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# The Influence of Object Height on Maximum Grip Aperture in Empirical and Modeled Data

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During a grasping movement, the maximum grip aperture (MGA) is almost linearly scaled to the dimension of the target along which it is grasped. There is still a surprising uncertainty concerning the influence of the other target dimensions on the MGA. We asked healthy participants to grasp cuboids always along the object's width with their thumb and index finger. Independent from variations of object width, we systematically varied height and depth of these target objects. We found that taller objects were generally grasped with a larger MGA. At the same time, the slope of the regression of MGA on object width decreased with increasing target height. In contrast, we found no effect of varying target depth on the MGA. Simulating these movements with a grasping model in which the objective to avoid contact of the digits with the target object at positions other than the goal positions was implemented yielded larger effects of target height than of target depth on MGA. We concluded that MGA does not only depend on the dimension of the target object along which it is grasped. Furthermore, the effects of the other 2 dimensions are considerably different. This pattern of results can partially be explained by the aim to avoid contacting the target object at positions other than the goal positions.

*Keywords:* visuomotor behavior, grasping, object dimensions, grip aperture



The maximum grip aperture (MGA) is a well-known indicator for the anticipated size of graspable objects in motor control (Jeannerod, 1986; Paulignan, Frak, Toni, & Jeannerod, 1997; Smeets & Brenner, 1999). The dimension of the object along which it is grasped, which we will refer to as the width of the object, influences the maximal opening of the grip. The MGA correlates linearly with the width, resulting in a slope of about 0.8 (Smeets & Brenner, 1999). This correlation of MGA with the width was successfully modeled by Verheij, Brenner, and Smeets (2012). In their model, multiple objectives were taken into account for each digit. One of the objectives that influence the MGA is to move to the preselected goal positions on the target object without hitting other parts of the target. If this objective is in accordance with the way humans control their grasping movements, we would expect that apart from the width of an object, other dimensions (i.e., depth and height) influence the MGA as well. In this study, we refer to the horizontal extent perpendicular to the width as the object's depth, and the third (vertical) dimension as height (Figure 1). We adhere to this nomenclature throughout this article and, if necessary, translate the dimension labels used in other studies for the sake of readability.

The influence of dimensions other than the width has already been investigated in several studies. Round objects were reported to be grasped with a smaller MGA than oblate ones, though the width was the same (Zaal & Bootsma, 1993). Bootsma, Marteniuk, MacKenzie, and Zaal (1994) varied the width and the size of the contact surfaces (depth and height) of rectangular blocks. Bootsma et al. (1994) found the expected dependency of the MGA on width, but also found depth and height to have strong influences. Unfortunately, they did not vary depth and height independently from each other. Thus, it remained unclear whether their effects were due to changes in depth or height or both. This issue was clarified later by Hu, Eagleson, and Goodale (1999) who, in contrast with Bootsma et al. (1994), varied depth and height independently. Hu et al. (1999) found no effect of depth, but did find a significant impact of the object's height. This was interpreted as a collision-avoidance strategy. Hu et al. (1999) presumed that the participants had to clear the top of the objects for a successful grasp because of

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*Figure 1.* Setup. Subjects sat at a table. Objects were always presented with their center at the same position, only the dimensions (width, depth, or height) of the objects varied. Vision was controlled with shutter glasses.

the orientation and position of the object relative to the main movement direction and starting point of the movement.

Later, Ganel and Goodale (2003) investigated again whether the depth of an object affects grip scaling. They did not vary the height of the objects. In line with the findings of Hu et al. (1999), they found no effect of depth on MGA during grasping. In contrast, perceptual estimates of the objects' width were influenced by the depth (Ganel & Goodale, 2003). They concluded that, in contrast to perception, ". . . the visual mechanisms mediating action are able to process the most relevant dimension while at the same time ignoring changes in the other, irrelevant, dimensions" (p. 667).

The current study addressed two questions. (a) Would we still see an effect of an object's height if the fingers of our participants would not have to clear the top of the objects to reach their goal positions? (b) Does a model that explains grasping in terms of moving the digits smoothly to their goal position on the object without hitting other surfaces (Verheij et al., 2012) show the same general pattern of MGA changes as the empirical measurements in response to changes in the objects' depth and height? To address these questions, we presented subjects with rectangular target blocks and systematically varied the targets' depth, height, and width. Extending the design of Hu et al. (1999), we not only examined the impact of each spatial dimension on its own, but also examined interactions of changes in depth and height with the width.

## Method

### Participants

Ten healthy participants (seven women) ranging in age from 22 to 38 years were tested. Stereoscopic vision was assessed by the screening plates of the Dutch Organization for Applied Scientific Research (TNO) test for stereoscopic vision (Laméris Ootech B.V., Nieuwegein, the Netherlands) and shown to be normal in all subjects. All participants passed at least the first plate of the TNO test and the median depth level that subjects could discriminate was 90 degrees. All participants had normal or corrected-to-normal visual acuity and were right-handed according to the Edinburgh Handedness Inventory (EHI: $M$ = 92, range: 70–100; Oldfield, 1971). The experiments were conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013) and all participants gave their written informed consent prior to testing.

### Procedure

Participants sat at a table with a white surface. A start button was fixed at the table, 300 mm to the right of the subjects' midline and 40 mm from the edge of the table. At the beginning of each trial, subjects pressed the start button with the index finger of the right hand. The tips of the index finger and thumb were touching before movement onset. A target block was placed in front of the start button, such that the distance between the start button and the center of the target block was 400 mm. Liquid crystal shutter glasses (PLATO, Translucent Technologies, Toronto, ON, Canada) were used to control vision of the target block. Each trial started when the liquid crystal glasses turned from opaque to clear. Each participant was instructed to grasp the target block at natural speed using only the thumb and index finger of the right hand. The target block was oriented in such a way that none of the digits had to move over the target to reach the side to be grasped (Figure 1).

Targets with width, depth, and height of 20 mm, 40 mm, and 60 mm were used. We labeled each target with a letter and number, with the letter (A, B, or C) indicating the width and the number, the combination of depth and height (Table 1). Because we conducted individual analyses of the effects of target height and target depth but did not aim for a comparison between the influence of these two dimensions, we selected subsets with a constant value of either target height or target depth from the full number of 27 possible combinations of object dimensions. Thus, subsets of nine objects were included in each analysis, resulting in a complete set of 15 wooden target blocks (Table 1). Each target block was presented 10 times in a randomized sequence with free vision for 3 s. Within this time each grasping movement was finished, that is, the object was grasped successfully.

## Kinematic Data Acquisition and Analysis

Seven infrared light-reflecting markers were attached to the right hand of the participant, at each side of the wrist, half way up the os metacarpale secundum, on the second proximal phalanx and to the distal phalanxes of the thumb, index finger, and middle finger (Figure 1). The 3D positions of the markers were recorded with a sampling rate of 200 Hz (Vicon Motion Systems, Oxford, UK). Data were analyzed offline using custom software based on Matlab 7.5 (Mathworks Inc., Sherborn, MA). Raw data were smoothed with an averaging window of 10 data points.

Movement onset was determined from the tangential speed of one of the wrist markers using a threshold of 50 mm/s. Movement offset was determined from the acceleration profile of the same wrist marker, using the second zero crossing as the endpoint of the trajectory, which, in the majority of trials, co-occurred with object touch of thumb and index finger (determined by a constant grip aperture for at least 20 samples directly following the second zero crossing). In less than 9% of the trials per participant, this time point was followed by another deceleration phase before the object was actually touched. In these cases we adopted the next zero crossing that preceded object touch. Less than 2.5% of the trials per participant were discarded due to at least five consecutive missing data points or invalid grasping movements (e.g., when the object fell down while grasping it). Altogether, for each participant seven to 10 ($M$ = 9.8) trials per object per condition were analyzed.

We calculated the mean MGA (maximal distance between the index finger and thumb marker) and its standard deviation for each object dimension. We conducted a regression analysis of MGA on the object width and compared the slope of the regression line and the correlation between a set of objects varying either in height or depth to assess the sensitivity and variability of the MGA to size changes across object dimensions. In addition, we calculated the number of peaks of the grip aperture (i.e., local maxima of grip aperture identified by zero crossings of the aperture velocity), the latency of the MGA, the peak wrist velocity, the number of peaks of the wrist velocity, the latency of the peak wrist velocity, and movement time.

To verify that target width by itself influenced the participants' grasping as reported in literature, we performed 3 (object width) $\times$ 5 (different combinations of object height and depth) ANOVAs for MGA and movement time. To test whether target height affects MGA we compared mean MGA values between blocks with the same width and depth but different heights (e.g., blocks A2, A4, and A5, Table 1). To test whether target height has an effect on the slope of the relation between target width and MGA, we compared the slopes across blocks with a small height (blocks A4, B4, C4), blocks with a medium height (blocks A2, B2, C2) and blocks with a large height (blocks A5, B5, and C5) (Table 1). Likewise, to test whether target depth affects MGA we compared the MGA between blocks with the same width and height but different depths (e.g., blocks A1, A2, and A3, Table 1). To examine the effect of target depth on the slope of the relation between target width and MGA, we compared the slopes across blocks with a small depth (blocks A1, B1, C1), blocks with a medium depth (blocks A2, B2, C2) and blocks with a large depth (blocks A3, B3, C3) (Table 1).

We performed two ANOVAs on the slopes and correlation coefficients, one with target block height and one with target block depth as within subject factor. To provide a detailed description of the observed behavior we in addition conducted multiple 3 (object height/depth) $\times$ 3 (object width) ANOVAs to assess whether any other measured variable (number of peaks of the grip aperture, latency of the MGA, peak wrist velocity, number of peaks of the

Table 1
*Target Dimensions*

| Target label | Width (mm) | Depth (mm) | Height (mm) | Included in depth analysis | Included in height analysis |
|---|---|---|---|---|---|
| A1 | 20 | 20 | 40 | x | |
| B1 | 40 | 20 | 40 | x | |
| C1 | 60 | 20 | 40 | x | |
| A2 | 20 | 40 | 40 | x | x |
| B2 | 40 | 40 | 40 | x | x |
| C2 | 60 | 40 | 40 | x | x |
| A3 | 20 | 60 | 40 | x | |
| B3 | 40 | 60 | 40 | x | |
| C3 | 60 | 60 | 40 | x | |
| A4 | 20 | 40 | 20 | | x |
| B4 | 40 | 40 | 20 | | x |
| C4 | 60 | 40 | 20 | | x |
| A5 | 20 | 40 | 60 | | x |
| B5 | 40 | 40 | 60 | | x |
| C5 | 60 | 40 | 60 | | x |

wrist velocity, latency of the peak wrist velocity and movement time) revealed effects of target height or depth.

To enquire the movement approach toward the target blocks, we compared the height of the fingers at object touch as well as the positions of the fingers and the wrist at the time point of the MGA between the target blocks. We conducted 3 (object height/depth) × 3 (object width) ANOVAs to assess whether the difference between index and thumb height or the difference between index and wrist height revealed effects of target height and depth at the time point of the MGA or at the time point of object touch.

## Model Simulations

We simulated our experiment with the model of Verheij et al. (2012). We used the same set of parameter values as in the paper in which the model was introduced, with the one difference that the parameter $R_t$ (mainly influencing the vertical component of the movement by setting how strongly the table surface repels the digits) was decreased to $1 \cdot 10^{-2}$ $m^2s^{-1}$. This decrease is justified by the experimental finding that the major part of the table surface had no effect on grasping height (Verheij, Brenner, & Smeets, 2013), whereas in the model, the whole table surface was taken into account to compute grasping height. A lower value for $R_t$ was necessary to be able to reach the target positions naturally because the target positions in our experiment were much closer to the table than in the experiment that was used to choose the model parameters. If we would have used the original value of $R_t$, the digits would approach the final aperture above or at the top of the target object, after which they slide down the target's surface to reach the goal positions. However, if the target positions are reached naturally, the exact value of $R_t$ is not relevant for our study because it barely influences the MGA, as was reported in the sensitivity analysis of the paper in which the model was introduced (Verheij et al., 2012). The value of $1 \cdot 10^{-2}$ $m^2s^{-1}$ was therefore a rather arbitrary choice. For each target block the goal positions of the digits were chosen based on the experimentally observed final positions averaged across subjects in the measurements reported in

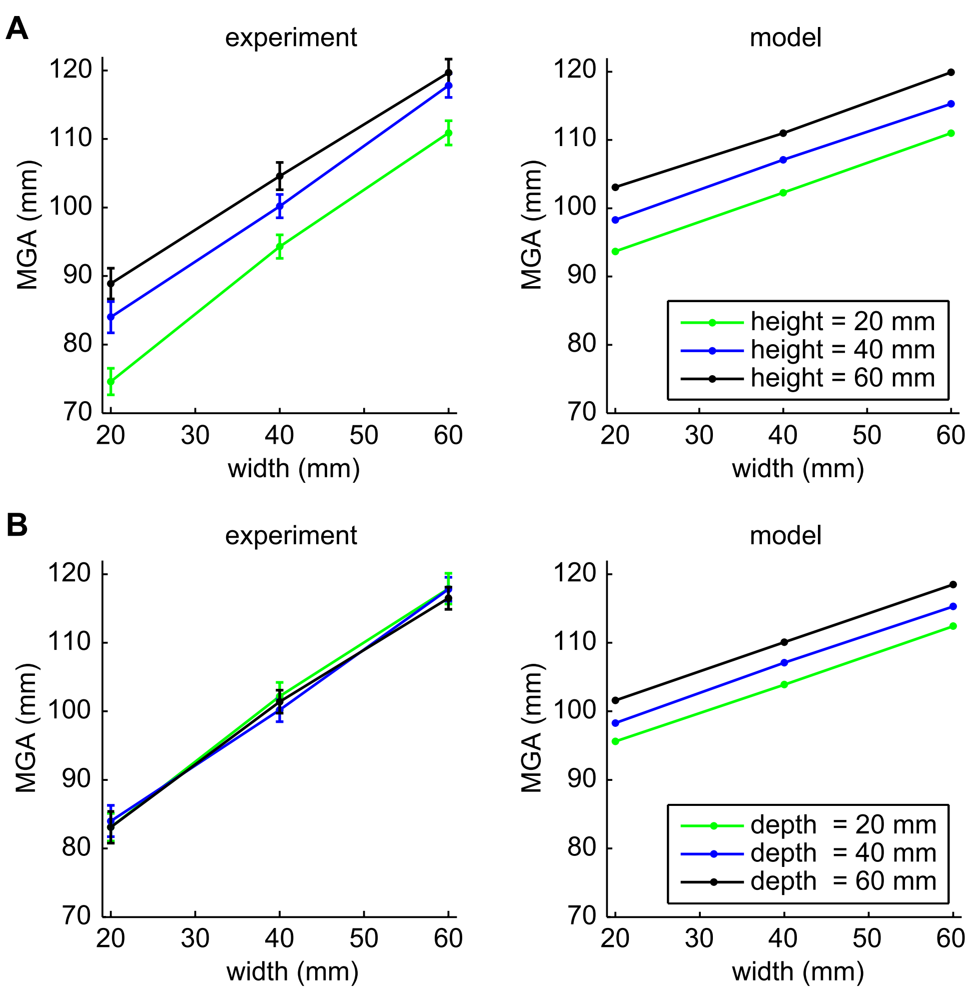


*Figure 2.* Comparison of the experimentally assessed and predicted MGA on target width. The model correctly predicted the experimental result that MGA depends on object height (A). The model incorrectly predicted that MGA depends on object depth. However, the predicted dependence on object depth is less than the predicted dependence on object height (B). Average group values of MGA are shown together with *SE*s for the experimental data.

this paper. These experimentally found positions were not located exactly on the target surface because the digits were between the markers and the target block. We therefore projected the experimentally found final positions of the markers on the target block, such that the goal positions used for the model simulations were always on the target surface. The model simulations ended when the thumb was at a distance of 1 mm from its goal position. Since the model does not simulate the movement of the wrist, we took the average velocity of the index finger and the thumb to predict the velocity of the wrist.

## Results

As expected, we found a scaling of the MGA to the target's width in the experimental measurement, $F(1.13, 10.17) = 803.93$, $p < .001$. We also found movement time to be increasing with object width, $F(2, 22) = 4.316$; $p = .026$. More interesting, we found participants to also scale their MGA to the target's height (Figure 2A and Figure 3). The MGA significantly increased with the height of target blocks. The slope of the MGA relative to object width decreased with target height, that is, the higher the objects, the lower the slope relative to object width (Table 2). Neither MGA nor the slope of the MGA relative to object width changed with target depth (Figure 2B and Figure 3) (Table 3). For both increasing target depth and height, the analyses of complementary variables showed the peak wrist velocity to occur relatively later. Only for increasing height, the number of grip aperture peaks reduced and the MGA occurred relatively earlier. Only for increasing depth, movement time became shorter (Table 2 and 3).

To enquire the different effects of varying target depth and target height, we calculated the height of the markers at object touch. We found that taller target blocks were grasped at higher positions than smaller ones (mean vertical position for the index finger 19.0, 30.4, 43.7 mm for 20, 40 and 60 mm high targets, respectively; $F(1.329,38.529) = 341.323$, $p < .001$). To further investigate the different effects of varying target height and target depth on finger and hand configuration, we analyzed the radial abduction of the hand, operationalized as the difference in height between the marker on the tip of the index finger and the wrist marker, and the positions of the thumb and index finger at the time point of MGA averaged over blocks with the same dimension.

We found that the position of the index finger was lower than the position of the thumb when grasping low target blocks. In contrast, when grasping taller target blocks, the position of the index finger was above the position of the thumb (average difference of index-finger–thumb position was −0.8, −0.1, and 1.4 mm for 20-, 40- and 60-mm high targets, respectively). The ANOVA comparing the differences between index-finger and thumb height yielded a significant difference between object heights, $F(2, 18) = 3.651$, $p = .047$; the single post hoc comparisons showed significant differences between the 40-mm and 60-mm tall targets, $t(29) = -2.518$; $p = .018$ and between the 20-mm and the 60-mm tall target, $t(29) = -3.174$; $p = .004$. In contrast, for objects varying in depth, such a difference between index-finger and thumb height was not observed (average difference of index-finger–thumb position was −0.1, −0.1, and −0.3 mm for 20-, 40- and 60-mm deep targets, respectively, $F(2, 18) = 0.267$, $p = .769$).

For the abduction of the hand we found a similar relationship. The taller the target block, the greater was the difference in height between the index finger and the wrist at the time point of the MGA (average difference of index–wrist height was 7.6, 8.9 and 12.6 mm for 20-, 40- and 60-mm high targets, respectively). The ANOVA comparing the differences between index-finger and wrist height yielded a significant difference between object heights, $F(2, 18) = 7.147$, $p = .005$. The single post hoc comparisons showed a significant difference between the 40-mm and 60-mm tall targets, $t(29) = -3.875$; $p = .001$ and between the 20-mm and the 60-mm tall targets, $t(29) = -4.733$; $p < .001$. In contrast, abduction did not differ for objects that varied in depth (average difference of index–wrist height was 9.9, 8.9 and 8.7 mm for 20-, 40- and 60-mm deep targets, respectively, $F(2, 18) = 1.597$, $p = .230$).

The grasping movements were simulated with the model of Verheij et al. (2012). The dimensions of the target blocks and

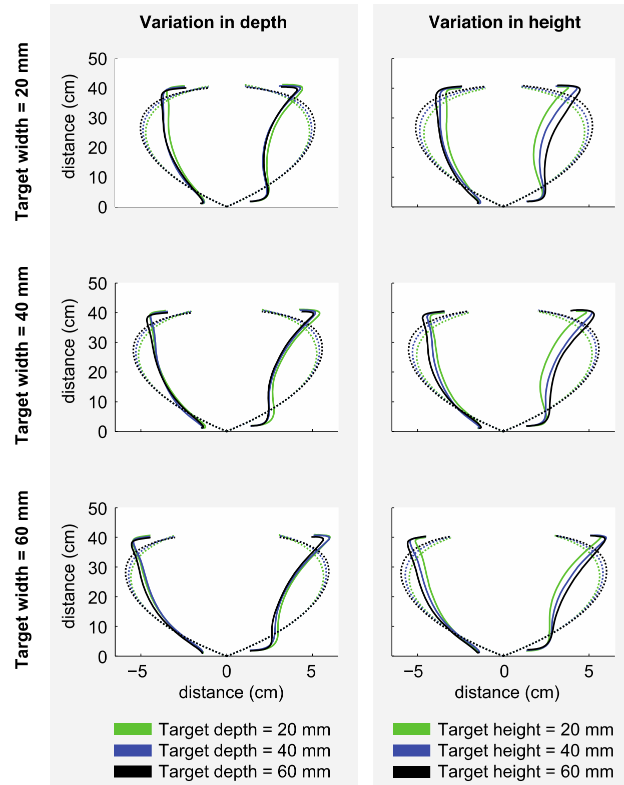


*Figure 3.* Top view of the trajectories of the index finger and thumb per target block for experimental data (mean group trajectories of all subjects, solid lines) and predictions of the model (dashed lines). The left column shows the effect of varying target depth and the right column shows the effect of varying target height. The first row shows the effects for targets with a width of 20 mm, the second row shows the effects for targets with a width of 40 mm and the third row shows the effects for targets with a width of 60 mm. Please note that the predicted trajectories are more convex than the experimental trajectories. A possible explanation for this is that the relative strength of the objective to avoid contact between the finger tips was stronger in the model than in the experiment. We chose not to change the model parameters to lower the strength of this objective because we want to show that our qualitative predictions are the result of the implemented objectives and not of parameter fitting.

Table 2
*Experimental Mean Movement Parameters for Target Blocks Differing in Height*

| Target height | Target label (width in mm) | Slope | *r* | MGA (mm) | GA peaks | tMGA (%) | PWV (mm/s) | WV peaks | tPWV (%) | MT (ms) |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 mm | A4 (20) | 0.91 (0.08) | 0.96 (0.01) | 74.6 (6.1) | 2.4 (0.5) | 72.1 (7.7) | 1055 (119) | 1.3 (0.2) | 42.1 (5.0) | 983 (122) |
| | B4 (40) | | | 94.3 (5.4) | 2.0 (0.4) | 74.9 (5.8) | 1059 (118) | 1.3 (0.3) | 42.3 (4.8) | 993 (119) |
| | C4 (60) | | | 110.9 (5.6) | 1.8 (0.4) | 76.1 (5.2) | 1056 (111) | 1.2 (0.1) | 42.0 (4.2) | 997 (103) |
| 40 mm | A2 (20) | 0.84 (0.12) | 0.95 (0.02) | 84.0 (7.2) | 2.1 (0.3) | 70.5 (7.8) | 1053 (98) | 1.2 (0.2) | 43.3 (5.5) | 968 (99) |
| | B2 (40) | | | 100.2 (5.4) | 1.9 (0.3) | 73.6 (5.4) | 1056 (109) | 1.2 (0.2) | 43.1 (4.9) | 975 (104) |
| | C2 (60) | | | 117.8 (5.5) | 1.6 (0.4) | 73.5 (5.9) | 1055 (105) | 1.4 (0.2) | 42.6 (4.6) | 997 (103) |
| 60 mm | A5 (20) | 0.77 (0.11) | 0.92 (0.04) | 88.9 (7.1) | 1.9 (0.4) | 68.8 (6.0) | 1048 (97) | 1.2 (0.1) | 43.3 (4.9) | 969 (98) |
| | B5 (40) | | | 104.6 (6.3) | 1.6 (0.4) | 72.0 (6.3) | 1051 (108) | 1.2 (0.2) | 43.1 (4.7) | 973 (103) |
| | C5 (60) | | | 119.7 (6.2) | 1.8 (0.3) | 72.4 (5.3) | 1045 (116) | 1.4 (0.3) | 42.5 (5.2) | 1001 (100) |
| ANOVA | $F$ (2, 18) | 9.788 | 8.447 | 306.074 | 6.252 | 8.745 | 0.987 | 0.143 | 3.610 | 1.189 |
| | $p$ | 0.001 | 0.003 | <0.001 | 0.009 | 0.002 | 0.392 | 0.867 | 0.048 | 0.327 |

*Note*. *SD*s are given in brackets; ANOVA statistics for the main effect of height are reported for each variable $r$ = Pearson correlation coefficient; GA peaks = number of grip aperture peaks; tMGA = latency of MGA (% movement time); PWV = peak wrist velocity; WV peaks = number of wrist velocity peaks; tPWV = latency of peak wrist velocity (% movement time); MT = movement time.

the experimentally found average digits' contact positions were used as input. Please note that no other information from the measurements was used as an input for the model. In accordance with the experimental data, the model of Verheij et al. (2012) predicted an effect of height on MGA (Figure 2). In particular, the predicted MGA increased when grasping movements to taller targets were simulated. In contrast to the experimental data, the model also predicted an effect of target depth on MGA. In line with the experimental findings, the predicted effect of target depth on MGA was smaller than the predicted effect of target depth (Table 4 and 5; Figure 2 and 3). In line with the experimental results, the model predicted a systematic decrease of the slope of the MGA with target height but no systematic decrease with target depth (Table 4 and 5). In contrast to the experimentally determined slopes of the MGA relative to object width, the values of the predicted slopes were lower: the model predicted too high values for the MGA of smaller targets. This is most probably due to the component of the force field implemented in the model to avoid collisions between the fingers (Verheij et al., 2012). This component seems to be too strong for the smaller objects in the current measurements. However, we refrained from adjusting the model's parameters to the current measurements to show that the observed model behavior arises from our general approach rather than from optimizing individual parameters to the particular experiment.

## Discussion

Systematically investigating the effect of height and depth of target objects on the grip aperture of healthy participants, we found an increase of the MGA with the height of objects and a decrease of the slope of the MGA relative to object width with the height of objects. In contrast, object depth neither influenced MGA nor the slope of the MGA relative to object width. The slope values we experimentally observed for the increase of MGA with target width ($M$ = 0.82, $SD$ = 0.12) are in accordance with the reports from Smeets and Brenner (1999), who have calculated a mean slope of 0.82 in healthy subjects in their meta-analysis. Our result that MGA does not scale to depth is in line with the studies of Hu et al. (1999) and Ganel and Goodale (2003). Our result that MGA increases with object height is in line with the results of Bootsma

Table 3
*Experimental Movement Parameters for Target Blocks Differing in Depth*

| Target depth | Target label (width in mm) | Slope | *r* | MGA (mm) | GA peaks | tMGA (%) | PWV (mm/s) | WV peaks | tPWV (%) | MT (ms) |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 mm | A1 (20) | 0.87 (0.12) | 0.94 (0.02) | 83.1 (6.4) | 2.1 (0.4) | 71.5 (5.2) | 1045 (119) | 1.3 (0.2) | 41.9 (5.1) | 1000 (118) |
| | B1 (40) | | | 102.2 (6.4) | 1.8 (0.4) | 73.2 (5.1) | 1045 (100) | 1.1 (0.2) | 42.4 (4.9) | 989 (104) |
| | C1 (60) | | | 117.9 (7.1) | 1.6 (0.3) | 73.8 (5.7) | 1053 (106) | 1.3 (0.3) | 42.3 (5.2) | 1017 (98) |
| 40 mm | A2 (20) | 0.84 (0.12) | 0.95 (0.02) | 84.0 (7.2) | 2.1 (0.3) | 70.5 (7.8) | 1053 (98) | 1.2 (0.2) | 43.3 (5.5) | 968 (99) |
| | B2 (40) | | | 100.2 (5.4) | 1.9 (0.3) | 73.6 (5.4) | 1056 (109) | 1.2 (0.2) | 43.1 (4.9) | 975 (104) |
| | C2 (60) | | | 117.8 (5.5) | 1.6 (0.4) | 73.5 (5.9) | 1055 (105) | 1.4 (0.2) | 42.6 (4.6) | 997 (103) |
| 60 mm | A3 (20) | 0.84 (0.12) | 0.94 (0.03) | 83.1 (7.3) | 2.1 (0.4) | 69.5 (6.4) | 1038 (103) | 1.2 (0.2) | 43.3 (5.5) | 974 (112) |
| | B3 (40) | | | 101.4 (5.3) | 1.7 (0.3) | 72.6 (7.6) | 1061 (117) | 1.3 (0.2) | 42.6 (4.6) | 977 (125) |
| | C3 (60) | | | 116.5 (5.1) | 1.6 (0.3) | 74.2 (6.1) | 1062 (111) | 1.2 (0.2) | 42.7 (4.8) | 989 (114) |
| ANOVA | $F$ (2, 18) | 0.920 | 0.136 | 0.727 | 1.476 | 0.368 | 0.683 | 0.007 | 5.003 | 5.319 |
| | $p$ | 0.416 | 0.874 | 0.497 | 0.255 | 0.697 | 0.518 | 0.994 | 0.019 | 0.015 |

*Note*. *SD*s are given in brackets; ANOVA statistics for the main effect of depth are reported for each variable; $r$ = Pearson correlation coefficient; GA peaks = number of grip aperture peaks; tMGA = latency of MGA (% movement time); PWV = peak wrist velocity; WV peaks = number of wrist velocity peaks; tPWV = latency of peak wrist velocity (% movement time); MT = movement time.

Table 4
*Model Predictions for Targets Differing in Height*

| Target height | Target label (width in mm) | Slope | MGA (mm) | tMGA (%) | PWV (mm/s) | tPWV (%) | MT (ms) |
|---|---|---|---|---|---|---|---|
| 20 mm | A4 (20) | 0.432 | 93.7 | 61.3 | 981 | 61.3 | 736 |
| | B4 (40) | | 102.3 | 62.5 | 976 | 60.9 | 739 |
| | C4 (60) | | 111.0 | 64.4 | 972 | 61.0 | 742 |
| 40 mm | A2 (20) | 0.425 | 98.3 | 63.2 | 976 | 59.8 | 750 |
| | B2 (40) | | 107.1 | 64.5 | 963 | 60.6 | 753 |
| | C2 (60) | | 115.3 | 65.6 | 952 | 59.8 | 753 |
| 60 mm | A5 (20) | 0.420 | 103.1 | 62.5 | 971 | 59.5 | 765 |
| | B5 (40) | | 111.0 | 65.0 | 951 | 57.9 | 765 |
| | C5 (60) | | 119.9 | 65.7 | 935 | 59.4 | 767 |

*Note*. tMGA = latency of MGA (% movement time); PWV = peak wrist velocity; tPWV = latency of peak wrist velocity (% movement time); MT = movement time.



et al. (1994) and the results of Hu et al. (1999). In contrast to Hu et al. (1999), we cannot interpret the significant influence of target height in our study as a result of simply clearing the top of the object.

Using a model to simulate grasping movements (Verheij et al., 2012), we predicted the same general pattern of an increase of the MGA and a decrease of the slope of the MGA relative to object width with object height. Next to this, the model predicted that the effect of object depth on MGA is smaller than the effect of object height on MGA and that the slope of the MGA relative to object width does not decrease systematically with object depth. These qualitative model predictions were caused by the implemented objective to avoid collisions of the digits with positions on the target object other than the goal positions. Because the aim of the model predictions was to understand why grasping kinematics are the way they are and not to copy them, we chose to use largely the same parameter values as in the study in which the model was introduced (Verheij et al., 2012). Our predictions were therefore not the result of parameter fitting, but of the objectives implemented in the model. Because we chose not to tune the model parameters to the current experiment, the predictions are not always quantitatively in line with the experimental findings.

Even though the depth and height of the target block were considered equally in the model, their effect is different because the eagerness to avoid the rectangular planes, which together form the surface of the target block, depends on how the digits move relative to the planes. When the digit is heading straight toward a plane the predicted drive to avoid is much stronger than when it approaches the plane under an angle. The drive to avoid contacting a plane also increases with digit velocity and with its proximity to the plane. Among the task constraints that influence these three factors are the goal positions at which the individual digits are directed. Experimentally we found that when grasping a taller object, the fingertips were directed toward the top half of the object (approximately half way between the center of mass and the top edge) rather than to the center of mass, an effect, which was also reported before (Desanghere & Marotta, 2011; Voudouris, Brenner, Schot, & Smeets, 2010).

When grasping toward different points in height, also the movement trajectory itself must be different. Indeed, the abduction of the wrist and the height of thumb and index finger relative to each other changed at the time point of the MGA, with the height of objects indicating changes not only at target positions, but also of the movement's trajectories. In contrast, no such changes were observed for variations in depth.

The goal positions of the digits are one of the factors that influence the MGA predicted by the model. Other factors are the starting position relative to the target object and the amount of repellent force. Although the starting position relative to the target object influences the predicted MGA, an extra set of model simulations showed that the model's qualitative predictions (that MGA increases with the height of the target block and that the

Table 5
*Model Predictions for Targets Differing in Depth*

| Target depth | Target label (width in mm) | Slope | MGA (mm) | tMGA (%) | PWV (mm/s) | tPWV (%) | MT (ms) |
|---|---|---|---|---|---|---|---|
| 20 mm | A1 (20) | 0.420 | 95.6 | 62.0 | 978 | 60.1 | 752 |
| | B1 (40) | | 103.9 | 62.6 | 966 | 60.9 | 753 |
| | C1 (60) | | 112.4 | 64.0 | 955 | 60.6 | 754 |
| 40 mm | A2 (20) | 0.425 | 98.3 | 63.2 | 976 | 59.8 | 750 |
| | B2 (40) | | 107.1 | 64.5 | 963 | 60.6 | 753 |
| | C2 (60) | | 115.3 | 65.6 | 952 | 59.8 | 753 |
| 60 mm | A3 (20) | 0.423 | 101.6 | 63.8 | 973 | 59.3 | 751 |
| | B3 (40) | | 110.1 | 65.7 | 959 | 59.6 | 752 |
| | C3 (60) | | 118.5 | 66.8 | 948 | 58.9 | 752 |

*Note*. tMGA = latency of MGA (% movement time); PWV = peak wrist velocity; tPWV = latency of peak wrist velocity (% movement time); MT = movement time.

effect of the height of the target block on MGA is larger than the effect of the depth of the target block on MGA) also hold when the target block is shifted 100 mm to the left and 13 mm to the front. These predictions do thus generalize to other configurations. The amount of repellent force is, among other factors, determined by the detailed dimensions of the target block.

An alternative explanation for our experimental results might be that the height and depth of an object could be perceived differently, influencing grasping computations via higher cognitive perceptual routes. Humans perceive tall objects as having more volume than shorter objects of exactly the same volume (Raghubir & Krishna, 1999; Wansink & van Ittersum, 2003). By using elliptical cylinders and presenting them in different orientations to induce uncertain perceptions to the subjects, Cuijpers, Brenner, and Smeets (2006) have shown that subjects may plan their grasps using information that is based on the misperceived shape. Moreover, by comparing several studies using visual illusions, Franz (2001) has shown that grasping can be influenced by perceptual deformations of shape. However, other experimental studies using visual illusions (e.g., Aglioti, DeSouza, & Goodale, 1995; Brenner & Smeets, 1996) have argued that misperceiving target size barely leads to a change in MGA.

Yet another factor influencing the MGA might be the distinctiveness of the target dimensions. Considering each subject's perspective in the current setup, the height of the object might be more pronounced than its depth, which is only seen as a prolongation to the reaching distance. Due to the perspective of the presentation of the target blocks, their height might have a bigger effect on the perceptual distinctiveness of the otherwise similar targets. In a series of studies, it has been previously shown that objects that are more distinctive have a higher influence on motor computations (Christensen, Borchers, & Himmelbach, 2013).

In conclusion, our findings indicate that MGA does not only depend on the width, but also on the height of a target object. In contrast, variations of depth have no detectable effect on MGA. Model simulations suggest that these effects might partially be explained by the objective to avoid contacting the target object at positions other than the goal positions with the individual fingers.

## References

Aglioti, S., DeSouza, J. F., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology, 5,* 679–685. doi:10.1016/S0960-9822(95)00133-3

Bootsma, R. J., Marteniuk, R. G., MacKenzie, C. L., & Zaal, F. T. J. M. (1994). The speed-accuracy trade-off in manual prehension: Effects of movement amplitude, object size and object width on kinematic characteristics. *Experimental Brain Research, 98,* 535–541. doi:10.1007/BF00233990

Brenner, E., & Smeets, J. B. J. (1996). Size illusion influences how we lift but not how we grasp an object. *Experimental Brain Research, 111,* 473–476. doi:10.1007/BF00228737

Christensen, A., Borchers, S., & Himmelbach, M. (2013). Effects of pictorial cues on reaching depend on the distinctiveness of target objects. *PLoS ONE, 8,* e54230. doi:10.1371/journal.pone.0054230

Cuijpers, R. H., Brenner, E., & Smeets, J. B. J. (2006). Grasping reveals visual misjudgements of shape. *Experimental Brain Research, 175,* 32–44. doi:10.1007/s00221-006-0531-6

Desanghere, L., & Marotta, J. J. (2011). "Graspability" of objects affects gaze patterns during perception and action tasks. *Experimental Brain Research, 212,* 177–187. doi:10.1007/s00221-011-2716-x

Franz, V. H. (2001). Action does not resist visual illusions. *Trends in Cognitive Sciences, 5,* 457–459. doi:10.1016/S1364-6613(00)01772-1

Ganel, T., & Goodale, M. A. (2003). Visual control of action but not perception requires analytical processing of object shape. *Nature, 426,* 664–667. doi:10.1038/nature02156

Hu, Y., Eagleson, R., & Goodale, M. A. (1999). The effects of delay on the kinematics of grasping. *Experimental Brain Research, 126,* 109–116. doi:10.1007/s002210050720

Jeannerod, M. (1986). Mechanisms of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia, 24,* 41–78. doi:10.1016/0028-3932(86)90042-4

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97–113. doi:10.1016/0028-3932(71)90067-4

Paulignan, Y., Frak, V. G., Toni, I., & Jeannerod, M. (1997). Influence of object position and size on human prehension movements. *Experimental Brain Research, 114,* 226–234. doi:10.1007/PL00005631

Raghubir, P., & Krishna, A. (1999). Vital dimensions in volume perception: Can the eye fool the stomach? *Journal of Marketing Research, 36,* 313–326. doi:10.2307/3152079

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

Verheij, R., Brenner, E., & Smeets, J. B. J. (2012). Grasping kinematics from the perspective of the individual digits: A modelling study. *PLoS ONE, 7,* e33150. doi:10.1371/journal.pone.0033150

Verheij, R., Brenner, E., & Smeets, J. B. J. (2013). Why are the digits' paths curved vertically in human grasping movements? *Experimental Brain Research, 224,* 59–68. doi:10.1007/s00221-012-3288-0

Voudouris, D., Brenner, E., Schot, W. D., & Smeets, J. B. J. (2010). Does planning a different trajectory influence the choice of grasping points? *Experimental Brain Research, 206,* 15–24. doi:10.1007/s00221-010-2382-4

Wansink, B., & van Ittersum, K. (2003). Bottoms up! The influence of elongation on pouring and consumption volume. *Journal of Consumer Research, 30,* 455–463. doi:10.1086/378621

World Medical Association. (2013). World medical association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *Journal of the American Medical Association*. Advance online publication. doi:10.1001/jama.2013.281053

Zaal, F. T. J. M., & Bootsma, R. J. (1993). Accuracy demands in natural prehension. *Human Movement Science, 12,* 339–345. doi:10.1016/0167-9457(93)90023-I

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