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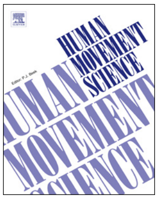

# The target as an obstacle: Grasping an object at different heights

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ABSTRACT

Humans use a stereotypical movement pattern to grasp a target object. What is the cause of this stereotypical pattern? One of the possible factors is that the target object is considered an obstacle at positions other than the envisioned goal positions for the digits: while each digit aims for a goal position on the target object, they avoid other positions on the target object even if these positions do not obstruct the movement. According to this hypothesis, the maximum grip aperture will be higher if the risk of colliding with the target object is larger. Based on this hypothesis, we made a set of two unique predictions for grasping a vertically oriented cuboid at its sides at different heights. For cuboids of the same height, the maximum grip aperture will be smaller when grasped higher. For cuboids whose height varies with grip height, the maximum grip aperture will be larger when grasped higher. Both predicted relations were experimentally confirmed. This result supports the idea that considering the target object as an obstacle at positions other than the envisioned goal positions for the digits is underlying the stereotypical movement patterns in grasping. The goal positions of the digits thus influence the maximum grip aperture even if the distance between the goal positions on the target object does not change.

## 1. Introduction

When humans reach to grasp a target object, their hand opens wider than the size of the target object (Jeannerod, 1981). For grasping with a precision grip, the maximum distance between the tip of the thumb and the tip of the index finger over the course of the movement is a well-studied parameter: the ‘maximum grip aperture’ (MGA). It scales with the final distance between the digits on the to be grasped object but is influenced by other aspects as well. The MGA is for instance affected by the location of nearby obstacles (Chapman, Gallivan, Culham, & Goodale, 2011; Jackson, Jackson, & Rosicky, 1995; Mon-Williams, Tresilian, Coppard, & Carson, 2001; Rice et al., 2006; Tresilian, 1998; Tresilian, Mon-Williams, Coppard, & Carson, 2005; Voudouris, Smeets, & Brenner, 2012), target object orientation (Cicerale, Ambron, Lingnau, & Rumiati, 2014; Paulun, Gegenfurtner, Goodale, & Fleming, 2016) and target object shape (Borchers, Verheij, Smeets, & Himmelbach, 2014; Cuijpers, Smeets, & Brenner, 2004; Eloka & Franz, 2011; Hu, Eagleson, & Goodale, 1999; Verheij, Brenner, & Smeets, 2014; Zaal & Bootsma, 1993). Several of the latter authors proposed that the effect of object shape can be explained in terms of the target object being considered an obstacle at positions other than the goal positions for the digits.

A first mention of an obstacle-like explanation of shape effects can be found in the work of Cuijpers et al. (2004). They studied grasping of elliptical cylinders with various sizes and aspect ratio’s, and found that when participants grasped elliptical cylinders with various aspect ratios, MGA depended not only on the length of the object at the axis on which it is grasped. They found larger MGAs when grasping along the minor axis, and proposed that this was the result of the protruding parts of the orthogonal major axis acting

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as obstacles.

More recently, Borchers et al. (2014) let participants grasp cuboids along the target object's width and varied the height and depth of the target object independently of its width (the direction of the grasp axis). They found an effect of target object height but not of target object depth on the MGA. They partly explained their findings using the grasping model of Verheij, Brenner, and Smeets (2012) which considers the target object as an obstacle at positions other than the envisioned goal positions for the digits. The risk of hitting the front surface of the target object (which increases with the height of the target object) with a digit is larger than the risk of hitting the side surface (which increases with the depth and height of the target object) and therefore there was no effect of depth on MGA while there was an effect of height. However, they also provided an alternative explanation, namely that humans perceive tall objects as having more volume than shorter objects of exactly the same volume (Raghubir & Krishna, 1999; Wansink & Van Ittersum, 2003), and that MGA might scale with volume.

The alternative explanation for the above-mentioned dependence of MGA on object shape (based on a systematically misperceived volume) was later proven to be unlikely by Verheij et al. (2014). They used five differently shaped target objects with the same maximal width, height, and depth. Verheij et al. (2014) showed that the effect of target object shape on MGA could better be explained by considering the target object as an obstacle at positions other than the envisioned goal positions for the digits, than by the desired precision of the digits' final positions (Smeets & Brenner, 1999), perceived width of the target object (Franz, 2001; Franz, Fahle, Bülthoff, & Gegenfurtner, 2001; Franz, Gegenfurtner, Bülthoff, & Fahle, 2000) or the perceived volume of the target object (Borchers et al., 2014).

Another movement parameter that is influenced by obstacles is the movement time (MT): obstacles in general lead to a longer MT (Biegstraaten, Smeets, & Brenner, 2003; Mon-Williams et al., 2001). Presumably, moving slower reduces the risk of collisions because slow movements can be more precise (Bootsma, Marteniuk, MacKenzie, & Zaal, 1994). For grasping movements, the expected effects of obstacle avoidance on MT are in the same direction as those on MGA.

In this paper, we put the hypothesis of considering the target object as an obstacle at positions other than the goal positions for the digits to a further test in two experiments. If humans indeed have the objective for each digit to avoid collisions between the digit and positions on the target object other than the envisioned goal position, not only characteristics of the target object but also the digit's goal position on the target object is expected to influence MGA. If the digits are placed such that the risk of colliding with the target object at other positions than the goal positions is larger, while the distance between the goal positions is the same, a larger MGA is expected. When grasping a tall target object, parts of the object that the digits pass are more collision-prone than parts of the object beyond the digits' final positions. When grasping a target object from a table, humans usually move their hand initially upwards and then downwards (Verheij, Brenner, & Smeets, 2013), so the digits pass the surface area above the digits' contact positions. Therefore, the collision-prone area of the target object's surface will decrease when grasping the target at a higher position, and a decrease in MGA is expected.

We will test the effect of the collision-prone area by varying the height of the digits' goal positions when grasping a tall cuboid in Experiment 1. To determine whether an effect of the digits' goal positions on MGA in Experiment 1 is indeed caused by a change in collision risk and not merely by an inevitable change of the movement trajectories as a result of changing the digits' goal positions we conducted a control experiment (Experiment 2) in which the change in the digits' goal positions was exactly the same as in Experiment 1, but now designed to let the collision risk increase with grasping height. We achieved this by letting participants grasp cuboids of varying height near the top. Because the part of the cuboid above the digits' final positions acting as an obstacle is absent, the collision-prone area does not depend on cuboid height, but there is more target object surface area to be avoided (below the goal positions) for higher target objects, so the overall collision risk should increase with grasping height. In sum, we predict a decrease in MGA with the height of the digits' goal positions in Experiment 1 due to a smaller collision-prone area and an increase in MGA with the height of the digits' goal positions in Experiment 2 due to a larger surface area that has to be avoided. As one can also deal with increasing risks by slowing down the movement, we predict a similar pattern of results for MT: it will decrease with increasing grasping height in Experiment 1, but increase with grasping height in Experiment 2.

## 2. Methods

### 2.1. Participants

12 naive right-handed participants (7 females, 5 males) took part in both experiments, ranging in age from 24 to 39 years in Experiment 1 and from 25 to 39 years in Experiment 2. Two Participants participated in both experiments. The study was part of a program that was approved by the local ethics committee. Participants signed an informed consent form before participating.

### 2.2. Experimental setup and procedure

Participants sat on a chair without armrests. Approximately 20 cm to the right of the right side of their trunk and approximately 10 cm in front of their trunk a starting location was marked on a table (Fig. 1). At the start of each trial, their hand rested on the table with their index finger and thumb touching each other at the starting location. A cuboid was placed 40 cm in front of the starting location and was oriented such that an imaginary line from the starting location to the cuboid's position would be perpendicular to the cuboid's front surface. Thus the starting location and the cuboid were both located to the right of the participants' body midline.

The cuboid consisted of up to five equally sized two-by-two Duplo bricks (the construction toy produced by the LEGO Group) stacked on top of each other, resulting in a cuboid height of up to 96.0 mm (without studs, 100.8 mm with studs) and a width and

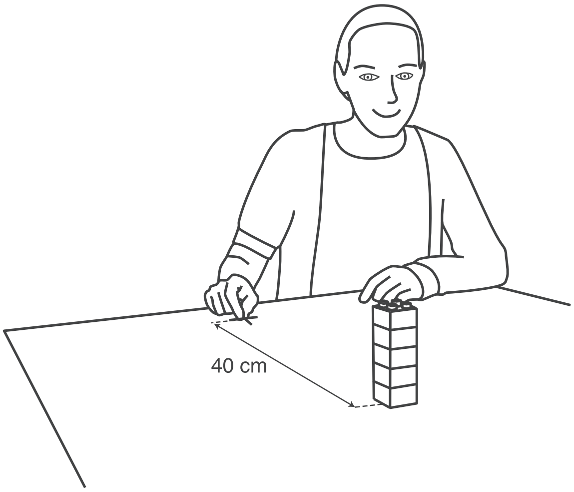

**Fig. 1.** Experimental setup. A person has her index finger and thumb touching each other at the starting location (indicated with a cross). The cuboid shown is five bricks (96 mm) high; this cuboid was used in all conditions of Experiment 1 and condition 5 of Experiment 2.

depth of 31.8 mm. Each Duplo brick had a different color (red, yellow, dark green, light green and blue). The order of the colors was always the same for a participant but differed randomly across participants.

Movements were recorded at 200 Hz with an Optotrak 3020 motion recording system (Northern Digital, Waterloo, ON, Canada). Single infrared emitting diodes (IREDs) were attached to the participant's right wrist (ulnar styloid process), and the distal corners of the nails of the thumb and index finger such that the diode on the thumb was on the right side of the nail and the diode on the index finger was on the left side of the nail seen from the participant.

Participants were instructed to reach and grasp the cuboid at a natural movement speed using the thumb and index finger of their right hand, in such a way that their digits ended on the left and right side of a specific Duplo brick, to lift the cuboid, and then put it back on the table and move their hand to the starting location. Before each trial, the experimenter placed the cuboid and mentioned the color of the Duplo brick at which the digits should end on the cuboid. This indirectly indicated the height at which the cuboid should be grasped, which we will refer to as 'instructed height'. After a verbal 'go' signal participants were allowed to begin their grasping movement.

There were five conditions in both experiments (Fig. 2). For condition 1 the height of the center of the to be grasped Duplo brick was 0.96 cm (the lowest Duplo brick). For condition 2, 3, 4 and 5 these heights were 2.88 cm, 4.80 cm, 6.72 cm and 8.64 cm respectively. In Experiment 1, the cuboid always consisted of five bricks, whereas in Experiment 2, we only used bricks up to the instructed height. Each participant performed 10 trials per condition. The in total 50 trials were presented in a random order.

### *2.3. Data analysis*

The start of each grasping movement was defined as the moment at which both the marker placed on the thumb and the marker placed on the index finger had a velocity greater than 0.1 m/s. The end of each grasping movement was defined using the Multiple Sources of Information method (Schot, Brenner, & Smeets, 2010). We used the following hard criteria: the markers on the index finger and thumb should both be within 30 mm of the cuboid's center in the main movement direction and less than the number of the condition times 20 and plus 10 mm above the table, the aperture is smaller than 60 mm and decreasing, the second derivative of aperture is positive. Within these constraints, we preferred an endpoint for which the MT is short (the objective function was 1 for the start of the movement and decreased linearly to 0.8 for the last sample) and the mean of the velocities of the markers on the index finger and thumb is low (the objective function was 1 for zero velocity and decreased linearly to 0 for the maximum velocity).

If the end of a grasping movement was not found or if there were more than four consecutive missing samples between the start and end of the grasping movement for the thumb or the index finger we rejected the trial. This resulted for Experiment 1 in the

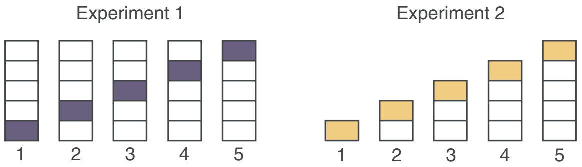

**Fig. 2.** Schematic view of the cuboids used in the 5 conditions of the two experiments. The Duplo brick the participants were instructed to grasp is indicated in the figure with a dark blue color for Experiment 1 and a light yellow color for Experiment 2. The numbers are the numbers of the conditions.

rejection of 9.8% of the trials (Appendix, Table A.1) (8.2% because of missing samples, 1.7% because the end of the movement was not correctly found). For Experiment 2, 13.8% of the trials were rejected (Appendix, Table A.2) (11.5% because of missing samples, 2.3% because the end of the movement was not correctly found). Missing samples were reconstructed using linear interpolation.

Our predictions are based on the assumption that the digits approached the target object in a downward movement. To be able to evaluate whether this is indeed the case for all grasping heights, we determined the mean height of the two digits as a function of horizontal displacement. Because the number of samples differed between trials we resampled each trial such that each step corresponds to 1% of the path length before averaging. We averaged over trials and participants, and plotted the resulting trajectories for each condition.

To examine the effect of grasping height on MGA, the mean of the heights of the marker placed on the index finger and the marker placed on the thumb at the end of the grasping movement (grasping height) and the maximum distance between these markers during the grasping movement (MGA) was calculated per trial. We fitted a linear line through the MGAs as a function of grasping height for each participant as a firstorder approximation of the effect of grasping height on MGA, using least squares linear regression (by the Matlab-function regress). A resulting positive slope corresponds to a larger MGA for a higher grasping position. We performed a 2-tailed one sample T-test on the slopes to test if the slopes differed significantly from zero (no effect of grasping height on MGA). We performed an independent samples T-test to test whether the slopes differed between Experiments 1 and 2. Although the datasets were not completely independent (two of the twelve participants participated in both experiments), this test is appropriate because it requires a larger effect for a significant difference than a test that would take the partial dependence into account. To examine the effect of grasping height on MT, the time between the start and end of the grasping movement was calculated for each trial. Next, MT was analyzed in the same way as MGA.

For visualization purposes the mean MGA, grasping height, and MT was calculated per condition for each participant and outcomes were averaged across participants. Next, the mean MGAs and MTs were plotted as a function of mean grasping height.

## 3. Results

For both experiments and for each condition the digits approached the target object in a downward movement as expected (Fig. 3). The peak height of the trajectory scales with the grasping height, as one would anticipate. In Experiment 1, the hand moves along a less curved path (lower peak) than in Experiment 2, leading to a less downward approach. According to our hypothesis that the part of the object above grasping height is more prone to collisions, this change of trajectory can be regarded as obstacle avoidance. On average, the target object was not grasped in the middle, but closer to the starting location (indicated with a cross in Fig. 1). Grasping an object off-center is more often observed (Paulun, Kleinholdermann, Gegenfurtner, Smeets, & Brenner, 2014).

As we predicted, both the MGA and MT decrease with increasing grasping height in Experiment 1 (Fig. 4). For Experiment 2, the MGA increases with grasping height as predicted, but MT seems invariant. For both experiments, the effects are small relative to the overall variability between participants (the 95% confidence intervals for all grasping heights are overlapping). As we are not interested in the difference in MT and MGA between participants, but only in how they varied with grasping height, we determined the slopes of the relations for each participant (Fig. 5), and used these for statistical testing our predictions. As we will show in the next paragraphs, these tests corroborate the pattern that is visible in Fig. 4.

For Experiment 1 the slope of the line fitted through the MGA's as a function of grasping height was negative for most participants (Fig. 5a). Negative values mean that MGA decreases with an increase in grasping height. The mean value of the slope was $-0.04 \pm 0.05$ (values are presented ± across-subject SD). The values of the slope differed significantly from zero $t(11) = -2.596$, $p = 0.025$. For Experiment 2 the slope was positive for all participants (Fig. 5b), indicating that MGA increases with an increase in grasping height. The mean value of the slope was $0.03 \pm 0.02$ and differed significantly from zero $t(11) = 5.832$, $p < 0.001$. The slopes also differed significantly between the two experiments $t(22) = -4.526$, $p < 0.001$ (Fig. 5c).

For Experiment 1 the slope of the line fitted through the MT's as a function of grasping height was negative for most participants (Fig. 5d). The mean value of the slope was $-7 \pm 5$ ms/cm, which was significantly different from zero $t(11) = -5.286$, $p < 0.001$. For Experiment 2 the slope of the line fitted through the MT's as a function of grasping height was positive but close to zero for most participants (Fig. 5e). The mean slope ($-0.04 \pm 6$ ms/cm) was not significantly different from zero $t(11) = -0.026$, $p = 0.98$. The slopes differed significantly between the two experiments $t(22) = -3.357$, $p = 0.003$ (Fig. 5f).

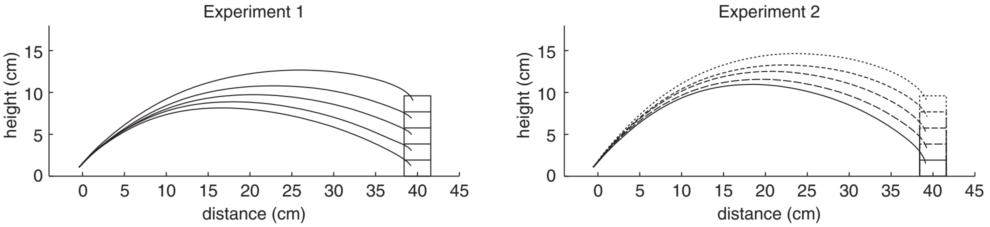

**Fig. 3.** Side view of the average trajectory of the thumb and index finger, averaged over participants for each condition. The dashed lines of the target object in the right figure indicate that the target object's height differed between conditions in Experiment 2.

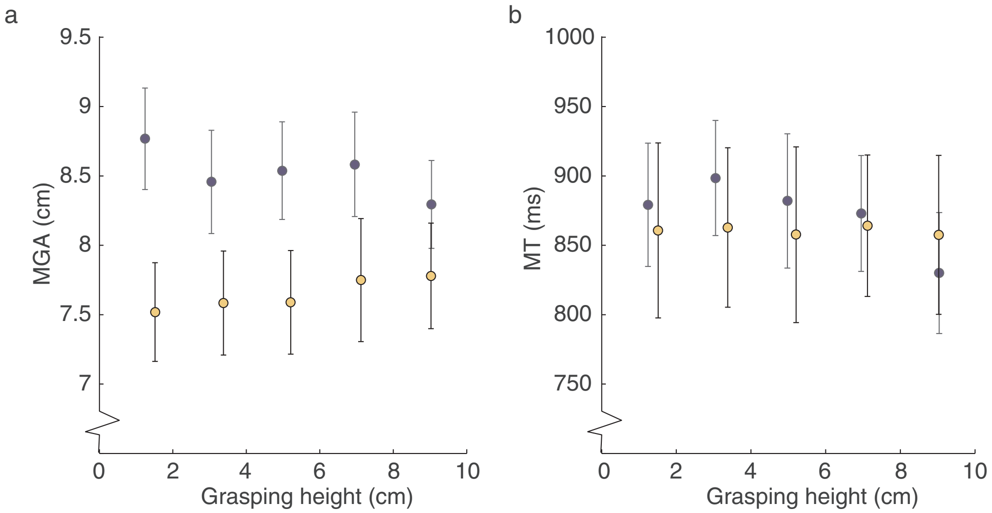

**Fig. 4.** a. The relation between the maximum grip apertures and grasping height for Experiment 1 (dark blue disks) and Experiment 2 (light yellow disks). b. Movement Times. The disks represent averages across participants and the error bars represent 95% confidence intervals. Both horizontal and vertical error bars are plotted, but only vertical error bars are visible because the horizontal error bars are smaller than the size of the disks.

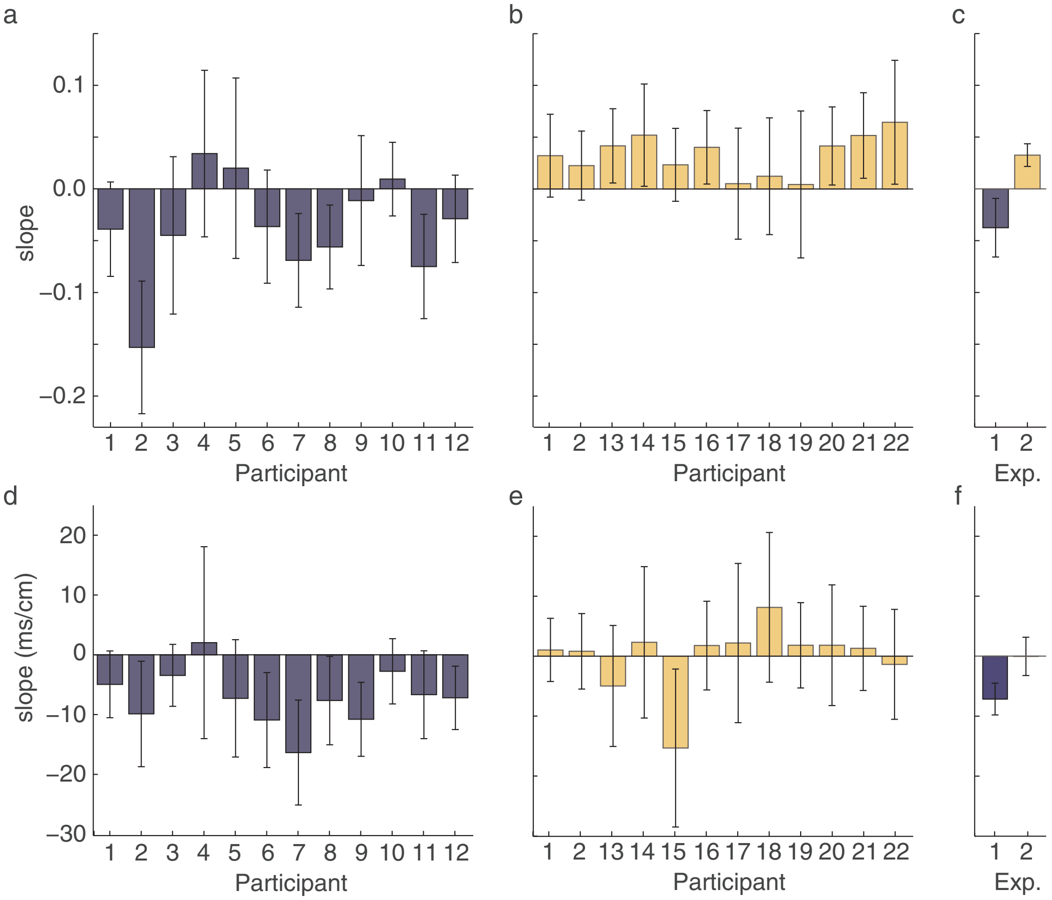

**Fig. 5.** Slopes of the fitted line through the MGAs as function of grasping height for each participant of Experiment 1 (a) and Experiment 2 (b) and slopes of the fitted line through the MTs as function of grasping height for each participant for Experiment 1 (d) and Experiment 2 (e), using least squares linear regression. Note that participants 1 and 2 participated in both experiments. Panel c shows the mean slope through the MGAs and panel f shows the mean slope through the MTs for Experiment 1 (dark blue) and Experiment 2 (light yellow). The error bars indicate the 95% confidence intervals of the slopes (panels a, b, d, e) and means (panels c, d).

## 4. Discussion and conclusion

The aim of this study was to further examine whether considering the target object as an obstacle, at positions other than the goal positions for the digits, is a factor that underlies the stereotypical movement patterns in grasping. If the target object is indeed considered as an obstacle at positions other than the envisioned goal positions for the digits not only changing the target objects size or shape would affect the MGA, but also the location of the goal positions of the digits on the target object. In this study, we put this to a test, by performing an experiment (Experiment 1) in which we varied the height of the goal positions on the target object and thereby the collision-prone area of the target object and thus the risk of a collision between the digits and the target object. Next, we performed a control experiment (Experiment 2) to determine whether the effect of the height of the goal positions in Experiment 1 was indeed the effect of collision risk or the mere effect of an inevitable change in digits' trajectories because of the change in goal positions. In this control experiment, the digits' goal positions were identical to the positions in Experiment 1 but the collision-prone area did not change. Instead, the total surface area of the target object was varied, leading to opposite predictions based on collision risk compared to Experiment 1.

In Experiment 1 we used a cuboid consisting of 5 Duplo bricks stacked on top of each other as a target object. Participants grasped the cuboid at different heights. In line with the predictions based on a smaller collision-prone area for higher grasping heights, the experimental data showed a decrease in MGA and MT with increasing grasping height. In the control experiment (Experiment 2) the target object was a cuboid consisting of Duplo bricks and grasping height was varied, as in Experiment 1, but the Duplo brick(s) above the to be grasped brick were removed. For this experiment, the collision-prone area did not vary between conditions. Nevertheless, the objective to avoid collisions with the target object at positions other than the digits' goal positions predicts an effect of grasping height: MGA and MT will increase with grasping height because there is more target object surface area to be avoided. Experimentally we indeed found an increase of MGA with grasping height for Experiment 2, but we did not find an effect of grasping height on MT. This might be because the increase in MGA was already sufficient to avoid collisions with the target object, or due to the change in trajectory we observed (Fig. 3).

There were a lot of missing trials for some participants. To test whether these participants might have influenced the conclusions, we repeated the analysis while excluding the participants for whom more than half of the trials were missing in one or more conditions (participant 4 in Experiment 1 and participants 17 and 22 in Experiment 2). For Experiment 1 the mean value of the slope of the line fitted through the MGA's as a function of grasping height with participant 4 excluded is still negative ($-0.04 \pm 0.05$) and significantly different from zero ($t(10) = -3.116$, $p = 0.011$). For Experiment 2 the mean value of the slope is still positive ($0.03 \pm 0.02$) and significantly different from zero ($t(9) = 6.289$, $p < 0.001$). For Experiment 1 the mean slope of the line fitted through the MTs as a function of grasping height was still negative ($-8 \pm 4$ ms/cm) and significantly different from zero ($t(10) = -6.845$, $p < 0.001$). For Experiment 2 the mean slope was still not significantly different from zero ($t(9) = -0.068$, $p = 0.95$). The conclusion is thus robust.

One could argue that the increase of MGA with grasping height in Experiment 2 was not caused by the larger surface area that had to be avoided but by the larger mass of the higher target objects (Eastough & Edwards, 2007). Although the effect of object mass on MGA is not undisputed (Weir, MacKenzie, Marteniuk, Cargoe, and Frazer (1991) did not find an effect of target object mass on MGA), we can estimate what part of the results might be explained. Eastough and Edwards found an increase in MGA of 3.1 mm for an increase in mass of at least 335 g. Since the mass of a Duplo brick is just 6.5 g this would explain an increase in MGA of 0.24 mm between conditions 1 and 5 of Experiment 2, only 9% of the 2.6 mm increase we found. It is thus not very likely that object mass is the main cause of the increase in MGA with grasping height in Experiment 2.

One could also argue that the decrease in MGA with grasping height in Experiment 1 and the increase in MGA with grasping height in experiment 2 might both be due to differences in stability. Grasping an object high and thus above its center of mass leads to a more stable grasp (Experiment 1) and higher target objects are less stable (Experiment 2). However, there is no clear relationship between MGA and stability. For instance, Verheij et al. (2014) compared grasping a cube and a sphere with the same maximum width, depth, and height. Although a sphere is less stable than a cube, they found that a sphere is grasped with a smaller MGA than a cube. This finding is in line with our target-as-obstacle explanation.

Based on our results, we want to emphasize the importance of including both the digits' goal positions and the target object shape, or the associated collision risk, in a grasping model if the model is used for predicting the MGA. The final digits positions combined with the target object shape, leading to an effect of collision risk on the MGA, are included in the grasping model of Verheij et al. (2012) but are not included in various other models of grasping (Friedman & Flash, 2009; Hoff & Arbib, 1993; Molina-Vilaplana & Lopez-Coronado, 2007; Rand, Shimansky, Hossain, & Stelmach, 2008; Simmons & Demiris, 2006; Ulloa & Bullock, 2003). In the model of Rosenbaum et al. (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 1999, 2001) preventing collisions with the target object at positions other than the goal positions is included, be it not in terms of collision risk but by evaluating various postures and selecting a posture that does not lead to a collision. In the model of Smeets and Brenner (1999) collision risk can easily be implemented by setting the 'approach parameter', the single parameter of their model that sets how accurate a movement has to be. A larger collision risk can be set by choosing a higher value for the approach parameter.

In sum, we tested predictions based on the proposal that in human grasping, the objective for each digit is to avoid collisions with the target object at positions other than the envisioned goal position. We found that the results followed the predictions of this proposal, which increases the credibility that this objective underlies the typical movement patterns observed in human grasping. This stresses the importance of the influence of the digits' goal positions on the MGA, even if the distance between the goal positions does not vary.

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## Appendix

**Table A.1**
The number of rejected trials per participant and condition for Experiment 1.

| Participant | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition 1 | 1 | 1 | 2 | 9 | 1 | 2 | 1 | – | – | 1 | – | 1 |
| Condition 2 | – | – | 2 | 6 | – | 1 | 2 | – | – | – | – | – |
| Condition 3 | – | – | 1 | 2 | – | – | 3 | – | – | – | – | 1 |
| Condition 4 | – | 1 | 5 | 1 | 1 | – | 2 | – | – | – | – | – |
| Condition 5 | – | 1 | 4 | 6 | – | – | 1 | – | – | – | – | – |

**Table A.2**
The number of rejected trials per participant and condition for Experiment 2.

| Participant | 1 | 2 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition 1 | – | 1 | 5 | 3 | 1 | – | 4 | 2 | – | 5 | – | 6 |
| Condition 2 | – | – | 1 | 5 | – | – | 3 | – | – | 5 | – | 2 |
| Condition 3 | – | – | 1 | – | – | – | 3 | – | – | 3 | – | 2 |
| Condition 4 | – | – | 1 | 1 | 3 | – | 6 | – | 1 | 4 | – | 4 |
| Condition 5 | – | – | 2 | – | – | – | 3 | – | – | 2 | – | 4 |

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.humov.2018.08.005.

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