Human Movement Science 31 (2012) 1090–1102

Contents lists available at SciVerse ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Do obstacles affect the selection of grasping points?

D. Voudouris *, J.B.J. Smeets, E. Brenner

MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, The Netherlands

A R T I C L E I N F O

Article history:
Available online 12 June 2012

PsycINFO classification:
2330

Keywords:
Grasping points
Obstacles
Grip orientation
Final posture
Prehension

A B S T R A C T

The selection of grasping points, the positions at which the digits make contact with an object's surface in order to pick it up, depends on several factors. In this study, we examined the influence of obstacles on the selection of grasping points. Subjects reached to grasp a sphere placed on a table. Obstacles were placed either near the anticipated grasping points or near the anticipated elbow position at the time of contact with the object. In all cases, subjects adjusted the way they moved when there was an obstacle nearby, but only obstacles near the thumb had a consistent influence across subjects. In general, the influence of the obstacle increased as it was placed closer to the digit or elbow, rather than the subject grasping in a manner that would be appropriate for all conditions. This suggests that under these circumstances the configuration of the arm and hand at the moment of contact was a critical factor when selecting at which points to grasp the objects.

1. Introduction

To grasp an object, points on it must be chosen for placing the digits. We will refer to these points as grasping points. Several factors have to be considered when selecting grasping points, such as the location of the object (Paulignan, Frak, Toni, & Jeannerod, 1997; Schot, Brenner, & Smeets, 2010), its orientation (Cuijpers, Smeets, & Brenner, 2004; Jeannerod, 1981), its shape (Goodale et al., 1994; Lederman & Wing, 2003), and its center of mass (Craje, Lukos, Ansuini, Gordon, & Santello, 2011; Lederman & Wing, 2003), as well as what one intends to do with the object (Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992), and experience with it (Fu, Zhang, & Santello, 2010). Combining all these factors makes people generally select specific grasping points even for objects that could be grasped in

* Corresponding author. Address: Van der Boechorststraat 9, 1081 BT, Amsterdam, The Netherlands. Tel.: +31 20 59 82632.
E-mail address: d.voudouris@vu.nl (D. Voudouris).

0167-9457/$ - see front matter
http://dx.doi.org/10.1016/j.humov.2012.01.005

many ways (Grea, Desmurget, & Prablanc, 2000; Schot et al., 2010). As the choice of grasping points is a compromise between the influences of many factors (Cuijpers et al., 2004), we can expect obstacles to influence this choice.

Several studies have examined how obstacles affect the execution of a grasping task. The maximal grip aperture is smaller (Chapman, Gallivan, Culham, & Goodale, 2011), the movement time longer (Biegstraaten, Smeets, & Brenner, 2003; Saling, Alberts, Stelmach, & Bloedel, 1998), or both (Mon-Williams, Tresilian, Coppard, & Carson, 2001), when obstacles are present near specified grasping points. People also tend to deviate away from objects that may interfere with the prehensile movement (Chapman & Goodale, 2008), presumably to maintain a minimal distance from any such object (Tresilian, 1998). However, little is known about how obstacles influence the choice of grasping points, and thereby grip orientation.

Since one must be able to reach the desired arm and hand configuration at the time of contact, obstacles have to be considered to some extent (Vaughan, Rosenbaum, & Meulenbroek, 2001), perhaps by evaluating previous experience with various arm postures and the constraints imposed by the obstacles throughout the movement (Rosenbaum, Vaughan, Meulenbroek, & Jansen, 2001). However, we have previously shown that the arm and hand configuration at the time of contact, rather than during the movement towards the object, are critical when selecting grasping points on an isolated object

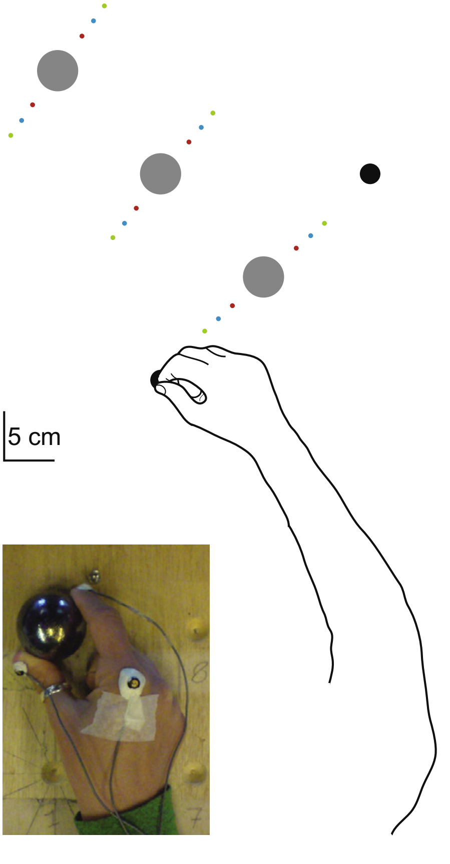

Fig. 1. Top view of the setup in Experiment 1. The three object locations are indicated by gray disks, and the obstacle locations by small colored dots. The two starting positions are shown as black disks. The picture at the lower left shows a participant's hand grasping the object, with the obstacle 2 cm from the index finger's grasping point. The scale only applies to the drawn figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Voudouris, Brenner, Schot, & Smeets, 2010), so perhaps obstacles only influence how one moves. We here examined the role of obstacles in selecting grasping points when grasping a sphere (see Fig. 1). We did so by placing obstacles at positions that could be expected to tempt subjects to select different grasping points than they would normally select. We either placed obstacles near a usual grasping point (constraining one digit's approach) or near the elbow (constraining the arm configuration at the moment of contact).

2. Experiment 1

2.1. Methods

2.1.1. Subjects and apparatus

Eight subjects, seven women and one man, aged from 23-41 years, participated voluntarily in this study. All subjects were right handed and had normal or corrected-to-normal vision. All subjects were naive as to the precise purpose of the study. The experiment was part of a program that has been approved by the local ethics committee.

Small markers (infra-red light emitting diodes) were attached to the nail of the thumb and index finger, and to the metacarpophalangeal joint of the index finger of the right hand, using elastic gum. Movements were measured at a sampling rate of 250 Hz (resolution 0.1 mm), using an Optotrak 3020 infrared tracking system with two cameras (Northern Digital, Waterloo, Ontario, Canada). The wires connecting the markers to the Optotrak system were taped to the subject's arm.

Subjects stood in front of a height-adjustable table (60×52 cm), with its surface at the same level as the upper part of the subject's coxal bone (hip). The object that was to be grasped was always the same: a colorful opaque glassy sphere (4.5 cm diameter, 123 g mass). A metal screw (2.5 cm length, 0.4 cm diameter including thread, 0.5 cm base diameter, tip pointing upwards) was used as an obstacle. It was not fixed in any way, so it would fall if touched.

The sphere was placed at one of three different locations, which were marked with small indentations (0.2 cm in depth) to help always position the sphere at the same location and to prevent it from rolling away. The locations were at the near-right, center or far-left relative to the subject's midline. We selected obstacle positions that were close to where subjects positioned the digits on the sphere when there was no obstacle, based on grasping movements made in pilot experiments. The obstacle, when present, was placed 2 cm, 3.5 cm or 5 cm from the sphere's surface (Fig. 1). It could be at either side of the object, along a line that was oriented at 42, 51 and 54° relative to the subject's frontal plane as the object's location changed from the nearest to the most distant one. For each object location, the six different obstacle positions and a configuration without any obstacle constituted seven obstacle configurations.

For every object location and obstacle configuration there were trials from two starting positions. One of them was located near the subject, along his or her midline ("near") and the other was farther away and to the right of the subject's midline ("side"). Both were marked with small indentations.

2.1.2. Procedure

Subjects were instructed to reach and grasp the sphere between their thumb and index finger, to lift it, to place it back at the same location, and then to move their hand back to the original starting position. They were instructed to avoid hitting the obstacle. The subject placed his or her hand comfortably at the starting position indicated by the experimenter while the latter placed the object and the obstacle at the appropriate locations. A verbal signal by the experimenter indicated that the subject could start moving. Subjects were told that they could execute the task at their own pace. No further instructions were given, so subjects were free to choose how they would place their digits on the object (Fig. 2). There were five consecutive blocks of 42 trials. Within each block, each of the 42 conditions (2 starting positions $\times$ 3 object locations $\times$ 7 obstacle configurations) was presented once, in a random order. This resulted in a total of 210 trials per subject.

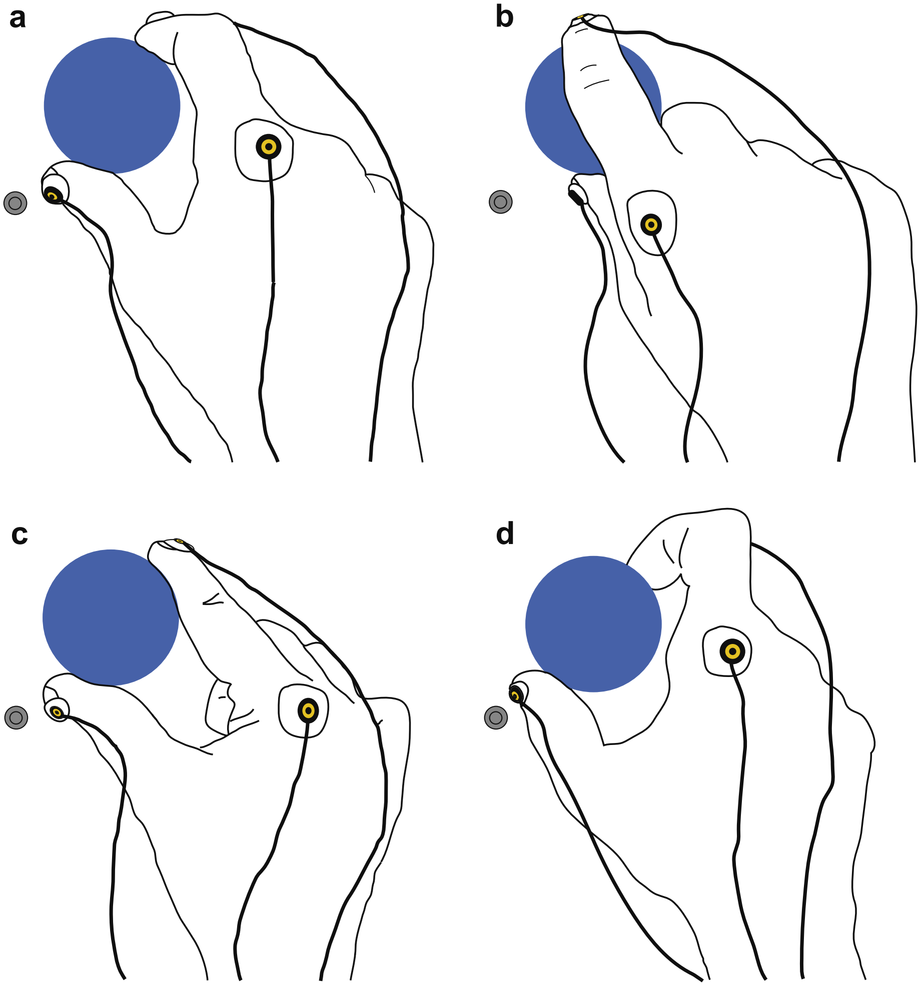

Fig. 2. Possible ways to grasp the object in the presence of an obstacle. Subjects could grasp the object close to the usual grasping points (a), or select totally different grasping points by pronating their forearm (b). They could also reach the usual grasping points with different configurations of the digits (c, d). The distance between the marker on the metacarpophalangeal joint and those on each digit is larger in c than in d.

2.1.3. Data analysis

We considered the average of the two digits' positions to represent the position of the hand. The velocity of the hand was calculated by numerical differentiation of its position. The onset of the movement was defined as the point at which the velocity of the hand exceeded a threshold of 0.25 m/s. The moment of the grasp was defined as the frame on which the position of the hand started moving upwards to lift the object off the table (since the hand moved downwards to grasp the object there was a clear minimum in the vertical position of the hand). The movement time was the time difference between the movement onset and the moment of the grasp.

The maximal grip aperture was defined as the largest distance between the markers on the nails of the digits during the reaching movement. The horizontal grip orientation was defined as the orientation of the line connecting the markers on the two digits at the moment of the grasp when projected on the horizontal plane (0° corresponding to the left-right direction). Grip orientation was considered to reflect the chosen grasping points, but it is important to remember that the markers were attached to the nails. The vertical grip orientation was defined as the angle between the line connecting the two digits and the horizontal plane. To judge whether posture changed in a manner that did not influence the choice of grasping points we also examined the distance between the marker on each digit and that on the metacarpophalangeal joint at the moment of the grasp (see Fig. 2c and d), as well as the deviation of a plane through the markers on the metacarpophalangeal joint and on the two digits from being horizontal.

The values of the above-mentioned variables were calculated for each trial and then averaged across the five repetitions of each condition for each subject. The effects on these variables were evaluated with 2 (Starting Positions) × 3 (Object Locations) × 7 (Obstacle Configurations) repeated measures analyses of variance. All significant effects ($p < .05$) are mentioned in the results section. When sphericity was violated, the Greenhouse-Geisser correction was applied. For drawing average paths for each digit to give an impression of the movements, positions on each trial were re-sampled in 100 equal steps, each corresponding to 1% (using linear interpolation), and the 101 coordinates were averaged across the five repetitions and across subjects.

2.2. Results

Subjects never knocked down the obstacle. Two trials in which the object slipped away from the subject's hand were discarded and repeated. The paths were largely the same for the different obstacle configurations, but there were some small but systematic effects of the obstacles. The paths were mainly affected if the obstacle was between the digit's starting position and its grasping point: this was most evident for the horizontal component of the thumb's path when starting from the "near" position with obstacles near the thumb's grasping point (Fig. 3a and c) and for the index finger's path when starting from the "side" position with obstacles near the finger's grasping point (Fig. 3b). In the paragraphs below we will present the main effects grouped by the independent variables, followed by other effects.

2.2.1. Effects of obstacle configuration

The obstacle configuration influenced the horizontal grip orientation, $F(6,42) = 8.80$, $p < .001$ (Figs. 4, 5a). Obstacles near the thumb's usual grasping point made all subjects adopt a more counter-clockwise grip at the moment of the grasp. Obstacles near the finger did not have a systematic effect across subjects, but Fig. 4 shows that individual subjects did change their grip axis. However the direction of the change was not consistent across subjects, and not directly related to the dimensions of their digits. The obstacle configuration affected maximal grip aperture, $F(6,42) = 4.76$, $p = .001$ (Fig. 5b), and movement time, $F(6,42) = 5.79$, $p < .001$ (Fig. 5c); the closer the obstacle to the object, the smaller the maximal grip aperture and the longer the movement time. The latter effects suggest a more careful approach of the object.

2.2.2. Effects of object location

Horizontal grip orientation was affected by the location of the object, $F(2,14) = 69.79$, $p < .001$; a more counter-clockwise grip was adopted when the object was placed farther away to the left. Moreover, the farther the object from the starting position, the longer the movement time, $F(2,14) = 20.80$, $p < .001$. On average the movement times were 672 ms, 689 ms and 809 ms for objects at the near-right, center and far-left, respectively. The orientation of the plane through the digits and the metacarpophalangeal joint was also affected by the object location, $F(2,14) = 8.39$, $p < .005$. Subjects oriented their hand at 35.2°, 36.1° and 36° when grasping at the close-right, central and far-left location, respectively.

2.2.3. Effects of starting position

Horizontal grip orientation was affected by the starting position, $F(1,7) = 19.23$, $p < .005$; a 4.4° more clockwise grip orientation was adopted when starting from the near position than when starting from the side position.

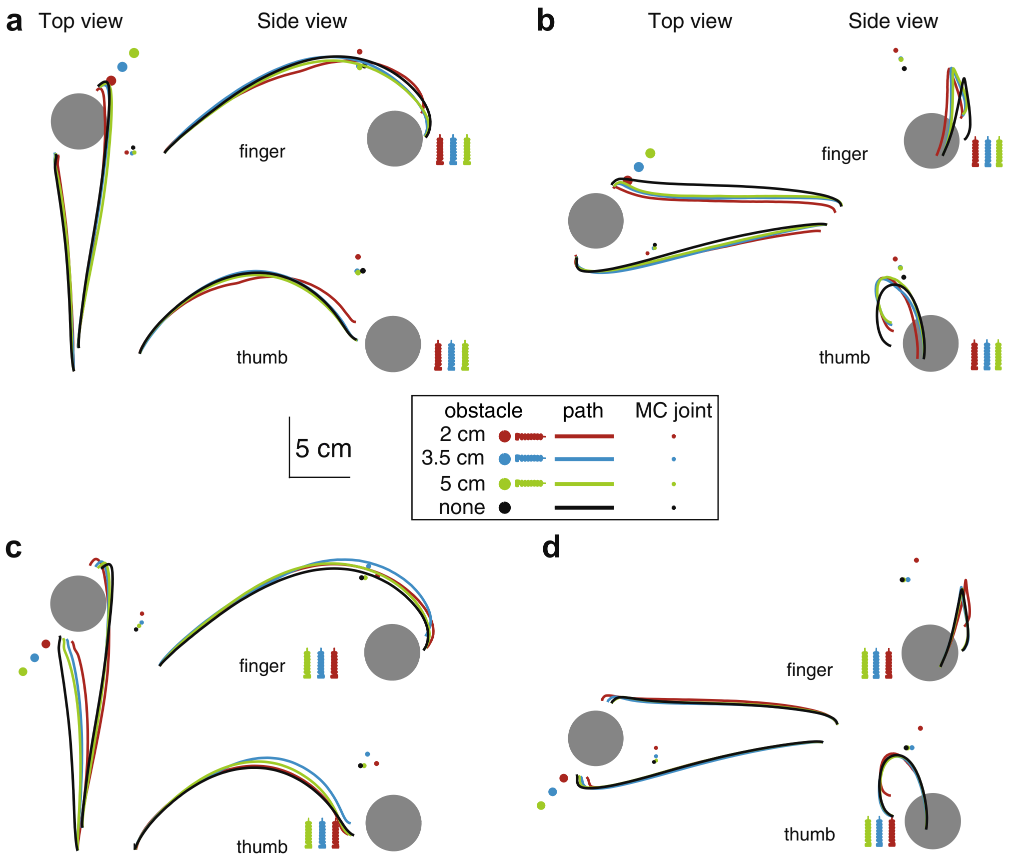

Fig. 3. Experiment 1. Top and side views of the digits' mean paths towards the central object location when starting near (a, c) or at the side (b, d), with obstacles near where the finger (a, b) or the thumb (c, d) contacts the sphere's surface. Paths with no obstacle are shown in all four panels. The paths are of the markers attached to the nails, so they are at some distance from the parts of the digits that contact the object. The small dots show the mean final positions of the metacarpophalangeal joint for each condition.

2.2.4. Other effects

For horizontal grip orientation there were also significant interactions between starting position and object location, $F(2,14) = 10.01$, $p < .005$, between starting position and obstacle configuration, $F(2.99,20.98) = 3.76$, $p < .05$, and a significant three-way interaction between starting position, object location and obstacle configuration, $F(12,84) = 2.78$, $p < .005$. We have no real explanation for these effects, but they show that the direction of the movement to the object does matter to some extent, because they all involve the factor "starting position".

The average distance between the index finger and the metacarpophalangeal joint was 8.6 cm and did not depend on any of the independent variables. The same was found for the distance between the thumb and the metacarpophalangeal joint, for which the average distance was 8.8 cm. Thus we see no evidence that subjects adopted a different hand configuration in different conditions. No significant effects were found for the vertical grip orientation.

2.3. Discussion

Placing an obstacle near where subjects would normally place their digits not only influenced movement time and grip aperture, but also the selection of grasping points. The effects on the latter variable that we found for object location and starting position have been reported before (Schot et al.,

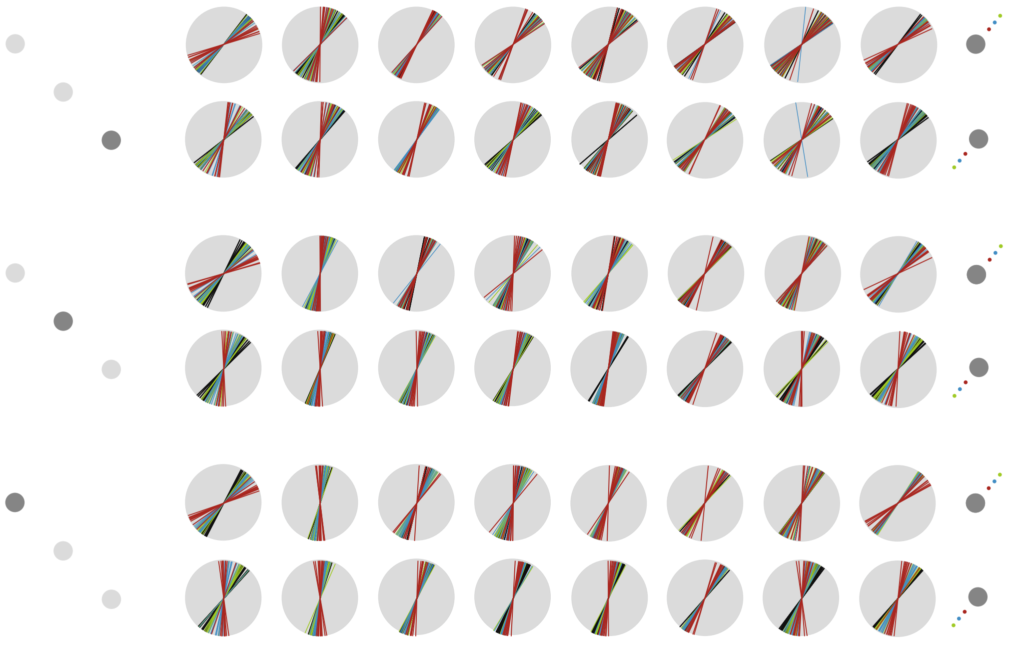

Fig. 4. Each subject's horizontal grip orientation for each obstacle configuration and each object location (irrespective of the starting position). The grip orientations when there was no obstacle (black lines) are shown in all panels for comparison. The only evident, consistent and systematic influence is a more counter-clockwise grip when the obstacle was near the thumb. Note that some subjects rotated their grip more clockwise whereas others more counter-clockwise, when the obstacle was closest to the finger (relative to the no obstacle condition). Each column represents one subject. They are ordered by the thumb's thickness (including the marker). Red, blue and green lines indicate obstacle distances of 2, 3.5 and 5 cm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2010; Voudouris et al., 2010), so we will concentrate our discussion on the effects of the obstacle. The horizontal grip orientation was further counter-clockwise when the thumb's grasping point was constrained, but not systematically further clockwise when the finger's grasping point was constrained. This difference might be due to the finger being thinner than the thumb, although there was no obvious relationship between the digits' thicknesses and the change in grip orientation (Fig. 4). Perhaps the finger is just more flexible due to the additional joint. Subjects selected a more counter-clockwise grip orientation when the obstacle was at the thumb's side, possibly because a more clockwise rotation would impose constraints on their palm. The fact that the distance between the metacarpophalangeal joint and the digits did not change significantly, which could have occurred if subjects had adopted a completely different configuration of the digits in some conditions, does not mean that it did not change in individual subjects. It means that this change was not systematic across subjects. Similar reasoning applies to the orientation of the plane through the three markers and vertical grip orientation.

Some changes in the way the object is grasped are not captured by our measure of grip orientation. For instance, the paths for the nearest obstacle in Fig. 3d (side view) seem to end up farther away from the object, despite it being spherical. Some differences between the end points of the markers might be due to the subjects grasping the object between different parts of their digits (closer to the end of the fingertip when the obstacle was placed closer to the object, to reduce the part of the digit that is between the obstacle and the object). Thus, altogether subjects grasped the object differently when obstacles were present, but only the horizontal grip orientation was changed systematically across subjects by obstacles near the thumb.

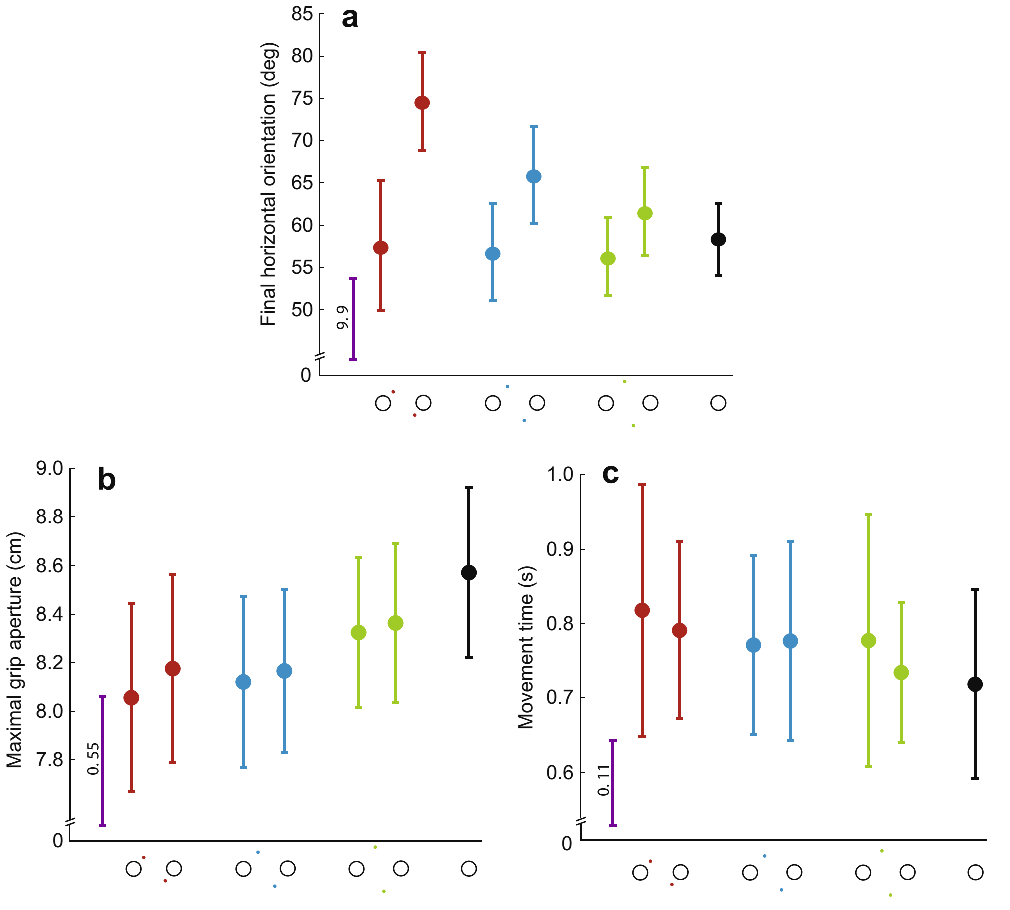

Fig. 5. Experiment 1. Some influences of obstacle configuration: from left to right for an obstacle 2 cm from the index finger or the thumb (red), 3.5 cm from the index finger or the thumb (blue), 5 cm from the index finger or the thumb (green), and no obstacle (black). Error bars represent the average standard deviations within the five repetitions performed by each subject. Purple bars in the lower left corner of each panel show the average standard deviation across subjects. (a) Horizontal grip orientation; (b) Maximal grip aperture; (c) Movement time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Experiment 2

3.1. Introduction

In Experiment 1, the extent to which subjects grasped with a different grip orientation depended on the distance of the obstacle, whereas they could have simply adopted a different grip orientation on all trials with an obstacle near the constrained digit. It seems that subjects considered their hand configuration at the time of contact to be very important. They approached the selected grasping points more slowly and with smaller maximal grip apertures, rather than choosing more distinct grasping points. If the selection of the grasping points is primarily based on the final arm configuration (Rosenbaum et al., 2001), we can expect grip orientation to change when obstacles do not obstruct the grasping points themselves but constrain the configuration of the arm at the moment of contact. Alternatively, if grasping points are selected without considering the configuration of the arm, there is no reason to expect the grasping points to change in such cases, although the overall posture must obviously change to avoid collision with the obstacle. In this context we cannot separate static end-state comfort from biomechanical considerations during the movement. We will refer to both as postural considerations.

3.2. Methods

3.2.1. Subjects and apparatus

Seven right-handed subjects, all of them women aged between 22 and 28, participated voluntarily in Experiment 2. Four of them had participated in Experiment 1. All of them were naive as to the precise purpose of the experiment and gave their informed consent for participating in the study. Except for the following details, the apparatus, procedure and data analysis were identical to those of Experiment 1.

In addition to the markers on the nails of the index finger and thumb, we had one on the ulnar head of the wrist and one on the ulna's olecranon of the elbow of the subject's right arm. We did not include maximal grip aperture in the analysis. Only the "near" starting position was used. Three locations, two of which were different from those used in Experiment 1, were marked with small indentations for placing the target object. A black cylinder made of polyoxymethylene (4.5 cm diameter, 14 cm height, 323 g mass) was used as the obstacle. When present, it was placed at one of three different positions, along a line parallel to the subject's mediolateral plane, and at a distance of 10 cm ("near"), 15 cm ("intermediate") or 20 cm ("far") to the right of the starting position. Small marks were made on the table to help place the obstacle at the correct position (see Fig. 6). There were five consecutive blocks of 12 trials, with one trial of each of the 12 conditions (3 object locations $\times$ 4 obstacle configurations) presented in random order within each block, resulting in a total of 60 trials.

3.3. Results

Subjects never knocked down the obstacle. In the one case that the sphere slipped away from the subject's hand, the trial was discarded and repeated. Generally, subjects moved their digits farther to the left and higher as the obstacle was placed closer to the subject's arm, in order to avoid hitting the obstacle with their elbow. The elbow was farther to the left at the time of the grasp when the obstacle was nearer the starting position (Fig. 7).

3.3.1. Effects of obstacle configuration

The horizontal grip orientation was affected by the configuration of the obstacle, $F(3,18) = 5.99$, $p < .05$. On average, a more clockwise grip was adopted when the obstacle was closer to the starting position, although not all subjects did so (Fig. 8). Movement time was also affected by the obstacle configuration, $F(3,18) = 21.28$, $p < .001$ (Fig. 9): movement times were longer when the obstacle was closer to the starting position.

3.3.2. Effects of object location

The location of the object affected the horizontal grip orientation, $F(2,12) = 52.94$, $p < .001$; the more to the right the object, the more clockwise the grip. There was a difference of about 17° between the left and the right object location.

3.3.3. Other effects

There were no significant interactions. Note that none of the independent factors influenced the vertical grip orientation ($-10.44 \pm 6.12°$) or the orientation of the plane through the digits and the wrist marker ($28.10 \pm 2.04°$) significantly.

3.4. Discussion

Placing an obstacle near the usual position of the elbow at the time of contact meant that the arm configuration at that time had to be different (see Fig. 7). This influenced movement time as well as the placement of the digits on the target object. In this experiment we constrained the configuration

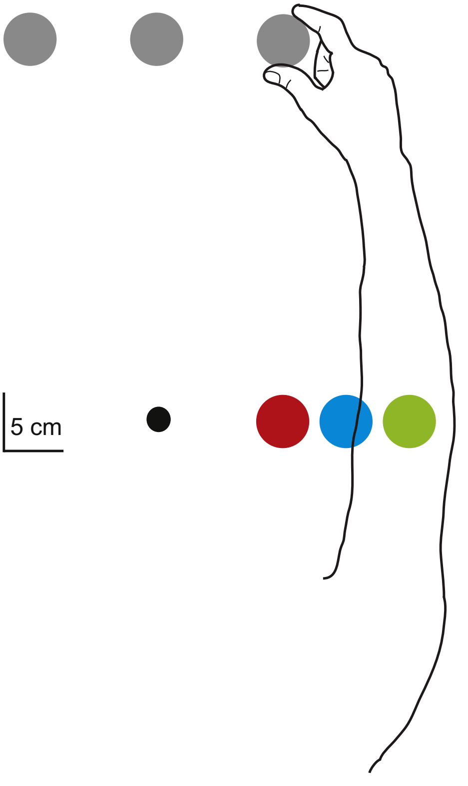

Fig. 6. Top view of the set-up in experiment 2. The three object locations are shown as gray disks. The three possible obstacle configurations are shown as colored disks and the starting position is marked as a black disk. The arm is shown extended to grasp the object at the right location when no obstacle was present. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the arm at the time of contact, rather than the grasping points. Subjects generally moved to the left to avoid the obstacle, but the selected path was very variable when the obstacle was closest to the starting position. The change in the horizontal grip orientation can be considered to support the idea that the grasping points are chosen on the basis of postural considerations because there was enough freedom in the wrist and arm for subjects to have grasped the object at the same points but with a different arm configuration. The slower movements when the obstacle was closer could mean that subjects were more careful, but there may be other reasons, such as that people move faster when moving towards the preferred grip orientation (Cuijpers et al., 2004) or joint angles (Wood & Goodale, 2010).

4. General discussion

In the present study we asked subjects to reach out and grasp a sphere. We compared conditions in which the reaching movements were constrained by different kinds of obstacles located at various positions within the workspace. In the first experiment the obstacle was near the anticipated grasping points, making it less advantageous to select the usual grasping points. In the second experiment the obstacle was near the elbow, making it impossible to adopt the usual arm configuration at the time of contact. The main finding of our study is that the obstacles influenced the choice of grasping points. Several details suggest that their choice is related to postural considerations. For the selection of grasping points in the situations without obstacle, postural considerations are likely to play an important role because when obstacles were placed at positions near the usual grasping points, subjects did

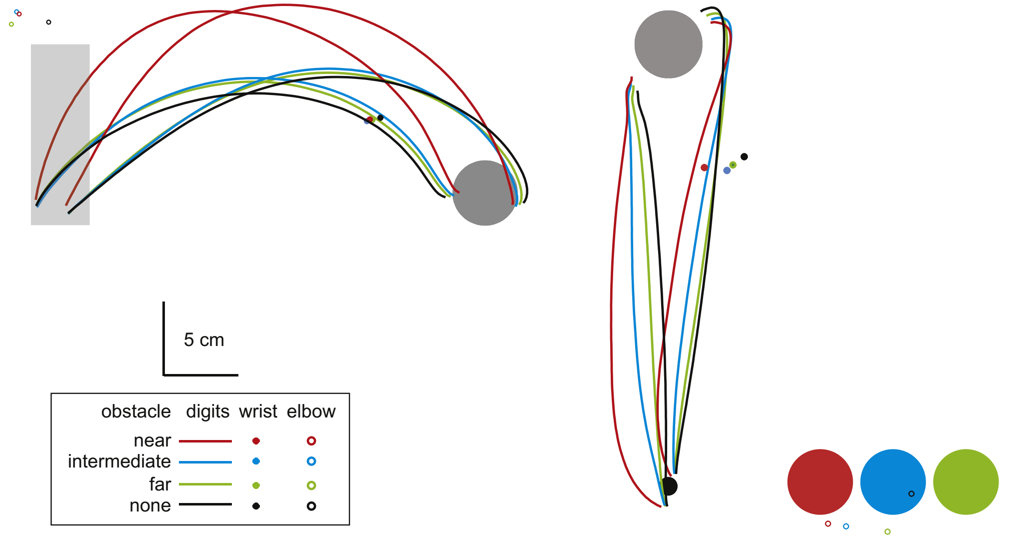

Fig. 7. Side and top views of the digits' mean paths towards the central object location, and end-points of the wrist and elbow joints in Experiment 2. Note that the marker for the elbow joint was placed on top of the elbow, so the final position of the nearest point of the elbow must have been considerably closer to the obstacle than it may appear in the side view.

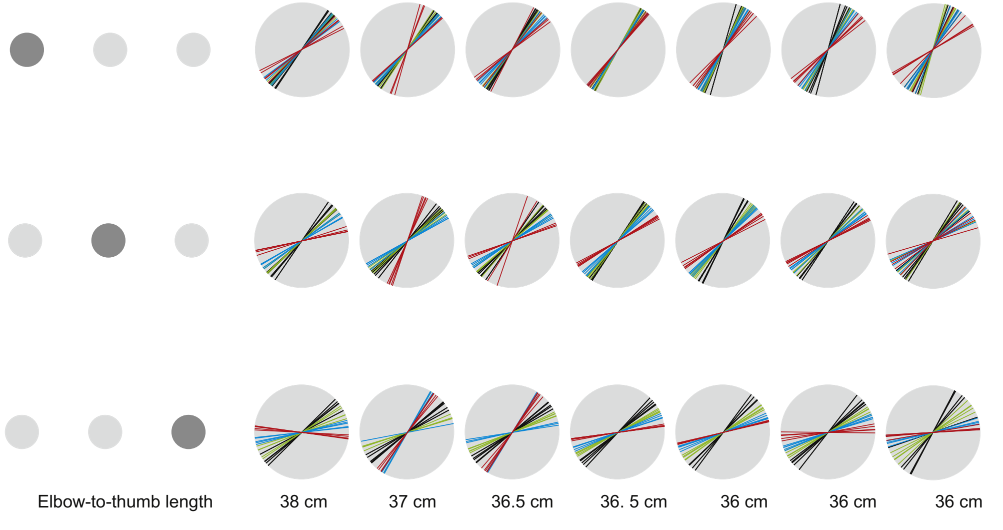

Fig. 8. Each subject's horizontal grip orientation for each obstacle configuration and object location. Note the large variability in grip orientation between subjects when the obstacle was near the starting position. Columns representing data from individual subjects are order based on forearm length. Red, blue and green lines indicate obstacle distances from the starting position of 10, 15 and 20 cm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not select completely different grasping points to be sure to avoid hitting the obstacles (see Fig. 2b), but took longer to move to similar positions on the object (Lommertzen, Costa e Silva, Cuijpers, & Meulenbroek, 2009; Smeets & Brenner, 1999). Movements also lasted longer when an obstacle was near the elbow's position at the moment of grasp. In both cases subjects also adjusted their grip orientation gradually with obstacle position, though the adjustments differed between subjects (Figs. 4 and 8).

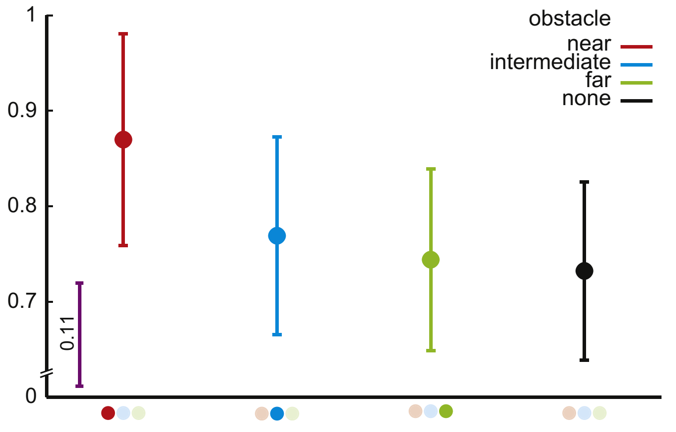

Fig. 9. Experiment 2. Influence of obstacle configuration on movement time. Error bars show the average standard deviations within the five repetitions performed by each subject. The purple bar is the standard deviation across subjects. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Considering our previous finding that the path along which the digits move does not influence the grasping points (Voudouris et al., 2010) we believe that it is the final arm configuration that is critical (Rosenbaum et al., 2001).

Subjects moved towards the object with deviations away from the obstacle to maintain a safe distance from it (Tresilian, 1998). If the object's shape and orientation had made a different grasping orientation more suitable, subjects would probably have adapted their grip orientation (Cuijpers et al., 2004). Similarly, if a later goal could better be achieved with a different configuration of the arm and hand they would perhaps have used a very different arm posture (Rosenbaum et al., 1992). The object and task of the current study provided a lot of freedom in picking grasping points. Nevertheless the variability in grip orientation was quite consistent across conditions and even across subjects (Figs. 4 and 8). The largest differences in the selected grasping points were detected when an obstacle was placed where subjects would normally have their elbow at the moment of the grasp.

It has been shown that an awkward final arm configuration can increase the end point variability in pointing tasks (Rossetti, Meckler, & Prablanc, 1994). Variability in reaching the planned endpoint should obviously be avoided in grasping movements, both to avoid placing the digit at unsuitable positions and to avoid obstacles. If one would place one's digits (or move them) farther from the obstacle, one could easily tolerate a slight increase in variability. Nevertheless, people did not do so in our study. Instead it appears that they moved slower and with smaller maximal grip apertures towards near the preferred points. Although this may seem strange, it may be a good choice because subjects occasionally failed to grasp the object, but they never knocked over the obstacle. Thus, our findings are consistent with the idea that people select grasping points in accordance with a preferred posture of the arm configuration at the time of contact (Butz, Herbort, & Hoffmann, 2007; Desmurget & Prablanc, 1997; Grea et al., 2000; Rosenbaum et al., 1992, 2001).

Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under Grant agreement number 214728-2 and from the Alexander S. Onassis public benefit foundation under Grant agreement F ZH 016/2011-2012.

References

Biegstraaten, M., Smeets, J. B. J., & Brenner, E. (2003). The influence of obstacles on the speed of grasping. *Experimental Brain Research, 149*, 530–534.

Butz, M. V., Herbort, O., & Hoffmann, H. J. (2007). Exploiting redundancy for flexible behavior: Unsupervised learning in a modular sensorimotor control architecture. *Psychological Review, 114*, 1015–1046.

Chapman, C. S., Gallivan, J. P., Culham, J. C., & Goodale, M. A. (2011). Mental blocks: fMRI reveals top–down modulation of early visual cortex when obstacles interfere with grasp planning. *Neuropsychologia, 49*, 1703–1717.

Chapman, C. S., & Goodale, M. A. (2008). Missing in action: The effect of obstacle position and size on avoidance while reaching. *Experimental Brain Research, 191*, 83–97.

Craje, C., Lukos, J. R., Ansuini, C., Gordon, A. M., & Santello, M. (2011). The effects of task and content on digit placement on a bottle. *Experimental Brain Research, 212*, 119–124.

Cuijpers, R. H., Smeets, J. B. J., & Brenner, E. (2004). On the relation between object shape and grasping kinematics. *Journal of Neurophysiology, 91*, 2598–2606.

Desmurget, M., & Prablanc, C. (1997). Postural control of three-dimensional prehension movements. *Journal of Neurophysiology, 77*, 452–464.

Fu, Q., Zhang, W., & Santello, M. (2010). Anticipatory planning and control of grasp positions and forces for dexterous two-digit manipulation. *Journal of Neuroscience, 30*, 9117–9126.

Goodale, M. A., Meenan, J. P., Bulthoff, H. H., Nicole, D. A., Murphy, K. J., & Racicot, C. I. (1994). Separate neural pathways for the visual analysis of object shape in perception and prehension. *Current Biology, 4*, 604–610.

Grea, H., Desmurget, M., & Prablanc, C. (2000). Postural invariance in three-dimensional reaching and grasping movements. *Experimental Brain Research, 134*, 155–162.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural vision objects. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 153–169). Hillsdale: Erlbaum.

Lederman, S. J., & Wing, A. M. (2003). Perceptual judgment, grasp point selection and object symmetry. *Experimental Brain Research, 152*, 156–165.

Lommertzen, J., Costa e Silva, E., Cuijpers, R. H., & Meulenbroek, R. G. J. (2009). Collision-avoidance characteristics of grasping. Early sign in hand and arm kinematics. Anticipatory behaviour in adaptive learning systems. *Lecture Notes in Computer Science, 5499*, 188–208.

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

Paulignan, Y., Frak, V. G., Toni, I., & Jeannerod, M. (1997). Influence of object position and size on human prehension movements. *Experimental Brain Research, 114*, 226–234.

Rosenbaum, D. A., Vaughan, H. J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: Selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 18*, 1058–1073.

Rosenbaum, D. A., Vaughan, H. J., Meulenbroek, R. J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review, 108*, 709–734.

Rossetti, Y., Meckler, C., & Prablanc, C. (1994). Is there an optimal arm posture? Deterioration of finger localization precision and comfort sensation in extreme arm-joint postures. *Experimental Brain Research, 99*, 131–136.

Saling, M., Alberts, J., Stelmach, G. E., & Bloedel, J. R. (1998). Reach-to-grasp movements during obstacle avoidance. *Experimental Brain Research, 118*, 251–258.

Schot, W. D., Brenner, E., & Smeets, J. B. J. (2010). Posture of the arm when grasping spheres to place them elsewhere. *Experimental Brain Research, 204*, 163–171.

Smeets, J. B. J., & Brenner, E. (1999). A new view on grasping. *Motor Control, 3*, 237–271.

Tresilian, J. R. (1998). Attention in action or obstruction of movement? A kinematic analysis of avoidance behavior in prehension. *Experimental Brain Research, 120*, 352–368.

Vaughan, J., Rosenbaum, D. A., & Meulenbroek, R. G. J. (2001). Planning reaching and grasping movements: The problem of obstacle avoidance. *Motor Control, 5*, 116–135.

Voudouris, D., Brenner, E., Schot, W. D., & Smeets, J. B. J. (2010). Does planning a different trajectory influence the choice of grasping points? *Experimental Brain Research, 206*, 15–24.

Wood, D. K., & Goodale, M. A. (2010). Selection of wrist postures in conditions of motor ambiguity. *Experimental Brain Research, 208*, 607–620.