does not prevent fixations on occluded object parts, but it does affect fixation locations especially in conditions where the preferred fixation location is occluded.

Keywords: fixations, saccades, eye movements, occlusion, grasping

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Introduction

Fixation locations during visuomotor actions

Several studies have examined eye movements during goal-directed hand movements. When pointing towards an object (either with their hand or with a pointing device), subjects tend to look at the position at which they are pointing. This suggests a tight coupling between gaze and pointing. Indeed, this link has been found in several studies. By looking at the target object, errors in pointing movements are reduced (Bock, 1986; Enright, 1995; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Medendorp & Crawford, 2002; Neggers & Bekkering, 1999). Furthermore, if target presentation is delayed (Frens & Erkelens, 1991) or the target position has to remembered (Admiraal, Keijsers, & Gielen, 2003), the direction and the variability of the errors in pointing movements are correlated with those in gaze. When making a combined eye–hand movement towards a target that changes position during the saccade (double step paradigm), Bekkering, Adam, van den Aarssen, Kingma, and Whiting (1995) showed that the eye as well as the hand adapts to the new position of the target. These studies suggest that the same information is used to drive the hand and the eye or that they use a common motor command (Bekkering, Abrams, & Pratt, 1995; Biguer, Jeannerod, & Prablanc, 1982; Biguer, Prablanc, & Jeannerod, 1984; Bock, 1986; Reina & Schwartz, 2003).

The coupling between eye and hand is not always so tight. Several experiments using visual illusions found

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different effects of illusions on eye and pointing movements (Bernardis, Knox, & Bruno, 2005; Binsted, Chua, Helsen, & Elliott, 2001; Binsted & Elliott, 1999; de Grave, Franz, & Gegenfurtner, 2006; de Grave, Smeets, & Brenner, 2006; Mack, Heuer, Villardi, & Chambers, 1985), indicating that the eyes and the hands can be decoupled. If visual information about the target is available during task performance, the eyes were affected by an illusion of length, but no bias could be found on the hand (Binsted & Elliott, 1999). Furthermore, hand movements are only affected by the illusion if they are performed with concurrent eye movements (Binsted et al., 2001).

A close correspondence between eye and hand is difficult when grasping objects since there are two (or more) contact positions of the grasping digits. However, when grasping an object often only one of the contact positions is visible. In a study of Johansson, Westling, Bäckström, and Flanagan (2001), subjects picked up blocks from the table to touch a target position with the block while avoiding obstacles. Johansson et al. argued that people look at the visible locations with which they want to make contact, which were in this case the block's target position, the position at which the block had to be put back and the contact position of the thumb on the block. However, in that study, only the contact position of the thumb was visible to the subjects while the contact position of the index finger was located at the backside of the block and thus hidden from view. The contact positions of the digits were almost at the same location in 2D. Therefore, it is hard to distinguish whether subjects fixated the visible contact position of the thumb or whether they fixated the invisible finger contact position. In a study by Brouwer, Franz, Kerzel, and Gegenfurtner (2005), subjects had to grasp vertically oriented objects in which both contact positions of the index finger and the thumb were visible. They showed that gaze was attracted to the contact position of the index finger.

Fixation locations when looking at occluded objects

Often objects cannot be seen completely because they are partly occluded by other objects. Still, we perceive them as whole objects and a specific idea is generated about the properties of the hidden object part (visual completion) (e.g., Boselie, 1994; Sekuler, 1994), indicating that cognitive information about the complete object is present in the visual system.

Most studies investigating occluded objects looked into the way the visual system completes occluded objects (Liinasuo, Kojo, Häkkinen, & Rovamo, 2004; Rensink & Enns, 1998; Ringach & Shapley, 1996; van Lier, van der Helm, & Leeuwenberg, 1995) or at the temporal aspects of completion (Bruno, Bertamini, & Domini, 1997; Guttman, Sekuler, & Kellman, 2003; Sekuler & Palmer, 1992; Shore & Enns, 1997). As far as we know, the only study that investigates which part of the occluded object is fixated is the study by Vishwanath, Kowler, and Feldman (2000). They asked subjects to look at partly occluded triangles "as a whole." If the completed shape of the triangle is taken into account by the visual system, subjects will look at the center of mass (COM) of the completed object, as when viewing non-occluded stimuli (Findlay, 1982; He & Kowler, 1989; Henderson, 1993; Kowler & Blaser, 1995; McGowan, Kowler, Sharma, & Chubb, 1998; Vishwanath & Kowler, 2003). In contrast, subjects looked at the center of mass of the visible fragment (COMvis) of the triangles. This suggests that even though information about the occluded object part is present in the visual system, this information is not used when making saccades towards that object. However, in the study of Vishwanath et al., only the first fixations on the object were investigated. Subjects started a trial by fixating a point located eccentrically from the target stimulus. Thus, information for the first saccade and the first fixation position were gathered from the periphery, which could have made it difficult to determine the completed shape of a partly occluded stimulus. This might have caused the first fixation to deviate from the center of mass of the completed stimulus. Once the eye has landed on the stimulus, more accurate information about the target stimulus will be available. Therefore, information about the completed shape of the stimulus might become apparent in the second fixation, which then might land around the COM.

Overall, several studies investigated fixation locations during visuomotor actions, whereas others studied fixation locations when visually exploring occluded objects. In this study, we will combine these two types of experiments. The main goal is to investigate the locations of the first and the second fixation when grasping partly occluded objects. We ask our subjects to start a trial by fixating an eccentrically located point. No further instructions regarding eye movements are given. Then subjects have to grasp a partly occluded object with a precision grip. Different objects are presented in the fronto-parallel plane, and occlusion of an object is manipulated in such a way that the contact position of the index finger, that of the thumb, or those of both contact positions are occluded. We also include a control condition in which a part of the object is occluded that does not involve the contact positions of the digits.

Furthermore, we will examine whether the used fixation strategy is comparable to fixation locations during object grasping or whether it shows more similarity to fixations when looking at occluded objects. To successfully grasp an object, information about the occluded object part needs to be determined (e.g., appropriately scaling the opening of the hand, anticipating lifting force, determining the accuracy of the contact positions of the digits to prevent slipping). Therefore, subjects might stick as close as possible to the fixation strategy used when grasping non-occluded objects (fixating around the contact position of the index finger). This means that when the object is occluded around this preferred fixation location, subjects will fixate this occluded region, indicating that they have extrapolated information about the occluded part from the visible parts in order to determine a suitable grasping position on the object. To vary extrapolation of object information, we used different shapes (three crosses and two triangles). However, when the preferred fixation location is occluded, no visual object information can be obtained there, and subjects might avoid looking at this location directly. They might then look at the contact position of the visible digit in order to get at least a stable grip for one digit.

On the other hand, object occlusion might disrupt the subject's strategy to look at (one of) the contact positions of the digits, especially in the condition in which both contact positions are occluded. In that case, they may switch to a fixation strategy that is more similar to the fixation strategy used in visual exploration. The first fixation is then expected to be around the center of mass of the visible part of the object (COMvis). A second fixation might be near the center of mass (COM) of the complete object since the object's shape might be completed after object information has become available on the fovea, which is after the first fixation.

Besides investigating the locations of fixation, we will also examine the number of fixations and the fixation duration. When the contact positions of the digits are occluded, subjects might look longer at the object (increased fixation duration) or increase the number of fixations in order to extract more information about the object.

Method

Subjects

Ten right-handed psychology students of the Justus-Liebig-University Giessen took part in this experiment for which they received payment. All participants were naive with respect to the aim of the study.

Apparatus and stimulus

A chin rest was placed in front of a monitor (40 × 30 cm, 1280 × 960 pixels, 100 Hz) to keep the subject's head fixed at a viewing distance of 45 cm. At this distance, 1 pixel corresponds to 0.04°. We used three different black plastic objects (Figure 1; a triangle [presented in two orientations], a "plus" and a cross [presented in two orientations]), resulting in five different shapes. A Plexiglas frame, on which the objects were mounted, was placed directly in front of the monitor. The objects were placed in front of the center of the screen (Figure 2). They had to be grasped with a precision grip (the finger on top of the shape and the thumb on the bottom) and removed by a movement perpendicularly away from the frame. The experiment consisted of four blocks of 50 trials (5 shapes × 10 repetitions). In each block, a different part of the shape was occluded (Figure 2A). The order of the blocks was counterbalanced across subjects, and the order of trials within a block was randomized. A black painted metal occluder was attached either to the top or the bottom of the plexi-glass frame. The occluder protruded 10 cm in front of the screen (Figure 2B). A short occluder (height × width: 21 × 4 cm) was used to occlude either the contact position of the thumb (lower half of the shape) or that of the index finger (upper half of the shape). A long occluder (height × width: 46 × 4 cm) was used to occlude either the contact positions of both digits or a part of the shape, which did not involve the contact positions. In the conditions in which a contact position was occluded, the size and position of the occluder and the shape were chosen in such a way that neither eye could see the contact position of the digit (i.e., to avoid so called "Da Vinci" stereopsis). In the control condition, it was made sure subjects could not see the complete shape with either eye.

Before the experiment started, subjects performed 15 practice trials (5 shapes × 3 repetitions) without occlusion in order to familiarize themselves with the shapes and the way of grasping (precision grip with the finger always on top of the shape and the thumb on the bottom of the shape).

Eye movements were recorded with an Eyelink II eye tracker (SR Research Ltd., Osgoode, Ontario, Canada) with a temporal resolution of 250 Hz and a spatial

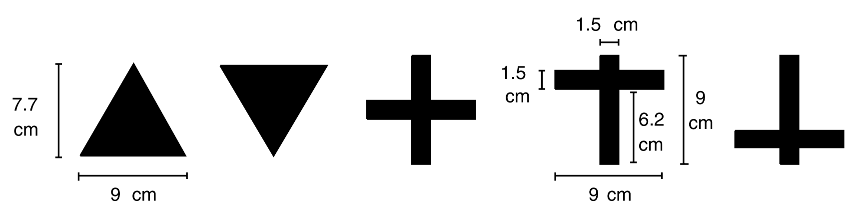

Figure 1. The five shapes that were used as stimuli (from left to right): the upward-pointing triangle, the downward-pointing triangle, the plus, the cross, and the upside-down cross.

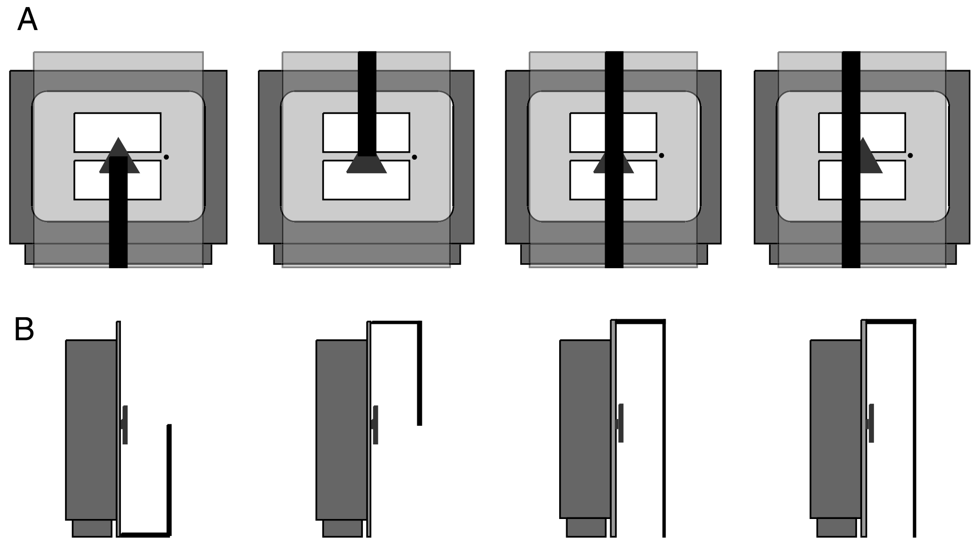

Figure 2. A schematic view of the setup from front view (A) and side view (B). Four different occlusion conditions were presented in different blocks: occlusion of the contact position of the thumb (leftmost column), of the finger (second column from left), of the thumb and the finger (second column from right), or of neither contact position (control, rightmost column). To the right of the middle of the screen, a black fixation position was presented at the beginning of a trial.

resolution of 0.2°. Both eyes were recorded during the standard 9-point calibration/validation procedure, but only the eye with the least error was recorded during the experiment. To determine when the object is touched, we measured the movements of the grasping digits with an ultrasonic 3D tracking device (Zebris, Zebris Medical GmbH, Germany) measuring at 100 Hz. Small sound emitting speakers were attached to the nail of the index finger and the side of the thumb.

Procedure

Before each trial, subjects rested their hands on the table in front of them and closed their eyes so the experimenter could place a shape on the frame. Then an auditory signal was given to the subjects to open their eyes and fixate a fixation point that was presented 11 cm to the right of the center of the screen (Figure 2A). When they did so, they pressed a button to trigger drift correction. This procedure corrects for errors in the eye position data due to, e.g., head movements and headband slipping. Immediately after the drift correction, the fixation point disappeared. This was a signal for the subjects that they could look at the shape and start grasping it using their thumb and index finger. After grasping the shape, subjects put the shape on the table in front of them and closed their eyes again returning their grasping hand to the table. Subjects were not instructed regarding eye movements. After each block, there was a break of several minutes in which subjects could rest and the experimenter changed the occluder on the frame. Each block of trials started with a new calibration and validation of the Eyelink.

Data analysis

Instantaneous velocity for the eye and the digits was computed from position samples of the Eyelink and the Zebris markers, respectively. Saccadic onset is defined as the last frame before peak velocity in which the tangential velocity was smaller than that on the preceding frame. Saccadic offset is defined as the first frame after peak velocity in which the tangential velocity was larger than that on the preceding frame. A fixation is taken as the interval between saccades. The first fixation on each trial, which is on the fixation point, was discarded. From now on, with "first fixation" we mean the first fixation after the initial fixation on the fixation point. For each trial, fixation locations were determined from the time that the fixation dot disappears until the time that the first digit touched the object to grasp. We considered a digit as touching the object when the digit's velocity was minimum at a distance within 5 cm from the screen. Analyses were performed on the first two fixations of a trial. Fixation positions are given in millimeters with positive values in the horizontal direction to the right of the center of the screen, and in the vertical direction positive values are in the upward direction with respect to the middle of the screen. Average values are given with standard errors of the mean between subjects.

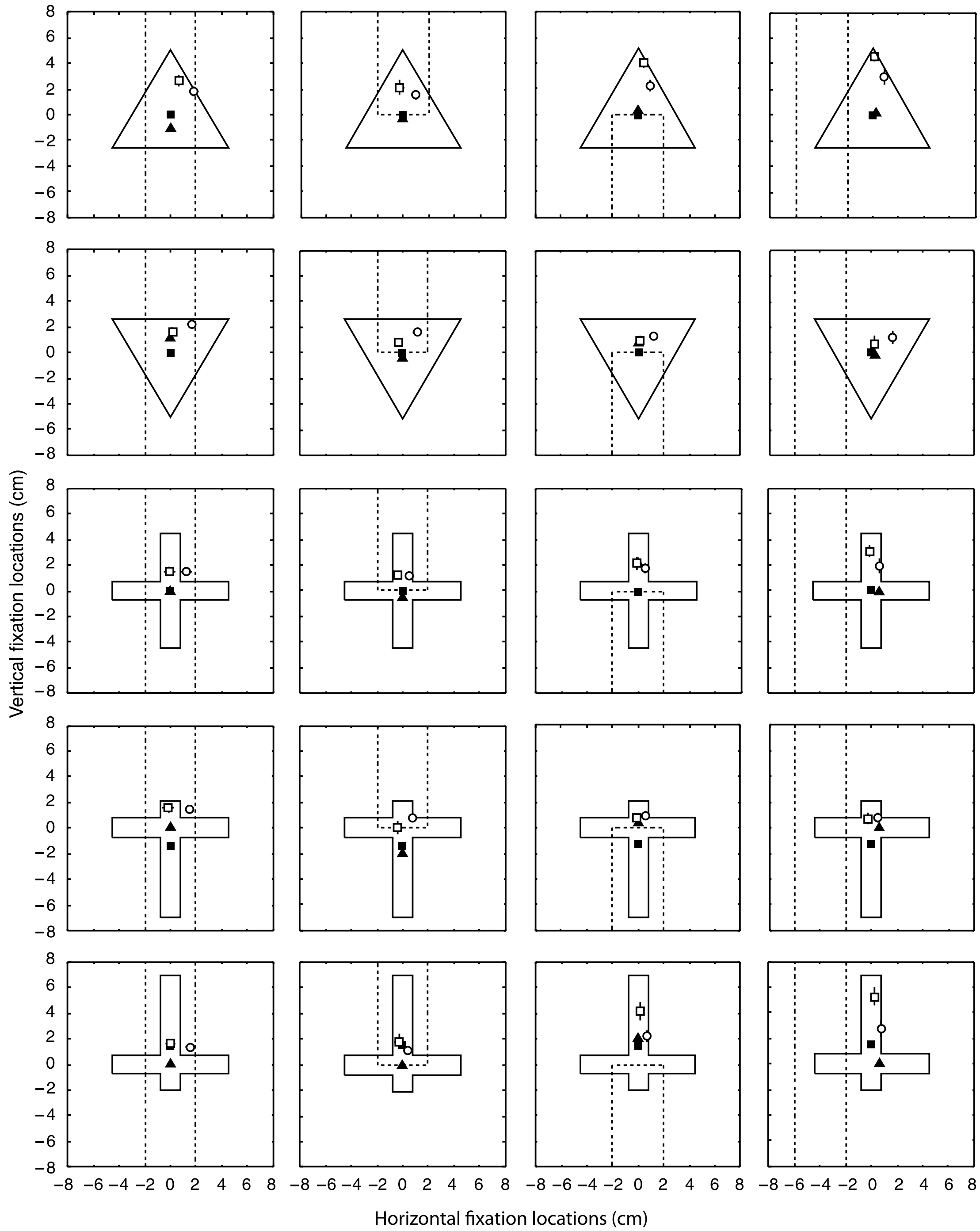

Figure 3. Fixation locations on the stimuli. Each row represents one shape and each column an occlusion condition. The location of the occluder is shown by a dotted line. The center of mass (COM) and the center of mass of the visible object part (COMvis) are represented by a filled square and a filled triangle, respectively. Locations of the first fixation (open circles) and second fixation (open squares) are also shown (with standard errors between subjects in the horizontal and vertical directions). The middle of the screen is at the position (0, 0).

Repeated measures ANOVAs with the factors shape and occlusion were performed on the horizontal and the vertical positions of the first and the second fixation, the durations of the first and the second fixations, the number of fixations and the distance of the first and the second fixation to the center of mass (COM), and to the center of mass of the visible part of the object (COMvis). Post hoc Tukey tests were used to calculate which levels of a factor differed.

	Fix 1	Fix 2
Horizontal position		
Shape	$F(4,9) = 12.12$, $p < 0.001$	$F(4,9) = 4.40$, $p = 0.004$
Occlusion	$F(3,9) = 4.04$, $p = 0.01$	
Shape × Occlusion	$F(12,108) = 2.33$, $p = 0.01$	
Vertical position		
Shape	$F(4,9) = 14.52$, $p < 0.001$	$F(4,9) = 81.60$, $p < 0.001$
Shape × Occlusion	$F(12,108) = 13.53$, $p < 0.001$	$F(3,9) = 7.31$, $p = 0.001$
Distance to COM		
Shape	$F(4,9) = 20.84$, $p < 0.001$	$F(4,9) = 23.19$, $p < 0.001$
Occlusion	$F(3,9) = 5.90$, $p = 0.003$	$F(3,9) = 9.11$, $p = 0.001$
Shape × Occlusion	$F(12,108) = 3.05$, $p = 0.001$	$F(12,108) = 6.18$, $p < 0.001$
Distance to COMvis		
Shape	$F(4,9) = 7.03$, $p < 0.001$	$F(4,9) = 28.35$, $p < 0.001$
Occlusion	$F(3,9) = 9.98$, $p < 0.001$	$F(3,9) = 17.55$, $p < 0.001$
Shape × Occlusion	$F(12,108) = 4.76$, $p < 0.001$	$F(12,108) = 8.38$, $p < 0.001$
Fixation duration		
Shape	$F(4,9) = 3.21$, $p = 0.02$	
Occlusion	$F(3,9) = 5.32$, $p = 0.005$	
Shape × Occlusion	$F(12,108) = 2.40$, $p = 0.008$	

Table 1. Significant results for 5 (shape) × 4 (occlusion) repeated measures ANOVAs on horizontal and vertical positions of the first and second fixations, distance of fixation positions (first and second) to the COM and COMvis, fixation duration.

Results

Fixation positions

Figure 3 shows the locations of the first (open circles) and the second fixations (open squares) for each shape and occlusion. In general, the first fixation is somewhat above the middle of the object. The second fixation was more upwards in the direction of the contact position of the finger (similar to the study of Brouwer et al., 2005). However, when this preferred fixation location is occluded (both occluded and finger occluded conditions), this tendency is less. Furthermore, the shape of the object also determines whether the second fixation goes upwards to the contact position of the finger. Neither the first nor the second fixation was on the COM or the COMvis of the object.

Table 1 shows all significant results of the 5 (shape) × 4 (occlusion) repeated measures ANOVAs on the horizontal and the vertical positions of the first and the second fixations. A post hoc Tukey test showed that horizontal positions of the first fixations in each of the three crosses differed from those in each of the triangles. Subjects looked on average 4.7 mm further to the right in triangular shapes than in the other three shapes (Figure 3 and Table 2). When both contact positions were occluded, first fixations were 7.4 mm more to the right compared to all other occlusion conditions. The first fixations in the upward-pointing triangle were significantly more upward (6.8 mm) than in the other shapes. For the cross, fixations were lower compared to the other shapes.

For the second fixations, subjects looked further to the left in the plus (3.1 mm) and in the cross (3.3 mm) than in the other shapes (Figure 3 and Table 2). Furthermore, fixation positions in the downward-pointing triangle and in the cross were more downward (18.6 and 21.4 mm, respectively) than in the other three shapes. Fixation positions in the upward-pointing triangle differed significantly from all other shapes. In the control occlusion condition, fixation positions were more upward than in the condition where both digits were occluded and the condition in which the finger was occluded. When the grasping position of the finger was occluded subjects fixated at a significantly lower position (12.1 mm) than in the condition where the thumb position was occluded.

Fixation positions compared to the COM and COMvis

For the first and the second fixation positions, the distance to the center of mass (COM) and the center of mass of the visible stimulus part (COMvis) were calculated. This was done for each subject, shape, and occlusion. Significant results of the 5 (shape) × 4 (occlusion) repeated measures ANOVA on these distances are shown in Table 1. Fixation positions differed significantly from the COM and the COMvis in all conditions (see Figure 3).

Shape		Occlusion: Both digits Fix 1	Both digits Fix 2	Finger Fix 1	Finger Fix 2	Thumb Fix 1	Thumb Fix 2	Control Fix 1	Control Fix 2	Average Fix 1	Average Fix 2
▲	*x*	18.1 ± 3.6	5.9 ± 2.2	10.2 ± 2.6	−2.7 ± 3.2	9.9 ± 1.3	4.2 ± 1.3	8.9 ± 2.4	0.9 ± 1.7	11.8 ± 2.8	2.1 ± 2.4
	y	18.3 ± 4.2	26.7 ± 3.6	15.8 ± 3.9	21.7 ± 6.1	23.1 ± 4.4	41.0 ± 4.5	30.1 ± 6.1	45.7 ± 4.1	21.8 ± 4.9	33.8 ± 5.6
▼	*x*	16.4 ± 3.4	1.5 ± 3.2	11.3 ± 2.9	−3.2 ± 3.6	12.0 ± 1.9	1.4 ± 1.8	16.1 ± 3.2	2.2 ± 1.7	14.0 ± 2.9	0.6 ± 2.7
	y	21.7 ± 2.9	16.3 ± 3.0	16.5 ± 3.1	8.0 ± 3.8	13.7 ± 2.7	9.3 ± 3.7	11.7 ± 5.1	6.6 ± 6.4	15.9 ± 3.6	10.1 ± 4.4
✚	*x*	12.6 ± 4.3	−0.7 ± 4.8	5.1 ± 2.8	−4.4 ± 3.0	5.5 ± 1.3	−1.7 ± 2.0	6.3 ± 2.7	−1.9 ± 1.8	7.4 ± 3.0	−2.1 ± 3.1
	y	14.6 ± 2.9	15.2 ± 3.3	11.6 ± 3.0	12.3 ± 3.5	17.3 ± 4.3	21.5 ± 5.1	19.1 ± 5.6	30.9 ± 4.3	15.6 ± 4.0	20.2 ± 4.6
⊤	*x*	15.2 ± 3.2	−1.9 ± 4.4	8.3 ± 2.7	−3.8 ± 3.2	5.6 ± 0.9	−1.4 ± 1.1	5.1 ± 2.3	−2.4 ± 1.5	8.6 ± 2.7	−2.3 ± 2.8
	y	15.0 ± 2.4	15.3 ± 3.4	8.5 ± 2.7	0.1 ± 5.0	9.5 ± 1.7	7.8 ± 2.5	7.9 ± 4.5	5.9 ± 5.2	10.2 ± 3.0	7.3 ± 4.4
⊥	*x*	15.5 ± 3.5	−0.2 ± 4.5	4.3 ± 2.3	−3.2 ± 3.1	6.7 ± 1.2	1.6 ± 2.5	8.0 ± 1.9	2.3 ± 1.7	8.6 ± 2.7	0.14 ± 3.1
	y	13.3 ± 1.8	15.6 ± 2.7	10.8 ± 2.7	18.2 ± 5.6	22.1 ± 5.0	41.8 ± 7.5	27.4 ± 6.8	52.1 ± 7.1	18.4 ± 4.8	32.0 ± 7.6
Average	*x*	15.6 ± 3.5	0.9 ± 3.9	7.8 ± 2.7	−3.4 ± 3.1	7.9 ± 1.6	0.8 ± 1.9	8.9 ± 2.7	0.2 ± 1.7	10.1 ± 2.9	−0.3 ± 2.8
	y	16.6 ± 3.0	17.8 ± 3.5	12.6 ± 3.1	12.2 ± 5.3	17.1± 4.0	24.3 ± 6.7	19.3 ± 6.1	28.2 ± 8.1	16.4 ± 4.3	20.7 ± 6.4

Table 2. Average horizontal (*x*) and vertical fixation (*y*) positions (with standard errors between subjects) for the first and the second fixation in each condition.

Fixation duration

Significant results for the durations of the first and the second fixations are shown in Table 1. Figure 4A shows the fixation durations of the first fixation. Fixation durations were shorter in the upward-pointing triangle (337 ± 22 ms) than in the downward-pointing triangle (454 ± 32 ms) and the cross (450 ± 32 ms). Subjects also fixated the control occlusion (332 ± 25 ms) shorter than the condition in which the finger was occluded (504 ± 29 ms). Differences between fixation durations in the control occlusion condition and the thumb-occluded condition (390 ± 25 ms) and the condition in which both digits were occluded (450 ± 29 ms) were only marginally significant. In Figure 4B, fixation durations for the second fixations are shown. An additional t-test showed that the second fixations (473 ± 13 ms) lasted significantly longer than the first fixations (418 ± 14 ms) (t = 3.18, p = 0.002).

Number of fixations

A repeated measures ANOVA with the factors shape and occlusion on the number of fixations in a trial showed no significant effects. The average number of fixations in a trial was 2.42 ± 0.05 (see Figure 5).

Discussion

In this study, we investigated where subjects fixated on partly occluded objects that had to be grasped and whether their fixations were comparable to visually exploring occluded objects or whether they showed more similarity to fixations when grasping objects. The first fixation, after the one on the fixation point, was located somewhat above and to the right of the middle of the object. The second fixation was more to the left compared to the first fixation. This shift to the left could be a correction made in response to an undershoot of the first saccade, which was planned to be more to the middle of the stimulus. Another possibility is that subjects first planned to fixate the edge of the stimulus to check out the location of the occluder relative to the object and then make a saccade on the object. Further studies are needed to find out which of

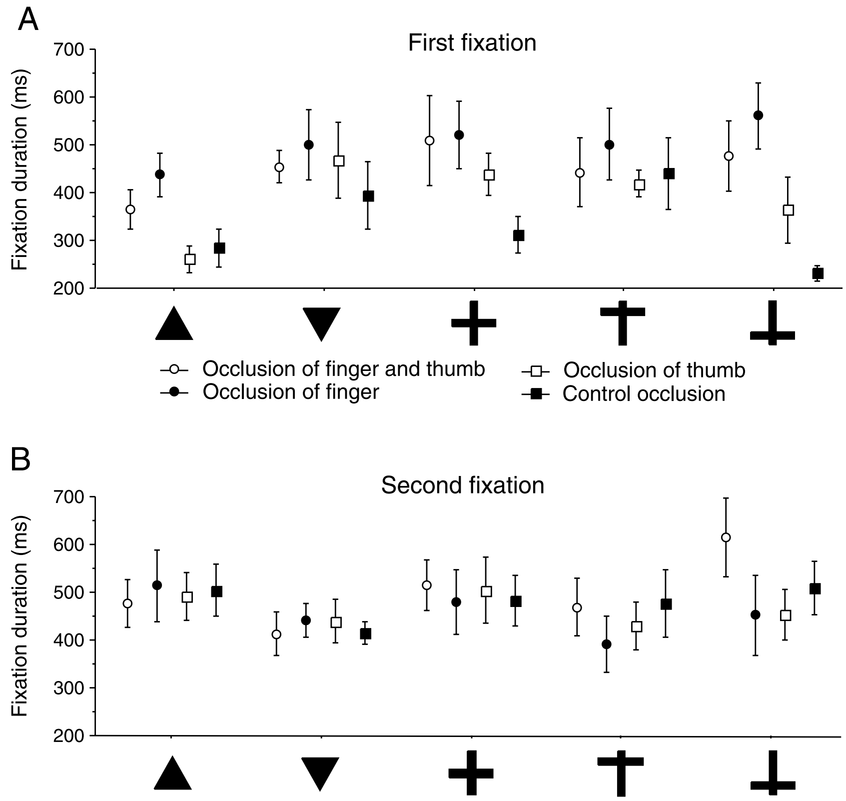

Figure 4. Fixation durations of the first fixations (A) and the second fixations (B) for each shape and occlusion condition. Error bars represent standard errors of the mean between subjects.

these two alternatives would be most likely. Furthermore, compared to the first fixation, the second fixation was also more upwards in the direction of the contact position of the finger. If the contact position of the finger was occluded (finger-occluded condition and the both occluded condition), the amplitude of the second saccade in the direction of the finger was less. Two shapes were an exception: the downward-pointing triangle and the cross. In both these shapes, the first fixation was already close to the contact position of the finger. Thus, there was no need to make an extra saccade toward the contact position of the finger. Furthermore, in the downward-pointing triangle, the small contact position at the bottom is an extra difficulty for the thumb, which might have caused subjects to make a saccade slightly downwards.

The first fixations were expected to be near the COMvis if a strategy is used similar to visually exploring occluded objects (Vishwanath et al., 2000). However, the first fixation was not around the COMvis (or the COM). In the introduction, it was suggested that the first fixation might be at an arbitrary location near or on the object due to the limited ability of the visual system to complete visual

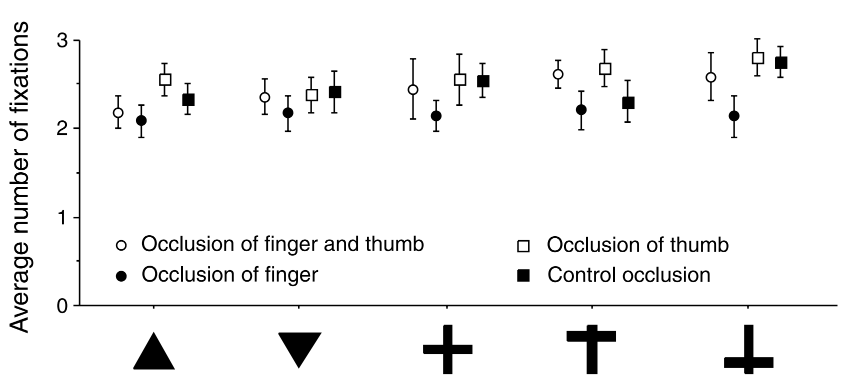

Figure 5. Average number of fixations for each shape and occlusion condition. Error bars represent standard errors of the mean between subjects.

object information in the periphery. After the first fixation on or near the object, information about the object has become available much closer to the fovea. Therefore, the second fixation might land around the COM. However, the second fixation was not near the COM (or the COMvis). Thus, the fixation strategy that subjects used was not comparable to visually exploring objects.

Similar to the study of Brouwer et al. (2005), in which non-occluded objects were grasped, we found that subjects preferred to look in the direction of the contact position of the index finger. However, when this position was occluded, the saccadic amplitude in the direction of the finger was relatively small. Since the contact position of the index finger was always on top of the object, an alternative explanation would be that subjects preferred to look upwards. This has already been tested by Brouwer et al. In one of their conditions, subjects had to grasp objects with a horizontal grip orientation in the fronto-parallel plane instead of a vertical one, such that when grasping with the right hand, the index finger is on the right side of the object and the thumb is on the left side and vice versa when grasping with the left hand. They found that subjects still preferred to look at the index finger in these conditions.

Plomp, Nakatani, Bonnardel, and van Leeuwen (2004) investigated amodal completion of partly occluded objects by recording eye movements in a visual search task. They found that highly familiar objects were fixated shorter than less familiar objects, suggesting that the former objects need less time to visually complete the shape of the object. In our study, fixation durations (for the first fixations) were shorter for the upward-pointing triangle compared to the other shapes. According to Plomp et al., this would mean that the upward-pointing triangle is the most familiar object. However, before the experiment started, we familiarized the subjects with all the shapes that would be used in the experiment. This suggests that the theory of Plomp et al. does not hold for fixation strategies during grasping.

Additionally, in our study, fixation durations were shortest in the control occlusion condition followed by the thumb-occluded, both occluded, and finger-occluded conditions. In contrast, Guttman et al. (2003) and Shore and Enns (1997) found the longest fixation durations when the largest part of the object was occluded. This could be caused by a difference in task. The studies of Guttman et al. and Shore and Enns used a perceptual task in which subjects had to visually explore the stimulus. In that case, the larger the part of an object that is occluded, the more visual completion needs to be performed by the subject, resulting in longer fixation times. However, when grasping an object, stable contact positions for the digits must be determined. In that case, subjects are mostly concerned about the shape of the object around the contact positions. Thus, when the object is occluded around the contact positions, the object might be fixated longer. This is indeed what we found: longest fixation durations for the finger-occluded condition and shortest in the condition in which an object part is occluded that did not interfere with the contact positions of the digits (control occlusion).

Furthermore, the differences in fixation durations (first fixations) between the conditions suggest that information about occlusion and completion of object shape is processed during the first fixation on the object and not prior to it (i.e., when the eyes are still on the fixation position and the object is in the periphery of the visual field). If object information is not processed before the first fixation, reaction times (RTs) of the saccades from the starting point toward the object should be similar in all conditions. Therefore, we performed an additional ANOVA on these RTs. No effect of shape or occlusion was found. There was also no interaction. Average RT was 324 ± 10 ms.

If information about occlusion and shape completion is processed once the eye has reached the object, the results of Vishwanath et al. (2000) can be understood in a different way. Vishwanath et al. asked subjects to look at visually occluded objects starting from a peripheral fixation point. The first fixations landed around the COMvis of the object instead of the COM. They concluded that information about visual completion is not used when visually exploring occluded objects. However, if this information is not processed until the first fixation on the object, this fixation will not show evidence of visual completion by landing near the COM. This effect might become apparent in one of the following fixations. We did not find this result here, but this may be due to differences in the performed task. In the Vishwanath et al. study, subjects only had to look at partly occluded objects whereas in our study they had to grasp them. Furthermore, Vishwanath et al. only used triangular shapes with three occluders, one at each corner of the triangle. In our experiment, we used one coherent occluder, which covered different parts of the object in each condition. How each of these differences affects the fixation strategy when grasping or viewing occluded objects needs further investigation.

The number of fixations did not differ between the conditions. This is probably due to the relatively small object size, which was used to comfortably grasp the objects. Once a fixation near or inside the object has been made, almost no extra fixations are needed to get an idea about the completed shape of the object.

Overall, subjects did fixate occluded object locations even though no direct visual information could be obtained from these locations. This suggests that the saccadic system has access to a visually completed object shape. However, due to the fact that the location of the second fixation changed with the location of the occlusion, it is suggested that the shape of the object might not be fully or not correctly completed in every occlusion condition. We conclude that although an occluder does not prevent occluded object parts from being fixated, it does affect fixation positions. The fixation strategy that is used when grasping occluded objects is most comparable to fixations during non-occluded object grasping.

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