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RESEARCH NOTE

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The influence of obstacles on the speed of grasping

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Abstract The movement time of a reach-to-grasp movement increases when obstacles are placed close to the target object. We investigated whether this increase can best be explained by limits on the grip aperture or by limits on the paths of the individual digits. In our experiment subjects were instructed to pick up an object with their index finger and thumb. There was an obstacle at either side of the object. The increase in movement time when either obstacle was placed closer to the object was best described by a model in which the movement amplitude and the distance between each obstacle and the target object are independent factors. We conclude that the way that obstacles influence the movement time in reach-to-grasp movements is determined by the extent to which they limit the digits' paths.

Keywords Human · Reaching · Grasping · Obstacle avoidance

Introduction

Placing an obstacle near the target of a reaching movement influences the kinematics of the hand: the movement time increases. The reaching movement slows down in order to increase accuracy, and thereby prevent the hand from touching the obstacle. How much the movement time increases depends on the gap between the target and the obstacle (Tresilian 1998). When grasping an object positioned between obstacles, there is more than one gap. What could determine movement time in this situation? The answer depends on how one thinks that grasping is controlled.

According to a hypothesis proposed by Jeannerod (1988, 1999), grasping an object consists of two more or less independent components. According to this *grip control hypothesis*, the wrist is transported towards the target object (transport component), and the fingers move relative to each other to grasp the object (grip component). Obstacles can influence each of these components. However, the wrist (and thus the transport component) does not come near to the target object and obstacles. Therefore, in this view, it is not clear why the transport component should be influenced by the presence of obstacles *beside* the target.

Recently, Smeets and Brenner (1999) proposed an alternative to the grip control hypothesis for grasping. They argued that in grasping the tips of the finger and thumb can be regarded as moving independently towards their designated places of contact on the surface of the object. The hand or the wrist does not play a role in their model. Obviously the digits cannot move completely independently, because they are anatomically linked. However, experiments have shown that the anatomical constraint does not have much influence on grasping (Smeets and Brenner 2001). Thus, the assumption that the tips of the digits move independently is not totally unreasonable. According to this *digit control hypothesis*, the characteristic grip preshaping is a result of the requirements of the task: both digits should arrive simultaneously and approximately perpendicular to the surface. The requirement of arriving simultaneously, so as not to knock over the object and to be able to continue to lift the object in a single smooth movement, means that a single obstacle will not only influence the movement time of the digit that it is obstructing, but will influence the movement time of both digits to a similar extent.

To discriminate between the two above-mentioned hypotheses on grasping, Mon-Williams and McIntosh (2000) performed an experiment involving obstacle avoidance. In their study, subjects were asked to reach for and pick up an object that was flanked by obstacles both at the side of the index finger and at the side of the thumb. The position of the obstacle at the side of the index finger was varied. Movement time was measured for each trial. Based on Fitts' law (Fitts 1954; Fitts and

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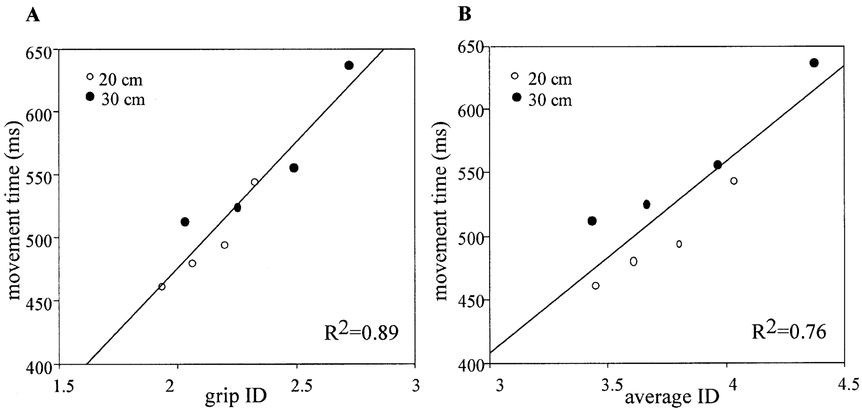

Fig. 1A, B Plots of the data of Mon-Williams and McIntosh (2000). Regression plots for movement time against *grip ID* (**A**) and *average ID* (**B**), as defined in the Methods section. *Open circles* and *filled circles* represent data for reaching distances of 20 cm and 30 cm, respectively. Note that the numbers on the horizontal axis in **A** and **B** are different from those in Figs. 2 and 3 of Mon-Williams and McIntosh (2000) because the numbers in the latter figures are not correct (M. Mon-Williams, personal communication). Furthermore, the R^2 values differ because we did not remove outliers

Peterson, 1964), Mon-Williams and McIntosh (2000) defined an index of difficulty (ID) both for the grip control hypothesis (named *visuomotor ID* by Mon-Williams and McIntosh, further referred to as *grip ID*) and for the digit control hypothesis (named *digit ID* by Mon-Williams and McIntosh, further referred to as *average ID*). In accordance with Fitts' law, Mon-Williams and McIntosh (2000) defined the ID as $\log_2(2A/W)$, with A being the amplitude of the movement (20 or 30 cm), and W the target width according to each of the hypotheses. For the *grip ID* they used the total distance between both obstacles (grip size) as the target width. For the *average ID* they calculated a separate index for each digit, using the gap between the obstacle and the target at that side as target width, and averaged the indices for index finger and thumb. Movement time was plotted as a function of these indices of difficulty. Movement time was more closely related to the *grip ID*, which they considered as supporting the grip control hypothesis. We have objections to their experiment and analysis.

We question whether Fitts' law is valid if the movement amplitude and the target width are perpendicular to each other, as is the case for avoidance of obstacles while grasping. The index of difficulty that Fitts used to derive his law is based on the amount of information (number of bits) used in the specification of movement distance. This amount of information only predicts the accuracy in the direction of motion. Fitts' law was also verified in experiments in which the target size was varied in the same direction as the movement amplitude (Fitts 1954; Fitts and Peterson, 1964; see Plamondon and Alimi (1997) for an overview).

In order to judge whether Fitts' law was appropriate for the obstacle avoidance data in Mon-Williams and McIntosh study, we replotted the data of Mon-Williams and McIntosh (2000) in Fig. 1, adding different symbols for the different reaching distances. There appear to be systematic differences between reaching distances: *open* and *closed circles* appear to each form a separate curve. Since Fitts' law was supposed to eliminate such differences, the use of Fitts' law may not be appropriate to describe the effect of obstacles on grasping in this configuration. However, in order to keep in line with the reasoning of Mon-Williams and McIntosh (2000), we used another way to quantify the difficulty of the task.

Based on similar findings, Welford et al. (1969) formulated a model in which movement amplitude (A) and target width (W_i) are independent factors. This model is described by the following equation:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \frac{W_0}{W_i}$$

with a and b being independent constants for amplitude and target width, respectively. W_0 is the "assumed accuracy without visual control" (Welford et al. 1969). We will call $\log_2 \frac{W_0}{W_i}$ the target difficulty and $\log_2 \frac{A}{W_0}$ the distance difficulty. How this model can be applied to grasping will be explained in the methods section.

In the experiment of Mon-Williams and McIntosh, the positions at which the subjects had to grasp the object were not controlled. According to Tresilian (1998) and Jackson et al. (1995), objects placed at the side of the thumb have less influence on the movement time of prehension than objects placed at the side of the index finger. This may appear to be inconsistent with both models, but it is easily explained by the tendency to place the thumb nearer to oneself and the finger slightly behind the object. Thus, objects placed at the two sides have different effects because the digits are positioned asymmetrically. When grasping in a natural manner, as was done in the experiment of Mon-Williams and McIntosh, the trajectory of the thumb is straighter then that of the index finger, making a collision between thumb and obstacle less likely. The asymmetrical grip can be avoided by indicating where the index finger and thumb should contact the object. If index finger and thumb move to equivalent positions on the target object (i.e. equal distance from the subject), the task constraints are expected to be the same for both, and so the influence of the obstacle should also be the same. We verified this by varying the obstacle positions at both sides of the target object.

Mon-Williams and McIntosh (2000) only varied the position of the obstacle at the side of the index finger. We repeated their study, but in contrast varied the distance between the obstacle and the target object both at the side of the index finger and at the side of the thumb. To ensure that the constraints were equal for the index finger and thumb, as explained above, subjects had to grasp the object at marked positions.

Methods

Subjects

Six subjects (four men, two women) volunteered to take part in the study after being informed about what they would be required to do. They were instructed to reach for, grasp and lift an object with their index finger and thumb, and to put it at a marked position on the table. This study is part of an ongoing research program that has been approved by the local ethics committee.

Experimental set-up

We designed the set-up to be as close as possible to that of Mon-Williams and McIntosh. The main difference is that we varied the positions of *both* obstacles. Obstacles were placed at either side of the target object (see Fig. 2). The target object (6 cm height × 3 cm width × 2 cm depth) and the obstacles (20 cm height × 3 cm width × 1 cm depth) were rectangular wooden blocks. Two black marks at the middle of the lateral sides of the target object indicated where the subject was expected to make contact with the object.

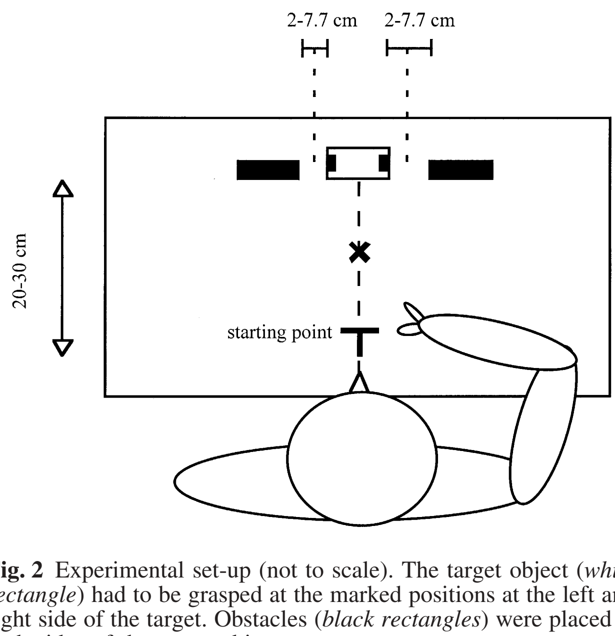

Fig. 2 Experimental set-up (not to scale). The target object (*white rectangle*) had to be grasped at the marked positions at the left and right side of the target. Obstacles (*black rectangles*) were placed at both sides of the target object

The target object was placed either 20 or 30 cm from the starting point. When it was 20 cm from the starting point there was a gap of 2, 2.75, 3.6 or 4.5 cm between the target object and the obstacle at one side. The obstacle at the opposite side was placed 3 cm from the target object. When the target was 30 cm from the starting point, the gap was 2.1, 3.7, 5.6 or 7.7 cm at one side and 4 cm at the other side. For each reaching distance the variable gap between obstacle and target object could be at either side of the target object. Ten movements were recorded for each obstacle position, resulting in a total of 160 trials (2 reaching distances × 4 gaps × 2 sides × 10 repetitions).

The positions of four infra-red-emitting diodes (IREDs) were measured with an Optotrak motion recording system. Two IREDs were placed on the distal phalanx of the thumb and index finger. The other two IREDs were placed on the target object. Positions of all IREDs were recorded for a period of 2 s at a sampling rate of 250 Hz.

Procedure

The hand was placed in the neutral position between pronation and supination with the thumb and index finger touching each other at the starting point. After the experimenter had given a verbal sign, the subjects reached for the object. They were instructed to reach as fast and accurately as possible without touching the obstacles, to pick up the object, and to place it at a marked position on the table (Fig. 2). The subjects were specifically instructed to grasp the target object at the marked positions. Trials in which the obstacles were touched were immediately re-run. The number of trials that were re-run varied between 0 and 14% across subjects.

Data analysis

Velocity was calculated by numerical differentiation of the position data. Movement onset was defined on the basis of the component of the velocity in the direction of the target. It was defined as the first frame of this velocity component after the last zero-crossing before peak velocity. The offset of the movement was defined as the lift of the target object, using a similar velocity criterion. A median value of the movement time (MT) was obtained for each subject under each condition. A paired t-test was carried out to determine whether the side at which the obstacle was varied influenced the MT.

We used multiple regression analysis to fit the Welford model to the data. We did this for both hypotheses, and for both our own data and those of Mon-Williams and McIntosh (2000). For the regression analysis of our own data, we first averaged the MT values over subjects. We assume that W_0 (2.37 cm) is the same as in Welford et al. (1969). For our data, the goodness of fit of the Welford model was assessed quantitatively with a χ^2 test (Press et al. 1990). This is a way to test whether the model fits the data points well, given the standard errors of the data points.

For the grip control hypothesis W_i is simply the total distance between the obstacles:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \sqrt{\frac{W_0^2}{grip^2}}.$$

Smeets and Brenner (1999), in their view on the control of grasping, assume that the index finger and the thumb move independently towards positions on the target object. Considering the constraints of a grasping task, whereby the digits should arrive more or less simultaneously, one would expect movement time to be influenced equally by the gap at the side of the index finger and at the side of thumb. However, it is very unlikely that the *average* difficulty is critical, because repositioning a near obstacle slightly closer to the target object constrains the movement to a much greater extent than does repositioning a distant obstacle slightly closer. We therefore extended the equation of Welford et al. (1969) for the digit control hypothesis by replacing the target difficulty by a term that considers the distance between each obstacle and the target object:

$$MT = a * \log_2 \frac{A}{W_0} + b * \log_2 \sqrt{\frac{W_0^2}{finger\ gap^2} + \frac{W_0^2}{thumb\ gap^2}}$$

where *finger gap* and *thumb gap* are the distances between each obstacle and the target object.

Results

In Fig. 3A, B we replotted the data of Mon-Williams and McIntosh (2000; see Fig. 1) in terms of the equations adapted from Welford et al. (1969). The figures show MT as a linear function of the target difficulty and an independent distance difficulty for both the grip hypothesis (R^2=0.93) and the digit hypothesis (R^2=0.99). The constants for distance difficulty and target difficulty are a=266 ms and b=88 ms for the grip control hypothesis and a=157 ms and b=117 ms for the digit control hypothesis. These fits are much better than the original regressions in Fig. 1A and B, which justifies our choice for this analysis.

Figure 4A, B show the MTs of our own experiment plotted against the target difficulty for the grip control hypothesis (R^2=0.65) and the digit control hypothesis (R^2=0.79), respectively. The higher R^2 value for the regression based on the digit control hypothesis (as found in Fig. 3) implies that variations in MT are better predicted by the gap between each of the obstacles and the target object than by the total gap between the obstacles. The χ^2 test reveals a significant deviation from the regression fit based on the grip control hypothesis at both 20 and 30 cm distance (χ^2_{14}=65.2, P<0.001). For the digit control hypothesis there is no such deviation (χ^2_{14}=9.5, P=0.80). The digit control model thus fits the data adequately (taking into account the standard errors of our data points), whereas the grip control model can be rejected. The constants for distance difficulty and target difficulty are a=402 ms and b=179 ms for the grip control hypothesis and a=180 ms and b=305 ms for the digit control hypothesis. The sides at which the obstacle's distance was varied did not significantly influence the MT (P=0.29; *circles* and *squares* in Fig. 4).

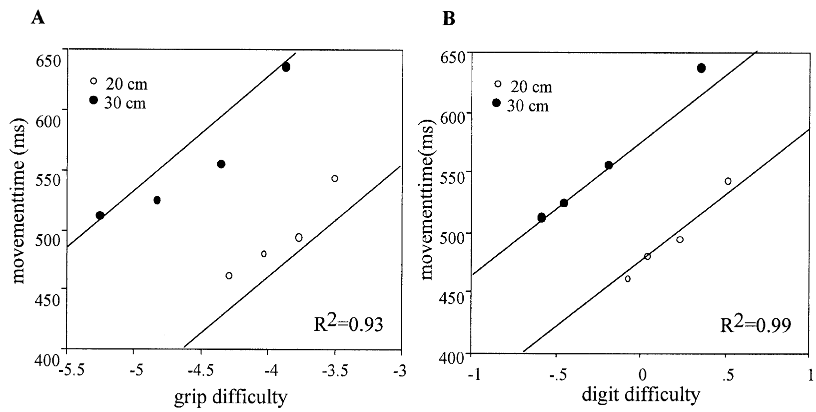

Fig. 3A,B Plots of the data of Mon-Williams and McIntosh (2000). Regression plots for movement time against the *grip difficulty* (**A**) and *digit difficulty* (**B**), as defined in the Methods section. *Open circles* and *filled circles* represent data for reaching distances of 20 cm and 30 cm, respectively

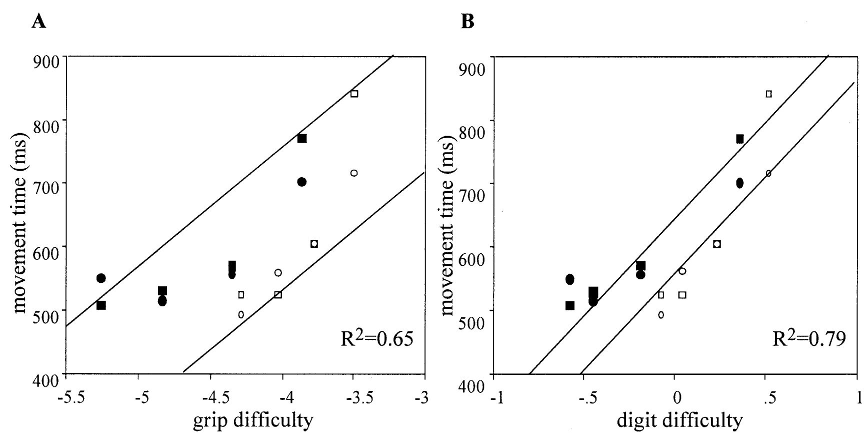

Fig. 4A, B Plots of our own data. Regression plots for movement time against *grip difficulty* (**A**) and *digit difficulty* (**B**), as defined in the Methods section. Each point represents the average movement time of six subjects for one of the sixteen conditions. *Open* and *filled symbols* represent data for reaching distances of 20 cm and 30 cm, respectively. *Circles* indicate trials in which the obstacle at the side of the thumb was varied. *Squares* indicate trials in which the obstacle was varied at the side of the index finger

Discussion

An obstacle can influence the time it takes to grasp an object. Based on different hypotheses for the control of grasping, one can argue that movement time is influenced either by a limitation on the grip aperture or by a limitation on the paths of individual digits. In our replication of the experiment of Mon-Williams and McIntosh (2000), we varied the obstacle positions at both sides of the target object. We instructed the subjects to grasp the target object at specified marks in order to ensure that the same obstacle distance leads to the same constraint for both digits. In the study of Mon-Williams and McIntosh no specifications were made, so that subjects could make the task easier and move faster by not grasping all targets at the same contact positions. We think that this difference in constraints caused the much larger range of MTs in our data (Fig. 4) than in the original study of Mon-Williams and McIntosh (2000) (Fig. 3). Mon-Williams and McIntosh analysed their data in terms of Fitts' law. A consequence of Fitts' law is that the movement time plotted as a function of an ID is independent of the movement amplitude. The use of Fitts' law was not appropriate for our task because the relationship between MT and the index of difficulty did depend on the amplitude of the movement (compare *open* and *filled circles* in Fig. 1). Therefore we used a model in which movement amplitude and target difficulty are independent factors instead (Figs. 3, 4). The main result was a better fit with *digit difficulty* than with the *grip difficulty*. The influence of obstacles is thus better explained by the *digit control hypothesis* than by the *grip control hypothesis*. The "third-way" hypothesis proposed by Mon-Williams and McIntosh (2000), also contains a grip component and is, therefore, also less suitable. Besides there being a more linear relationship between MT and obstacle position, there are two more aspects of the data that favour the digit control hypothesis of Smeets and Brenner (1999).

Firstly, in our experiment varying the positions of the obstacles had a significant effect on the movement time. According to the grip control hypothesis, the transport component and grip component are controlled independently. Several studies (Marteniuk et al. 1990; Paulignan et al. 1991; Bootsma et al. 1994) have already shown evidence for interactions between the two components. Jeannerod (1999) summarised these results with the claim that the transport component can influence the grip component, but not the converse. If so, it is not clear why obstacles placed beside the target object, which only impose restrictions on the grip component, should influence movement time.

Secondly, in contrast to Tresilian (1998) and Jackson et al. (1995), we found that the side at which the position of the obstacle was varied made no difference to the MT (Fig. 4, *squares* and *circles*). This is presumably because we forced our subjects to grasp symmetrically. This is consistent with the digit control hypothesis in which a grasping movement is constrained by the demands on the independent digits, without consideration of any of the anatomical differences between index finger and thumb.

We conclude that the influence of obstacles on a reach-to-grasp movement can best be explained by a model based on the control of the individual digits.

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