J Neurophysiol 110: 1484–1489, 2013.
First published July 10, 2013; doi:10.1152/jn.00066.2013.

Ultra-fast selection of grasping points

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Submitted 28 January 2013; accepted in final form 2 July 2013

Voudouris D, Smeets JB, Brenner E. Ultra-fast selection of grasping points. *J Neurophysiol* 110: 1484–1489, 2013. First published July 10, 2013; doi:10.1152/jn.00066.2013.—To grasp an object one needs to determine suitable positions on its surface for placing the digits and to move the digits to those positions. If the object is displaced during a reach-to-grasp movement, the digit movements are quickly adjusted. Do these fast adjustments only guide the digits to previously chosen positions on the surface of the object, or is the choice of contact points also constantly reconsidered? Subjects grasped a ball or a cube that sometimes rotated briefly when the digits started moving. The digits followed the rotation within 115 ms. When the object was a ball, subjects quickly counteracted the initial following response by reconsidering their choice of grasping points so that the digits ended at different positions on the rotated surface of the ball, and the ball was grasped with the preferred orientation of the hand. When the object was a cube, subjects sometimes counteracted the initial following response to grasp the cube by a different pair of sides. This altered choice of grasping points was evident within ~160 ms of rotation onset, which is shorter than regular reaction times.

grasping points; perturbation; fast responses; latency

WHEN YOU REACH OUT TO GRASP a glass of water that your friend is offering you, it is unlikely that you can precisely predict every detail of your friend's movements, so you need to be able to quickly adjust your movements to those of your friend. There is abundant evidence that people can adjust various aspects of their movements to new visual information with a latency of only 100–150 ms. People can quickly correct for unexpected perturbations in features of an object that they are reaching or grasping for such as its position (Paulignan et al. 1997; Briere and Proteau 2011), shape (Ansuini et al. 2007; Eloka and Franz 2011), size (Paulignan et al. 1997; Hesse and Franz 2009; van de Kamp et al. 2009), and orientation (Desmurget et al. 1996; Brenner and Smeets 2009; van Mierlo et al. 2009). They also respond quite quickly to background motion (Brenner and Smeets 1997) and to changes in visual information about the hand (Saunders and Knill 2003; Karok and Newport 2010) or about a cursor that is moved by moving the hand (Brenner and Smeets 2003). Even the fastest of such responses, the response to a change in target position with a latency of ~100 ms is scaled to the size of the perturbation and to the remaining movement time (Oostwoud Wijdenes et al. 2011).

The responses to perturbations generally have a much shorter latency than the time it takes to initiate a movement (Veerman et al. 2008), probably because not all aspects of the movement are reconsidered. Consequently, when confronted with a moving obstacle during a goal-directed movement, people initially follow the motion of the obstacle. If doing so is inappropriate, they correct the response ~50 ms later (Aivar et al. 2008). Similarly, when instructed to respond to a target jump by moving in the opposite direction than the target, people briefly follow the target before moving in the opposite direction (Day and Lyon 2000). These findings suggest that the initial responses do not arise from new movements being added to the originally planned ones (Flash and Henis 1991) or from the original movements being replaced by new ones (Georgopoulos et al. 1981) but are "automatic" responses that direct the digits towards their targets (Pisella et al. 2000). Such automatic responses being responsible for short latency corrections to the digit movements may have interesting consequences for grasping.

We can distinguish between two aspects of grasping (once a target object has been identified): selecting grasping points on the object (Cuijpers et al. 2004; Voudouris et al. 2010) and bringing the digits to the selected points (Smeets and Brenner 1999). Most of the fast corrections that have been reported are concerned with the control of movements to selected points. We here examine whether people can also quickly adjust the selection of grasping points after a perturbation. Our hypothesis was that people would be unable to do so because the reason that online corrections are faster than normal reaction times is that the choice of suitable points is not reconsidered.

EXPERIMENT 1

Subjects were asked to reach and grasp either a cube or a ball. In some trials the cube or ball rotated, either in a clockwise or anticlockwise direction, soon after the subject's hand started to move. We examined whether the digits followed the selected points on the surface of the object. We expected subjects to follow the rotation of the cube, because it is beneficial to rotate the grip to reach the originally planned grasping points on the surface of the cube. However, when a ball suddenly rotates, there is no need to adjust the paths of the digits because the only thing that changes is that different parts of the surface of the ball are at the originally planned grasping positions in space. These positions would still be appropriate for grasping the ball. The question in the first experiment is whether subjects follow the rotation of the ball as an automatic reaction to visual motion and thus grasp the ball at the predetermined points on its surface or whether they reevaluate the choice of grasping points during the movement and thus select new points, or even neglect the irrelevant rotation of the ball altogether.

Methods

Subjects and apparatus. Ten right-handed subjects (1 man, 9 women; age: 24–30 yr) with normal or corrected-to-normal vision participated voluntarily in the experiment. They were unaware of the purpose of the study. The experiment was part

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of a program that has been approved by the local ethics committee of the Faculty of the Human Movement Sciences of the VU University Amsterdam.

Small clusters of three infrared markers were attached to the nails of the thumb and index finger of the subject's right hand. The positions of these markers were measured at 200 Hz with an Optotrak 3020 motion tracking system (Northern Digital, Waterloo, ON, Canada). The wires of the marker were taped to the subject's arm so as not to hinder the arm movements.

Subjects stood in front of a table (0.90 × 52 cm) that was adjusted so that its surface was at the same height as the subject's hip. They started each movement with the tips of their digits aligned laterally with their right shoulder at a distance of 20 cm from their body. At the starting position, their arm was resting comfortably on a wooden block (6-cm high; 25-cm wide). They had to reach and grasp either a ball (6.7-cm diameter; 14.1 g mass) or a cube (6.7-cm sides; 33.5 g mass), both made of foam. Small nails were pushed into the bottom of each object, so that they could be placed stably on a magnet attached to a motor (8-cm high), 30 cm to the left of and 10 cm farther from the body than the starting position. The motor was beneath a wooden board, so subjects only saw the object on the board.

The motor rotated the object in 33% of the trials. Half of the rotations were in a clockwise direction and the other half in an anticlockwise direction. In 67% of the trials there was no rotation. The rotation occurred about 10 ms after the onset of the movement was detected (movement threshold of 25 cm/s for all six markers). The 12° rotation took 45 ms. After grasping the object, subjects had to place it on top of a cylinder with an elliptical base (10 cm high; 2.2 and 3.5 cm axes) that was placed 25 cm to the right of the initial position of the object and 10 cm farther away. A scaled top-view of the setup can be seen in Fig. 1.

Procedure. Subjects placed their thumb and index finger at the starting position. The experimenter initiated the data collection and a tone generated by the computer indicated that the subject could start moving. Subjects reached for the object, grasped it between thumb and index finger, placed it on the cylinder, and then moved their hand back to the starting position for the next trial. Subjects were informed that after hearing the starting tone they had 5 s to fulfill the task. Other than this, they were not given any instructions about movement speed. To foster careful, natural grasping movements, we emphasized that the object was to be placed on the tall and narrow cylinder without it falling off. In total there were 120 trials per subject: for each object there were 10 trials for each direction of rotation and 40 trials for the conditions without rotation. The trials were presented in random order.

Data analysis. To determine the positions of the fingertips, a calibration trial was done in which a single infrared marker was held between the thumb and index fingertips. The hand-held marker position relative to the clusters was determined, and during the rest of the experiment this relationship was used to calculate the position of each fingertip from the positions of the markers on the clusters.

We determined the velocity of the hand by numerical differentiation of the average of the positions of the two fingertips. A velocity threshold of 20 cm/s defined the onset of the movement. Grip aperture was defined as the three-dimensional distance between the two fingertips. The moment of the grasp was defined using the MSI method (Schot et al. 2010): the hand had to be within 6 cm of the center of the object, its velocity had to be $<$20 cm/s, and grip aperture had to be between 6 and 8 cm. The probability of a moment being the moment of the grasp decreased over time, so the first moment at which all three other criteria were met was considered to be the end of the reach-to-grasp movement. The peak velocity and the maximal grip aperture were determined during the reach-to-grasp movement.

The final grip orientation was the angle of the projection on the horizontal plane of the line connecting the two fingertips at the moment of the grasp. This was considered to represent the chosen grasping points in space. Grasping points on the surface of the object were defined with the help of the average thumb and index finger positions in space at the moment of the grasp when no rotation occurred (averaged over all trials of all subjects for that object). Grasping points were defined with respect to the points on the surface of the object that were at these average positions before any rotation. These points shifted in space when the object rotated. The grasping points on the surface of the objects are signed horizontal displacements across the surface, with anticlockwise displacements being considered positive. The values were averaged across the two digits.

To determine whether the rotation influenced the interaction with the object after the contact, we also determined the time it took to lift the object (which is related to the grip and lift forces; Johansson and Westling 1988; Gordon et al. 1991; Brenner and Smeets 1996). This loading time was the time

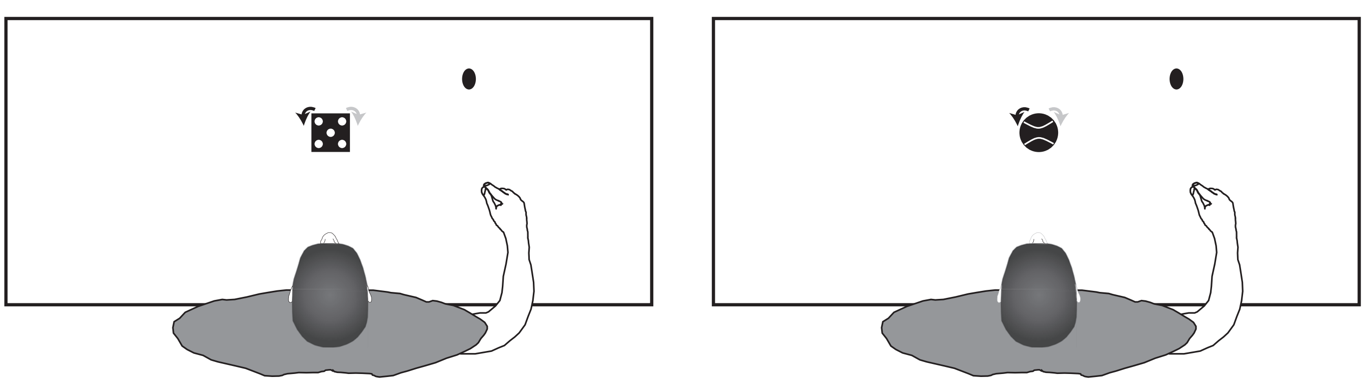

Fig. 1. Schematic top view of the setup. Subjects saw a cube or ball on a wooden board. They were to grasp this object and place it on a small elliptical cylinder. On some trials the object rotated as soon as their hand started to move.

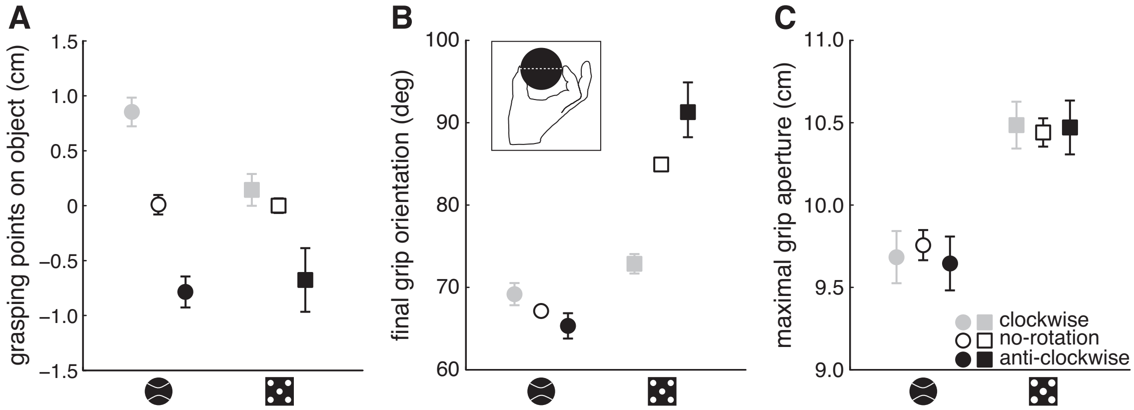

Fig. 2. Influences of rotation of the ball and cube on grasping points on the object (*A*), final grip orientation (*B*), and maximal grip aperture (*C*). Mean values for *experiment 1*, with error bars indicating averages of the individual subjects' standard errors. *Inset*: final grip orientation of 0° (thumb and index finger in frontal plane, with the thumb on the *left*; positive orientation is anticlockwise).

interval between the end of the grasping movement and the next moment that the upward velocity of the hand exceeded a threshold of 0.01 m/s. To verify that subjects always grasped the objects with their fingertips, we calculated the grip aperture variability: the average within-subjects standard deviation of the grip aperture at the moment of the grasp. The grip aperture variability will increase if subjects use various ways to grasp the object in a condition. The values of the above-mentioned variables were calculated for each trial and then averaged across the repetitions of each condition by each subject. The influence of object rotation on these average values was evaluated with repeated-measures ANOVA.

To evaluate the time courses of responses to the perturbations, we determined the rate at which subjects' grips rotated during the first 250 ms after the onset of the rotation of the object. At the beginning of the movement the fingertips were too close together to reliably determine a grip orientation on the basis of their positions, so we used the average positions of the three markers of each of the two clusters to determine the grip orientation. For judging how fast subjects rotated their grip, it is obviously not necessary to accurately reconstruct the positions of the fingertips. For each trial, we calculated the velocity at which the projection of the grip on the horizontal plane was rotating at each moment from when the object started rotating. We then averaged these grip rotation velocities across replications for each subject, object, and rotation condition. Using these average values, we compared the velocities after clockwise and anticlockwise rotations for each object and moment from the onset of object rotation with paired *t*-tests. We considered the first frame on which this difference in grip rotation was significant to be the onset of the response.

Results

General grasping characteristics. Subjects placed their digits at different points on the object after a rotation occurred [Fig. 2*A*; main effect of rotation: $F(2,18) = 68$; $P < 0.001$], especially when grasping the ball [object type by rotation interaction: $F(2,18) = 6$; $P < 0.05$]. Subjects adopted a 16° more clockwise final grip orientation when grasping the ball than when grasping the cube [Fig. 2*B*; $F(1,9) = 184$; $P < 0.001$]. The overall final grip orientation depended on the direction of rotation [$F(2,18) = 16$; $P < 0.001$], but this was completely due to responses to the rotation of the cube [object type by rotation interaction: $F(2,18) = 22$; $P < 0.001$].

Maximal grip aperture was 0.8 cm larger when reaching to grasp the cube than the ball [Fig. 2*C*; $F(1,9) = 55$, $P < 0.001$; see Verheij et al. 2012]. No significant effects of the rotation were found for movement time, peak velocity of the hand, grasp aperture variability, or loading time (overall averages of 503 ms, 0.9 m/s, 0.1 cm, and 64 ms, respectively).

Responses to the rotations. Subjects responded to rotations of the cube and of the ball with latencies of 115 and 130 ms, respectively (Fig. 3). The response to the rotation of the ball was no longer significant 170 ms after the onset of the rotation, whereas the response to the rotation of the cube continued until at least 250 ms after rotation onset. The response already

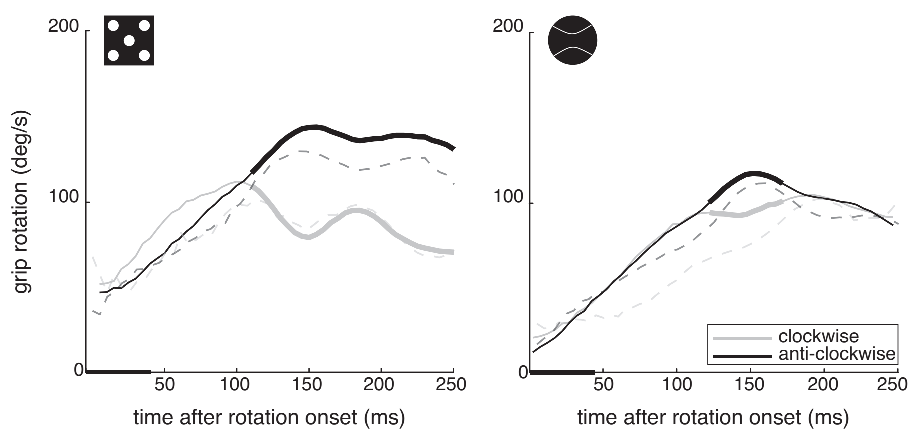

Fig. 3. Velocity at which the grip rotates for the clockwise and anticlockwise object rotation conditions of *experiment 1*. Bold parts show the periods for which the velocity of the grip rotation differed significantly between the 2 rotation conditions. Dashed lines show the average velocities when only considering each subject's first trial for each kind of rotation. Thick horizontal black line at *bottom left* shows the duration of the rotation of the object. *Left*: cube; *right*: ball. The fast response (present for both objects) persists for the cube but disappears before a normal reaction time for the ball.

appears to be present in the first trial in which the object rotates (dashed lines in Fig. 3).

Discussion

The way people grasp an object depends on its orientation (Cuijpers et al. 2004; Voudouris et al. 2012a). Consequently, our subjects responded to a clockwise rotation of a cube by placing their digits at similar points on its surface (compare white and grey square in Fig. 2*A*) at different locations in space (white and grey square in Fig. 2*B*). When the cube rotated in an anticlockwise direction, the variability in where the digits contacted the surface of the cube (Fig. 2*A*) and in the final grip orientation (Fig. 2*B*) was large because although most of the subjects grasped the cube at the same points on its surface, some subjects occasionally grasped the cube by a different pair of sides. That subjects could switch between pairs of sides shows that the choice of grasping points can be modified during the movement, although the present data do not tell us how quickly.

For the ball, subjects also responded to the rotation (Fig. 3*B*) but ultimately placed their digits on different parts of the surface (circles in Fig. 2*A*) at about the same locations in space as without the rotation (circles in Fig. 2*B*; positions even displaced slightly in the direction opposite to the rotation of the ball). Why did our subjects respond to the rotation of the ball at all? An interpretation that would be consistent with earlier studies (Day and Lyon 2000; Pisella et al. 2000; Aivar et al. 2008; van Mierlo et al. 2009) is that the initial response was an automatic reaction to motion of the selected points on the surface of the ball. The response was aborted after an additional 40 ms. This could be because the ball stopped moving after 45 ms, but the response did not stop after 40 ms for the cube (Fig. 3*A*), so it is not only a direct response to the motion. The additional 40 ms may therefore be the time it took for subjects to select new grasping points on the object and suppress the automatic following response. This pattern of responses was already evident on the first rotation trials (dashed lines in Fig. 3), so it cannot be the result of having learnt about our rotations.

EXPERIMENT 2

Since subjects occasionally switched between pairs of sides when grasping the cube, we decided to use this to examine how quickly people can modify their choice of grasping points. Since orientation of the cube largely determines the pair of sides by which it is grasped (Voudouris et al. 2012a), we selected the initial and final cube orientation in such a way that the most suitable grasping points required a grip rotation in the opposite direction than the direction in which the cube rotated. By doing so, we can dissociate automatically responding to the motion of the cube from reselecting the best way to grasp the cube, and can determine a latency for the latter response.

Methods

Fourteen subjects (2 men, 12 women) who were unaware of the purpose of the study participated in *experiment 2*. Eleven of them had participated in *experiment 1*. Except for the details mentioned below, the apparatus, procedure, and data analysis were identical to those of *experiment 1*.

Only the cube was used. It was initially oriented at one of two different angles: 20° or 30° relative to the frontal plane (Fig. 4). These angles were chosen to cover the region for which it is not evident by which pair of sides one can best grasp the object (Wood and Goodale 2011; Voudouris et al. 2012a), so subjects might choose different pairs of sides on different trials. Consequently, it is meaningless to average measures of grasping point selection across trials, so we did not analyze overall changes in grasping points or final grip orientation. In total there were 120 trials per subject: for each initial cube orientation there were 10 trials for each direction of rotation and 40 trials for the conditions without rotation.

To reliably determine how quickly people change their selection of grasping points, we needed subjects who regularly switched between pairs of sides by which they grasped the cube if it rotated. To detect such switches, we categorized grasps with a final grip orientation of $<60°$ as clockwise and all others as anticlockwise. If subjects systematically switched between pairs of sides, they would select a final grip orientation in a rotation condition that was uncommon in the no-rotation condition. We therefore examined whether a final grip orientation that was adopted in $<25\%$ of the trials in the no-rotation condition was adopted in $>50\%$ of the trials in a rotation condition (for the same initial cube orientation). Subjects for whom this was the case were assigned to the *switch group* and were asked to participate in an additional, identical session to obtain more switch data. Both these subjects' data (*switch group*) and those of the remaining subjects (*no-switch group*) will be shown.

For analyzing the timing of the responses of the *no-switch group*, we averaged each subject's responses for each rotation condition across the two initial cube orientations. For analyzing the *switch group* responses, we determined for which of the two initial cube orientations our subjects showed the most switch responses and averaged the responses to the rotations for that initial cube orientation across the two sessions. Consequently, the presented responses are based on 40 trials per subject for both groups (20 per direction of rotation). All other variables were averaged over all subjects and orientations.

Results

General grasping characteristics. When the cube rotated, the reach-to-grasp movement was performed with a slightly lower peak velocity [1.08, 1.08, and 1.09 m/s for the clockwise, anticlockwise, and no-rotation conditions; $F(2,24) = 17$; $P <$

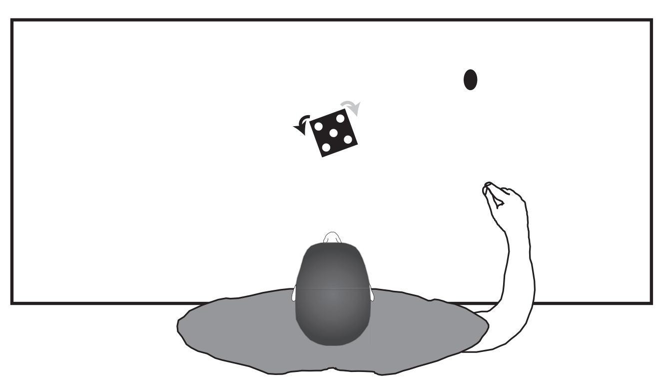

Fig. 4. Schematic top view of *experiment 2* (with a 20° cube orientation). Details as in Fig. 1.

0.001]. No significant differences were found for maximal grip aperture, movement time, grasp aperture variability, or loading time (overall averages of 10.3 cm, 451 ms, 0.3 cm, and 113 ms, respectively).

No-switch responses. Seven of the fourteen subjects selected grasping points on the same pair of sides, irrespective of the orientation or rotation of the cube. Their responses to the rotation of the cube were significant 115 ms after the onset of rotation (as in *experiment 1*; Fig. 5*A*).

Switch responses. All seven of the remaining subjects switched most frequently for the 20° initial cube orientation. For that initial orientation, six of them adopted an anticlockwise grip in <15% of the trials in the no-rotation condition and in >55% of the trials in the clockwise rotation condition. The seventh subject adopted a clockwise grip in 8% of the trials in the no-rotation condition and in 70% of the trials in the anticlockwise rotation condition. Only two of the subjects also regularly switched between surfaces when the cube was initially oriented at 30°. An initial response in the direction of the rotation of the cube was significant 115 ms after the onset of the rotation (Fig. 5*B*). The relative direction of the response had reversed by ~160 ms after rotation onset and reached significance in the opposite direction 190 ms after the onset of the rotation of the cube. The reversal (intersection of black and grey lines) is slightly earlier in the second session (dotted lines) than in the first (dashed lines), but the responses are very similar in both sessions.

Discussion

Subjects again quickly responded to the rotation of the cube. Half of the subjects just followed its rotation (*no-switch group*). The others frequently selected grasping points on the pair of sides that they would not have ended on if no rotation had occurred (*switch group*). Importantly, switching to the other pair of sides required a grip rotation in the opposite direction than the direction in which the cube rotated, making it easy to distinguish between the two kinds of responses. The *switch group* clearly reconsidered their choice of grasping points when the cube rotated but only after initially responding in the direction of the rotation of the cube. The direction of rotation reversed ~160 ms after the onset of the rotation of the cube (Fig. 5*B*). The switch responses did not result from slowing down the movement, because the movement time was no different between the *no-switch* and the *switch group* (averages of 437 and 467 ms, respectively).

It is important to realize that even within the *switch group*, the switch responses were not found in all rotation trials. We averaged all trials for which the cube was initially oriented at 20°, without separating trials in which subjects switched from trials in which they did not, because separating the trials might result in selecting trials in which subjects started with a slightly different grip orientation (which could bias the findings). By averaging across large switch responses and modest no-switch responses in the opposite direction, we underestimate the intensity of the responses, but switch responses dominate because the switch is associated with a 78° change in cube orientation whereas following the rotation of the cube only involves a change of 12°, and response magnitude is known to depend on the amplitude of the required change (Oostwoud Wijdenes et al. 2011).

Some variability in responses to the rotations (in both experiments) might arise by not only considering the cube configuration after the rotation when selecting grasping points but also the change itself and experience on previous trials (Kelso et al. 1994). For instance, two subjects of the *switch group* usually grasped both the 20 and 30° cubes with a clockwise grip, but when the 30° cube rotated in a clockwise direction to 18°, they usually switched to an anticlockwise grip. The subjects may have overresponded to the rotation of the cube because they did not realize how large it would be. It is unlikely that the 2° difference in cube orientation was critical.

Half the subjects completely changed their grasping points even if a large adjustment of their movement was required to do so and although they could have grasped the object without doing so. Thus subjects did not appear to be reluctant to change their grip orientation. The changes in grasping points took place without substantially increasing the movement time.

GENERAL DISCUSSION

We examined whether fast responses to the rotation of an object that one is reaching to grasp are limited to automatic pursuit of the motion of the planned grasping points or whether the choice of grasping points is also reconsidered. The brief response to the motion of the ball in *experiment 1* and the reversal of the direction of the response in *experiment 2* indicate that although the fastest responses follow the motion of the initial grasping points, people also quickly reevaluate the circumstances and adjust their selection of grasping points.

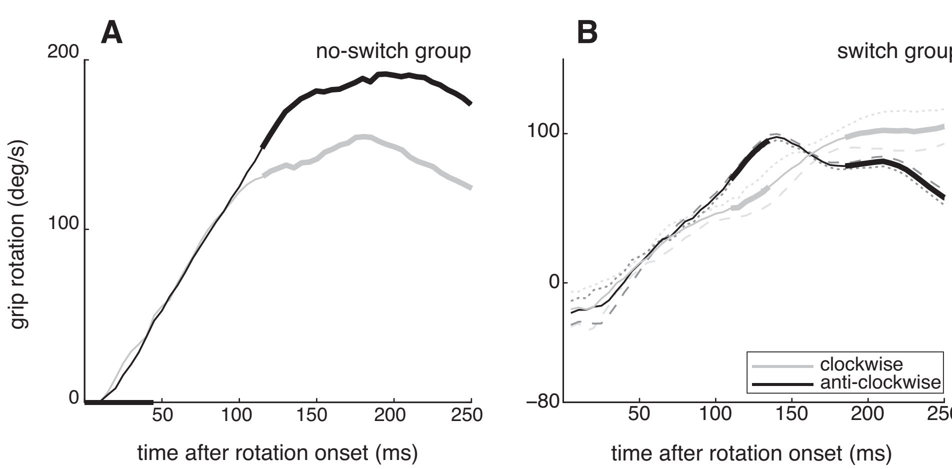

Fig. 5. Velocity at which the grip rotates for the clockwise and anticlockwise cube rotation conditions of the *no-switch group* (*A*) and the 20° initial cube orientation condition of the *switch group* (*B*) in *experiment 2*. Dashed and dotted lines at *right* show the average responses in the 1st and 2nd session, respectively. Details as in Fig. 3.

The initial response latencies that we found are similar to the 100- to 125-ms latencies of other tasks (Day and Lyon 2000; Oostwoud Wijdenes et al. 2010) and faster than the 150-ms latencies observed in tasks involving detection of changes in orientation (Brenner and Smeets 2009; van Mierlo et al. 2009). This is in line with the view that grasping arises from controlling the digits' movements towards positions, rather than controlling grip formation (Smeets and Brenner 2001, 1999). The reversal of the responses in *experiment 2* had a similar latency to that found in tasks involving the detection of changes in orientation. Note that these responses are still ~45 ms faster than the shortest reaction times to target motion (Smeets and Brenner 1994), which implies that if responses to perturbations have a shorter latency than the time it takes to initiate a movement because some aspects of the movement are not reconsidered, the selection of grasping points is not such an aspect.

We conclude that people can quickly alter their choice of grasping points during the grasping movement, probably mainly to grasp the object with a configuration of their arm and hand that is closer to their preferred configuration (Rosenbaum et al. 2001; Butz et al. 2007; Voudouris et al. 2012b). Such a reevaluation of the circumstances takes longer than responding directly (automatically) to visual motion (Aivar et al. 2008). That half the people often switched their grip for a rotation of the cube of only 12° suggests that postural preference is considered important and that switches do not come at a high cost. These findings suggest that even complex aspects of an action, such as selecting grasping points, are constantly evaluated during the on-going movement.

GRANTS

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

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: D.V., J.B.J.S., and E.B. conception and design of research; D.V. performed experiments; D.V. analyzed data; D.V., J.B.J.S., and E.B. interpreted results of experiments; D.V. prepared figures; D.V. drafted manuscript; D.V., J.B.J.S., and E.B. edited and revised manuscript; D.V., J.B.J.S., and E.B. approved final version of manuscript.

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