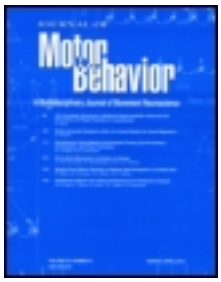

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RAPID COMMUNICATION

The Influence of Initial and Final Precision on Motor Planning: Individual Differences in End-State Comfort During Unimanual Grasping and Placing

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ABSTRACT. People will often grasp an object with an uncomfortable initial grasp if this affords more comfort at the end of the movement. The authors' primary objective was to examine whether grasp planning is influenced by precision demands at the start and end of the movement. Twenty right-handed individuals performed a unimanual grasping and placing task in which the precision requirements at the start and end of the movement were either identical (low initial and final precision, high initial and final precision) or different (low initial and high final precision, high initial and low final precision). The major finding to emerge was the presence of individual differences. 50% of participants changed their initial grasps based on the precision requirements of the task, and were more likely to satisfy end-state comfort when the final precision requirements were high than when they were low. In contrast, 50% of participants generally planned their movements to satisfy end-state comfort (regardless of precision requirements). The authors hypothesized that the former group of participants was sensitive to the precision demands of the task, and participants planned their grips in accordance with these demands. In contrast, the latter group of participants reduced the cognitive costs by using previously successful grasp plans.

Keywords: end-state comfort, grasping, individual differences, precision

There is strong evidence that the hand postures used to grasp objects are particularly sensitive to future actions and task goals. For example, Rosenbaum et al. (1990) asked participants to grasp a horizontally positioned bar and place it in a vertical position in either a left or right target. The left side of the bar was painted black, and the right side of the bar was painted white. When the left side of the bar was to be placed in either the left or right target, all participants grasped the bar with an underhand grip. However, when the right side of the bar was to be placed to either target, participants always grasped the bar with an overhand grip. Thus, regardless of target location, participants always grasped the object so that it ensured a comfortable hand posture at the end of the movement. Often called the *end-state comfort effect*, it provides evidence that people are sensitive to comfortable end postures, and that these postures are represented and planned prior to movement initiation.

A number of explanations have been postulated to explain the sensitivity toward comfortable end postures, the most prominent of these being the precision hypothesis (Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993). This hypothesis predicts that the probability of planning for comfortable end postures is related to the precision required for task completion, such that high-precision requirements should enhance the end-state comfort effect, whereas low-precision requirements should reduce or even eliminate the effect. The precision hypothesis is supported by empirical research (Rosenbaum, van Heugten, & Caldwell, 1996; Short & Cauraugh, 1999). For example, in the study of Short and Cauraugh (1999: Experiment 1) participants picked up a dowel with the dominant right hand and touched it to either a small (2 cm) or large (8 cm) target on a wall. They found that participants were less likely to use a grip that satisfied end-state comfort for the larger target than for the smaller target, indicating that precision demands influence adopted grasps.

Additional support for the precision hypothesis comes from a recent study that examined precision constraints in an end-state comfort task with children (Thibaut & Toussaint, 2010: Experiment 2). In that study children between 4 and 10 years old grasped a horizontally oriented pencil and made a dot on a sheet of paper (pointing-with-pencil task), drew a line on a sheet of paper (tracing-with-pencil task), or drew a line in an alley without crossing the edges (pencil-alley task). In the pencil-alley task, the ability to plan for comfortable end states increased as a function of age, and the tendency to satisfy end-state comfort was only observed for the 10-year-old children. However, a different pattern of results was obtained for the pointing-with-pencil and tracing-with-pencil tasks. Although the data for the 4-, 6-, and 10-year-old children indicated that anticipatory motor planning improves with age, end-state comfort satisfaction was lower for 8-year-old children than for the 6-year-old children. Thibaut and Toussaint argued that the observed differences in developmental grasp planning arose from a reorganization of planning strategies that occurs at the age of 8 years, which is influenced by the constraints and the degree of precision required for successful task completion. When the constraints of the task were defined (i.e., in the pencil-alley task) the need for high precision when drawing a line in an alley without crossing the edges was more readily apparent. This affordance enabled the 8-year-old children to analyze the task more efficiently, and thus select grasps that afforded more comfort and

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control at the end of the movement. In contrast, when the task did not afford a set of clearly defined constraints (i.e., the pointing-with-pencil and tracing-with-pencil tasks), 8-year-old children were unable to integrate all of the available information, which resulted in a decrease in end-state comfort. In sum, the ability to plan movements is highly influenced by perceived affordances and constraints, such that when the affordances of the task indicate the need for high-precision requirements, children are more able to integrate these cues, and select grasps that allow them to complete the task in a successful manner.

In sum, support for the precision hypothesis comes from studies that manipulated the degree of precision at the end of the task (i.e., final precision). Our aim in this experiment was to build on this corpus of work, and examine whether grasp planning is influenced by initial and final precision demands. In this task, participants reached for a cylinder located in a start disc and moved it to a target disc with either the non-dominant left or dominant right hand. The size of the start and target discs was manipulated so that the precision requirements at the start and end of the movement were either identical (low initial and final precision, high initial and final precision) or different (low initial and high final precision, high initial and low final precision). Based on the underlying assumptions of the precision hypothesis, we can outline expected results that would further support the importance of precision on grasp planning. We expect that the end-state comfort effect is enhanced when the precision requirements at the end of the movement are high, and reduced when the precision requirements at the end of the movement are low. Further, if precision is a major determinant of grasp planning, we expect that individuals would be less likely to plan their movements for comfortable end postures when the precision requirements at the start and end of the movement are low. Of critical interest, however, is the condition in which the precision requirements are high at the start and end of the movement. The question of primary importance is whether participants would plan their movements to ensure comfort (and control) at the start, or the end, of the movement, as they are mutually exclusive.

Method

Participants

Twenty right-handed participants from Bielefeld University (M age = 24.4 years, SD = 4.8 years; 7 men, 13 women) participated in the present study. Participants were paid 3€ for their participation. All participants had normal or corrected-to-normal vision, and had no known neuromuscular disorders. The experiment was conducted in accordance with local ethical guidelines, and in conformation with the Declaration of Helsinki.

Apparatus

The experimental apparatus consisted of a PVC cylinder, a start disc, and a target disc, which was placed on a height adjustable shelf (200 cm × 60 cm). The manipulated cylinder was a PVC cylinder (14 cm high, 6 cm diameter) that had a band of blue electrical tape (2 cm) wrapped around one end, and a band of yellow electrical tape (2 cm) wrapped around the other end. The cylinder was oriented in a vertical position at the start of each trial, so that the blue band was on the bottom and the yellow band was on the top. The start and target discs were 5 cm in height, and contained centrally located holes of either 8 cm (high-precision requirements) or 14 cm in diameter (low-precision requirements) that served as start and target location. The start disc was located 12 cm from the front edge of the shelf, and the target disc 29.5 cm behind the start disc.

Procedure

After filling out the informed consent form, the participant stood in front of the apparatus with the body vertically aligned with the start and target discs, and the shelf was adjusted to the height of the participant's navel. At the start of the trial the experimenter verbally informed the participant which hand to grasp the cylinder with and which end of the cylinder should be placed into the target disc (e.g., left blue for left-hand movements that did not require rotation, left yellow for left-hand movements that required rotation). After hearing the command signal, the participant grasped the cylinder, and placed the cylinder into the target disc. At the end of the trial, participants brought their hand back to the start position, and the experimenter placed the cylinder back to the start position. Participants were told to grasp the cylinder with a power grip (Napier, 1956), but were free to select the grip (thumb up or thumb down) with which they grasped the cylinder. We informed participants that movement accuracy was of utmost importance, but to perform the task at a comfortable speed.

There were 16 unique conditions comprising the factors hand (left, right), rotation (no rotation, rotation), and precision (low initial and low final, low initial and high final, high initial and low final, high initial and high final). Each condition was performed five times, yielding a total of 80 trials. The factor precision was blocked and the order of blocks was randomized across participants. Within each block, the different possible combinations of hand and rotation trials were presented in a completely randomized fashion. Between each testing block, there was a rest period of 2 min. The entire testing session lasted approximately 20 min.

Data Analysis

Trials in which the cylinder contacted either the start disc or the target disc were counted as errors (5.5%) and not included in analysis. The total number of errors was higher for high initial and high final precision trials (3.1%), than for the high initial and low final (1.3%), low initial and high final (0.8%), and low initial and low final (0.3%) precision trials.

The behavioral data were analyzed with respect to how participants grasped the cylinder (thumb-up vs. thumb-down

grip) and whether the selected grip led to a comfortable posture at the end of the movement (i.e., end-state comfort). In accordance with recent comfort ratings studies in our laboratory using a similar experimental setup (Seegelke, Hughes, & Schack, 2011), end-state comfort satisfaction was defined by initial grasps that resulted in thumb-up postures at the end of the movement. For no rotation trials, both initial-state comfort and end-state comfort were satisfied by the adoption of initial thumb-up grasps. For rotation trials, initial-state comfort was satisfied by the adoption of initial thumb-up grasps, whereas end-state comfort was satisfied by the adoption of initial thumb-down grasps. Thus, for trials that required rotation, participants could satisfy initial-state comfort or end-state comfort, but not both.

Previous studies that have employed similar experimental paradigms have reported end-state comfort satisfaction values between 61% and 69% (Hughes & Franz, 2008; Seegelke et al., 2011). These values are lower than typically observed in the traditional bar transport paradigm (Rosenbaum et al., 1990; Thibaut & Toussaint, 2010), and are thought to arise from biomechanical factors or increased cognitive load associated with mental rotation (Hughes & Franz; Hughes, Haddad, Franz, Zelaznik, & Ryu, 2011; Hughes, Reißig, & Seegelke, 2011; Seegelke et al.). Thus, the results from the present experiment were compared with those reported in previous studies that also require 180° rotation.

Statistical Analysis

Initial examination indicated that participants grasped the cylinder with a thumb-up grasp posture in every trial during no-rotation trials. Thus, statistical analysis was restricted to trials that required object rotation. The proportion of trials in which end-state comfort was satisfied was determined for each participant and normalized using an arcsine transformation. The behavioral data were then analyzed using a 2×4 repeated measures analysis of variance (ANOVA) with hand (left, right) and precision (low initial and low final, low initial and high final, high initial and low final, high initial and high final) as factors.

Results

Proportions of trials in which initial grasp postures resulted in comfortable end postures (end-state comfort) during trials that required rotation for the left and right hand for all four initial and final precision conditions are shown in Figure 1A.

Analysis revealed that end-state comfort satisfaction was similar regardless of whether the movement was performed with the nondominant left (69%) or the dominant right (67%) hand, $F(1, 19) = 1.793$, $p = .196$, $\eta_p^2 = .086$. However, there were differences in end-state comfort based on precision, $F(3, 57) = 3.378$, $p = .024$, $\eta_p^2 = .151$. A priori planned comparisons indicated that end-state comfort was significantly higher for the low initial and high final precision trials (82%) relative to the low initial and low final (64%) and high initial and low final (54%) precision trials (both ps $< .05$). End-state comfort was also higher for the low initial and high final precision condition (82%) compared with the high initial and high final precision condition (68%). However, this difference failed to reach statistical significance ($p = .09$). Furthermore, end-state comfort satisfaction was similar for the high initial and high final (68%) and low initial and low final (64%) and the high initial and low final (54%) precision conditions (all ps $> .05$).

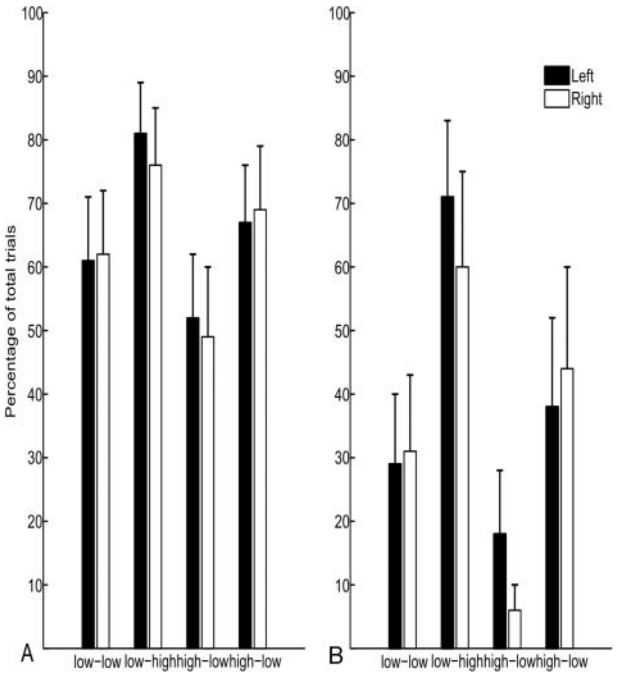

FIGURE 1. Proportions of trials in which initial grasps resulted in comfortable end postures (end-state comfort) for the left (black bars) and right hand (white bars) for all four precision conditions. Given that 50% ($n = 10$) of the sample population grasped the cylinder with a grip that led to comfortable postures at the end of the movement in 80% or more trials regardless of the precision requirements the data are displayed for **(A)** the entire sample population ($n = 20$), and **(B)** the precision-sensitive participants ($n = 10$). The error bars represent standard errors.

Closer inspection of the data revealed the presence of individual differences in initial grasps. 50% of participants ($n = 10$) altered their initial grasps to the specific precision demands of the task. We classified these participants as precision-sensitive. In contrast, the other 50% grasped the cylinder with a grip that led to comfortable postures at the end of the movement in 80% or more trials regardless of the precision requirements. These participants were classified as end-state comfort-consistent (ESC-consistent). Given that this latter group of individuals might have altered the findings, we removed the data from these individuals and reran the analysis on the precision-sensitive participants. Although these participants selected initial grasps that satisfied

end-state comfort in 66% of low initial and high final precision trials, they were more likely to select initial grasps that satisfied initial-state comfort during the high initial and low final (end-state comfort = 12%) and low initial and low final precision conditions (end-state comfort = 30%). Thus, for these conditions, initial grasp selection corresponded to what would be expected from the precision hypothesis. However, end-state comfort satisfaction for the high initial and high final precision condition (41%) was influenced by individual differences, such that 50% of the precision-sensitive participants ($n = 5$) consistently planned their grasps in alignment with end-state comfort, whereas 40% of these participants ($n = 4$) preferred to adopt initial grasps that would afford comfort at the start of the movement.[1]

A 2 (Hand) × 4 (Precision Condition) repeated measures ANOVA indicated that end-state comfort satisfaction was higher for the low initial and high final precision trials (66%), compared with the high initial and high final (41%), low initial and low final (30%), and high initial and low final (12%) precision trials, $F(3, 27) = 3.509$, $p = .029$, $\eta_p^2 = .281$. Planned comparisons revealed that end-state comfort was significantly higher for the low initial and high final precision trials than for the low initial and low final ($p = .049$), and high initial and low final ($p = .010$) precision trials (Figure 1B). There were no hand differences, nor was the interaction between hand and precision statistically significant.

We also examined initial grasp consistency for the participants who altered their initial grasps to the specific precision demands during trials that required rotation. In line with previous research (Thibaut & Toussaint, 2010) we calculated the percentage of trials in which the participants adopted an initial grasp that satisfied end-state comfort for each individual precision condition. Each participant was then classified into one of the following four categories: 0–20%, 21–50%, 51–80%, and 81–100%. It is our conjecture that a high percentage of participants who fall into either the 0–20% or 81–100% category would indicate that participants maintained the same grasp strategy across trials.

In line with the precision hypothesis, participants employed a consistent initial grasp strategy for the low initial and high final and high initial and low final precision trials. As seen in Figure 2, participants consistently satisfied initial-state comfort in the high initial and low final precision condition (85%), but end-state comfort for the low initial and

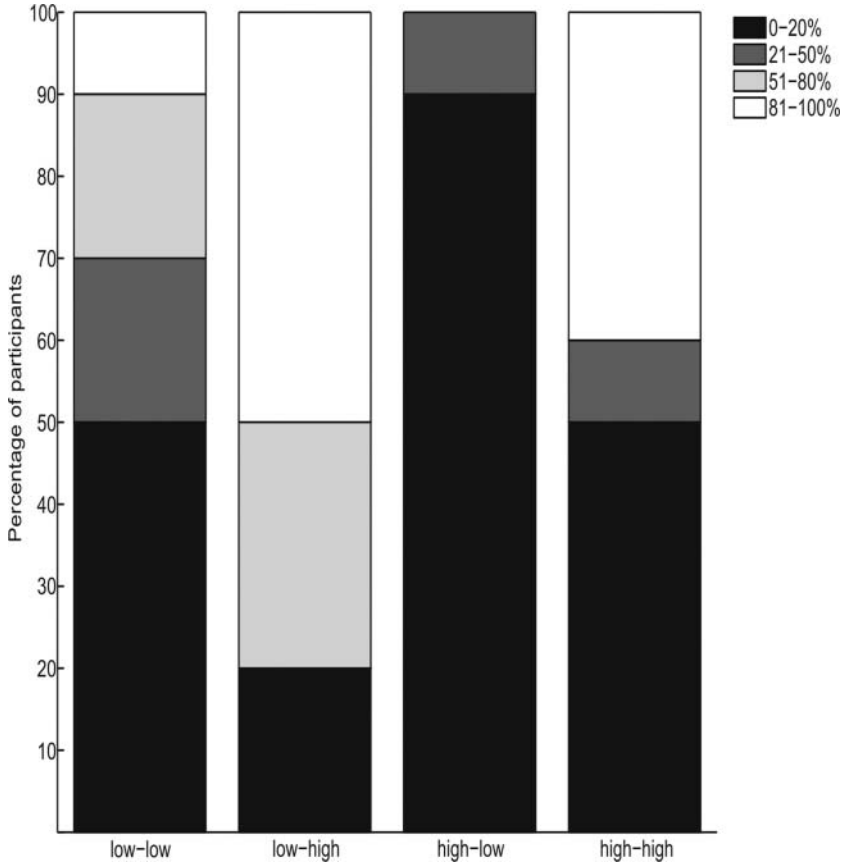

FIGURE 2. Proportions of participants who employed an initial grasp that satisfied end-state comfort in 0–20%, 21–50%, 51–80%, and 81–100% of trials.

high final precision condition (70%). For the high initial and high final precision condition, participants either consistently selected grasps that afforded comfort and control at the start or the end of the movement, but did not change strategies from one trial to another. Last, for the low initial and low final precision condition, although 50% of participants selected grasps that afforded comfort and control at the start of the movement, there were also a number of participants who did not employ a consistent grasp strategy.

Discussion

The purpose of the current experiment was to examine the influence of initial and final precision on grasp planning during a unimanual grasping and placing task that required 180° rotation. Based on the precision hypothesis (Rosenbaum et al., 1996), we expected that high precision requirements at the end of the movement should enhance the bias toward comfortable postures, whereas low precision requirements at the end of the movement should reduce this bias. Thus, when the precision requirements are high at the start of the movement, participants should plan their movements to afford comfortable start postures, and when the precision requirements are high at the end of the movement, participants should plan their movements to afford comfortable end postures.

A major, yet unexpected, finding to emerge from the present experiment was the presence of individual differences. We found that 50% of participants altered their initial grasps depending on the precision requirements at the start and end of the movement (i.e., were precision-sensitive). In contrast, the other 50% of participants selected grasps in alignment with end-state comfort regardless of whether there was high or low precision at the start and end locations (i.e., they were ESC-consistent). Because of these observed individual differences, the discussion is structured into three sections. In the first section we focus on the precision-sensitive participants, and the second section is centered on the ESC-consistent participants. In the third section, we summarize the results and interpretations from the present experiment.

Precision-Sensitive Individuals

Overall, the precision-sensitive participants selected initial grasps that satisfied end-state comfort in 66%[2] of total trials during the low initial and high final precision condition, but selected initial grasps that afforded comfort and control at the start of the movement (initial-state comfort) during the high initial and low final (end-state comfort = 12%) and low initial and low final precision conditions (end-state comfort = 30%). These findings are in alignment with the precision hypothesis (Rosenbaum et al., 1996), which states that high-precision requirements at the end of the movement enhance the bias toward comfortable end postures, whereas low-precision requirements at the end of the movement reduce the bias toward end-state comfort.

The employed grasp strategies were similar across the entire subset of participants for the high initial and low final, low initial and low final, and low initial and high final precision conditions. However, individual differences in grasp strategy were observed when the precision demands were high at both the start and the end of the movement (high initial and high final precision condition). For the high initial and high final condition, 50% of the precision-sensitive participants ($n = 5$) consistently planned their grasps in alignment with end-state comfort, whereas 40% of participants ($n = 4$) preferred to adopt initial grasps that would afford comfort at the start of the movement.

The presence of individual differences in grasp planning has been reported in previous studies (Fischman et al., 2003; Janssen et al., 2010; Rosenbaum et al., 1996). One account for these individual differences is that individuals who do not plan their grasps in accordance with end-state comfort effect have compromised motor planning abilities (Janssen et al., 2010). Is it possible that the individuals who did not satisfy end-state comfort are less proficient planners than those who prioritized comfort at the end of the movement? If these individuals had compromised motor planning abilities then we would expect that they would select initially comfortable grasps regardless of precision condition. Although these individuals selected initially comfortable grasps (at the cost of comfortable end postures) for the high initial and low final, low initial and low final, and high initial and high final precision conditions, they adopted initial grasps that satisfied end-state comfort during the low initial and high final precision condition. Thus, given that these individuals were capable of planning for comfortable end postures in the low initial and high final precision condition, we do not believe that the participants who planned for initial-state comfort have compromised planning abilities.

An alternate explanation for these results comes from the work of Rosenbaum et al. (1996), who suggested that there are individual differences in the perception of precision. In that study, participants grasped a handle mounted to a freely rotating wheel and turned the handle past a designated target, which caused a bolt to drop into a hole at the target location. Because the task did not require precise position at the end of the movement, Rosenbaum et al. hypothesized that individuals would use the same initial grasp regardless of the target position. Although 50% ($n = 4$) of participants acted in accordance with this expectation, the other 50% ($n = 4$) selected initial grips that resulted in comfortable postures at the target position. Rosenbaum et al. argued that the participants who satisfied end-state comfort perceived the task as one that demanded a high degree of precision when the bolt approached the target position, and selected initial grasps that afforded more precise control at the end of the movement.

We hypothesize that the individual differences for the high initial and high final precision condition resulted from the perception of precision. In our opinion, participants who planned for end-state comfort perceived the need for more control at the end of the movement. In contrast, participants who perceived the task as requiring more control at the start of the movement planned their grasps in alignment with

this perceived need. Thus, rather than individual differences arising from limitations in motor planning, we hypothesize that grasp planning is influenced by the perceived need for control, which is weighted differently for each participant.

ESC-Consistent Individuals

We now turn our attention to the participants who consistently (>80% of trials) selected initial grasps that satisfied end-state comfort in all four initial and final precision conditions. The results indicate that these participants acted in accordance with the precision hypothesis in the low initial and high final and the high initial and high final precision conditions, but not for the low initial and low final and high initial and low final precision conditions. The results from the latter two conditions are contrary to our original hypothesis that participants would select initial grasps that would afford comfort and control at the start of the movement (initial-state comfort). To explain these results, we speculate that the innate sensitivity toward end-state comfort biased individuals toward thumb-down grasps in the first few trials of the experiment, and given that participants were able to perform the task without touching either the initial or final target discs, they recalled what grasp they used on the last trial (trial $n-1$), and used the same grasp thumb-down grasp on the following trial (trial n).

The disposition for using previously used grasps has been observed in previous studies (Cohen & Rosenbaum, 2004). In that study, participants reached out and grasped a plunger, placed it to a platform of varying height and lowered the hand (home-to-target move), then grasped the plunger from the platform and transported it back to the home position (target-to-home move). In accordance with the end-state comfort effect, grasp heights on the plunger were inversely related to the height of the target position, such that the higher the target shelf, the lower the plunger was grasped, and vice versa. The results of that study also provided empirical support for plan recall. Cohen and Rosenbaum found that when participants returned the plunger back to the home position (target-to-home move) they tended to grasp the plunger close to where they had grasped it during the home-to-target move. According to the authors, the benefit of recalling a previously used grasp posture is that it reduces the time and cognitive burden associated with generating a new motor plan for each individual trial.

In line with this research, we hypothesize that if a movement can be successfully performed with a current motor plan, then recalling a previously used plan allows for faster responses and reduces computational costs associated with motor planning. Unfortunately, the number of movement errors in the present experiment was very low (5.5%), and thus this hypothesis is speculative and mandates further investigation. One way in which this hypothesis could be tested is by inducing movement errors at either the initial or final target position. Imagine a task in which an electromagnet is embedded in the manipulated object. In some trials, the electromagnet is not activated, whereas in other trials the electromagnet is activated. In these latter trials, lifting the object from the initial position triggers the electromagnet, resulting in a perturbation. This perturbation at the initial position causes the object to contact the target disc, and thus induces a movement error. Based on the results of the current experiment, we would predict that individuals would select an initial thumb-down grasp on trial $n-1$ (no-perturbation trial) and trial n (perturbation trial). If our hypothesis were correct, then the perturbation (on trial n) would cause individuals to change their grip on trial $n+1$ (from a thumb-down to a thumb-up grasp). This thumb-up grasp would allow for more control to counteract the induced perturbation, and thus reduce the likelihood of committing a movement error.

Although we hypothesize that ESC-consistent individuals sought to reduce computational demands by recalling a previously used initial grasp, we cannot rule out the possibility that these individuals are simply prioritizing end-state comfort. If this were the case, we would predict that the results of the aforementioned thought experiment would differ. If individuals are prioritizing end-state comfort, we would expect that they would select initial grasps that afford comfortable end postures regardless of whether the electromagnet was activated.

Summary

The results of the present study provide evidence of individual differences in grasp planning during unimanual object manipulation. We found that 50% of participants altered their initial grasps to the precision requirements at the start and end of the movement, and typically selected grasps in alignment with the precision hypothesis (Rosenbaum et al., 1996). In contrast, the other 50% of participants selected grasps in alignment with end-state comfort, regardless of initial and final precision. We speculate that the former subgroup of participants was sensitive to the precision demands of the task, whereas the latter group of participants avoided the cognitive costs of motor planning by using previously successful grasp posture plans.

Why did some individuals consistently plan their movements in accordance with end-state comfort, whereas other individuals changed their grasps depending on the precision demands at the start and the end of the movement? Inspection of individual participant characteristics revealed that the age of the participants and the proportions of men and women were similar regardless of initial grasp posture strategy. Thus it is unlikely that age or gender effects can account for this difference. Individual differences in decision making have been well studied in the field of cognitive psychology (see Mohammed & Schwall, 2009 for a review). Based on that work, it would certainly be worthwhile to examine the influence of factors such as past experience (Juliusson, Karlsson, & Gärling, 2005), personality traits (Brandstätter & Königstein, 2001; Cohen, Young, Baek, Kessler, & Ranganath, 2005),

and cognitive ability and biases (Stanovich & West, 2008) on decision making during goal-directed motor planning.

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NOTES

1. One participant did not employ a consistent strategy in the high initial and high final condition.

2. The results from the low initial and high final condition are similar to those reported in previous studies that use a similar experimental paradigm (Hughes & Franz, 2008; Seegelke et al., 2011).

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