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RAPID COMMUNICATION

Perturbations in Action Goal Influence Bimanual Grasp Posture Planning

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ABSTRACT. The authors examined the effects of perturbations in action goal on bimanual grasp posture planning. Sixteen participants simultaneously reached for 2 cylinders and placed either the left or the right end of the cylinders into targets. As soon as the participants began their reaching movements, a secondary stimulus was triggered, which indicated whether the intended action goal for the left or right hand had changed. Overall, the tendency for a single hand to select end-state comfort compliant grasp postures was higher for the nonperturbed condition compared to both the perturbed left and perturbed right conditions. Furthermore, participants were more likely to plan their movements to ensure end-state comfort for both hands during nonperturbed trials, than perturbed trials, especially object end-orientation conditions that required the adoption of at least one underhand grasp posture to satisfy bimanual end-state comfort. Results indicated that when the action goal of a single object was perturbed, participants attempted to reduce the cognitive costs associated with grasp posture replanning by maintaining the original grasp posture plan, and tolerating grasp postures that result in less controllable final postures.

Keywords: bimanual coordination, end-state comfort, grasping, perturbation

The sensitivity toward comfortable (and more controllable) final goal postures is called the end-state comfort effect. The end-state comfort effect was first reported by Rosenbaum et al. (1990) who asked participants to grasp a horizontally positioned bar and place either the left or right end of the bar into a left or right target. The authors found that regardless of target location, participants always used an underhand grasp posture when the left end of the bar was to be placed into the target, and an overhand grasp posture when the right end of the bar was to be placed into the target. Thus, initial grasp postures were selected so that the hand would end up in a comfortable (and more controllable) position at the end of the movement (i.e., when the bar was placed into the target). Moreover, a recent study by Hughes, Seegelke, Spiegel et al. (2012) examined the influence of perturbations in action goal on unimanual grasp posture planning. In that study, participants' selected initial grasp postures that resulted in end-state comfort compliance during nonperturbed trials, and modified their unimanual grasp posture plans so that the object could be grasped with an end-state comfort compliant grasp posture when there was a change in action goal (i.e., perturbed trials). In sum, the end-state comfort constraint demonstrates that movements are planned with respect to the action goals of the task (i.e., goal-directed planning), and that controllable final postures are a highly prioritized planning constraint, which is controlled via both feedforward and feedback mechanisms.

Researchers have also investigated the constraints that underlie grasp posture planning in tasks that require the use of both hands (Fischman, Stodden, & Lehman, 2003; Hughes & Franz, 2008; Hughes, Haddad, Franz, Zelaznik, & Ryu, 2011; Hughes, Reißig, & Seegelke, 2011; Hughes, Seegelke, Reißig, & Schütz, 2012; van der Wel & Rosenbaum, 2010; Weigelt, Kunde, & Prinz, 2006). Bimanual object manipulation tasks provide an excellent opportunity to examine how goal-directed planning constraints (end-state comfort) interact with the preference toward spatial coupling. This latter constraint refers to the strong tendency for the two hands to stay spatially coupled when performing bimanual actions (Jackson, Jackson, & Kritikos, 1999; Kelso, Southard, & Goodman, 1979), which reflect interaction costs that arise when different efferent motor commands have to be simultaneously specified (e.g., Heuer, 1993) or carried out (Carson, Riek, Smethurst, Lison, & Byblow, 2000).

Weigelt et al. (2006) were the first to examine the interaction between end-state comfort and bimanual spatial coupling using a bimanual version of the bar transport task. Congruent with the results of Rosenbaum et al. (1990), participants almost always selected grasp postures that afforded end-state comfort during unimanual trials performed with the left or right hand. More interestingly, participants also showed a strong sensitivity for end-state comfort during bimanual trials, even if this meant that they had to adopt two different initial grasp postures (e.g., overhand grasp posture with one hand, and underhand grasp posture with the other hand). On the basis of these results Weigelt et al. argued that goal-directed action planning constraints are prioritized over motor commands, and that the desire for comfortable goal postures is a predominant action planning constraint.

In this study we explored the extent to which perturbations in action goal would influence bimanual grasp posture planning. To examine this issue we used a bimanual version of the bar transport task (Weigelt et al., 2006) and introduced a perturbation in the action goal of the left or right object at reach-to-grasp onset. Participants were required to simultaneously reach for two horizontally oriented objects and place

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either the left or right end of the objects into corresponding targets. When the reach-to-grasp movement was initiated, a secondary audiovisual stimulus was triggered, which indicated whether there was a perturbation in action goal for the left or right object. The auditory stimulus merely indicated that a change in action goal was required, but did not specify whether the action goal perturbation affected the left hand or right hand. In contrast, the visual stimulus provided specific information regarding the hand affected by the perturbation in action goal.

With respect to bimanual grasp posture planning, it is expected that participants would show a strong sensitivity toward end-state comfort during nonperturbed trials. Of critical interest, however, are the trials in which the action goal for either object is perturbed. One possibility is that individuals would modify their grasp posture plans to ensure end-state comfort when faced with an unexpected change in action goal. This hypothesis would be supported if similar end-state comfort values were found for both nonperturbed and perturbed trials, and would provide strong evidence that the end-state comfort effect is prioritized over bimanual spatial coupling. However, it is possible that the interaction costs associated with grasp posture modification would exceed the information processing capabilities of the participant. If this is the case, end-state comfort compliance should be significantly lower for perturbed compared with nonperturbed trials.

Method

Participants

Sixteen right-handed individuals from the Technical University of Munich (*M* age = 26.7 years, *SD* = 3.10 years; 7 men and 9 women) participated in this experiment. All participants reported normal or corrected-to-normal vision, and did not have any known physical or neuromuscular disorders. The methodology and written consent form for this study were approved by the local ethics committee and conformed to the declaration of Helsinki. All participants gave their informed written consent to participate in the study.

Apparatus and Procedure

The setup of the bimanual bar transport task is shown in Figure 1, and was designed to be as similar to Weigelt et al. (2006) as possible. The manipulated objects were two grey PVC cylinders (20 cm in height, 6 cm in diameter) that had a band of black electrical tape (2 cm) wrapped around one end, and a band of white electrical tape (2 cm) wrapped around the other end. The objects were horizontally positioned on wooden cradles (20 cm length) that held the objects 20.5 cm above the table top.[1] The targets were hollow PVC cylinders (4 cm in depth, 8 cm in diameter) located 10 cm in front of each object cradle. Two start buttons (5 cm × 5 cm × 2 cm) were positioned at the front edge of the table top and 30 cm to either side of the body midline. The start buttons were used to trigger the secondary stimulus, and to collect reaction time values during the experiment.

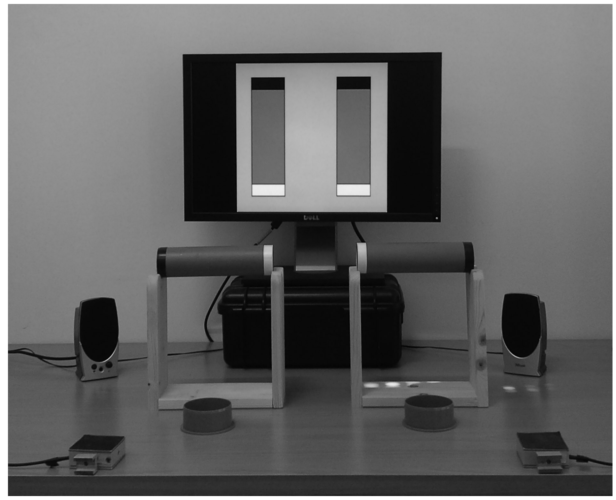

FIGURE 1. Front view of the experimental setup.

The temporal sequence for the experimental paradigm during nonperturbed and perturbed trials is depicted in Figures 2A and 2B, respectively. At the start of each trial, the message “Put your hands on the start buttons!” was displayed (in German) on a 43 cm flat screen monitor (syncMaster943T, Samsung, Seoul, South Korea; placed 15 cm behind the

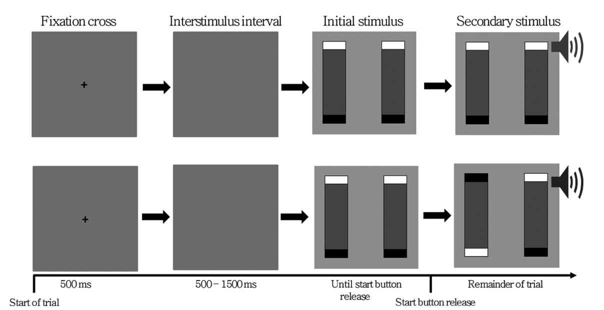

FIGURE 2. The temporal sequence of the experimental paradigm. At the beginning of each trial, a fixation cross was presented (500 ms). After a randomized interstimulus interval (500–1500 ms), the initial stimulus appeared and displayed which end of the objects was to be placed on the target. After the participant lifted their hand from the start buttons, a secondary stimulus was triggered. (**A**) During nonperturbed trials, the visual stimulus was identical to the initial stimulus, and was paired with an auditory cue indicating that the action goals for both hands had not changed. (**B**) During perturbed trials, the secondary visual stimulus differed from the initial stimulus, and was paired with an auditory cue indicating that the intended action goal for one of the hands had changed. Shown is a trial in which the action goal for the left object was perturbed (i.e., perturbed left condition).

object cradle), which prompted participants to close the thumb and index finger of each hand and push down on the start buttons with the side of their palms. After the start buttons were depressed, a fixation cross was presented for 500 ms, and after a random interval (500–1500 ms) the initial (visual) stimulus appeared on the screen. The visual stimulus consisted of a representation of the required end orientation of the object. In response to the visual stimulus, participants lifted their hands from the start buttons, grasped the objects from the cradle, and placed the objects in the respective targets. A secondary stimulus was triggered as soon as one of the hands was lifted from the start buttons. The secondary (final) stimulus consisted of a visual object representation and a low (400 Hz) or high (750 Hz) tone, which was presented simultaneously. The tone was presented at 60 dB (500 ms duration) through two loudspeakers (Logitech Z 323 2.1-CH PC, Logitech, Morges, Switzerland) situated 15 cm to either side of the computer monitor (45° and 135° in azimuth). The secondary stimulus indicated whether the required object end orientation for one of the objects had changed (perturbed trial) or not (nonperturbed trial). In nonperturbed trials, the secondary visual stimulus was identical to the initial stimulus and the auditory cue indicated that the intended action goal had not changed. In perturbed trials, the secondary visual stimulus differed from the initial stimulus and the auditory cue indicated that the intended action goal for the right or the left object had changed. For half of the participants, the high tone (750 Hz) was associated with nonperturbed trials, and the low tone (400 Hz) was associated with perturbed trials. For the other participants, the auditory mapping was reversed. The auditory mapping was counterbalanced across participants and was known prior to the experiment. Stimulus presentation was controlled via Presentation (Neurobehavioral Systems, Albany, CA).

Participants were instructed to move naturally, and to wait for the secondary stimulus to appear before lifting the hands from the start buttons and reaching for the objects. In addition, participants were instructed to grasp the both objects simultaneously, using either a full grip overhand or underhand grasp posture. We emphasized speed of responding and that the final placement of the objects in the targets should replicate what was displayed on the computer monitor.

Each experimental session began with a series of 12 acclimatization trials (three to each nonperturbed object end-orientation condition). These trials served to familiarize the participant with the auditory mapping and the general task procedures (e.g., performing the task using natural reaching and grasping movements, using full grips when grasping the objects). The order of presentation was randomized. Following the acclimatization trials, participants took a 2-min rest break, after which the experiment started. There were a total of 128 trials, comprised of the factors condition and object end-orientation. To reduce expectancy effects, the ratio of perturbed to nonperturbed trials was set to 1:3 (24 trials per nonperturbed conditions, and four trials per perturbed left and perturbed right condition). The experimental trials were divided into two blocks of 64 trials, separated by a 2-min rest period. All trials were fully randomized. The entire experiment lasted approximately 50 min.

Data Processing and Analysis

Before data analysis, we excluded trials performed in a noninstructed manner (e.g., moving prior to stimulus presentation, placing the wrong end of the object[s] into the targets, lifting the hands from the start buttons and waiting for the secondary stimulus before reaching for the targets) and response times that were less than 200 ms (anticipation errors) or exceeded 800 ms (delay errors). Error trials comprised less than 1.25% of the data, and were approximately equally distributed across condition and participants. Given the low error rate, mean substitution was used to replace missing values.

Based on the start orientation of the objects and the instructed final object orientations (as instructed by the secondary stimulus), we were able to differentiate between four object end-orientation conditions: (a) when both objects required overhand grasp postures to satisfy end-state comfort (OO), (b) when end state was satisfied by the adoption of an overhand grasp posture for the left object and underhand grasp posture for the right object (OU), (c) underhand grasp posture for the left object and overhand grasp posture for the right object (UO), and (d) end-state comfort was satisfied by grasping both objects with underhand grasp postures (UU). Given that the grasp posture data did not meet the assumptions of parametric statistical tests (i.e., homogeneity and normal distribution), the proportion of end-state comfort compliant trials was determined for each participant, and then normalized using an arcsine transformation prior to statistical analysis. Differences in reaction time (time period from initial stimulus presentation to start button release) were also analyzed using a repeated measures analysis of variance (ANOVA) with the factors perturbation (nonperturbed, perturbed left, perturbed right) and object end orientation (OO, OU, UO, UU).

Results

Grasp Posture

To examine bimanual end-state comfort (i.e., grasp postures that ensured end-state comfort for both hands) during nonperturbed trials we used a one-way repeated measures ANOVA with the factor object end orientation. Analysis revealed that participants selected initial grasp postures that ensured end-state comfort for both hands in 78.1% of trials. There was no statistically significant difference in bimanual end-state compliance between object end orientations, $F(3, 45) = 2.365$, $p = .084$, although there was a tendency for higher bimanual end-state compliance in the OO condition (93.5%) than for the OU (71.5%), UO (76.6%), and UU conditions (70.8%).

We also analyzed whether there were any hand-based differences in end-state comfort compliance during nonperturbed trials using a 2 Hand (left, right) × 4 Object End Orientation (OO, OU, UO, UU) repeated measures ANOVA. Analysis indicated that the level of end-state comfort was similar regardless of hand, $F(1, 15) = 3.244$, $p = .095$, and object end orientation, $F(3, 45) = 1.858$, $p = .153$. There was, however, a significant interaction between hand and object end orientation, $F(3, 45) = 3.089$, $p = .038$. Post hoc analysis indicated that end-state comfort was higher for the left hand than the right hand during the OU condition (left hand = 98.8%, right hand = 77.4%), whereas end-state comfort was higher for the right hand than the left hand during the UO condition (left hand = 83.3%, right hand = 94.6%), both ps < .05. There were no hand-based differences during the OO (left hand = 94.9%, right hand = 97.0%) and UU conditions (left hand = 84.5%, right hand = 78.9%), both Fs < 1.

To examine the effects of action goal perturbation on bimanual end-state comfort, we conducted a 3 Perturbation (nonperturbed, perturbed left, perturbed right) × 4 Object End Orientation (OO, OU, UO, UU) repeated measures ANOVA. The proportion of trials in which participant's satisfied bimanual end-state comfort is shown in Figure 3. The main effect of condition was nonsignificant, $F < 1$, with similar bimanual end-state comfort values for nonperturbed (78.1%) and perturbed trials (left hand perturbation = 60.9%, right hand perturbation = 60.2%). However, the main effect of object end orientation, $F(3, 45) = 9.900$, $p < .001$, and the interaction between perturbation and object end orientation, $F(6,90) = 2.074$, $p < .005$, were both significant. Post hoc analysis on the significant interaction revealed that bimanual end-state comfort was similar regardless of perturbation for the OO condition (nonperturbed = 93.5%, perturbed left = 86.7%, perturbed right = 76.3%), Fs < 1. There were, however, significant differences in bimanual end-state comfort between nonperturbed (71.5%) and both the perturbed left (58.3%) and perturbed right trials (52.5%) for the OU condition, both ps < .05. A similar pattern of results was observed for the UO condition, with significantly higher bimanual end-state comfort values for nonperturbed trials (76.6%), compared to both perturbed left (51.7%) and perturbed right trials (53.3%), both ps < .05. There was a significant difference in bimanual end-state comfort between nonperturbed (70.8%) and perturbed left trials (46.7%) for the UU condition, $p < .05$. The difference between nonperturbed and perturbed right trials (70.8% vs. 58.6%) was not significant.

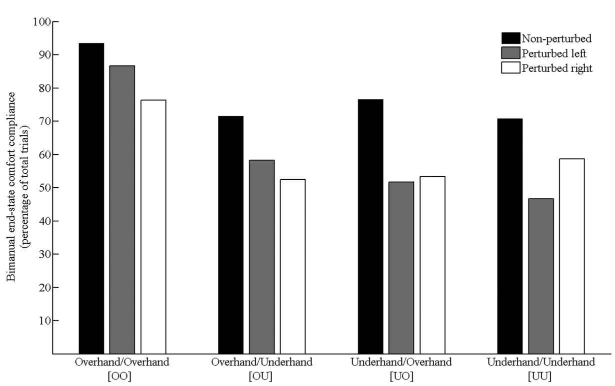

FIGURE 3. Percentage of trials in which participants satisfied bimanual end-state comfort for the four object end-orientation conditions. Black bars refer to nonperturbed trials, gray bars refer to left hand perturbed trials, and white bars refer to right hand perturbed trials.

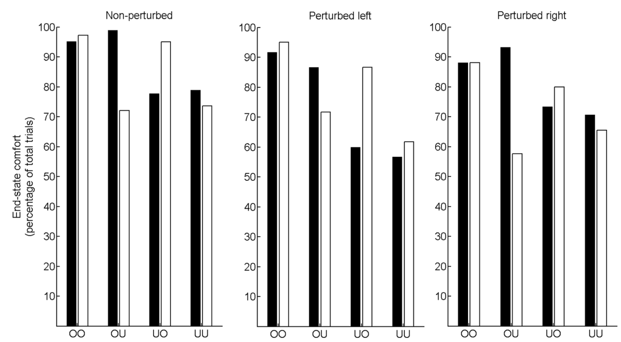

FIGURE 4. Percentage of trials in which participants satisfied end-state comfort. Black bars refer to the left hand, and white bars refer to right hand.

We also examined whether perturbations in action goal influenced end-state comfort compliance for the left and right hand (Figure 4). Results of the 2 Hand (left, right) × 3 Perturbation (nonperturbed, perturbed left, perturbed right) × 4 Object End Orientation (OO, OU, UO, UU) repeated measures ANOVA revealed a significant main effect of perturbation, $F(2, 30) = 11.046$, $p < .001$. Post hoc analysis indicated that end-state comfort was higher for the nonperturbed condition (88.7%) compared with both the perturbed left (78.1%) and perturbed right condition (79.4%), $p < .01$. The difference between perturbed conditions was nonsignificant, $F < 1$. There was also a significant main effect of object end orientation, $F(3, 45) = 4.648$, $p = .006$. Post hoc analysis indicated that end-state comfort compliance was higher for the OO condition (92.1%) than the OU (82.2%), UO (80.8%), and UU conditions (73.1%), all ps < .05. End-state comfort did not significantly differ between OU, UO, and UU conditions, all Fs < 1.

Reaction Time

Average reaction time values were similar regardless of perturbation (nonperturbed = 822 ms, perturbed left = 848 ms, perturbed right = 856 ms), $F(2, 30) = 0.341$, $p = .714$. The main effect of object end-orientation was also nonsignificant (OO = 851 ms, OU = 849 ms, UO = 852 ms, UU = 815 ms), $F(3, 45) = 0.793$, $p = .504$. In short, reaction time values were remarkably similar regardless of perturbation or the required end-orientation of the objects.

Discussion

Nonperturbed Trials

In this study we examined the extent to which perturbations in action goal influence bimanual grasp posture planning. We found that participants planned their movements to ensure end-state comfort for both hands in 78.1% of nonperturbed trials, with slightly higher bimanual end-state compliance values for the OO object end-orientation condition compared to all others (difference range = 16.9–22.8%). Furthermore, we observed higher end-state comfort compliance values for the hand that had to use an overhand grasp posture to end the movement in a comfortable position during nonperturbed trials.

The finding that end-state comfort planning was higher for the hand that could satisfy end-state comfort with an overhand grasp posture highlights the interaction of the habitual and goal-directed systems in action planning (Herbort & Butz, 2011; Stöckel, Hughes, & Schack, 2012). Specifically, when both the goal-directed and habitual systems call for an overhand grasp posture, there was no conflict between the two systems, and thus the selection of the appropriate grasp posture is facilitated. In contrast, in situations when the habitual and goal-directed systems favored different grasps (e.g., the goal-directed calls for underhand grasp posture while the habitual system calls for an initial overhand grasp posture), the conflict between the two systems influenced the ability of participants to select the grasp posture that complied with end-state comfort.

In addition, there were differences in end-state comfort compliance levels in our study and that of Weigelt et al. (2006) who reported that individuals almost always satisfied bimanual end-state comfort regardless of condition (> 11 of 12 participants). In the present study, participants selected bimanual end-state comfort compliant grasp postures in 78.1% of trials, with a trend toward greater end-state comfort compliance for the condition in which grasping the two objects with initial overhand grasp postures afforded comfortable final states (i.e., OO), compared to the conditions in which participants had to select at least one underhand grasp posture to satisfy bimanual end-state comfort (i.e., OU, UO, UU). We believe that the differences in bimanual end-state comfort compliance are due to methodological differences between the two studies. In Weigelt et al. (2006), participants began each trial standing on a line 150 cm away from the table, and after the object end orientations were verbally instructed by the experimenter, walked toward the apparatus, grasped the objects and placed them into the targets. In contrast, in our study, participants were seated in front of the apparatus, the stimulus was presented visually, and the instructions emphasized speed of responding. In light of these methodological differences, it is likely that the experimental paradigm used in Weigelt et al. afforded the participants more time to plan their grasp postures, which improves grasp posture planning.

Perturbed Trials

When the effects of perturbations in the action goal on bimanual grasp posture planning were considered, we found that participants were more likely to plan their movements to ensure end-state comfort for both hands during nonperturbed trials, than perturbed trials, especially for the OU, UO, and UU object end-orientation conditions. Furthermore, the tendency for a single hand to select end-state comfort compliant grasp postures was higher for the nonperturbed condition compared to both the perturbed left and perturbed right condition. We hypothesize that individuals planned their grasp postures based on the action goals of the initial stimulus, and did so with the intent to satisfy end-state comfort. However, when a change in the action goal occurred, complying with end-state comfort required that participants replan the grasp posture of one hand.

Given the emphasis on response speed in the present experiment, as well as the costs associated with movement replanning (Hughes, Seegelke, Spiegel et al., 2012; Spiegel, Koester, & Schack, 2013), participants may have maintained the original grasp posture plan, and tolerated less controllable final postures in order to mitigate the cognitive demands associated with grasp posture replanning. The observation that individuals are less likely to employ a cognitively demanding planning strategy (i.e., bimanual end-state comfort) when faced with an unexpected change in action goal suggests that individuals are concerned not only with comfortable end states, but also with computational efficiency during movement (re)planning. This idea is supported by recent studies demonstrating that individuals employ strategies, such as recalling previously successful grasp posture plans (Cohen & Rosenbaum, 2004; Hughes, Seegelke, & Schack, 2012), or selecting identical grasp postures during bimanual object manipulation (Hughes, Seegelke, Reißig et al., 2012), in order to save cognitive resources.

As mentioned previously, the instructions emphasized speed of responding, which likely impacted the strategies that participants used when planning their grasp postures. Thus, in this study we are unable to distinguish whether the observed effects are due to cognitive difficulty associated with movement replanning, or available planning time.[2] Current experiments in our laboratories aim to delineate between these two possibilities (movement replanning costs, available planning time), and examine the extent to which available planning time influences the relationship between grasp posture planning constraints (e.g., end-state comfort, bimanual spatial coupling, habitual grip preference).

Comparisons of the present results to those of our previous study investigating unimanual grasp posture planning using the same grasping and placing paradigm (Hughes, Seegelke, Spiegel et al., 2012) revealed two differences. First, end-state comfort was lower during bimanual than unimanual object manipulations during both nonperturbed and perturbed trials. Second, when a perturbation in action goal occurred, participants were more likely to modify their grasp postures during unimanual object manipulations, compared to when two objects were manipulated (i.e., bimanual object manipulation). The decrease in end-state comfort compliance in nonperturbed trials, as well as the reduced ability to modify grasp posture plans to comply with end-state comfort in perturbed trials during bimanual (relative to unimanual) object manipulation, are consistent with previous behavioral (Hughes & Franz, 2007, 2008; Kunde & Weigelt, 2005) and neuroimaging studies (Debaere et al., 2001; Sadato, Yonekura, Waki, Yamada, & Ishii, 1997; Toyokura, Muro, Komiya, & Obara, 2002) demonstrating that planning and executing simultaneous bimanual movements require greater cognitive resources than unimanual actions.

In sum, the results of nonperturbed trials indicated that participants planned their movements to ensure end-state comfort for both hands, but that end-state comfort compliance was higher for the hand that had to use an overhand grasp posture to end the movement in a comfortable position. In addition, we found that end-state comfort compliance was lower when the intended action goal for the left or right object had changed (i.e., perturbed trials), compared to when it had not (i.e., nonperturbed). We hypothesize that during perturbed trials, participants attempted to reduce the cognitive costs associated with replanning their grasp postures in a task which emphasized speed of responding, by maintaining the original grasp posture plan, and tolerating grasp postures that result in less controllable final postures.

NOTES

1. The four possible start orientations of the objects—(a) left object white end to the left and right object white end to the left, (b) left object white end to the left and right object white end to the right, (c) left object white end to the right and right object white end to the left, (d) left object white end to the right and right object white end to the right)—were counterbalanced across participants, but kept constant for each participant throughout the experiment.
2. We thank an anonymous reviewer for pointing out this possibility.

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