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RESEARCH ARTICLE

Why does an obstacle just below the digits' paths not influence a grasping movement while an obstacle to the side of their paths does?

Rebekka Verheij · Eli Brenner · Jeroen B. J. Smeets

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Abstract When we grasp objects in daily life, they are often surrounded by obstacles. To decrease the chance of colliding with an obstacle, people tend to move in a manner that does not bring body parts too near to the obstacle. However, in a previous study, when we compared moving above empty space and moving above an obstacle (a table), we did not find an effect of the obstacle on the height of the digit's paths despite the fact that the distance between the final positions of the digits and the obstacle was marginal. This lack of effect seems to be inconsistent with what we know about avoiding obstacles, because we would expect an increase in the height of the digits' paths when the obstacle is present. We consider four possible explanations for the lack of effect: that people changed movement speed rather than movement path, that the height component is not sensitive to obstacles that do not physically obstruct the movement, that obstacles below the starting position are not taken into account because the digits do not enter the space below the starting position, and that manipulable obstacles interfere with movement planning while a table does not. We found that from these four explanations only not taking obstacles placed below the starting position into account can be responsible for the lack of effect found in our previous study.

Keywords Prehension · Limb movements · Visuomotor behavior · Movement control

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Introduction

When we grasp objects in daily life, they are often surrounded by other objects. To successfully grasp the target object, we need to move our digits toward it without colliding with the surrounding non-target objects. In this study, we will refer to non-target objects as 'obstacles.'

To decrease the chance of colliding with an obstacle, one can move more slowly and remain further from the obstacle when passing it (Tresilian 1998). A decrease in maximum speed (Jackson et al. 1995), reflecting a slower movement, an increase in movement time (MT) (Mon-Williams and McIntosh 2000; Biegstraaten et al. 2003; Rice et al. 2006; Voudouris et al. 2012), reflecting a slower movement and/or an increase in path length, or both a decrease in maximum speed and an increase in MT (Tresilian 1998; Mon-Williams et al. 2001; Tresilian et al. 2005) are often observed.

When making two-dimensional movements with a pointer toward a target, it has been proposed that people keep a minimum preferred distance between the pointer and obstacles (Dean and Brüwer 1994). In line with this, Tresilian (1998) proposed that when grasping a target object, people move so as not to bring body parts within a minimum preferred distance from obstacles, and he suggested that this distance depends on factors related to the cost that a person attaches to a collision and movement speed. The larger the speed, the larger the minimum preferred distance.

Keeping a minimum preferred distance from obstacles can explain why the maximum grip aperture (MGA) decreases when an obstacle is placed to the side of a target object, and why this effect on MGA decreases when the distance between the target object and the obstacle increases (Jackson et al. 1995; Mon-Williams et al. 2001; Rice et al. 2006; Tresilian 1998; Tresilian et al. 2005; Chapman et al.

2011). Jackson et al. (1995) found that an obstacle placed such that the distance between the target object's surface and the obstacles' surface is as large as 7.5 cm still leads to a decrease in MGA. This was not due to a high movement speed, because subjects were instructed to make their movements as naturally as possible. In many studies that found an effect of obstacles on MGA, the distance between the target object's surface and the obstacles' surface was quite large. This distance was 3.5 cm in the study of Chapman et al. (2011), 4 cm in the study of Mon-Williams et al. (2001), 4.5 cm for the adults in the study of Tresilian et al. (2005), and 6.5 cm in the study of Tresilian (1998).

Given this effect of obstacles, we find the results of our previous study, in which we studied the effect of a table on grasping kinematics, very puzzling (Verheij et al. 2013). In that study, the shortest distance between a digit and the tabletop was only approximately 1 cm, and yet the table did not affect the digit's paths in the way that obstacles placed to the side of a target object do. In the two relevant conditions of the experiment in our previous study, the target was mounted on a vertically placed rod that was bent at the top so that the final part was horizontal. The distance between the starting position and the center of the target object was 29 cm. People were instructed to grasp the target object, lift it, and place it back on the rod. In one condition ('table'), a table was placed directly under the rod. The other condition ('all up') was exactly the same, except that there was no table present. In both conditions, the digit's paths were curved vertically (the digits moved higher than the line between their starting positions and the positions at which they end on the target object). If humans prefer to keep a certain distance between their body parts and any obstacle, we would expect them to lift their digits higher when there was a table. Surprisingly, they did not: The height of the digits' paths did not differ between the conditions 'table' and 'all up.' Why does a table not influence the height of the digits' paths although the body parts move so close to it?

That the table does not obstruct the digit's paths cannot explain this lack of effect, because others have shown that obstacles that do not obstruct body parts still have an effect on the digit's paths (Tresilian 1998; Mon-Williams et al. 2001; Tipper et al. 1997). A possible explanation for the lack of effect on the digits' height is that the minimum preferred distance from obstacles depends on movement speed (Tresilian 1998), so subjects may have moved their hand more slowly rather than higher in order to avoid colliding with the table. We did not analyze movement speed in our previous study.

We tested this first possible explanation by doing an additional analysis on the data measured in our previous study (Verheij et al. 2013). We averaged the speed of the thumb and index finger and calculated the maximum value, the relative time of the maximum value, and the mean value of this averaged speed for each trial of the relevant conditions in our previous experiment. Next, we calculated the mean of these values per variable, subject, and condition. A paired-samples t test was conducted on these mean values to test whether they were affected by the presence of a table. There was a significant difference in maximum speed between the condition with the table (838 $\pm$ 79 mm/s, mean $\pm$ standard deviation) and the condition without the table (813 $\pm$ 77 mm/s); $t(8) = 2.64$, $p = 0.03$. There was no significant difference in the relative time to maximum speed between the condition with the table (34.7 $\pm$ 2.7 %) and the condition without the table (35.3 $\pm$ 2.1 %); $t(8) = -1.08$, $p = 0.31$. There was also no significant difference in mean speed between the condition with the table (437 $\pm$ 43 mm/s) and the condition without the table (432 $\pm$ 45 mm/s); $t(8) = 0.62$, $p = 0.6$. The significant difference in maximum speed is in the opposite direction than expected on the basis of the table being an obstacle: The maximum speed was larger in the condition with the table than in the condition without the table. This together with the nonsignificant differences in relative time to maximum speed and mean speed demonstrates that the absence of a spatial effect in our previous study cannot be ascribed to changes in movement speed.

A second possible explanation for the lack of effect is that the height component might be insensitive to obstacles that do not physically obstruct the movement. There are studies that have found effects of obstacles on the height component (Saling et al. 1998; Alberts et al. 2002), but in those studies, the obstacle dimensions were such that the obstacle obstructed the paths taken in the absence of the obstacle. Since the grasping kinematics had to be altered to reach the target object, we cannot draw any conclusions from these studies regarding the sensitivity of the height component to obstacles that do not obstruct the paths taken in the absence of the obstacle. In many models, it is assumed that motor control is the same in all directions (for instance, our grasping model; Verheij et al. 2012). However, it is also known that vertical movements are curved differently than horizontal movements (Atkeson and Hollerbach 1985). This difference might be due to gravity, but the control might also be different. Obstacles being treated differently in the control of the vertical component than in the control of the horizontal component could explain the lack of effect of the table in our previous study.

A third explanation for the lack of effect of the table is that the digits did not enter the space below the starting position. Knowing this might have been implemented in the movement plan by not taking obstacles below the starting position into account. In the two relevant conditions of our previous experiment, the starting position was on top of a rod's end, so the constraints at the start made the digits move upward at the start of the movement, irrespective of the presence of a table (Verheij et al. 2013). Because of this upward motion, the digits approached the goal positions on the target object from above, so that at the end of the movement, the digits did not enter the space below the goal positions. Considering that the goal positions for the digits were always located above the starting position and the obstacle was always located below the starting position, taking the obstacle into account is not necessary to avoid colliding with it.

A fourth explanation for the lack of effect of the table is that the effect that is found for common obstacles (manipulable objects) might not be caused by keeping a preferred minimum distance from the obstacles' surfaces, but by interfering with movement planning (Tipper et al. 1997). Possibly, manipulable objects have an effect because they evoke competing responses, while the table has no effect because it is not a manipulable object and therefore does not evoke a competing response.

We chose to test these three explanations experimentally by placing an obstacle in between the starting position and the target object. Subjects moved their digits over the obstacle. We chose the obstacle dimensions such that, like the table in our previous study, the obstacle did not obstruct the digits' paths taken in the absence of the obstacle. We used two diameter sizes for the obstacle to simultaneously test whether the effect of an obstacle depends on its surface size.

We performed two new experiments. The aim of Experiment 1 and an associated control experiment was to test the second explanation, that the height component is insensitive to obstacles that do not physically obstruct the movement. The aim of Experiment 2 was to simultaneously test the third explanation, that obstacles below the starting position are not taken into account when it is unlikely that the digits will enter the space below the starting position, and the fourth explanation, that manipulable obstacles interfere with movement planning while a table does not.

Experiment 1

Methods

Subjects

Nine naive right-handed subjects took part in the experiment (7 females, 2 males) ranging in age from 25 to 42 years. The experiment was part of a program that was approved by the local ethics committee. Before participating, subjects signed an informed consent form.

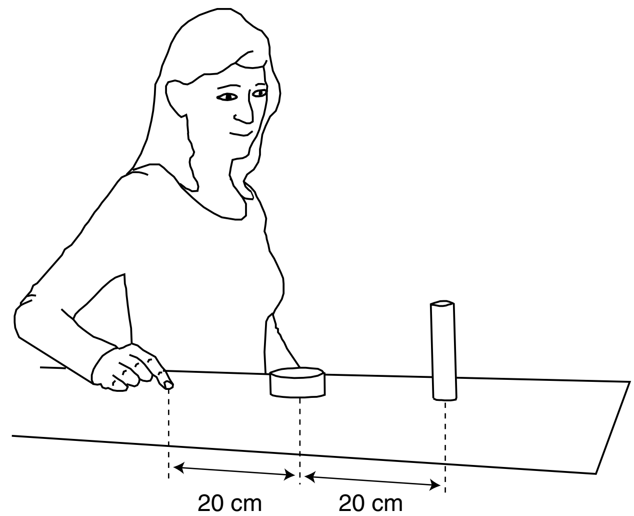

Fig. 1 Experimental setup (condition 'wide obstacle' of Experiment 1)

Apparatus

Subjects sat on a stool and placed their index finger and thumb on a start position located 20 cm to their right and 10 cm in front of the center of their trunk. They were presented with a target object (cylinder, diameter 3.0 cm, height 12.3 cm, made of polyoxymethylene), which was located 40 cm in front of the start position. In certain conditions, a low obstacle (cylinder, height 3.0 cm, made of polyoxymethylene) was presented 20 cm in front of the start position. Its diameter was either 5.0 cm (slender obstacle) or 7.7 cm (wide obstacle) (Fig. 1). We used two obstacle diameters to test whether the effect of an obstacle depends on the size of the obstacle's surface (Verheij et al. 2012). Movements were recorded at 100 Hz with an Optotrak 3020 motion recording system (Northern Digital, Waterloo, ON, Canada). Single infrared emitting diodes (IREDs) were attached to the subject at the nail of the thumb, at the nail of the index finger, and at the wrist (proc. styloideus ulnae). An additional marker was attached to the top surface of the target object.

Procedure

The experiment consisted of a simple grasping task performed at a natural movement speed with free vision. Subjects were instructed to grasp the target object using the thumb and index finger of their right hand, to lift it and put it back at the same location. Subjects were allowed to begin their grasping movement when they heard a verbal 'go' signal. Before movement onset, the index finger and thumb touched each other and the table at the starting position. There were three conditions, one condition in which no obstacle was present (apart from the table), one condition in which the slender obstacle was present, and one condition in which the wide obstacle was present. Each subject performed 20 trials in each condition. The trials of the different conditions were randomly interleaved.

Data analysis

We defined the start of the grasping movement as the moment at which the velocities of the tip of the thumb and of the tip of the index finger both exceeded 0.1 m/s. The end of the grasping movement was defined in three steps. First, we determined the interval from the start of the movement to the moment when the displacement of the target object exceeded 1 mm in the vertical direction. Next, we calculated the average of the velocities of the thumb and index finger for each sample during this interval. Finally, the moment at which this average velocity was minimal was considered to be the end of the grasping movement.

We rejected the trial if there were two or more consecutive missing samples between the start and end of the grasping movement for the thumb, index finger, or wrist, or if the end of the grasping movement was not found using the algorithm described above. This resulted in the rejection of 2 (out of 540) trials. Both trials were rejected because the end of the grasping movement was not found. Isolated missing marker samples were reconstructed using linear interpolation.

To evaluate whether the presence of an obstacle influences grasping kinematics, we calculated the maximum of the mean height of the two digits (maximum digit height), the relative time to maximum digit height, the relative path length at maximum digit height, the maximum height of the wrist marker (maximum wrist height), the MT, the MGA, and the maximum of the mean speed of the two digits (maximum speed) for each trial. We subsequently calculated the mean of each variable per subject and condition. For each variable, the effect of the obstacles was then tested using a one-way repeated measures analysis of variance (ANOVA). We defined zero height to be at the tabletop.

In order to get an overview of the movement trajectories of the digits and the wrist, we averaged over trajectories. Because the number of samples varied across trials, we resampled each trial such that each step corresponds to 1 % of the path length before averaging. We calculated the means of the resampled trajectories per subject, marker, and condition and averaged these mean trajectories across the subjects. To see whether the subjects veered around the obstacles by moving over them or by moving sideward, we constructed both a top view by plotting the average sagittal distance-component against the average lateral-component and a side view by plotting the average height component against the average sagittal distance-component.

Results and discussion

The top view of the average movement trajectories shows that there was hardly any difference in two-dimensional trajectory between the conditions (Fig. 2a). The side view of the average movement trajectories illustrates that the digits and the wrist all moved higher when there was an obstacle than when there was none (Fig. 2b). This indicates that the height component is sensitive to obstacles. There was indeed a significant effect of obstacle on maximum digit height [$F(2, 16) = 18.3$, $p < 0.001$] (Figs. 2b, 3a). Post hoc comparison showed that maximum digit height increased when the slender obstacle was present compared to when no obstacle was present ($p = 0.001$), and when the wide obstacle was present compared to when no obstacle was present ($p = 0.005$). There was no significant difference in maximum digit height between the two conditions with an obstacle ($p = 0.10$).

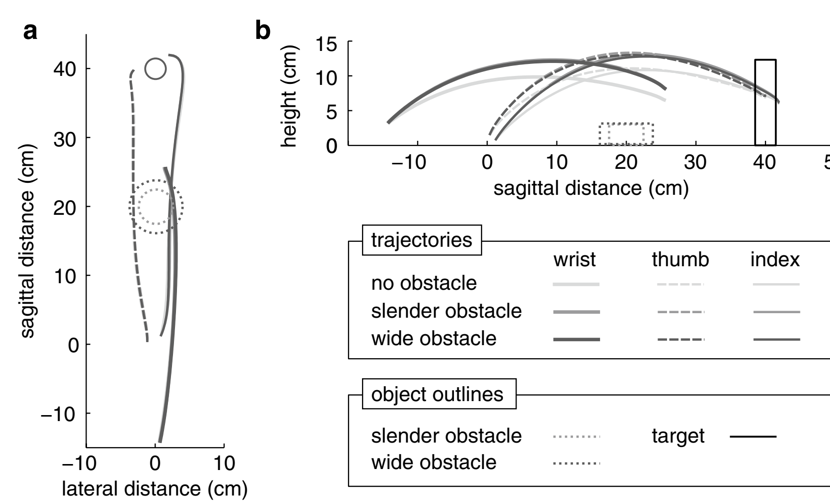

Fig. 2 Average trajectories of the wrist (proc. styloideus ulnae), the thumb, and the index finger per condition for Experiment 1. **a** *Top view.* The trajectories of the three conditions are so precisely superimposed that it is almost impossible to see that there are three sets of paths. **b** *Side view*. The trajectories of conditions 'slender obstacle' and 'wide obstacle' are so precisely superimposed that it is almost impossible to see that there are three sets of paths

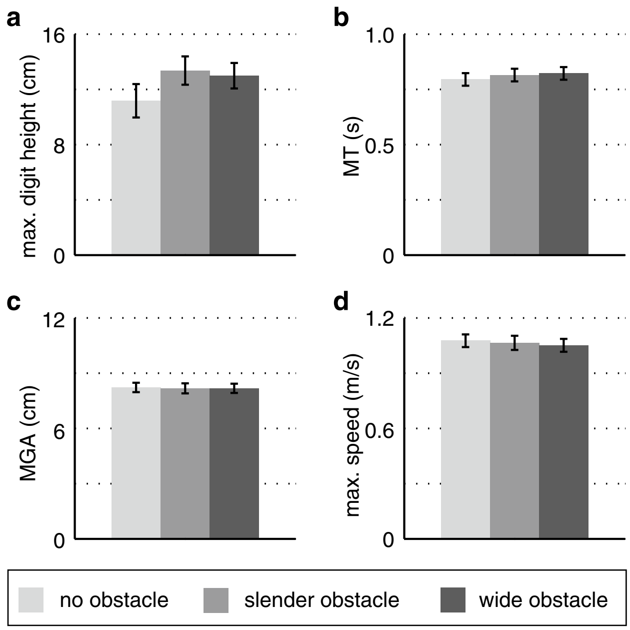

Fig. 3 Effects of obstacles on grasping kinematics in Experiment 1. Values are averages across subjects for each condition; *error bars* indicate the associated standard errors. **a** Maximum digit height. **b** Movement time. **c** Maximum grip aperture. **d** Maximum speed

There was also a significant effect of obstacle on maximum wrist height [$F(2, 16) = 48.2$, $p < 0.001$] (Fig. 2b). Post hoc comparison showed that maximum wrist height was larger when the slender obstacle was present (125 ± 20 mm) than when no obstacle was present (100 ± 25 mm) ($p < 0.001$), and when the wide obstacle was present (122 ± 19 mm) than when no obstacle was present ($p < 0.001$). There was no significant difference in maximum wrist height between the two conditions with an obstacle ($p = 0.10$).

There was a significant effect of obstacle on the relative time to maximum digit height [$F(2, 16) = 3.9$, $p = 0.04$], but post hoc comparison showed no significant differences between any of the three conditions (all $p > 0.06$). Averaged across subjects and conditions, the maximum digit height occurred at 43 % of the movement time. There was a significant effect of obstacle on the relative path length at maximum digit height [$F(2, 16) = 4.9$, $p = 0.02$]. Post hoc comparison showed that the relative path length was larger when no obstacle was present (58.4 ± 7.0 %) than when the wide obstacle was present (54.9 ± 3.9 %) ($p = 0.04$). There was no significant difference between the relative path length when the slender obstacle was present (55.4 ± 4.9 %) and the other two conditions (all $p > 0.06$).

There was a significant effect of obstacle on MT [$F(2, 16) = 8.5$, $p = 0.003$] (Fig. 3b). Post hoc comparison showed that MT increased when the slender obstacle was present compared to when no obstacle was present ($p = 0.02$), and when the wide obstacle was present compared to when no obstacle was present ($p = 0.01$). There was no significant difference in MT between the two conditions with an obstacle ($p = 0.17$). There was neither a significant effect of obstacle on MGA [$F(2, 16) = 0.9$, $p = 0.41$] (Figs. 2a, 3c) nor one on maximum speed [$F(2, 16) = 3.5$, $p = 0.06$] (Fig. 3d).

We can conclude from this experiment that the height component of grasping movements is not insensitive to obstacles that do not physically obstruct the movement (Fig. 2b). However, in this experiment, the wrist came closer to the obstacle than the tips of the thumb and index finger (Fig. 2b). Voudouris et al. (2012) found that an obstacle's hindrance of the elbow influenced the digit's paths. This might also hold for the wrist. The digits usually came closer to the obstacle than the wrist in the experiments that found an effect on the digits' paths when an obstacle was placed to the side of a target object (Jackson et al. 1995; Tresilian et al. 2005; Rice et al. 2006; Chapman et al. 2011). We therefore decided to make sure that the obstacle's influence on the digits' paths in our experiment was not merely the result of the obstacle's influence on the wrist. To do so, we designed a control experiment that was as similar as possible to Experiment 1 but in which the tips of the thumb and index finger would come closer to the obstacle than the wrist.

Methods control experiment

Five naive right-handed subjects took part in the experiment (4 females, 1 male) ranging in age from 25 to 30 years. None of them had participated in Experiment 1. The apparatus and procedure were identical to Experiment 1, with the one difference that the subject was standing instead of sitting. To insure that the digits would come closer to the obstacle than the wrist and that the target object was within reach, the height of the table was adjusted for each subject, such that when the subject stood upright with his arms hanging along his sides the tabletop was at the same height as the wrist. The data analysis was identical to Experiment 1. For 24 trials, there were two or more consecutive missing samples between the start and end of the grasping movement, and for 5 trials, the end of the grasping movement was not found, leading to the rejection of 29 (out of 300) trials.

Results and discussion on control experiment

The top view of the average movement trajectories shows that there was hardly any difference in two-dimensional trajectory between the conditions (Fig. 4a). The side view of the average movement trajectories shows that at the distance at which the obstacle was placed, the digits were lower than the wrist (Fig. 4b).

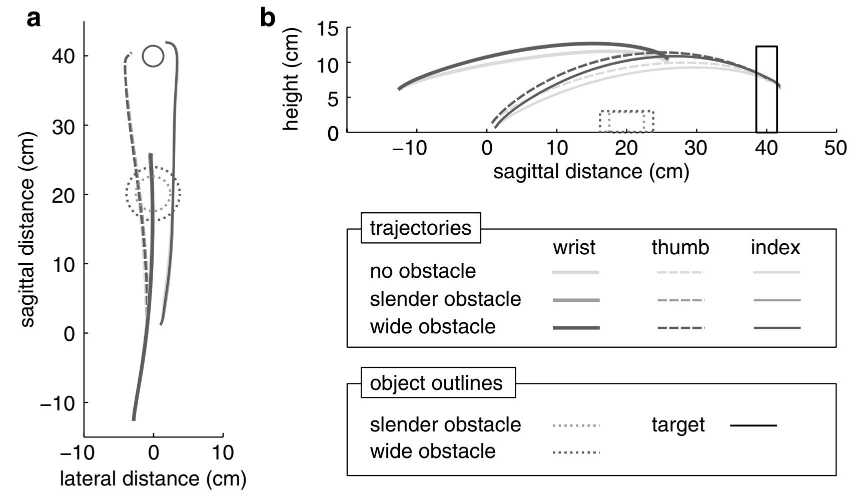

Fig. 4 Average trajectories of the wrist (proc. styloideus ulnae), the thumb, and the index finger per condition for the control experiment. **a** *Top view*. The trajectories of the three conditions are so precisely superimposed that it is almost impossible to see that there are three sets of paths. **b** *Side view*. The trajectories of conditions 'slender obstacle' and 'wide obstacle' are so precisely superimposed that it is almost impossible to see that there are three sets of paths

There was a significant effect of obstacle on maximum digit height [$F(2, 8) = 18.6$, $p = 0.001$] (Figs. 4b, 5a). Post hoc comparison showed that the maximum digit height was larger when the slender obstacle was present than when no obstacle was present ($p = 0.01$), and when the wide obstacle was present than when no obstacle was present ($p = 0.01$). There was no significant difference in maximum digit height between the two conditions with an obstacle ($p = 0.62$). There was also a significant effect of obstacle on maximum wrist height [$F(2, 8) = 22.7$, $p = 0.001$] (Fig. 4b). Post hoc comparison showed that maximum wrist height was larger when the slender obstacle was present (130 ± 18 mm) than when no obstacle was present (120 ± 16 mm) ($p = 0.007$), and when the wide obstacle was present (130 ± 18 mm) than when no obstacle was present ($p = 0.009$). There was no significant difference in maximum wrist height between the two conditions with an obstacle ($p = 0.46$).

There was a significant effect of obstacle on the relative time to maximum digit height [$F(2, 8) = 5.7$, $p = 0.03$], but post hoc comparison showed no significant differences between any of the three conditions (all $p > 0.05$). Averaged across subjects and conditions, the maximum digit height occurred at 48 % of the movement time. There was a significant effect of obstacle on the relative path length at maximum digit height [$F(2, 8) = 9.2$, $p = 0.009$]. Post hoc comparison showed that the relative path length was larger when no obstacle was present (70.2 ± 12.6 %) than when the slender obstacle was present (61.4 ± 7.0 %) ($p = 0.03$) and than when the wide obstacle was present (63.0 ± 9.6 %) ($p = 0.03$). There was no significant difference between the two conditions with an obstacle ($p = 0.3$). There was no significant effect of obstacle on MT [$F(2, 8) = 1.3$, $p = 0.33$] (Fig. 5b), MGA [$F(2, 8) = 0.2$, $p = 0.84$] (Figs. 4a, 5c), or maximum speed [$F(2, 8) = 1.4$, $p = 0.30$] (Fig. 5d).

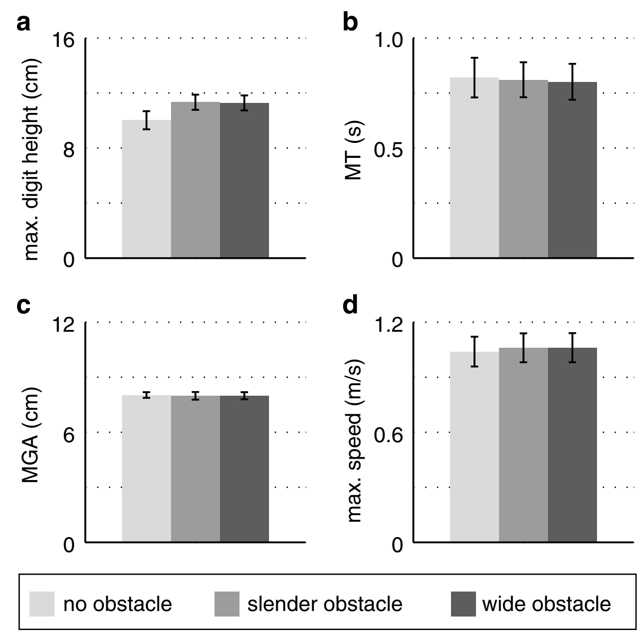

Fig. 5 Effects of obstacles on grasping kinematics in the control experiment. Values are averages across subjects for each condition. *Error bars* indicate standard errors. **a** Maximum digit height. **b** Movement time. **c** Maximum grip aperture. **d** Maximum speed

The tips of the thumb and index finger came closer to the obstacle than the wrist in the control experiment, as opposed to Experiment 1. The obstacle's effect on the digits' trajectories was nevertheless similar to that in Experiment 1, which indicates that the obstacle's influence on the digits' paths in Experiment 1 was not merely the result of the obstacle's influence on the wrist. The results of the control experiment confirm the finding of Experiment 1 that insensitivity of the height component to obstacles that do not physically obstruct the movement cannot explain the lack of effect of a table on the height of the digits' paths found in our previous study.

Experiment 2

In our attempt to explain why the presence of a table did not influence the height of the digits' paths in our previous study (Verheij et al. 2013), we have now eliminated the suggestion that people change their movement speed rather than their movement path (through an additional analysis of the data of our previous study) as well as the suggestion that the height component of grasping movements is insensitive to obstacles that do not physically obstruct the movement (Experiment 1 and the associated control experiment). Two possible explanations remain to be tested: That obstacles below the starting position (including the table) are not taken into account when it is unlikely that the digits will enter the space below the starting position, and that manipulable obstacles interfere with movement planning while a table does not. We evaluate these two possible explanations in this experiment.

Methods

Nine naive right-handed subjects took part in the experiment (5 females, 4 males) ranging in age from 25 to 43 years. Three of these subjects had participated in Experiment 1 and one had participated in the control experiment. The apparatus and procedure were similar to Experiment 1, but only the wide obstacle was sometimes placed between the starting position and the target object. The slender obstacle was now sometimes used as a platform on top of which the starting position was located.

There were four conditions (Fig. 6). The conditions 'no obstacle' and 'obstacle' were identical to conditions that were used in Experiment 1 and the control experiment, although the 'obstacle' condition was called 'wide obstacle' in those experiments. In the other two conditions, the starting position was located on the platform. In one condition, there was no obstacle present (apart from the table; 'platform'). In the other condition, the obstacle was present ('platform obstacle'). Each subject performed 20 trials of each condition. The trials of the different conditions were randomly interleaved.

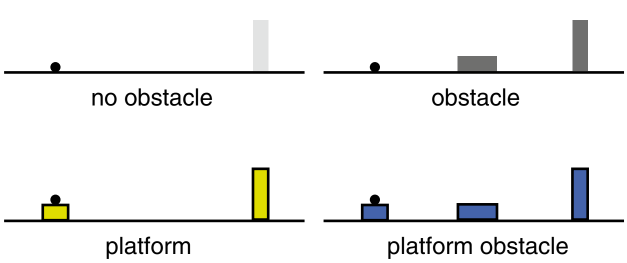

Fig. 6 The four conditions of Experiment 2. A *black dot* indicates the starting position

For 12 trials, there were two or more consecutive missing samples between the start and end of the grasping movement, and for 12 trials, the end of the grasping movement was not found, leading to the rejection of 24 (out of 720) trials. For each variable (maximum digit height, relative time to maximum digit height, relative path length at maximum digit height, maximum wrist height, MT, MGA, and maximum speed), the effects of the obstacle and starting on a platform were tested using a two-way repeated measures analysis of variance (ANOVA). We also evaluated the obstacle's influence on maximum digit height, relative time to maximum digit height, relative path length at maximum digit height, and maximum wrist height within conditions with the same height of the starting position using paired-samples t tests. Height was always measured from the table, even when starting on the platform.

Results and discussion

The top view of the average movement trajectories shows that there was hardly any difference in two-dimensional trajectory between the conditions (Fig. 7a). The side view of the average movement trajectories illustrates that if the starting position was located on the table, the digits and the wrist all moved clearly higher when there was an obstacle than when there was none, whereas if the starting position was located on the platform, they did not (Fig. 7b). There was a highly significant effect of obstacle [$F(1, 8) = 87.5$, $p < 0.001$] and of platform [$F(1, 8) = 60.6$, $p < 0.001$] on maximum digit height (Figs. 7b, 8a), and a highly significant interaction effect between obstacle and platform [$F(1, 8) = 31.7$, $p < 0.001$]. Maximum digit height was significantly larger in condition 'obstacle' compared to condition 'no obstacle' [$t(8) = 8.9$, $p < 0.001$], and there was no significant difference in maximum digit height between the conditions 'platform' and 'platform obstacle' [$t(8) = 1.7$, $p = 0.13$]. There was also a highly significant effect of obstacle [$F(1, 8) = 107.5$, $p < 0.001$] and of platform [$F(1, 8) = 78.9$, $p < 0.001$], and a highly significant interaction effect between obstacle and platform [$F(1, 8) = 75.5$, $p < 0.001$], on maximum wrist height (Fig. 7b). Maximum wrist height was significantly larger in condition 'obstacle' (117 ± 13 mm) than in condition 'no obstacle' (95 ± 15 mm) [$t(8) = 10.8$, $p < 0.001$] and in condition 'platform obstacle' (124 ± 15 mm) than in condition 'platform' (121 ± 17 mm) [$t(8) = -2.8$, $p = 0.02$].

There was a highly significant effect of obstacle [$F(1, 8) = 25.9$, $p < 0.001$] on the relative time to maximum digit height, and a significant interaction effect between obstacle and platform [$F(1, 8) = 9.5$, $p = 0.02$]. There was no significant effect of platform on the relative time to maximum digit height [$F(1, 8) = 3.5$, $p = 0.1$]. The relative time to maximum digit height was significantly larger in condition

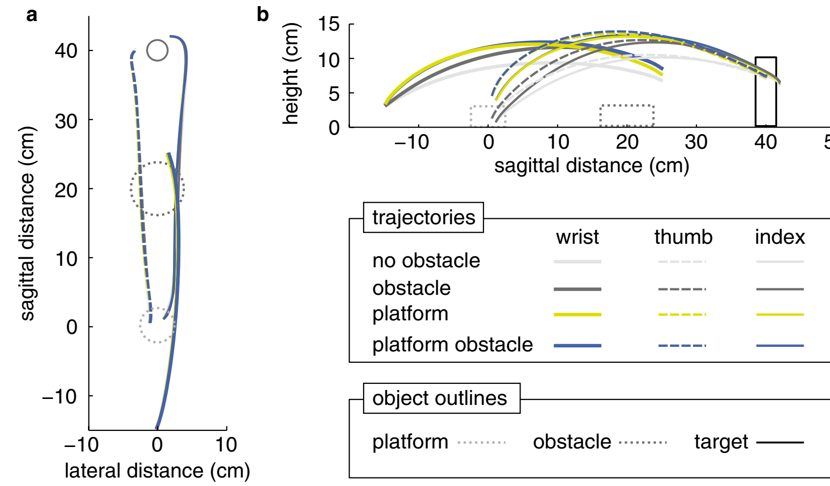

Fig. 7 Average trajectories of the wrist (proc. styloideus ulnae), the thumb, and the index finger per condition for Experiment 2. **a** *Top view*. **b** *Side view*

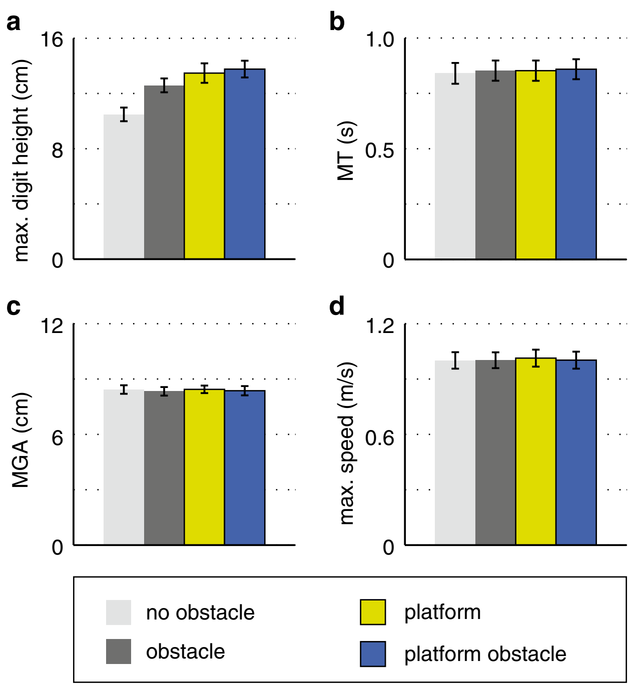

Fig. 8 Effects of an obstacle and starting on a platform on grasping kinematics in Experiment 2. Values are averages across subjects for each condition. *Error bars* indicate standard errors. **a** Maximum digit height. **b** Movement time. **c** Maximum grip aperture. **d** Maximum speed

'no obstacle' (45.3 ± 3.9 %) than in condition 'obstacle' (43.2 ± 2.7 %) [$t(8) = 3.5$, $p = 0.009$], and there was no significant difference in the relative time to maximum digit height between the conditions 'platform' and 'platform obstacle' [$t(8) = -2.1$, $p = 0.07$].

There was a significant effect of obstacle [$F(1, 8) = 30.3$, $p < 0.001$] and of platform [$F(1, 8) = 6.0$, $p = 0.04$], and a significant interaction effect between obstacle and platform [$F(1, 8) = 9.0$, $p = 0.02$], on the relative path length at maximum digit height. The relative path length at maximum digit height was significantly larger in condition 'no obstacle' (59.6 ± 5.9 %) than in condition 'obstacle' (56.1 ± 3.3 %) [$t(8) = 3.5$, $p = 0.008$]. There was no significant difference in relative path length between the conditions 'platform' and 'platform obstacle' [$t(8) = -2.0$, $p = 0.08$]. There was no significant effect of obstacle, platform, or interaction effect between obstacle and platform on MT, MGA, or maximum speed (all $p > 0.05$) (Figs. 7a, 8b–d).

The finding that the obstacle affected the kinematics of the digits' paths when starting from the table, but not when starting from the platform, supports the third explanation, that obstacles below the starting position are not taken into account when it is unlikely that the digits will enter the space below the starting position. Since the visual layout was similar in the 'platform obstacle' and the 'obstacle' conditions, and we found highly significant interaction effects between obstacle and platform on the kinematics of the digits' paths, we reject the fourth explanation, that manipulable obstacles interfere with movement planning while a table does not.

General discussion

In this study, we aimed to find out why in our previous study (Verheij et al. 2013) a table did not influence the height of the digits' paths during grasping movements, although the digits moved close to the table. This lack of effect is remarkable because one of the leading theories on obstacle avoidance states that people keep a preferred distance between the digits and an obstacle (Tresilian 1998), and various experimental studies in which an obstacle was placed to the side of a target object show that the presence of an obstacle leads to changes in the digits' paths. We tested four possible explanations for the lack of effect: that people changed movement speed rather than movement path, that the height component is insensitive to obstacles that do not physically obstruct the movement, that obstacles below the starting position are not taken into account when it is unlikely that the digits will enter the space below the starting position, and that manipulable objects interfere with movement planning while a table does not.

An additional analysis on the experimental data of our previous study allowed us to reject the first explanation; that the lack of effect might be related to a lower movement speed in the condition with the table than in the condition without the table. We found a significant difference in maximum speed, but in the opposite direction: The maximum speed was larger in the condition with the table than in the condition without the table.

In Experiments 1 and the associated control experiment, we sometimes placed a low obstacle between the starting position and the target object. In Experiment 1, subjects were sitting, and in the control experiment, subjects were standing. The maximum height of the digits and the maximum wrist height increased significantly when there was an obstacle present. In addition, the relative path length at maximum digit height decreased when the wide obstacle was present. These findings demonstrate that the height component is sensitive to obstacles that do not physically obstruct the movement. We can therefore also reject the second explanation.

In Experiment 2, we evaluated the remaining two explanations for the lack of effect of a table on the height of the digits: The third explanation that obstacles below the starting position are not taken into account when it is unlikely that the digits will enter the space below the starting position, and the fourth explanation that only manipulable objects interfere with movement planning because they do so by evoking competing responses (Tipper et al. 1997). Experiment 2 was similar to Experiment 1, except that the obstacle was always the same size, and in two conditions the movement started from a platform. The height of the platform was such that the starting position was at the same height as the top surface of the obstacle. In support of the third explanation, we found no effect of the obstacle on kinematic parameters of the digits when the movement started from the same height as the top surface of the obstacle. The absence of these effects of the manipulable obstacle when starting only 3 cm higher shows that it is the vertical distance from the starting position rather than whether the object is manipulable that is critical in influencing the vertical curvature of the digits' paths. When one considers that the table surface was 1 cm below the starting position in our previous study (Verheij et al. 2013), only considering obstacles above the starting position would explain the lack of effect of the table on the height of the digits in that study.

Our results are in line with the findings of Menger et al. (2012), who found that even if one keeps the visual layout of the workspace more or less constant, the effect of an obstacle depends on starting posture. Our results provide additional evidence for their conclusion that obstacles act as physical obstructions to movement, showing that this also holds when the changes in starting posture are marginal (Fig. 7).

One could argue that the lack of effect in our previous study can also be explained by people attaching a higher cost to colliding with obstacles placed to the side of a target object than to a table placed underneath the target object. One reason for doing so might be that obstacles placed at the side are fragile and the table is not (Tresilian 1998). However, most studies we referred to in the introduction to demonstrate that an obstacle placed at the side of the target object decreases the MGA used obstacles made of the non-fragile material wood (Jackson et al. 1995; Chapman et al. 2011; Mon-Williams et al. 2001; Tresilian et al. 2005; Tresilian 1998). Another reason for attaching a higher cost to colliding with obstacles placed to the side might be that there is a higher cost to hitting an obstacle if it can be knocked over, and such obstacles could be knocked over, whereas the table could not. However, Mon-Williams et al. (2001) placed 2.5 cm diameter cylindrical obstacles to the side of a target object and found no difference between the decrease in MGA for obstacle heights of 10 cm (easy to knock over) and 5 cm (more difficult to knock over). Moreover, the obstacles that Chapman et al. (2011) placed to the side of their target object could not be knocked over, because they were controlled by the experimenter via handles, and they too led to a decrease in MGA. Yet, another reason for attaching a higher cost to colliding with obstacles placed to the side of a target object than to a table placed underneath the target object might be that people tend to avoid collision with an object's edges, because they might be sharp. However, this is in conflict with our finding in Experiment 2 that an obstacle with clear edges hardly influences the digit's paths when its top surface is at the same height as the starting position. We see no other reason why colliding with obstacles placed to the side of a target object should have a higher cost than colliding with the table underneath the target object. Therefore, we think that the lack of effect in our previous study is not caused by the difference in the cost people attach to a collision.

In Experiment 1, we found a significant increase in MT when an obstacle was present. This is probably due to an increase in path length because we found no change in maximum speed. In the control experiment and Experiment 2, we did not find an effect of the obstacle on maximum speed either. In all three experiments, the strategy of avoiding obstacles by moving around them is apparently preferred over the strategy of moving slower.

In all experiments, we found a significant effect of obstacle on maximum digit height, but not on MGA. Increasing the height in these experiments is an effective way to increase the distance between the digits and the obstacle and thus to avoid colliding with the obstacle. In contrast, altering the MGA is not an effective way to increase the distance between the digits and the obstacle in these experiments. Therefore, the effect on maximum digit height but not on MGA indicates that changes in grasping kinematics to avoid obstacles are specifically tuned to the geometry of the task.

We found that the effect of an obstacle on maximum digit height does not depend on the size of the top surface of the obstacle. This is inconsistent with one of the assumptions implemented in the grasping model of Verheij et al. (2012). The information acquired from our experiments could be used to revise this incorrect assumption related to obstacle avoidance in order to improve the model.

In sum, we found that changes in grasping kinematics to avoid obstacles are specifically tuned to the geometry of the task. When the starting position is as high as the top surface of an obstacle, and the local constraints at the start make the digit's paths curve upward, the obstacle does not affect the maximum height of the digits. This can explain why a table does not influence the height of the digit's paths when both the starting position and the target object are located on it.

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References

Alberts JL, Saling M, Stelmach GE (2002) Alterations in transport path differentially affect temporal and spatial movement parameters. Exp Brain Res 143:417–425. doi:10.1007/s00221-002-1005-0

Atkeson CG, Hollerbach JM (1985) Kinematic features of unrestrained vertical arm movements. J Neurosci 5:2318–2330

Biegstraaten M, Smeets JBJ, Brenner E (2003) The influence of obstacles on the speed of grasping. Exp Brain Res 149:530–534. doi:10.1007/s00221-003-1374-z

Chapman CS, Gallivan JP, Culham JC, Goodale MA (2011) Mental blocks: fMRI reveals top-down modulation of early visual cortex when obstacles interfere with grasp planning. Neuropsychologia 49(7):1703–1717. doi:10.1016/j.neuropsychologia.2011.02.048

Dean J, Brüwer M (1994) Control of human arm movements in two dimensions: paths and joint control in avoiding simple linear obstacles. Exp Brain Res 97:497–514

Jackson SR, Jackson GM, Rosicky J (1995) Are non-relevant objects represented in working memory? The effect of non-target objects on reach and grasp kinematics. Exp Brain Res 102(3):519–530

Menger R, Van der Stigchel S, Dijkerman HC (2012) How obstructing is an obstacle? The influence of starting posture on obstacle avoidance. Acta Psychol 141:1–8. doi:10.1016/j.actpsy.2012.06.006

Mon-Williams M, McIntosh RD (2000) A test between two hypotheses and a possible third way for the control of prehension. Exp Brain Res 134(2):268–273. doi:10.1007/s002210000479

Mon-Williams M, Tresilian JR, Coppard VL, Carson RG (2001) The effect of obstacle position on reach-to-grasp movements. Exp Brain Res 137(3–4):497–501. doi:10.1007/s002210100684

Rice NJ, McIntosh RD, Schindler I, Mon-Williams M, Démonet JF, Milner AD (2006) Intact automatic avoidance of obstacles in patients with visual form agnosia. Exp Brain Res 174(1):176–188. doi:10.1007/s00221-006-0435-5

Saling M, Alberts J, Stelmach GE, Bloedel JR (1998) Reach-to-grasp movements during obstacle avoidance. Exp Brain Res 118(2):251–258

Tipper SP, Howard LA, Jackson SR (1997) Selective reaching to grasp: evidence for distractor interference effects. Vis Cogn 4(1):1–38. doi:10.1080/713756749

Tresilian JR (1998) Attention in action or obstruction of movement? A kinematic analysis of avoidance behavior in prehension. Exp Brain Res 120(3):352–368

Tresilian JR, Mon-Williams M, Coppard VL, Carson RG (2005) Developmental changes in the response to obstacles during prehension. J Motor Behav 37(2):103–110

Verheij R, Brenner E, Smeets JBJ (2012) Grasping kinematics from the perspective of the individual digits: a modelling study. PLoS ONE 7(3):e33150. doi:10.1371/journal.pone.0033150

Verheij R, Brenner E, Smeets JBJ (2013) Why are the digits' paths curved vertically in human grasping movements? Exp Brain Res 224(1):59–68. doi:10.1007/s00221-012-3288-0

Voudouris D, Smeets JBJ, Brenner E (2012) Do obstacles affect the selection of grasping points? Hum Mov Sci 31(5):1090–1102. doi:10.1016/j.humov.2012.01.005