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RESEARCH ARTICLES

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Where grasps are made reveals how grasps are planned: generation and recall of motor plans

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Abstract The end-state comfort effect (Rosenbaum et al. 1990, 1992, 1993, 1996) predicts that people will grasp an object for transport in a way that allows joints to be in mid-range at the end of the transport. When participants in the present study took hold of a vertical cylinder to move it to a new position, grasp heights on the cylinder were inversely related to the height of the target position, as predicted by the end-state comfort effect. This demonstrates that *where* people grasp objects can give insight into the planning of movement. In the computational model of motor planning developed by Rosenbaum et al. (1995, 2001) it is assumed that goal postures are planned by a two-stage process of recall and generation. The distinction between recall and generation had not so far been tested. In the present study, the pattern of grasp heights in successive transports was consistent with the view that participants generated a plan the first time they moved the cylinder between two points, and that they subsequently recalled what they had done before, making small adjustments to that recalled plan. This outcome provides evidence for distinct effects of recall and generation on movement planning.

Keywords Human arm movements · Motor planning · Prehension · End-state comfort effect · Hysteresis · Sequential effects

Introduction

There has been a great deal of research on the kinematics of the hand as it moves toward to-be-grasped objects (e.g., Arbib et al. 1985; Iberall et al. 1986; Glover and Dixon 2001; MacKenzie and Iberall 1994; Jeannerod 1984; Rosenbaum et al. 2001; Wing et al. 1996). Related research has focused on the postures that are adopted when grasps are completed (Marteniuk et al. 1987; Rosenbaum et al. 1990, 1992, 1993, 1996; Stelmach et al. 1994), and on the forces that are applied to objects once the objects have been grasped (Forssberg et al. 1992). This research has indicated that people alter their behavior in anticipation of future task demands. For example, Jeannerod's seminal studies (1984) indicated that the arm, hand, and fingers move toward objects to be grasped in ways that are sensitive to the position, size, and orientation of the objects. Marteniuk et al. (1987) showed that the way people pick up objects depends on how the objects will be used. Similarly, people pick up a dowel with the thumb pointing to one end or the other depending on how they will orient the dowel after moving it to a new location (Rosenbaum et al. 1990, 1992, 1993, 1996).

Such demonstrations reveal that planning plays a role in grasping objects. All of the demonstrations pertain, however, to how the hand is oriented or shaped to grasp the object rather than to where the object is grasped. Surprisingly, there has been little research on the question of where actors place their hands on objects they grasp depending on what the objects are, where the objects are located, where the objects will be placed, and for what purpose it will be moved. The current research focuses on grasp location and pursues two hypotheses. The first is that identifying where people grasp objects may provide useful data about action planning. The second concerns the nature of the cognitive processes underlying the formation of plans for prehension.

Two kinds of cognitive processes can be said to underlie the formation of plans for action (prehension or otherwise). One is based on generation. The other is based on recall. The distinction between generation and recall is well known in mathematical problem solving. The first few times one encounters a mathematics problem, such as finding the product of 12 times 12, one may generate the answer by applying a series of rule-based operations. Later, however, one may simply recall that the product is 144 and give that answer in the form of pre-stored proposition. Cognitive psychological studies of skill acquisition indicate that the switch from generation to

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recall is a common concomitant of the growth of automaticity (Logan 1988, 2002).

The distinction between generation and recall may also apply to motor planning. When one has to carry out some physical action, such as taking hold of an object to be moved from one place to another, one may determine how to carry out the action through recall of an action that was performed in the same circumstance or through generation of a new plan. When a plan is recalled, the actor may simply remember how the action was previously performed and then perform (or try to perform) it the same way again. By contrast, when a plan is generated, the actor may rely on internal models to determine which movements should be performed in order to achieve desired perceptual consequences (e.g., Blakemore et al. 2002; Miall and Wolpert 1996; Wolpert and Flanagan 2001). Generating plans has the advantage of allowing for adaptive performance in novel circumstances, and the capacity for generating plans by relying on internal models has been demonstrated in studies that have tested participants' capacity to generalize from familiar to unfamiliar tasks (e.g., Conditt et al. 1997). Recalling plans, by contrast, has the advantage of allowing for rapid responses and potentially freeing up cognitive resources (i.e., recalling plans may take less attention than recalling them).

Despite the growing body of evidence for internal models, it is unclear how and whether recall and generation can occur for the same perceptual-motor task. Following Logan (1988), it is reasonable to hypothesize that after a perceptual-motor task is performed via plan generation, it can later be performed via plan recall. We are unaware of any direct evidence for this hypothesis, but we are interested in testing it because in the computational model of motor planning developed by Rosenbaum et al. (2001) it is assumed that goal postures are planned by a two-stage process of recall and plan. In the first stage, previously adopted goal postures are recalled and evaluated for their suitability for the task at hand, and one is chosen as "best." In the second stage, if more planning time is available, the most promising recalled goal posture for the task at hand is modified or "tweaked" to see whether an even better goal posture can be generated. Details concerning the procedures and their rationale, which (for reasons of convenience) so far apply only to kinematics, can be found in Rosenbaum et al. (2001) and in Jax et al. (2003). The two-stage process of recall and generation of goal postures proposed by Rosenbaum et al. (2001) differs somewhat from the earlier scheme for goal-posture planning suggested by Rosenbaum et al. (1995). In the earlier model, previously adopted goal postures were recalled, and the subsequent generation process consisted of taking a special weighted average of the remembered goal postures. The reasons for the change from weighted averaging to "tweaking" of the most promising recalled goal posture are given in Rosenbaum et al. (2001) and are unimportant here. What is important is that both versions of the model assumed a distinction between recall and generation. Testing that distinction was a primary aim of the present experiments.

Experiment 1

We concentrated on an everyday task that we thought would be sensitive to participants' psychological and physical states. We asked participants to reach out and take hold of a vertical cylinder that was to be moved between platforms of varying height (see Fig. 1). Because we were interested in participants' planning, we made sure participants knew the location to which the cylinder would be moved before they initiated each reach. The main dependent variable was where along the length of the cylinder the hand was placed when the cylinder was grasped. We called this measure the *grasp height*.

In the first experiment (see Fig. 1), participants transported a vertical cylinder between a home platform and each of five target platforms of varying height. The home platform was to the participants' left, and the five target platforms were directly in front of where the participants stood. For each target platform, participants performed a sequence of four object grasps: (1) they reached out and grasped the cylinder at the home position to move it to the target position; (2) after moving the cylinder to the target position and then lowering the hand, they then reached out and grasped the cylinder again, this time moving it from the target position back to the home position; (3) next, after lowering the hand again, they again took hold of the cylinder to bring it from the home to the target position; (4) finally, after lowering the hand again, they took hold of the cylinder for the fourth time to bring the cylinder from the target position back to the home position for the last time, whereupon they released it. It is important to be clear that each transport maneuver consisted of three distinct submoves of the hand: (a) the hand moved from its resting position by the side of the

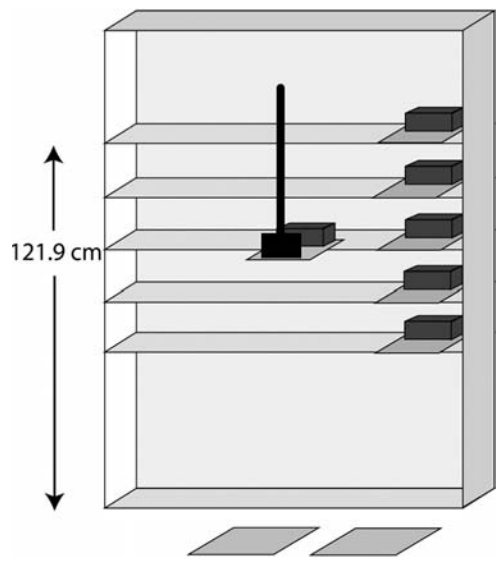

Fig. 1 Experimental setup

body to grasp the cylinder, then (b) the hand carried the cylinder to its destination, and finally (c) the hand returned to rest by the side of the participant's body.

The home platform was at the same height in all conditions (about stomach level for most participants). By varying the heights of the target platform and by using two successive round trips between the home platform and each target platform, we could test different hypotheses about planning in this situation. The two main hypotheses of interest differed with respect to their claims about recall and generation of motor plans. According to one hypothesis, motor planning relies only on plan generation. According to the other hypothesis, motor planning relies on plan recall as well as plan generation. (The hypothesis that planning relies only on recall could not be tested, at least for first grasps, since there was no way to know what actions participants performed before entering the laboratory.)

Based on prior research showing that people typically take hold of objects in an awkward posture when this enables them to complete object transports in less awkward or more comfortable final postures (Rosenbaum et al. 1990, 1992, 1993; Short and Cauraugh 1997, 1999; Steenbergen et al. 2000; Hermsdörfer et al. 1999), we expected participants to grasp the cylinder at the home position in a way that would enable them to end in a relatively comfortable posture at the target position. Because extreme joint angles are uncomfortable (see Rosenbaum et al. 1993; Rossetti et al. 1994, for psychophysical evidence), this meant that participants would use low grasp heights for high targets and high grasp heights for low targets. Such an inverse relation between grasp height and target height would allow the arm to end at or near the middle of its range of motion when the cylinder was brought to the target positions.

The key question regarding the two planning hypotheses concerned the second move, bringing the cylinder back from the target position to the home position. If participants relied only on generation of motor plans, then at the target position, before returning the cylinder back to its home site, they would use the single grasp height that would afford a comfortable end posture back at the home position. In other words, the grasp height on the cylinder would be the same at all target positions, namely, the grasp height that ensures end-state comfort back at the fixed home position. By contrast, if participants relied on recall as well as generation, they would vary the grasp height at the target positions so those grasp heights would approximate the ones used to bring the cylinder from the home position to the target positions. In other words, participants would *recall* where they had previously grasped the cylinder when they brought the cylinder from the home position to the target position. That first grasp was presumably based on plan generation. The second grasp would be based mainly on recall. If this prediction were confirmed, the outcome would violate the end-state comfort effect, making this a strong prediction, insofar as the end-state comfort effect has proven to be robust (see above references).

Method

Participants

The ten participants were graduate students and faculty who volunteered to participate. All characterized themselves as right-handed and neurologically healthy, and all were naive to the purpose of the study. They ranged in age from 18 to 38 years. All were tall enough to comfortably reach the top of the cylinder when it was on the top platform. Each participant was tested individually. The Penn State University Institutional Review Board approved the experiment, and the rights of all participants were protected.

Procedure and materials

After filling out an informed consent form, the participant was asked to stand on a rectangular piece of paper (21.6 cm by 27.9 cm) that was taped to the floor with its long side parallel to the front edge of a bookshelf and 30.5 cm from this front edge. The bookshelf was empty except for the five platforms used in this study (see Fig. 1).

To the left of the participant, a wooden platform, 86.4 cm above the floor, extended 13 cm from the middle shelf. This platform served as the *home shelf*. On it stood a wooden cylinder, 23 mm in diameter and 51 cm in length. The cylinder had a sturdy rubber base, 13 cm in diameter and 8 cm high. Two bricks lay on the platform behind the cylinder to counterbalance the weight of the cylinder and rubber base. The mass of the cylinder was 135 g, and the mass of the rubber base was 178 g.

On each of the five shelves directly in front of the participant lay a wooden platform like the one holding the cylinder. These five wooden platforms, when not in use, were slid in so their front edges (the edges facing the participants) were flush with the edge of the bookcase. When one of the wooden platforms was pulled out toward the subject (13 cm, like the home shelf), it became the *target shelf*. Two of the target shelves were lower than the home shelf, one was at the same height as the home shelf, and two were higher than the home shelf. The heights of the wooden shelves were 50.8 cm, 68.6 cm, 86.4 cm, 104.1 cm, and 121.9 cm above the floor.

Participants were told that we were making a video for a later experiment on memory of observed action sequences. According to the cover story, we needed the videos so we could show future participants series of actions to remember. We told the participants this cover story to encourage them to perform without being self-conscious of how they took hold of and moved the cylinder. This instruction was important because an analog video camera stood on a tripod to the left of the bookshelf, in full view of the participants. The camera's lens was at the same height as, and focused on, the home platform.

Once the participant stood on the paper, the experimenter pulled out one of the five target platforms. The participant was then given instructions on how to perform. Under the pretext that the performed actions would need to be uniform for the later video, participants were asked to keep their left hands by their sides at all times and to keep their right hands by their sides until they were told where to place the cylinder. They were asked to take hold of the cylinder with the right hand and to move it to its next placement site, then to set the cylinder's base down on that site, and then to return the hand to the side of the body (i.e., let it hang down). Participants were asked to perform in a relaxed manner, moving at a comfortable speed. At the same time, they were asked to hold the cylinder securely enough that it would not slide down through their fingers when they held it.

As mentioned earlier, at the start of the first trial, the cylinder rested on the home shelf, which was on the participant's left side. When the participant was told, "Please move the cylinder," he or she reached out and took hold of the cylinder with the right hand, moved it from the home shelf to the target shelf, and then returned the hand to his or her side. The experimenter then said, "Please bring it back," whereupon the participant reached out and grasped the cylinder, returned it to the home site, and returned the hand to his or her side. The next two events were the same: The experimenter instructed the participant to move the cylinder to the target platform, then to bring his or her hand to his or her side, then to return the cylinder to the home shelf, and then to lower his or right hand to his or her side once again. The experimenter carefully monitored the participant's performance and reminded him or her of the instructions if necessary.

When the first four events were completed, the experimenter pushed the first target shelf back into the bookcase and, consulting a previously prepared design sheet, pulled out the next target shelf, whereupon the sequence of four events (home to target, target to home, home to target, and target to home) was repeated. This cycle of four events was subsequently repeated for each of the three remaining target shelves.

After all five target shelves were used, the experimenter debriefed the participant. The entire session took about 15 min.

Design

The order of target shelves was balanced over participants. The design ensured that each target shelf was tested in each serial position equally often. Such a design required five participants. Ten participants were tested so the full design could be tested twice.

Off-line video analysis

Because each participant's performance was captured on videotape, it was possible to estimate grasp heights from the video records. The plan for the analysis was to record the position of the hand on the cylinder at the home position at two critical moments in each transport cycle: (1) when the participant took hold of the cylinder to carry it to the target position; and (2) when the participant returned the cylinder from the target position and set it down on the home shelf. Given the instruction that participants received not to let the cylinder slide in their hands (which was carefully checked during performance), we assumed that the position of the hand on the cylinder when it was returned to the home position was the same as the position of the hand on the cylinder when the cylinder was first grasped at the target position. Measuring the grasp position at the same place for every movement promoted standardization of measurement.

To assess the grasp heights, we used a video playback device that permitted frame-by-frame inspection of individual video frames. The experimenter froze the frame of interest for each measurement and then measured the distance from the bottom of the cylinder to the judged point of thumb contact on the cylinder. A second measure, taken for each frozen frame, was the length of the cylinder. This measure was taken as an extra precaution, because the distance of the cylinder from the camera lens could vary slightly from trial to trial if the participant did not set the base down exactly on the middle of the platform every time. We divided the distance from the bottom of the cylinder to the central point of thumb contact by the distance from the bottom of the cylinder to the cylinder's top. Then, to express the grasp height in centimeters from the floor, the known length of the cylinder was multiplied by the ratio obtained in the preceding step and that value (in cm) was added to the height of the home shelf.

Results and discussion

Informal inspection of the videos revealed that participants mainly accomplished the cylinder transports by moving their right hands, elbows and shoulders, with just a small amount of twisting of the torso. Participants did not adopt postures that entailed significant bending of the hips, knees or ankles, or raising the right clavicle. The correlation between subject height and mean grasp height was positive (r=.347).

We analyzed the grasp height data (see Fig. 2) by conducting an analysis of variance (ANOVA) that evaluated the effects of target shelf height (1–5) × direction (home to target or vice versa) × repetition (first time or second), in a repeated measures design with α set to .05. There was a main effect of target shelf height, $F_{(4,36)}$=13.20, p<.001, and a main effect of repetition, $F_{(1,9)}$=6.84, p=.028.[1] The mean grasp height for the first repetition was 120.6 cm and the mean grasp height for the second repetition was 122.5 cm. The interaction between target shelf height and direction approached but did not reach statistical significance, $F_{(1,9)}$=2.44, p=.065. The p values for all other interactions exceeded .50.

Figure 2 shows the mean grasp heights as a function of target shelf height for both the home-to-target conditions and the target-to-home conditions.[2] All the grasp positions were above the center of mass of the cylinder plus base. As shown in Fig. 2, grasp height was inversely related to target shelf height. When we fitted straight lines to the mean values in these conditions, we found that the slopes of the best-fitting straight lines were −0.15 for the home-to-target movements and −0.09 for the target-to-home movements. All four slopes differed significantly from zero, as shown in Table 1. Table 1 also displays the associated intercepts and correlations. The correlation

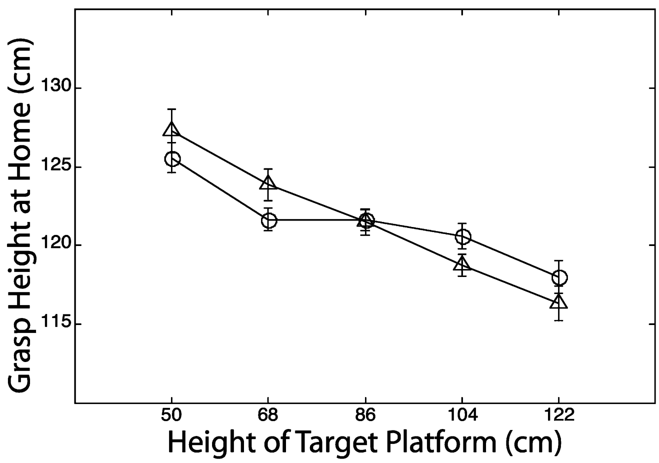

Fig. 2 Mean grasp heights as a function of target shelf height for home-to-target grasps (*triangles*) and target-to-home grasps (*circles*) in Experiment 1. Estimates of ±1 SE reflect between-subject differences after grand mean differences among subjects were removed

[1] We did not predict a main effect of repetition in any of our hypotheses. Since this effect did not recur in subsequent experiments, we consider it a statistical artifact.

[2] Figure 2 does not show first-time and second-time transports separately even though the ANOVA yielded a significant repetition effect. The reason for not showing the two transports is that the repetition effect was small and not replicated in subsequent experiments. We averaged over first- and second-time grasp heights in each direction of movement here to make this figure comparable to the analogous figures for Experiments 2 and 3.

between mean home-to-target grasp heights and mean target-to-home grasp heights was .95.

These data are consistent with the hypothesis that grasp heights can provide useful data about action planning. Consistent with previous research demonstrating the end-state comfort effect, we found that when participants grasped the cylinder to move it from the home position to the target positions, grasp heights at the home position were inversely related to the heights of the target shelf. This is what would be expected if participants generated plans that enabled them to complete the home-to-target moves in relatively comfortable (or easy-to-control) postures (see Rosenbaum et al. (1996) for evidence on controllability versus comfort of final postures).

The data also bear on the recall hypothesis. Consistent with this hypothesis, the grasp heights for the return, target-to-home moves did not ensure end-state comfort. That is, even though the home position was fixed and so should have resulted in the same grasp height upon completion of target-to-home moves, grasp heights for the target-to-home moves were very similar to the grasp heights for the home-to-target moves. This outcome accords with the hypothesis that participants would rely on recall to select grasp heights.

Experiment 2

The aim of the second experiment was to replicate and extend the findings of Experiment 1 to a wider range of conditions. In Experiment 1 participants reached across their body midlines to take hold of the cylinder at its home position. They also placed the cylinder at its target positions in front of their body midlines. Therefore, the hand had to travel a greater distance from its resting position to the initial grasp location than it had to travel from the target location back to the rest position. Inspection of the video reveals that many participants had to twist their torsos slightly to accomplish the first submove. It was possible that the need to reach farther for the first submove could have influenced the initial grasp height, making "initial-state effects" (the relative priority of keeping joints closer to neutral position at the beginning of a transport) stronger than they would have been otherwise. Considering these effects, we reasoned that by changing the location of the home and target platforms, we might be able to influence the home-to-target and target-to-home slopes differentially. We predicted that when participants had to reach across their bodies to the target instead of to the home, end-state effects would be enhanced relative to initial-state effects. In order to balance the experiment, we also included two conditions in which participants did not have to reach across their bodies. We predicted that in these two conditions the results would be in between the results of the other two. We also predicted that the *general* pattern of results would be the same as in Experiment 1, with relatively minor deviations among the different conditions.

Experiment 2 had four conditions (see Fig. 3). The home shelf was either to the left or to the right of the target shelves, and participants stood either in front of the home shelf or in front of the target shelves. Given that all participants in Experiment 2 used their right hands (as was true in Experiment 1), the design ensured that participants in the second experiment either reached across their body midlines (conditions A and C, depicted in panels A and C) or did not reach across their body midlines (conditions B and D, depicted in panels B and D). In Condition A, they crossed their body midline in the first submove, and in Condition C they crossed it in the second submove. The first submove in Condition B was of roughly the same amplitude as the first submove in Condition D, and the same was true for the second submove. We reasoned that if the results of Experiment 1 were affected by reaching across the body midline, we would obtain analogous results only in condition A. Conditions B and D, in contrast, would lead to relatively steeper slopes for the initial movement than for the return, and Condition C would lead to an even steeper slope.

Method

Participants

Forty Penn State University undergraduates participated in exchange for course credit. All were right-handed, neurologically healthy, and naive to the purpose of the study. In addition, all were tall enough to comfortably reach the top of the cylinder when it was on the top platform.

Table 1 Slopes, intercepts, and correlations (*r*) for best-fitting straight lines relating grasp height (cm) to target height (cm) in home-to-target tasks and target-to-home tasks within the conditions tested in Experiments 1, 2, and 3

Experiment	Condition	Home to target			Target to home		
		Slope	Intercept	*r*	Slope	Intercept	*r*
1	A[a]	−.15	134.44	−.998*	−.09	129.21	−.940**
2	A	−.17	138.07	−.995**	−.12	132.71	−.951**
	B	−.10	129.30	−.976**	−.04	123.95	−.697*
	C	−.17	136.93	−.976**	−.11	130.88	−.987**
	D	−.16	137.59	−.992**	−.11	132.46	−.934**
3	A	−.04	127.11	−.692*	−.11	133.16	−.962**
	B	.00	119.50	.006	−.07	126.09	−.878**
	C	−.12	130.81	−.953**	−.17	135.25	−.975**
	D	−.00	122.98	−.091	−.15	136.84	−.973**

[a]The one condition tested in Experiment 1 was identical to condition A of Experiment 2 and is referred to as condition A for comparison purposes

*p<.05, two-tailed test

**p<.01, two-tailed test

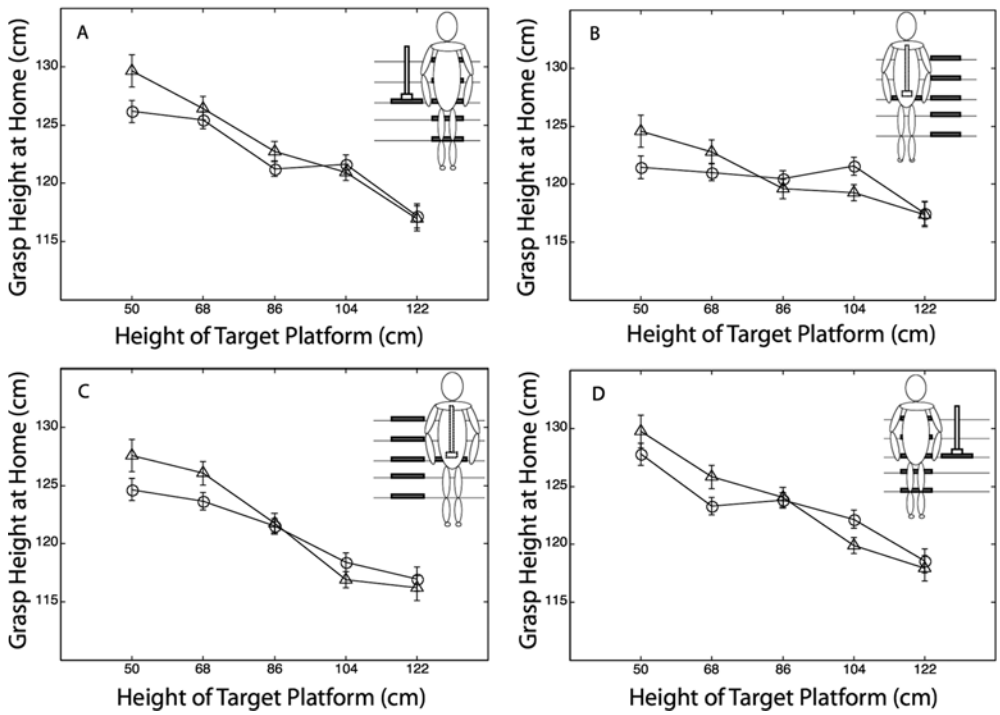

Fig. 3A–D Mean grasp heights as a function of target shelf height for home-to-target grasps (*triangles*) and target-to-home grasps (*circles*) in Experiment 2. **A–D** correspond to the four conditions in the experiment. Estimates of ±1 SE reflect between-subject differences after grand mean differences among subjects were removed

Design and procedures

The design was the same as in the first study, except that there were four between-subject conditions. Ten participants were randomly assigned to each condition.

Off-line digital video analysis

To increase precision of measurement, the analog video camera used in Experiment 1 was replaced with a digital video camera. After the experiment, digital video stills were transferred to a computer. The digital video camera was plugged into the serial port of the computer and also into a TV monitor so the images could be viewed on a larger screen. Images were selected for storage on the hard drive of the computer using the interactive program JLIP Video Capture (Multimedia Navigator, Inc.). The saved images corresponded to the

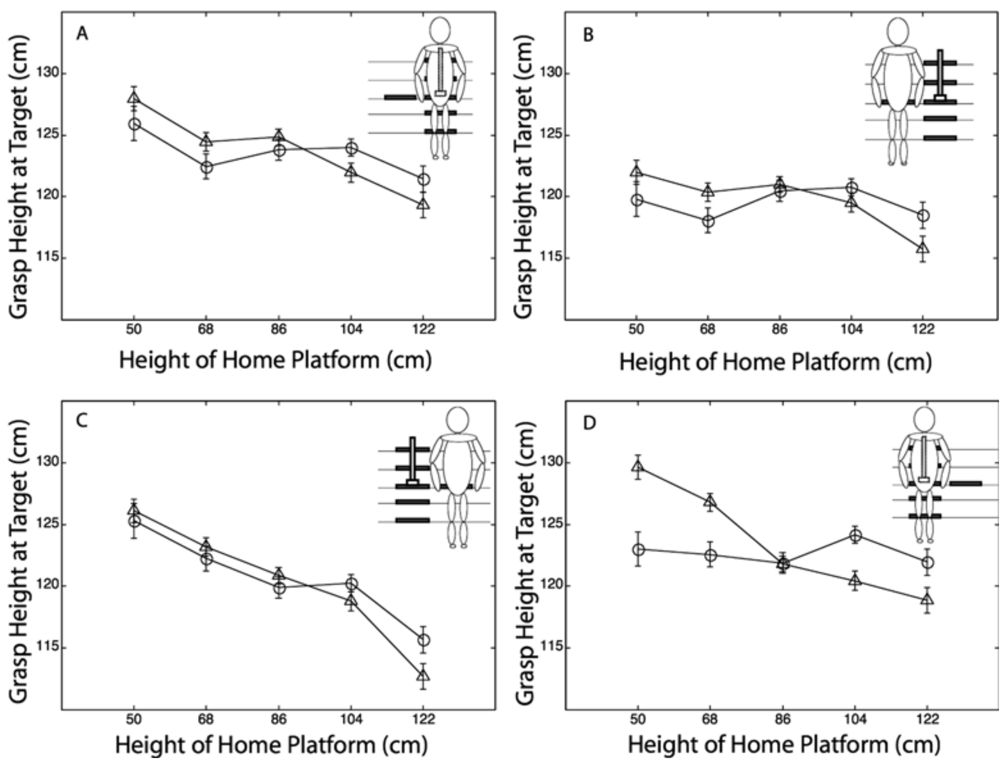

Fig. 4A–D Mean grasp heights as a function of target shelf height for home-to-target grasps (*triangles*) and target-to-home grasps (*circles*) in Experiment 3. **A–D** correspond to the four conditions in the experiment. Estimates of ±1 SE reflect between-subject differences after grand mean differences among subjects were removed moment when the subject lifted the cylinder from the home platform and the moment when the subject returned the cylinder to the home platform from the target. Twenty images were obtained for each subject. These corresponded to the four events for each of the five movement sequences. The individual picture files were stored in JPEG format and used to estimate grasp heights. A research assistant used a computer mouse to click on three locations in each image: (1) the bottom of the cylinder; (2) the top of the cylinder; and (3) the judged point of contact between the subject's thumb and the cylinder. A program written in Matlab (Mathworks, Inc.) was used to record the click locations and to estimate the proportion of the cylinder length at which the thumb made contact with the cylinder.

Results and discussion

Overall, the results of Experiment 2 (see Fig. 4, Table 1) were similar to those of Experiment 1. The correlation between subject height and mean grasp height was positive (r=.271). More importantly, as in Experiment 1, grasp heights at the home position decreased as the height of the subsequent target position increased. As seen in Table 1, the negative correlation between grasp height at the home position and the height of the subsequent target position was statistically significant in each condition of Experiment 2. This outcome confirms the hypothesis that end states would be anticipated prior to moving the cylinder from the home position to the target positions.

Grasp heights at the target position also decreased as the height of the current target position increased. As seen in Table 1, the negative correlation between grasp height at the target position and the height of the target position was statistically significant in each condition of Experiment 2. This finding replicates what was found Experiment 1 and again corroborates the hypothesis that plan recall as well as plan generation plays a role in grasp height selection. In Experiment 2, as in Experiment 1, grasp heights for the target-to-home moves were correlated with grasp heights for the home-to-target moves. The correlations between mean home-to-target grasp heights and mean target-to-home grasp heights were all positive: .97, .68, .99, and .94 in conditions A-D, respectively.

Table 1 and Fig. 4 reveal other features of the grasp height data that bear notice. First, the slopes were steeper for home-to-target grasps than for target-to-home grasps. This difference was also present in Experiment 1, although it was not statistically significant there. In Experiment 2, the difference was statistically significant, as reflected in a shelf × direction interaction, $F_{(4,144)}$=17.14, p<.001. The statistically steeper slope for home-to-target grasps than for target-to-home grasps suggests that plan recall, if it occurred, was systematically modified in favor of end-state comfort. Recall that if end-state comfort had completely dominated grasp height choices for target-to-home moves, there would have been no effect at all of target height on grasp height since the home position had a fixed height. This outcome suggests that the grasp height choices for the target-to-home moves were based on a combination of recall and generation. In deciding how to grasp the cylinder for the target-to-home moves, participants apparently recalled where they had most recently grasped the cylinder (or what posture they had adopted) but modified that recalled posture to accommodate, at least partly, the demands of end-state comfort. This interpretation is consistent with the hypothesis that recall as well as generation led to grasp height choices. Moreover, this claim is consistent with the two-stage planning scheme of the posture-based motion planning theory of Rosenbaum et al. (2001).

One other notable feature of the grasp height data shown in Fig. 4 and Table 1 is the general absence of differences among conditions, including the absence of repetition effects (i.e., first home-target-home cycles were statistically indistinguishable from second home-target-home cycles. To a first approximation, the conclusions stated above applied to all the conditions tested. Table 1 did show one difference that was not predicted: the slopes were somewhat flatter in condition B than in any other condition. We note this effect but observe that it was not supported by relevant statistical tests. Neither the shelf × condition interaction nor the shelf × direction × condition interaction was significant.

Experiment 3

In the third experiment we tested an alternative interpretation of the results of Experiments 1 and 2. In those experiments we argued that the reason grasp heights for target-to-home moves were similar to grasp heights for home-to-target moves was that participants relied on recall as well as generation of motor plans. An alternative interpretation is based on the *range effect*. For behavioral experiments with a range of conditions, within-subject designs (in which participants experience all conditions) tend to produce bigger differences than between-subject designs (in which participants do not experience different conditions). A similar phenomenon could explain our results. In Experiments 1 and 2 the target positions had variable heights but the home position had a fixed height. The range effect would predict that participants would assign greater priority to comfort at the variable positions than to comfort at the fixed position. Although previous studies of object grasps have shown that participants consistently prioritize end-state comfort over initial-state comfort, none of those studies had the imbalance of fixed and variable conditions that was present in Experiments 1 and 2. Therefore, we take the alternative interpretation seriously.

To investigate the alternative account of the results of Experiments 1 and 2, in the third experiment we simply reversed the mapping of fixed versus variable heights to home versus target positions (Fig. 4). Thus, in contrast to Experiments 1 and 2, we used variable-height home positions and a fixed-height target position in Experiment 3. The predictions were straightforward. If the pattern of results in Experiments 1 and 2 stemmed from participants assigning greater priority to comfort or control at variable than at the fixed positions, they should vary their grasp heights as much for the variable home positions in

Experiment 3 as they did for the variable target positions in Experiments 1 and 2. Similarly, they should vary their grasp heights as little for the fixed target position in Experiment 3 as they did for the fixed home position in Experiments 1 and 2. On the other hand, if the pattern of results in Experiments 1 and 2 stemmed from participants using end-state-comfort-based generation for home-to-target moves and recall plus end-state-comfort-based modification for subsequent target-to-home moves (as we suggested above), we should see a strong end-state comfort effect for the home-to-target moves and evidence of recall effects for the subsequent target-to-home moves. Thus, we should find an essentially flat function relating grasp height to home height for home-to-target moves and an almost flat function for the return moves.

Method

Participants

Forty Penn State undergraduates were drawn from the same pool used for the previous experiments. None had been in either of the previous experiments. All participants were right-handed, neurologically healthy, and naive to the purpose of the study. All were tall enough to reach the top of the cylinder when it was placed on the top platform.

Design and procedure

The design was the same as in Experiment 2 except that the home platforms had variable heights and the target platform had a single height (see Fig. 4). As in the second experiment, standing position and side of home or target shelves varied between participants. The assignment of participants to groups was random except for the restriction that ten participants were assigned to each group.

Off-line digital video analysis

The data were analyzed in the same way as in Experiment 2.

Results and discussion

As in Experiments 1 and 2, the correlation between subject height and mean grasp height was positive (r=.415), and first home-target-home cycles were statistically indistinguishable from second home-target-home cycles. The more detailed results are shown in Fig. 4, with the corresponding statistics concerning the best-fitting straight lines for the grasp height data shown in Table 1. As in Experiments 1 and 2, grasp heights were high when the variable shelf was low, and grasp heights were low when the variable shelf was high. An ANOVA revealed a significant main effect of variable shelf height $F_{(4,144)}$=21.05, p<.001, and a significant interaction between variable shelf height and direction, $F_{(4,144)}$=12.81, p<.001, such that the effect of shelf height was greater for the target-to-home moves than for the home-to-target moves. This finding strengthens the conclusion that end states were emphasized more than initial states and goes against the range-effect interpretation of the previous results.

Another finding that goes against the range-effect interpretation and strengthens the recall interpretation relates to the prediction of an essentially flat function relating grasp height to home height and that same flat function for subsequent target-to-home moves. We tested this prediction by comparing the results of Experiment 3 to those of Experiment 2, testing for experiment interactions using an ANOVA design. Such a design was possible because Experiments 2 and 3 had essentially the same setup, the only difference being the "phase shift" in the home-to-target or target-to-home moves. The ANOVA showed that the interaction of shelf height, direction of movement (fixed to variable position versus variable to fixed position), and experiment was significant, $F_{(4,312)}$=26.49, p<.001. The slopes for the variable-to-fixed moves in Experiment 3 were shallower than the slopes for the variable-to-fixed moves in Experiment 2, as predicted by the recall hypothesis. The slopes for these movements ranged from 0 to −.09 (mean=−.04) in Experiment 3 but ranged from −.04 to −.12 (mean=−.10) in Experiment 2. In addition, the slopes for the moves from fixed to variable positions in Experiment 3 (the moves back to the home position) were shallower than the corresponding slopes in Experiments 1 and 2. In the third experiment these slopes ranged from −.07 to −.17, with a mean of −.125, whereas in the first two experiments the corresponding slopes ranged from −.10 to −.17, with a mean of −.15. The latter finding is consistent with the recall hypothesis, as is the fact that in Experiment 3 the correlations between mean home-to-target grasp heights and mean target-to-home grasp heights were all positive: .82, .42, .98, and .12 in conditions A–D, respectively.

One aspect of the result that is not perfectly consistent with the recall hypothesis is that the grasp heights for the home-to-target moves varied somewhat as a function of home height. That is, the function relating grasp height to home platform height had a slope different from zero (see Fig. 4, Table 1). This outcome indicates that there was some role of initial-state comfort in this study. In this connection, it is notable that shelf height had a greater effect on grasp height in condition C than in any of the other three conditions, as confirmed in a statistically significant shelf height × condition interaction, $F_{(4,144)}$=3.00, p<.05.[3] In condition C, the first submove (bringing the hand to the cylinder at its home position) involved twisting the body and reaching up or down. No

[3] The ANOVA revealed two other interactions: (1) direction × repetition, $F_{(1,36)}$=4.50, p<.05; and (2) repetition × condition, $F_{(3,36)}$=3.3, p<.05. However, when we compared individual points with the best-fitting lines through the remaining four points for every subject, direction, and repetition, we found that 8 points out of 800 were more than 3.5 standard deviations away from the best-fitting, theoretical value on the line. When each of these outliers was removed and replaced with its corresponding theoretical point on the line, both of the foregoing interactions disappeared. Based on this outcome, we considered these two interactions to be statistical artifacts.

other condition in this experiment involved such a large twisting and vertical motion combination for the first submove. It is possible that when such a large motion was required, participants assigned more weight to initial-state comfort than they did otherwise. This fits with the observation, mentioned at the start of this paragraph, that participants assigned some priority to initial-state comfort in all the conditions of Experiment 3. It is not surprising that when the first submove is large, the need to end that first submove comfortably may be greater than when it is small. Being able to flexibly modulate emphasis on initial-state versus end-state comfort is presumably important for adaptive performance even if, in general, more weight is assigned to end-state comfort than to initial-state comfort.

General discussion

In the three experiments reported here, we tested two main hypotheses—first, that grasp placement would change as a function of where one planned to move an object, and, second, that motor plans are recalled as well as generated. Our participants grasped a cylinder with the goal of moving it to one of several positions that varied principally with respect to height. We found that the higher the position to which the cylinder would be moved, the lower it was grasped. This grasp-height effect was replicated in three experiments and across a range of movement directions, confirming our first hypothesis. When subjects returned the cylinder to its former site, they usually took hold of it close to where they had grasped it in the immediately preceding move, confirming our second hypothesis.

Our interpretation of the grasp-height data is similar to the interpretation given in earlier object-transport studies that focused on the postures people adopted when taking hold of to-be-moved objects. Those studies, which relied solely on the likelihood of orienting the hand one way or the other when taking hold of an object, showed that people generally adopted initially awkward postures for the sake of more comfortable or more easily controlled final postures (Rosenbaum et al. 1990, 1992, 1993, 1996). The present results, like the earlier ones, suggest that actors skillfully anticipate the positions they will adopt upon completing object transport movements. This capacity was reflected here in our subjects' tendency to adopt grasp heights that enabled them to complete object transports in comfortable or easily controlled postures (i.e., postures that kept the joints at or near the middle of their rotation ranges).

The evidence that actors anticipate final postures was strongest in Experiment 3, where participants altered grasp heights very little in taking hold of the cylinder at home positions of different heights before moves to a target of fixed height. Even in Experiment 3, however, there was some concern for initial comfort, as reflected in grasp-height functions whose slopes differed from zero. We note in connection with this last finding that it would be odd to suggest that only end states are taken into account in motor planning. It makes more sense to think that people can flexibly modulate the priority they give to one factor or the other. That end-state comfort usually triumphs over initial-state comfort in the studies done so far indicates that the span of motor planning typically extends to two submoves rather than one. It does not follow from this observation, however, that if a participant wished to focus on just one submove at a time he or she could not, nor does it follow that if, for a particular series of object transports, a participant adopted a comfortable grasp at the end of the first submove, this would necessarily result in an uncomfortable grasp at the end of the second submove. Whether a comfortable initial state leads to an uncomfortable end state depends on the particular submoves that must be performed. Indeed, it is possible that one would see greater emphasis on initial-state comfort than on end-state comfort if more precision were required to pick the cylinder up than to set it down. See Rosenbaum et al. (1996) for an analogous demonstration involving hand orientation.

With respect to the cognitive processes underlying object-transport control, the present study provided evidence for the hypothesis that motor plans are recalled as well as generated. When subjects returned the cylinder to where it had just been, they tended to take hold of it close to where they had grasped it before. This strategy was computationally efficient, for if a grasp was effective in bringing the cylinder from one position to another, it would have been reasonable to expect the same grasp to work for bringing the cylinder back again. Detailed analysis of our grasp-height data indicates that grasp heights for return moves were close to but not exactly where they had been for immediately preceding moves. This could mean that participants failed to recall exactly where they last grasped the cylinder. However, the differences between grasps for initial and return transports were not random. There was a clear indication that the return movements were altered in the direction of increasing end-state comfort, consistent with the theory of motor planning that set stage for the present work (Rosenbaum et al. 2001). The present data do not allow us to assert that goal postures per se were recalled as opposed to locations on the cylinder. The latter issue could be addressed by asking participants to change position vis-à-vis the cylinder before returning it to the home position (e.g., by stepping up on a platform). This issue aside, the present study adds to the body of evidence that a given motor act may change both as a function of what motor act will follow it—a sign of planning—and as a function of what motor act preceded it (de Lussanet et al. 2001, 2002)—a sign of memory. Finding that participants use plan recall as well as plan generation to determine how to grasp objects shows that retrospective and prospective influences work hand in hand in the planning of manual behavior.

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