

The influence of target object shape on maximum grip aperture in human grasping movements

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Abstract The shape of a target object could influence maximum grip aperture in human grasping movements in several different ways. Maximum grip aperture could be influenced by the required precision of digit placement, by the aim to avoid colliding with the wrong parts of the target objects, by the mass of the target objects, or by (mis)judging the width or the volume of the target objects. To examine the influence of these five factors, we asked subjects to grasp five differently shaped target objects with the same maximal width, height and depth and compared their maximum grip aperture with what one would expect for each of the five factors. The five target objects, a cube, a three-dimensional plus sign, a rectangular block, a cylinder and a sphere, were all grasped with the same final grip aperture. The experimentally observed maximum grip apertures correlated poorly with the maximum grip apertures that were expected on the basis of the required precision, the actual mass, the perceived width and the perceived volume. They correlated much better with the maximum grip apertures that were expected on the basis of avoiding unintended collisions with the target object. We propose that the influence of target object shape on maximum grip aperture might primarily be the result of the need to avoid colliding with the wrong parts of the target object.

Keywords Prehension · Obstacle · Limb movements · Visuomotor behavior · Movement control

Introduction

Humans have the capacity to grasp a target object in many different ways. Yet, they show characteristic movement patterns. Differences between movement patterns under different circumstances can reveal how various variables are taken into account when planning a grasping movement. One of these variables is target object shape, the focus of the present paper. It has repeatedly been shown that target object shape influences the maximum grip aperture (MGA) for a certain distance between the final positions of the digits (Zaal and Bootsma 1993; Cuijpers et al. 2004; Eloka and Franz 2011; Hu et al. 1999; Borchers et al. 2014).

In this study, we test several explanations for why MGA depends on target object shape: because the shape influences the desired precision of the digits' final positions ('desired precision,' Smeets and Brenner 1999), because humans have the objective to avoid collisions between the digits and other parts of the target object than the goal positions ('collision avoidance,' Cuijpers et al. 2004; Borchers et al. 2014; Verheij et al. 2012), because the grip aperture scales with target object mass (Eastough and Edwards 2007), or because, if a target object is grasped along its width, MGA is not scaled to the actual width of the target object but to the perceived width ('perceived width,' Franz 2001; Franz et al. 2000, 2001) or to the perceived volume ('perceived volume,' Borchers et al. 2014). In the following paragraphs, we will address these five explanations and their explanatory value.

Desired precision

Planning how to grasp a target object starts by selecting suitable positions on the target object's surface, after which the digits are moved toward these goal positions (Smeets

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and Brenner 1999). To determine suitable positions on the target object's surface, the target object's shape is taken into account to ensure a stable grasp (Cuijpers et al. 2004). Because human movements are variable, the digits will not always end exactly at these selected goal positions. The size of the surface available for digit placement influences how important it is to end close to the selected goal positions. A strategy to increase the precision is to approach the target object's surface more perpendicular, leading to a larger MGA (Smeets and Brenner 1999). This strategy is used when the movement variability is large, for example, in fast movements or movements without predictably available visual feedback (Wing et al. 1986; Jakobson and Goodale 1991), or when the desired precision is large. MGA can therefore be expected to be influenced by target object shape through the size of the surface on the target object available for digit placement and any other variables that influence the desired precision.

Desired precision can explain why oblate target objects (cylindrical target objects from which two parts are removed so that the target object becomes a bar with two rounded sides with small grasp surfaces) are grasped with a larger MGA than full cylinders (with large grasp surfaces) (Zaal and Bootsma 1993) and why slender bars grasped at their ends (small grasp surfaces) are grasped with a larger MGA than disks (large grasp surfaces) (Eloka and Franz 2011). However, it cannot explain why the MGA increases with the length of the axis orthogonal to the axis that is grasped when grasping an elliptic cylinder at its short axis (Cuijpers et al. 2004) or why MGA scales with target object height but not with target object depth (Hu et al. 1999; Borchers et al. 2014).

Collision avoidance

Cuijpers et al. (2004) proposed that the objective to avoid collisions between the digits and other parts of the target object than the goal positions also influences MGA. They based this proposal on an experimental finding that could not be explained by desired precision. They found that when grasping an elliptic cylinder the increase in MGA with target object size depends on the length of the axis orthogonal to the axis that is grasped. They suggested that when elliptical cylinders are grasped by their short axis, the protruding parts of the orthogonal major axis act as obstacles, giving rise to a larger MGA. In the study of Borchers et al. (2014), our grasping model (Verheij et al. 2012), in which the idea of collision avoidance is implemented, was used to examine whether collision avoidance could explain why MGA scales with target object height but not with target object depth. In line with the experimental findings, our model predicted an increase in MGA with target object height. In contrast to the experimental findings, our model

also predicted an increase in MGA with target object depth, although the predicted effect of target object depth on MGA was smaller than the predicted effect of target object height. Collision avoidance can thus partially explain the findings of Hu et al. (1999) and Borchers et al. (2014).

Mass

Eastough and Edwards (2007) found that heavy cylinders are grasped with a large MGA than light cylinders of the same dimensions. Based on this finding, one might expect that target object shape influences MGA because target object shape influences target object mass. However, it should be noted that Weir et al. (1991) did not find an effect of target cylinder weight on MGA. Differences in mass can explain some effects of target shape, for instance, why the MGA increases with the length of the axis orthogonal to the axis that is grasped when grasping an elliptic cylinder at its short axis (Cuijpers et al. 2004). However, it cannot explain why oblate target objects (relatively low mass) are grasped with a larger MGA than full cylinders (relatively high mass) (Zaal and Bootsma 1993), why slender bars grasped at their ends (relatively low mass) are grasped with a larger MGA than disks (relatively high mass) (Eloka and Franz 2011) or why MGA scales with target object height but not with target object depth (Hu et al. 1999; Borchers et al. 2014).

Perceived width or volume

One might expect MGA to only scale with the true size of the dimension along which the target object is grasped (e.g., Aglioti et al. 1995; Brenner and Smeets 1996; Haf-fenden and Goodale 1998), but there is evidence that MGA also scales with the perceived size of the target object (Franz et al. 2000, 2001; Franz 2001). A likely candidate for a dimension to use to scale ones MGA is perceived width. However, it might be that a more generic measure of object size is used, such as perceived volume. As tall objects are perceived as having more volume than lower objects of exactly the same volume (Raghubir and Krishna 1999; Wansink and Van Ittersum 2003), using perceived volume might explain why, while grasping target objects along their width, MGA scales with target object width and target object height but not with target object depth (Borchers et al. 2014).

Aim

In this study, we aimed to get more insight into the role of desired precision, collision avoidance, mass, perceived width and perceived volume in influencing the MGA. We performed an experiment in which subjects grasped five

differently shaped target objects with the same maximal width, height and depth and that were grasped with the same final grip aperture. The predicted effect of collision avoidance was based on simulations with the grasping model of Verheij et al. (2012). We based our predictions for the effects of the four other explanations on measures independent of the digits' trajectories: the variance in the endpoints of the digits in the grasping experiment (desired precision), the actual mass of the target objects and the perceived width and volume of the target objects as judged in two psychophysical experiments involving large groups of subjects. To evaluate the relative explanatory value of the five explanations, we calculated the squared correlation coefficient between the predicted MGAs and the experimentally measured MGAs for each explanation.

Methods

Grasping experiment

Subjects

Nine naive right-handed subjects took part in the experiment (6 females, 3 males) ranging in age from 22 to 44 years (mean = 30 years, SD = 7.7 years). The experiment was part of a program that was approved by the local ethics committee. Before participating, subjects signed an informed consent form.

Experimental setup and procedure

The experiment consisted of a grasping task performed with free vision. Subjects sat on a stool. At the start of each trial, their hand rested on a table and their index finger and thumb were touching each other at a starting position located 20 cm to their right and 10 cm in front of the center of their trunk. They were presented with a wooden target object, which was placed on the table, 40 cm in front of the starting position (Fig. 1).

There were five different target objects. The expected effects of desired precision, collision avoidance, mass, perceived width and perceived volume on MGA differed for this set of target objects. We used a cube ('cube'), a three-dimensional plus sign ('plus'), a rectangular block ('block'), a cylinder ('cylinder') and a sphere ('sphere') (Fig. 2). The dimensions and orientation of each target object were such that its height, width (the dimension along which the target object is grasped) and depth (the horizontal dimension perpendicular to the width) were all 6.0 cm. The $4.24 \times 4.24 \times 6.0$ cm 'block' was grasped by the 6.0-cm-long vertical edges that were 6.0 cm apart. The 'plus' was made of 6.0 cm beams with a cross-sectional

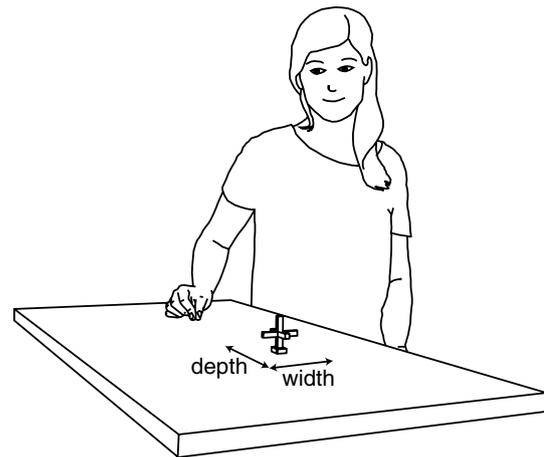


Fig. 1 Experimental setup (target object 'plus')

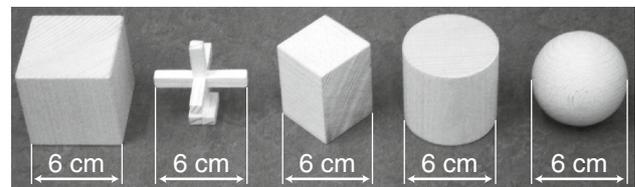


Fig. 2 Target objects. From left to right 'cube,' 'plus,' 'block,' 'cylinder' and 'sphere'

area of 0.76×0.84 cm. The area available for digit contact was much smaller for the plus and the block than for the cube, the cylinder and the sphere. The masses of the objects were 149, 7, 76, 111 and 80 g for the cube, plus, block, cylinder and sphere, respectively. Each subject performed 12 trials per target object. Thus in total, there were 60 trials per subject. These 60 trials were presented in a different random order for each subject.

Subjects were instructed to reach and grasp the target object at a natural movement speed using the index finger and thumb of their right hand, to lift it, and then put it back at the same location. To ensure that subjects grasped the target object by positions that were 6 cm apart, they were instructed to grasp the 'plus' at the ends of the horizontal beam perpendicular to the main movement direction and to grasp the 'block' at the two vertical side edges. The subjects were also instructed to grasp the 'cube' by its side surfaces. This was necessary because grasping the cube by its front and back surfaces rather than by its left and right surfaces will, according to our grasping model (2012), yield a different MGA for the same target object if collision avoidance is a major factor. Subjects began their grasping movement when they heard a verbal 'go' signal.

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 nails of the subject's index finger and thumb and to the subject's wrist (proc. styloideus ulnae).

Data analysis

The start of the grasping movement was defined as the moment at which the velocities of the tip of the thumb and the tip of the index finger both exceeded 0.1 m/s. The end of the grasping movement was defined using the Multiple Sources of Information method (Schot et al. 2010). We used the criteria that both the index finger and thumb are within 30 mm of the target object's center in the sagittal direction and <70 mm above the table, that the aperture is decreasing, that the second derivative of aperture is positive, that the mean of the velocities of the thumb and index finger is low (the objective function was 1 for zero velocity and decreased linearly to 0 for the maximum velocity) and that the movement time is short (the objective function was 1 for the start of the movement and decreased linearly to 0.8 for the last sample). We rejected the trial if the endpoint was not found using this paradigm or if there were more than two consecutive missing samples between the start and end of the grasping movement for the thumb, the index finger or the wrist. Together, this resulted in the rejection of 14 of the 540 trials. Isolated or pairs of missing samples were reconstructed using linear interpolation.

In order to get an overview of the movement trajectories of the digits and of the wrist, we constructed a top view of the trajectories by plotting the average sagittal component against the average lateral component. Because the number of samples varied across trials, we resampled the data of each marker for each trial such that each step corresponds to 1 % of the path length of the concerning marker before averaging. We calculated the means of the resampled trajectories per subject, marker and target object and averaged these mean trajectories across the subjects.

To examine the influence of target object shape on MGA, we calculated the MGA for each trial as the maximum distance between the marker placed on the index finger and the marker placed on the thumb in the interval between movement start and movement end. We subsequently calculated for each subject the mean MGA per target object. The effect of target object shape on MGA was tested using a one-way repeated-measures analysis of variance (ANOVA) with factor: target object shape (five levels). Next, we averaged these mean MGAs across subjects in order to be able to calculate the correlation coefficients (across target object shapes) between the mean predicted MGAs and the experimentally found mean MGAs.

Predictions

For collision avoidance, we used model simulations to generate predictions (Verheij et al. 2012). The four other explanations are based on a single variable: desired precision, mass, perceived width and perceived volume. In order to predict the MGA for the various target objects for each of these four explanations, we quantified the relevant variables for each target object on a scale that was normalized so that the value for the relevant variable was 1.0 for the cube. Based on these normalized values and the MGA that was found for the cube, we predicted the MGA for the other four target objects. The details of this method are explained in the remainder of this subsection.

Normalized desired precision

Assuming that our subjects succeeded in achieving the desired precision, desired precision is reflected in the variability of the endpoints. To quantify this variability, we determined the surface area of the 95 % endpoint confidence ellipses (Messier and Kalaska 1997, 1999) for the thumb and index finger per subject and condition. In order to calculate this surface area, we used the final positions of the digit in the sagittal direction and its final heights. We defined 'desired precision' as 1 divided by the average of the surface area of the ellipse for the thumb and the ellipse for the index finger, so that the value for desired precision increases when the variability of the endpoints decreases.

Desired precision

$$= \frac{2}{\text{surface area thumb} + \text{surface area index finger}}$$

The normalized desired precision was calculated per subject and condition by dividing the desired precision for each condition by the desired precision for the 'cube.'

The MGA that is needed to acquire the desired precision might depend on the variability of the movement and thus on movement speed. Therefore, one might expect that faster movements require a larger MGA (Wing et al. 1986; Jakobson and Goodale 1991), even though the same desired precision is acquired. We checked for this by calculating the mean movement time per condition and calculating the squared correlation coefficient (r^2) between these mean movement times and the mean MGAs.

Collision avoidance

To evaluate how collision avoidance is reflected in behavior, we used the grasping model of Verheij et al. (2012) in which the objective of collision avoidance is implemented. In this model, two point masses, representing the tips of the

index finger and the thumb, move in a force field. We will refer to these points as ‘tips.’ The force field is the sum of multiple forces that each represent one or two objectives that hold for each tip.

The model predicts an influence of target shape on MGA because one of the model’s assumptions is that the influence of the objective to avoid collisions between the digits and surfaces depends on how the digits move relative to these surfaces. For example, the drive to avoid contacting a surface increases when the distance between the surface and the digit decreases and when the digit’s movement direction is more toward the surface.

We did not fit the model’s parameter values to the experimental data, but we used the same values for the parameters A , R_o , K , E and D as in the paper in which we introduced the model (Verheij et al. 2012). In that study, the values for the parameters were chosen such that the simulated kinematics was in line with the experimentally found kinematics in a study of Jeannerod (1981). The parameter A sets the strength of the objective to arrive at the preselected goal position. The parameter R_o sets the strength of the objective to avoid collision with obstacles or positions on the target object other than the goal position. The parameters K and E set the strengths of the objectives to prevent collisions between the tips and limit the distance between the tips. The parameter D sets the strength of the objective to move smoothly and arrive simultaneously with both tips.

One of the objectives originally implemented in the model was that humans avoid collisions between their digits and the table’s surface. This objective mainly caused the vertical curvature of the predicted movement. It did so to an extent that is set by the parameter R_t . In this study, we changed the value of R_t to zero because we experimentally found that the table does not affect the vertical curvature, but that the curvature is mainly caused by local constraints at the start of the movement (Verheij et al. 2013). In line with that finding, we added an upward ‘force’ of 4 m/s^2 to the force field if the tip was lower than 5 mm. These values (4 m/s^2 and 5 mm) and the abrupt transition between the force being active and no longer being active (instead of a gradually changing force) are rather arbitrary. Since the quantitative model predictions will depend on the values for the parameters and we do not claim to use the most appropriate set of parameters, we are primarily interested in the model’s qualitative predictions.

For the model simulations, the target object’s dimensions and its position relative to the starting position were set in accordance with the experimental setup. The locations of the goal positions, to which the tips are attracted, are given as an input to the model. For each target object, the goal positions for the tips were chosen based on the experimentally observed final positions of the digits, averaged across subjects. These experimentally found positions were not

located exactly on the target object’s surface because the markers were attached to the nails, so that the digits were between the markers and the target objects. We corrected for this using the knowledge of the experimental geometry.

Mass

The mass of each target objects was determined with a balance. The normalized mass was calculated by dividing each of the five masses by the mass of the ‘cube.’

Normalized perceived width

We determined the perceived width of the five target objects used in the grasping experiment by asking fifty naive subjects (32 females, 18 males) ranging in age from 18 to 73 years (mean = 25 years, SD = 12 years) to quantify the perceived width of each target object. None of the subjects had participated in the grasping experiment. We tested different subjects because asking the same subjects to judge the perceived width before the grasping experiment would direct their attention to perceived width (which might possibly influence MGA) and asking them to judge the width after they grasped the objects would give them additional information about the target objects’ widths from having grasped the objects.

The five target objects were each presented once, in a random order, at the same position relative to the subject as in the grasping experiment. The subjects were not allowed to touch the target objects. To quantify the perceived width, the subject could either use an existing unit or a self-chosen unit that scaled linearly with perceived width. The normalized perceived width was calculated per subject by dividing each of the five reported values by the value reported for the ‘cube.’

Normalized perceived volume

We determined the perceived volume of the five target objects used in the grasping experiment by asking fifty naive subjects (27 females, 23 males) ranging in age from 18 to 58 years (mean = 31 years, SD = 9.6 years) to quantify the perceived volume of each target object. None of the subjects had participated in the grasping experiment or in the experiment in which the width had to be judged (for the same reasons as those given in the section ‘Normalized perceived width’).

The five target objects were each presented once, in a random order, at the same position relative to the subject as in the grasping experiment. The subjects were not allowed to touch the target objects. To quantify the perceived volume, the subject could use either an existing unit or a self-chosen unit that scaled linearly with perceived volume. The normalized perceived volume was calculated per subject

by dividing each of the five reported values by the value reported for the ‘cube.’

From various values to predictions

The normalized values for desired precision, mass, perceived width and perceived volume were converted into predictions for the MGA in cm using the following equation:

$$\text{predicted MGA} = 0.8 \cdot 6 \cdot \text{normalized value} + 6.82$$

We multiplied the normalized value by 0.8 and 6 because in the literature, it has been reported that MGA scales with target object size with a slope of around 0.8 (Smeets and Brenner 1999) and the size (width) of the target objects that we used was 6 cm. We added 6.82 cm to ensure that the predicted MGA will be equal to the experimentally found MGA for the ‘cube.’ For each prediction that was based on measurements on subjects (desired precision, perceived width and perceived volume), we calculated the predictions per subject and condition, and subsequently averaged them across subjects of the concerning experiment, resulting in one predicted MGA with associated standard error of the mean per explanation and condition.

Our prediction for obstacle avoidance was not based on a normalized value. In order to have a perfect prediction for the cube, we subtracted the difference between our model’s prediction for the MGA for the ‘cube’ and the experimentally found mean MGA (averaged across subjects) for the ‘cube’ (0.34 cm) from all MGAs predicted by our model. Because our model (2012), only predicts one value for the MGA per target object no further averaging was needed. Together, these transformations made it possible to directly compare the relationships between measured and predicted effects of target object shape on MGA across the five explanations.

Testing the predictions

To examine to what extent, the five explanations could account for the experimentally found influence of target object shape on MGA the squared correlation coefficient (r^2) between the mean experimentally found MGAs and the (mean) predicted MGAs was calculated per explanation. The larger r^2 , the better the explanation accounts for the experimentally found dependence of MGA on object shape.

Note that the value of the correlation coefficient depends neither on the predictions being precise nor on the slope of the relationship. For desired precision, mass, perceived width and perceived volume the predicted MGAs were calculated by multiplying the normalized values of the

concerning factor with a constant and adding another constant. If we would have used other values for the constants or would have used the normalized values directly to calculate the squared correlation coefficients, the values for the squared correlation coefficients would have been exactly the same. Likewise, not subtracting a constant from the MGAs predicted by the model would not have affected the value of the squared correlation coefficient for collision avoidance. Our choice to let the predicted MGA for the ‘cube’ be equal to the experimentally found MGA for the ‘cube’ and our choice of the strength of the relation between MGA and desired precision, mass, perceived width or perceived volume is therefore irrelevant for conclusions based on the correlation coefficients. It only makes it easier to interpret differences between the experimental results and the predictions.

Results

The mean MGAs per subject and target object shape (Table 1) and the top view of the average movement trajectories (Fig. 3) suggest that there was a difference in MGA between the target objects. A one-way repeated-measures ANOVA showed that there was indeed a significant effect of target object shape on MGA ($F(4,32) = 30.0, p < 0.001$). Post hoc comparison showed that the MGA was significantly larger for the ‘cube’ than for all other target shapes (all $p < 0.01$), the MGA was significantly smaller for the ‘sphere’ than for all other target shapes (all $p < 0.01$), and that the MGA did not differ significantly between the ‘plus,’ the ‘block’ and the ‘cylinder’ (all $p > 0.6$).

Table 1 Mean experimentally found MGA in cm per subject for each target object shape, and the mean predicted MGA in cm per explanation, for each target object shape

	Cube	Plus	Block	Cylinder	Sphere
Subject 1	12.06	11.35	11.29	11.60	11.19
Subject 2	11.80	10.97	11.27	10.96	10.59
Subject 3	12.01	10.61	10.68	10.90	10.59
Subject 4	11.03	10.28	9.97	10.16	9.75
Subject 5	11.59	10.74	10.93	10.97	10.41
Subject 6	10.77	9.91	10.11	9.94	9.94
Subject 7	11.58	11.14	11.17	10.86	10.70
Subject 8	12.19	10.64	10.80	11.22	10.03
Subject 9	11.53	11.58	11.22	11.12	10.84
Desired precision	11.62	16.99	11.86	11.31	12.96
Collision avoidance	11.62	10.82	10.56	10.82	10.78
Mass	11.62	7.04	9.27	10.39	9.39
Perceived width	11.62	11.08	10.56	11.39	11.17
Perceived volume	11.62	7.65	9.63	10.78	9.86

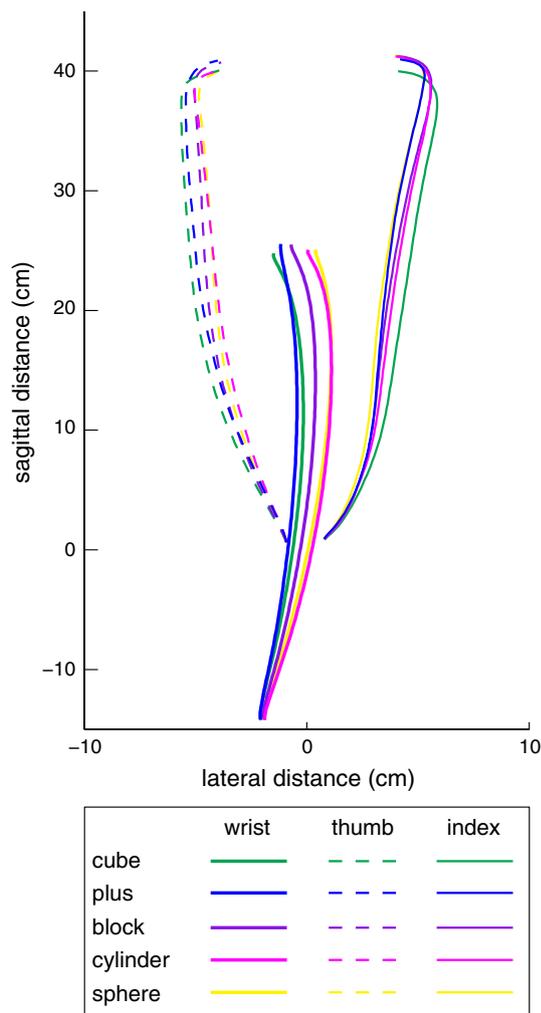


Fig. 3 Top view of the average trajectories of the wrist (proc. styloideus ulnae), the thumb and the index finger per target object

Note that from all explanations tested, only collision avoidance predicts relatively small differences in MGA between the ‘plus,’ the ‘block’ and the ‘cylinder,’ which is in line with our experimental results. All other explanations predict a relatively large difference between these target objects (Table 1; Fig. 4). The squared correlation coefficient between the mean predicted MGAs and the experimentally found mean MGAs was highest for collision avoidance ($r^2 = 0.76$, $p = 0.05$), lowest for desired precision ($r^2 = 0.06$, $p = 0.7$) and had intermediate values for mass ($r^2 = 0.38$, $p = 0.3$), perceived width ($r^2 = 0.29$, $p = 0.3$) and perceived volume ($r^2 = 0.33$, $p = 0.3$) (Fig. 4). The p values are the probabilities of getting a correlation as large as the observed value by chance (when the true correlation is zero), so from the five proposed explanations, collision avoidance can explain our results best.

The squared correlation coefficient between the experimentally found mean movement times (Fig. 5) and the

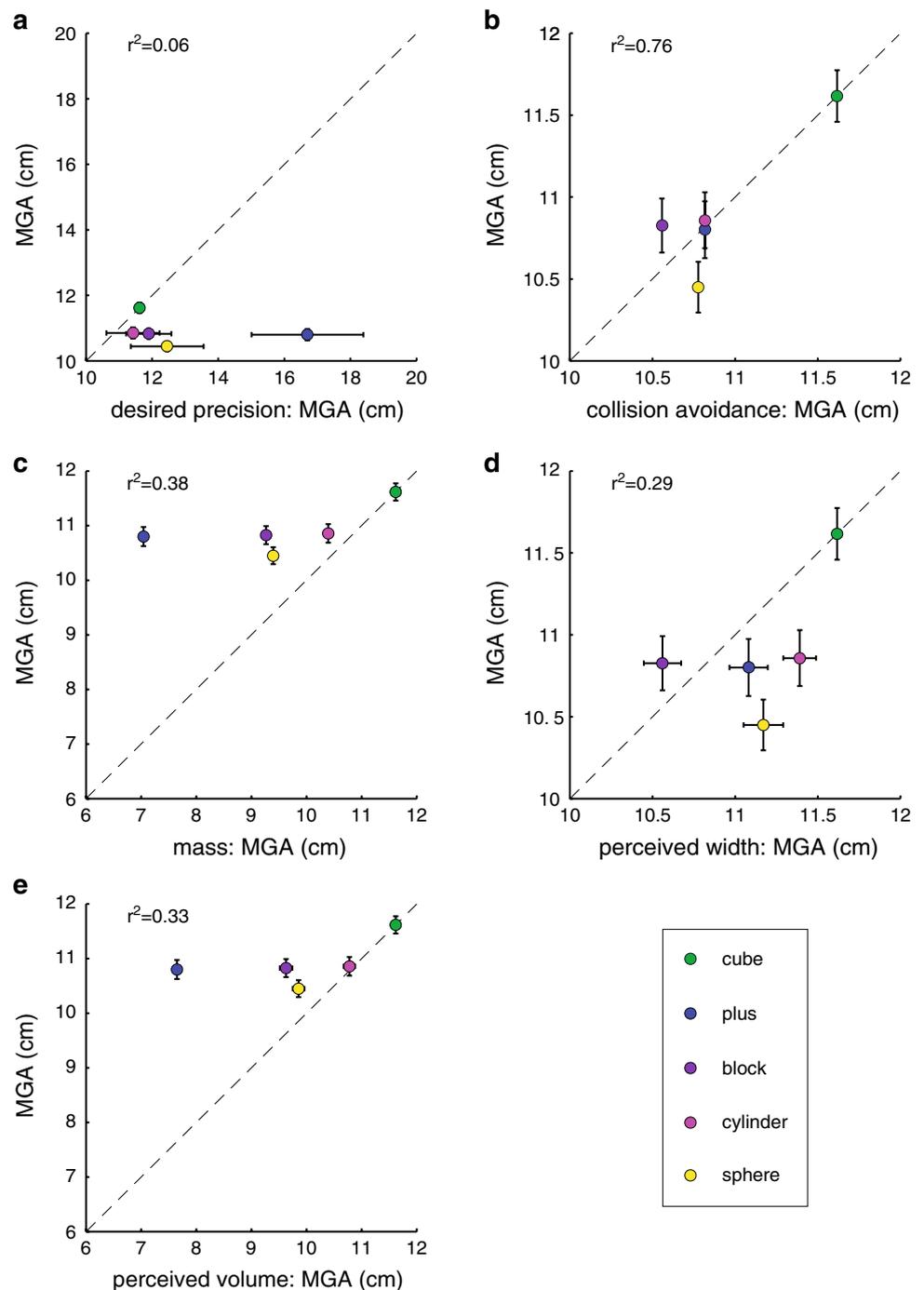
experimentally found mean MGAs was low ($r^2 = 0.19$, $p = 0.46$), and the correlation was negative (overall larger movement times corresponded to smaller MGAs), so we can reject differences in movement time as a possible explanation of the difference in MGA between object shapes.

Discussion

We aimed to get more insight into how target object shape influences MGA. In the introduction, we mentioned that the desired precision of the digit’s final positions (‘desired precision,’ Smeets and Brenner 1999), avoiding collisions between the digits and other parts of the target object than the goal positions (‘collision avoidance,’ Cuijpers et al. 2004; Borchers et al. 2014; Verheij et al. 2012), target object mass (‘mass,’ Eastough and Edwards 2007), and relying on perceived target object width (‘perceived width,’ Franz 2001; Franz et al. 2000, 2001) or volume (‘perceived volume,’ Borchers et al. 2014) might all contribute to the influence of target object shape on MGA. We examined the relative importance of these five explanations by performing an experiment for which the expected outcome differed between these explanations. In our experiment, subjects grasped five differently shaped target objects with the same maximal width, height and depth, with the same final grip aperture. We used a ‘cube,’ a ‘plus,’ a ‘block,’ a ‘cylinder’ and a ‘sphere’. We found that MGA was largest for the ‘cube’ and smallest for the ‘sphere.’ There was no significant difference in MGA between the ‘plus,’ the ‘block’ and the ‘cylinder’.

To quantify the desired precision, we determined the surface area of the 95 % confidence ellipses for the experimentally found endpoints of the digits. To get an estimate of the effect of collision avoidance on MGA, we simulated our experiment with the model of Verheij et al. (2012). To quantify the mass, we used a balance. To quantify the perceived width and the perceived volume, we performed separate experiments in which subjects judged the width and volume of the five target objects that were used in the grasping experiment. Based on these values, we then predicted the MGA and calculated the squared correlation coefficient between the experimentally found and the predicted mean MGAs per explanation. The squared correlation coefficient was low (<0.4) for desired precision, mass, perceived width and perceived volume and much higher (0.76) for collision avoidance. It might very well be that multiple factors are responsible for the effect of object shape on MGA. Whether or not this is the case, the squared correlation coefficients show that variations in desired precision, mass and misperceiving width or volume are unlikely to play major roles in shape-related variations in MGA. The role of collision

Fig. 4 Experimentally measured maximum grip aperture (MGA) as a function of predicted MGA for the proposed explanations: **a** desired precision, **b** collision avoidance, **c** mass, **d** perceived width, **e** perceived volume. Note that the axes differ between the panels. Values are averages across subjects for each target. *Error bars* indicate the associated standard errors (and are only visible if larger than the radius of the point). There are no *error bars* for the predicted MGAs based on collision avoidance and mass, because we have only one prediction per target object shape. Points on the *dashed line* indicate that the experimentally measured MGA is equal to the predicted MGA. The way we make the predictions ensures that this is always the case for the ‘cube’



avoidance cannot be excluded. The importance of collision avoidance awaits further research.

An alternative variable that has been related to MGA is maximum object extent [‘the maximum (diagonal) extent of the object or a diagonal formed by an approximately 45° slice through the object, whichever is less’ (Lee et al. 2008)]. Assuming a vertical slice perpendicular to the grasping surfaces (Mon-Williams and Bingham 2011), this measure cannot explain our findings because it is equal for

the ‘cube,’ the ‘block’ and the ‘cylinder’ (8.5 cm), while experimentally, we found that MGA is larger for the ‘cube’ than for the other target objects. Moreover, this measure of object extent is smaller for the ‘plus’ (6.1 cm) than for the ‘block’ and the ‘cylinder,’ while experimentally, we found that the MGA did not differ significantly between the ‘plus,’ the ‘block’ and the ‘cylinder.’

The idea that collision avoidance influences MGA argues against the suggestion that target object distance is treated

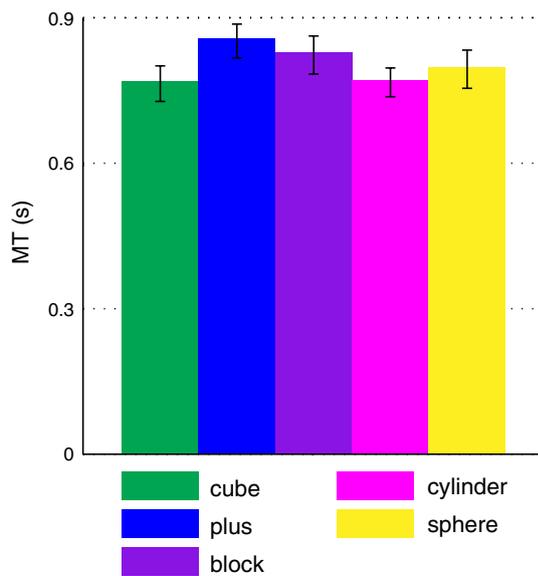


Fig. 5 Effect of target object shape on movement time. Values are averages across subjects for each target object; *error bars* indicate the associated standard errors

independently of target object shape in grasping (Jeannerod 1981), because distance and shape must be combined to avoid collisions. Collision avoidance is possible without taking the whole shape of the target object into account, as long as the distance to the relevant surface of the target object is taken into account for each individual digit (Verheij et al. 2012). Thus, the influence of collision avoidance on MGA is consistent with the view that grasping is nothing more than pointing with the individual digits toward selected positions on the target object (Smeets and Brenner 1999).

The MGA that we found for the ‘sphere’ was smaller and that for the block larger than predicted by collision avoidance. One reason for this might be that humans (in contrast with the model of Verheij et al. (2012)) are more determined to avoid collisions with edges than with smooth surfaces and therefore open their hand more when grasping the block (which is grasped at its edges) and less when grasping the sphere (which has no edges). However, MGA may also be influenced by other factors that were not included in the model of Verheij et al.

MGAs for collision avoidance were predicted using a model (Verheij et al. 2012) in which multiple objectives with certain strengths are converted into mathematical formulas with certain parameter values. It might appear evident that a more complex model can predict the data better. However, we did not fit the model’s parameter values to the experimental data. Moreover, in our experiment, we only manipulated target object shape, which only influences grasping via the objective to avoid collision with the target object at positions other than the goal positions. Therefore,

only one model parameter, R_o , was directly related to the predicted differences in MGA. The alternative explanations for the differences in MGA were all the result of influencing one variable (desired precision, mass, perceived width or perceived volume). For those predictions, the MGA was scaled to the concerning variable, while for collision avoidance, the MGA was not scaled, but was the result of the interaction of multiple implemented objectives. From the explanations tested, collisions avoidance could explain our experimental results best. Therefore, we propose that the MGA is the result of achieving multiple objectives (Verheij et al. 2012), among which the objective to avoid collisions between the digits and the target object at positions other than the goal positions, and is not the result of scaling MGA to a certain variable (Smeets and Brenner 1999) as is often proposed (e.g., Aglioti et al. 1995; Haffenden and Goodale 1998; Jeannerod 1981, 1984).

To examine the effects of object shape on grasping kinematics, we analyzed the MGA. Since we think that the MGA is not explicitly controlled, but follows from the movements of the individual digits (Smeets and Brenner 1999), we might as well have chosen a different measure (e.g., the maximum lateral position of one of the digits). We chose to analyze the MGA because this is often done in grasping studies and therefore makes comparing our work with other studies more straightforward.

In sum, the influence of target object shape on maximum grip aperture is not primarily the result of the required precision, mass, perceived width or the perceived volume of the target object. The influence might largely be the result of the aim to avoid colliding with the wrong parts of the target object.

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