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Grasping movement plans

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Despite the great amount of research that has been done regarding the time it takes to move the hand to targets of varying distances and widths, it is unclear whether target distance and width are both represented in movement plans prior to movement initiation. We addressed this question by studying performance in an object manipulation task. Our participants reached out and took hold of a familiar object (a bathroom plunger) to move it to wide or narrow targets of varying heights. Grasp heights on the plunger were additively affected by target height and target width, suggesting that both factors were taken into account by participants prior to moving the plunger from its initial position. Another factor we manipulated was the width of the base from which the plunger was lifted on its way to its next position. This factor also affected grasp heights, but no more so than target widths. The latter result contradicts the view that movement starts are planned in more detail than movement ends, as might be expected from the fact that movement starts come sooner. Together, our results suggest that forthcoming movements are planned in considerable detail. A surprising methodological implication of this study is that recording how people prepare to move can reveal as much—or in some cases more—about what they have planned than can recording their subsequent movements.

This study was designed to contribute to the understanding of the planning and control of physical actions and, in particular, actions involving object manipulation, an important functional activity and a rich venue for exploring the information actors have about their own bodies vis-à-vis the external environment (MacKenzie & Iberall, 1994). Our starting point was a classic observation by Fitts (1954) on the time it takes to move the hand from one point to another. Fitts found that this time increases as the distance between points increases, and that this time increases as the width of the target gets smaller. This dual influence of distance and target width on movement time has been demonstrated so many times and in such a wide range of conditions that the relation, or its more specific quantitative formulation (which need not be repeated here), has come to be called *Fitts's law* (for a review, see Elliott, Helsen, & Chua, 2001).

How distance and target width are internally represented prior to movement initiation remains unclear from the many studies that have been done on Fitts's law. Are both factors represented, or is only one factor represented in advance, so that the unrepresented or minimally represented factor is only dealt with while movement is underway? If both factors are considered before movement initiation, are they considered independently or in some dependent fashion?

The available methods for addressing these questions have relied mainly on the kinematics of ongoing hand movements (i.e., the positions of the hand over time), but these methods have been less than wholly satisfactory in illuminating premovement planning. Such studies have generally shown that target width has an observable effect on observed movement speed later than does required distance. Thus, the starting phase of the movement is strongly affected by the distance to the target but is largely unaffected by the size of the target, whereas the ending phase of the movement is strongly affected by the size of the target but is less affected by the distance of the target from the launch point (for a review, see Elliott, Helsen, & Chua, 2001). Such observations suggest that homing in to smaller targets occurs late in movement, but they do not prove that target width is not considered prior to movement initiation. Planning with respect to target width could be carried out before movements start but not be manifested kinematically until movements are under way.

Given this uncertainty about the nature of movement planning for manual positioning movements, we sought another way to address the issue. Rather than focusing on hand kinematics during movement, we focused on where participants grasp an object to be moved to another location. Previous research has shown that people grasp objects differently, depending on what they intend to do with the objects (Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). More recently, Cohen and Rosenbaum (2004) showed that when university students reached out

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to take hold of a bathroom plunger to move it to a target location, they grasped the plunger low for high target locations and high for low target locations. Cohen and Rosenbaum argued that this *grasp height effect*, as they called it, suggested that people take end states into account in movement planning (see Rosenbaum, Cohen, Meulenbroek, & Vaughan, 2006, for further review). Insofar as one can say that target heights were a large-scale movement feature like distance, the question broached here was whether the grasp height effect could also be exploited to determine whether target width is represented in advance of movement.

To address this question, we conducted a replication of Cohen and Rosenbaum's (2004) study and also varied the widths of the targets (see Figure 1). We predicted that if target height and target width are both taken into account before the plunger is grasped and brought from its home position to its target position, then grasp heights should depend on both target height *and* target width. A second, more detailed, prediction was that if target height and target width are planned independently, grasp heights should be additively rather than interactively affected by these two factors.

In addition to asking whether target widths are planned in advance, we also addressed a third issue about motor planning—whether movement *starts* are planned in more detail than movement *ends*. One might expect this to be the case, given that movement starts come earlier than movement ends.

To address this question, we varied the width of the ring from which the plunger was removed at the home site. We hypothesized that if movement start planning is more detailed than movement end planning, grasp heights should be more strongly affected by the widths of the *home* rings than by the widths of the *target* rings. Conversely, if movement start planning is not more detailed than movement end planning, grasp heights should be just as strongly affected by the widths of the target rings as by the widths of the home rings.

METHOD

There were four precision conditions: EE, EH, HE, and HH, where E means *easy* and H means *hard*, and the position of the letter refers to whether the easy or hard precision requirement was at the home site (first ordinal position in the two-letter series) or at the target site (second ordinal position in the two-letter series). Each of the four precision requirements was tested at each of the five target heights previously used by Cohen and Rosenbaum (2004)—namely, 50.8 cm, 68.6 cm, 86.4 cm, 104.1 cm, and 121.9 cm above the floor. As in the study by Cohen and Rosenbaum, the plunger stood on a home platform 86.4 cm high, to the left of the vertical column in which all the targets were located.

The participant stood in front of the home platform, which protruded from an empty bookshelf. After watching the experimenter pull out one of five target platforms from its resting position in the empty bookcase, the participant reached out with his or her right hand and took hold of the plunger to move it there. After placing the plunger on the target platform, the participant lowered his or her right hand to his or her side and then reached out again to return the plunger to the home position, whereupon he or she lowered his or her right hand again and repeated the sequence one more time. The experimenter then pulled out a different shelf and had the participant perform the next sequence of four moves defined by a combination of target height, home ring width, and target ring width. The

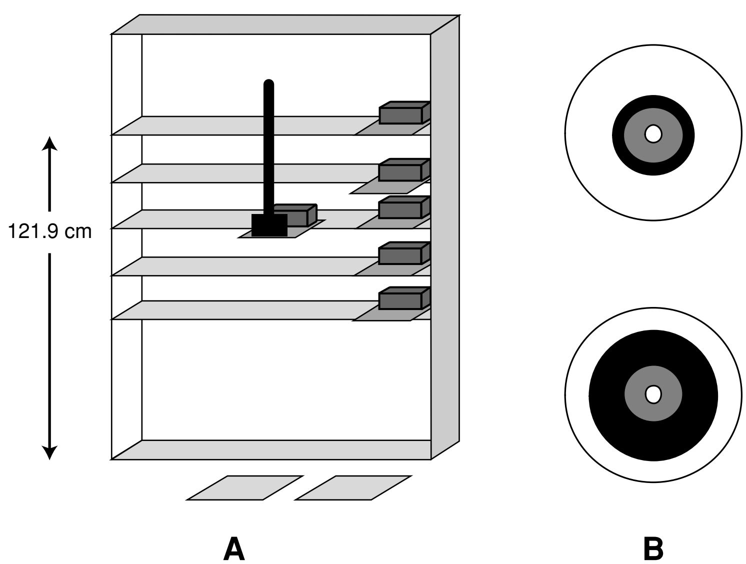

Figure 1. Experimental setup. A: Bookcase with home platform and cylinder on the left and target platforms on the right. B: Top-down view, not drawn to scale, of plunger with its base in the narrow ring (upper picture) and in the wide ring (lower picture). Figure in left panel from "Where Objects Are Grasped Reveals How Grasps Are Planned: Generation and Recall of Motor Plans," by R. G. Cohen and D. A. Rosenbaum, 2004, *Experimental Brain Research*, 157, p. 487. Copyright 2004 by Springer. Reprinted with permission.

conditions defined by target shelf height and precision requirement (e.g., EH) were ordered so that no target shelf height or precision requirement was tested twice in a row for any participant, and the order of conditions was balanced over participants. Each participant completed a total of 80 (i.e., $4 \times 5 \times 4$) transports of the plunger. There were no practice trials.

A small-diameter ring (14.0 cm) or a large-diameter ring (20.0 cm) occupied the home and/or target position. These were the diameters of the inner widths of the rings (from inner edge to inner edge). The outer widths of the rings (from outer edge to outer edge) were 30 cm in both cases. The rings were 5 cm high and were made of Styrofoam. The participants had visual, tactile, auditory, and kinesthetic feedback about the positions of the plunger relative to the rings. Visual information was available about where the plunger was located as it was being removed from a ring and as it was brought toward a ring. All participants were able to look down into the ring at all target heights. Tactile and auditory feedback inherent to the task provided information about when the plunger contacted a ring, either during removal or during placement. Kinesthetic feedback may have also provided information about the ongoing progress of the move in comparison with perceptual traces of previous moves (Adams, 1984).

The plunger consisted of a wooden cylinder, 51 cm high and 23 mm in diameter, which stood on a sturdy rubber base, 13 cm in diameter and 8 cm high. The mass of the cylinder was 135 g, and the mass of the rubber base was 178 g. Given the diameter of the base, its horizontal clearance with respect to the wide ring was 20 cm − 13 cm = 7 cm (3.5 cm on average in every horizontal direction), and its horizontal clearance with respect to the narrow ring was 14 cm − 13 cm = 1 cm (0.5 cm on average in every horizontal direction). We assumed that the precision requirements of placing the plunger into the narrow ring were greater than those of placing it into the wide ring (Fitts, 1954) and that the precision requirements of removing the plunger from the narrow ring were greater than those of removing it from the wide ring. We made no specific assumptions about the precision requirements of removing versus placing the plunger.

To obtain participants' grasp choices, we filmed their grasps with a digital video camera that was rigidly mounted on a tripod and situated to the right of the testing area. The principal purpose of the video recording was to record where the thumb of each participant's right hand was at critical moments in the movement sequences. The camera was in full view of the participants, who were told that we were planning to put video segments of their reaches into a longer video that would be shown to patients in a future study of memory for movement sequences. We told our participants to perform in a comfortable, unhurried way, but to grasp the plunger firmly enough that it would not slide through their fingers during the transport maneuvers. We also told them not to reach for the plunger until they knew where it would be placed.

The participants were 16 right-handed Penn State undergraduates who earned course credit and were treated in accordance with the ethical guidelines of the American Psychological Association. They ranged in height from 160 to 183 cm, with a mean height of 174 cm. All participants were tall enough to reach the top of the plunger shaft when it was placed on the highest shelf.

After the experiment was completed, we selected single video frames for storage on the hard drive of a computer, using the interactive program JLIP Video Capture (Multimedia Navigator, Inc.). In view of the fact that the participants were instructed not to let the cylinder slide down in their hands (which was carefully checked during performance), the video frames we stored corresponded to two events: (1) the moment the participant lifted the plunger from the home platform, and (2) the moment the participant returned the plunger to the home platform from the target platform. Eighty frames were saved for each participant. The individual picture files were stored in JPEG format and used to estimate grasp heights. For the analysis of each video frame, we used a computer mouse to click on three locations in each image: (1) the bottom of the plunger, (2) the top of the plunger, and (3) the location of the participant's thumb on the plunger. We used a MATLAB program (MathWorks, Inc.), written by the first author, to record the click locations in order to estimate the proportion of the length of the plunger handle at which the thumb made contact with the handle. As in our earlier studies of grasp height, we used this measure as a proxy for the participants' postures. We recognized that many other aspects of their postures could have been recorded. However, by limiting the analysis to the thumb position on the plunger, we could focus on the aspect of performance that we believed was most functionally relevant for our purposes.

RESULTS

The overall average grasp position was at 51.45% of the plunger shaft. The correlation between participant height and average grasp height did not approach statistical significance.

The main results, shown in Figure 2, reveal four outcomes: (1) Grasp heights decreased as target heights increased; (2) grasp heights were higher in the EE condition than in any other condition; (3) grasp heights in the other conditions were more or less the same; and (4) grasp heights for return moves from the target positions to the home position were similar to those for moves from the home position to the target positions. These summary statements were confirmed in a repeated measures ANOVA that tested the effects of target height (1–5), required precision (EE, EH, HE, HH), direction of motion (home–target or target–home), and repetition (first or second time). The main effect of target height was statistically significant [$F(4,60) = 41.58$, $MS_e = .042$, $p < .01$], as was the main effect of precision [$F(3,45) = 5.78$, $MS_e = .041$, $p < .05$], but no other main effect or interaction was statistically significant (all ps $> .05$).

DISCUSSION

Previous research has shown that people reaching out to move an object (a bathroom plunger) from one place to another took hold of the object low for high target placements and high for low target placements (Cohen & Rosenbaum, 2004). This outcome indicates that participants took into account the large-scale feature of target height before moving the plunger. In the present experiment, we replicated this finding and found as well that the width of the ring at the target site also influenced the observed grasp heights: When the target ring was narrow, participants grasped the plunger lower than when the target ring was wide. Thus, participants took into account the small-scale feature of object manipulation (the width of the target) as well as the large-scale feature (the height of the target).

Other features of the data allow for further inferences. One concerns independence of planning with respect to target width and target height. Consistent with the hypothesis that these features are planned independently, target width and target height had additive effects on grasp heights. Of course, obtaining evidence for additivity means that we failed to reject the null hypothesis that the contribution of target width would be the same at all target

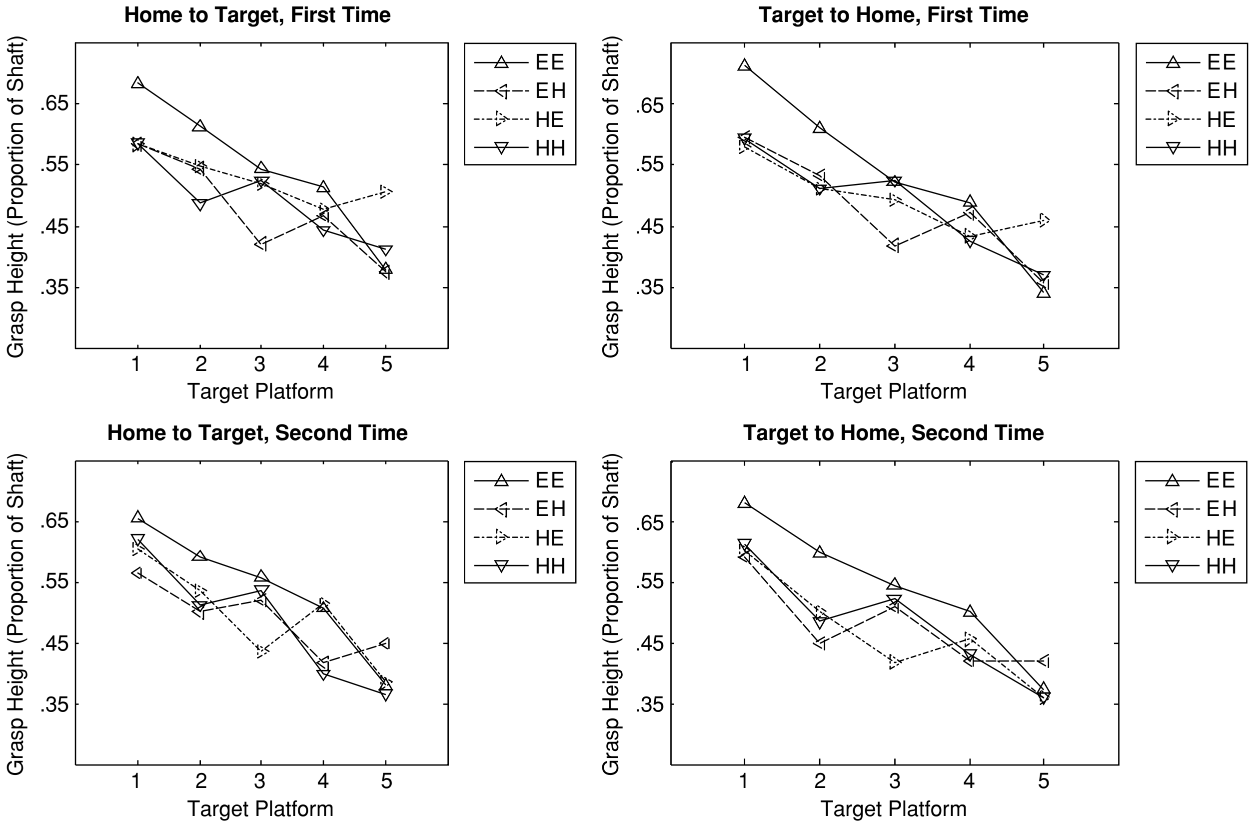

Figure 2. Grasp height, expressed as a proportion of the length of the cylinder handle, plotted as a function of target height (1 = lowest, 5 = highest) for the first home-to-target transports (top left), first target-to-home transports (top right), second home-to-target transports (bottom left), and second target-to-home transports (bottom right), when the precision requirements for lifting and lowering were, respectively, easy and easy (EE), easy and hard (EH), hard and easy (HE), and hard and hard (HH). The mean estimate of ±1 *SE* for the data points in the graph was .0316 (after removing mean differences among participants).

heights. We cannot say, however, that the null hypothesis would definitely fail to be rejected with a much larger group of participants and/or with a different combination of target heights and target widths.

A third inference concerns planning of movement starts and movement ends. As discussed in the introduction, one might expect that movement starts are planned in more detail than are movement ends because movement starts come earlier. Our data are inconsistent with this proposal, however, for we found that grasp heights were just as strongly affected by the widths of the *target* rings as by the widths of the *home* rings. This outcome indicates that the movement as a whole, or at least aspects of its start and end, was known by the time the plunger was grasped for movement.

A fourth inference concerns learning. Our data suggest that anticipation of target heights and target widths was not just learned after the first trip to and from the target. As can be seen in Figure 2, the effects of target height and target width were evident for the first home-to-target move as well as the second. Moreover, there was no main effect or interaction involving trip number. Thus, participants anticipated the demands of bringing the plunger to the different target heights and to the different target widths the first time they carried out each home-to-target move. They made no appreciable changes to their grasp heights when they performed these moves again.

A fifth inference concerns participants' knowledge of, and exploitation of, biomechanics. By grasping the plunger lower for high targets and higher for low targets, participants ensured that their joints would be at or near the middle of their ranges of motion during the object transports. This was a sensible strategy in view of the fact that greater physical power (Winters & Kleweno, 1993) and faster oscillations (Rosenbaum, van Heugten, & Caldwell, 1996) are achieved at or near the middle of a joint's range of motion than at its extremes. Similarly, grasping the plunger lower when high precision was required also made sense from a biomechanical perspective. A lower grasp height ensures that rotation of the hand, whether intended or unintended, has a smaller effect on the angle of the plunger than does a higher grasp height. This follows from the elementary fact of physics that the length of the lever arm was shorter in the low than in the high grasp height case. Our participants behaved in accordance with the principle that when it was important to carefully control the orientation of the plunger, it was better to hold it near its base than higher up. Presumably, they noticed whether either ring was narrow, and if so, they took hold of the plunger lower than they would have if they had noticed that neither ring was narrow. Similarly, they presumably noticed how high the target was and selected the plunger's grasp height with this in mind as well. One could imagine that the latter decision was made before the former, though insofar as addition is commutative, we have no basis for favoring this hypothesis over the alternative or over a model that could allow for the decisions to be made in some mixed or even random order.

A sixth inference concerns the relation between home-to-target moves and return, target-to-home moves. We included the return moves not only to study learning effects (i.e., we let participants perform each move sequence twice), but also to see whether a result obtained by Cohen and Rosenbaum (2004) would hold here as well. The previously obtained result was that participants tended to grasp the plunger for return moves close to where they grasped it for home-to-target moves. As seen in Figure 2, this pattern was replicated here and was further confirmed by the finding, reported in the Results section, that there was no significant main effect or interaction involving direction of motion (home–target or target–home). Cohen and Rosenbaum suggested that participants relied on a strategy of *generating* plans for first home–target moves in each trial and then *recalling* just-used grasp heights for subsequent moves in that trial. Such a strategy would have been computationally convenient. It is also reminiscent of the well-known view that the development of automaticity is accompanied by a switch from generation to recall of problem solutions (Logan, 1988, 2002). Discovering that the same result was obtained here adds to the generality of the grasp height recall effect, as Cohen and Rosenbaum called it, and to the generality of Logan's (1988, 2002) proposal.

A final remark concerns the implications of our results for the understanding of the Fitts (1954) aiming task. We began this article by observing that it was unclear from previous research whether the two factors that enter into Fitts's law—target distance and target width—are taken into account prior to movement initiation. We said that movement speed, which has been the main measure of performance in the Fitts task, has not resolved this issue. Consequently, we introduced a measure that has not been previously used in the study of Fitts's law to address this issue. The measure we used was grasp height, and we treated target height as a proxy for movement distance. The proxy goes only so far, however. Strictly speaking, the only way to equate target height with distance is to take the absolute value of the difference between target and home heights, appreciating that this value is proportional to the distance to be moved. Another reason to be cautious about drawing inferences about the Fitts task from our plunger transfer task is that our task was unspeeded, whereas Fitts's aiming task involved going as quickly as possible.

These reservations aside, there is reason to believe that participants in Fitts's aiming task may in fact represent target width as well as target distance prior to movement. Two recent studies support this claim. In one, participants moved objects to two targets in rapid succession (Rand, Van Gemmert, & Stelmach, 2002). The speed of the second movement was affected by the accuracy constraints of the first movement. If the first target was small, both the first and second moves were slower than if the first target was large. This suggests that the two movements were planned together. Further evidence comes from a study in which participants placed a computer cursor wherever they wished between two targets, one of which was then designated as the target to be reached as quickly as possible (Augustyn & Rosenbaum, 2005). The distance between the targets was varied, as were the widths of the targets. Participants placed the cursor between the targets almost exactly where Fitts's law would predict (i.e., closer to the smaller target by an amount related to the distance between the targets). This outcome suggests that participants were sensitive to the demands of covering different distances to targets of different widths when they prepared to move. We have reached the same conclusion here using another measure of participants' preparation for action. Evidently, recording how people prepare to move can reveal as much, or in some cases more, about their movement planning than can recording of their movements.

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