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RESEARCH ARTICLE

Effects of stimulus cueing on bimanual grasp posture planning

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Abstract The purpose of the present study was to investigate whether difficulties in bimanual grasp posture planning arise from conflicts in response selection. Forty-five participants were assigned to one of three groups (symbolic cueing, semi-symbolic cueing, and direct cueing) and instructed to reach for, grasp, and place two objects on a board in various end-orientations, depending on condition. In general, the tendency to adopt initial grasps that resulted in end-state comfort was significantly higher for the semi-symbolic, than that for the other two groups. There were, however, noticeable individual differences in grip behavior in the symbolic and direct cueing groups. Although the majority of participants performed the task in a similar fashion to the semi-symbolic group, there was a subset of participants (40 % in each group) who grasped the two objects using an overhand grip in virtually all trials, regardless of condition. It is hypothesized that the observed individual differences in grasp posture strategy arise from differences in motor planning abilities, or the strategies participants employ in order to comply with task demands. A secondary finding is that the degree of interlimb coupling was larger for congruent, than incongruent, conditions irrespective of stimulus cueing. This finding indicates that the interference in the execution of bimanual grasping and placing tasks arises from interference during the specification of movement parameters specific to planning and execution of bimanual movements, or neuronal cross-talk in efferent pathways, rather than response selection conflicts.

Keywords Bimanual coordination · Grasping and placing · End-state comfort

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Introduction

People often take hold of objects with awkward grasp postures in order to ensure comfortable hand postures at the end of the movement. This end-state comfort effect has been observed in a variety of unimanual tasks (for an overview, see Rosenbaum et al. 2006) and provides evidence that final goal postures are represented and planned prior to movement execution. Since the initial report (Rosenbaum et al. 1990), more recent studies have examined whether the end-state comfort effect extends to simultaneous bimanual movements (Fischman et al. 2003; Hughes and Franz 2008; Hughes et al. 2011a, b; Weigelt et al. 2006; van der Wel and Rosenbaum 2010). Bimanual movements provide an interesting scenario in which to examine grasp posture planning, as the sensitivity toward end-state comfort often competes with the strong tendency for the two hands to grasp objects with identical postures (bimanual spatial coupling).

The investigation of end-state comfort during bimanual object manipulation tasks has demonstrated that individuals typically select initial grasp postures that allow them to satisfy end-state comfort for both hands when the object end-orientations are congruent (Hughes and Franz 2008; Hughes et al. 2011a, b; Weigelt et al. 2006). However, during incongruent movements, the sensitivity for comfortable end postures is strongly influenced by object rotation congruency. When the degree of rotation for both objects was identical (e.g., both objects placed from a vertical start-orientation to a horizontal end-orientation), participants almost always selected grasp postures that resulted in end-state comfort (Weigelt et al. 2006). However, when the object end-orientations for the two hands differed (e.g., one object placed to a vertical end-orientation and the other object placed to a horizontal end-orientation), the proportion of trials in which participants satisfied end-state comfort or satisfied bimanual coupling were not statistically different (Hughes and Franz 2008; Hughes et al. 2011a, b).

Although it has not been difficult to replicate these general results, understanding why neither end-state comfort nor bimanual coupling emerges as the dominant planning constraint during incongruent movements has proved to be much more elusive. One possibility is that the planning of initial grasp postures may suffer from the same bimanual interference often observed during the preparation of discrete (e.g., Heuer 1993; Heuer et al. 2001; Marteniuk and MacKenzie 1980; Spijkers et al. 1997) and continuous bimanual tasks (e.g., Franz et al. 1991, 1996). For example, Spijkers et al. (1997) examined rapid bimanual reversal movements that had to be made to congruent (i.e., either both short or both long) or incongruent (i.e., one short and one long) targets. The target distances were cued with words ("long" or "short") or as long or short pairs of horizontal bars. Reaction times were longer, and movement amplitudes were higher, for movements to incongruent target distances than for congruent target distances. However, when the movements were precued, the reaction time cost for incongruent movements was eliminated, suggesting that the increased reaction time cost associated with incongruent movements arose from coupling during response programming of different movement distances for each arm.

More recently, Diedrichsen and colleagues (Albert et al. 2007; Diedrichsen et al. 2001, 2003, 2006; Hazeltine et al. 2003) have demonstrated that the increased costs associated with incongruent movements can be reduced or even eliminated when direct visual cues are provided instead of symbolic cues. As in previous examinations (e.g., Heuer 1993; Heuer et al. 2001; Spijkers et al. 1997), responses were initiated much faster for congruent conditions (than for incongruent conditions) when the movement goals were symbolically cued. However, when the movement goals were directly cued, reaction time values were similar for both congruent and incongruent conditions. Diedrichsen et al. (2006) hypothesized that the increased reaction time costs associated with incongruent movements resulted from response selection conflicts during the translation of symbolic cues into their associated responses. When movements are performed to symbolically cued targets, individuals must translate the symbolic cues into specific actions. In the case of incongruent movements, the computational costs associated with translating the symbolic cues into two different actions "place unusual demands on selection processes" (Diedrichsen et al. 2001: 493), resulting in spatial interference at the cognitive level (Diedrichsen et al. 2001, 2003; Weigelt 2007; Weigelt et al. 2006). In contrast, when the movements are directly cued, the movement goals for the two hands are externally specified, which eliminates the need to translate and assign specific action responses for the two hands.

Motivated by these findings, the purpose of the current experiment was to examine whether the interference in initial grasp postures during bimanual grasping and placing is due to goal-selection conflicts. We borrowed from Diedrichsen et al. (2001) the idea of manipulating the manner in which the movement end-goals for the two hands were cued. In the present study, participants grasped two objects from a table and placed them onto a board to targets that required either identical (congruent object end-orientations) or non-identical degrees of rotation (incongruent object end-orientations). In addition to displaying the required movement end-goals as two-dimensional images of the objects (as has been done in previous studies, see Hughes et al. 2011a, b), the stimuli were also cued symbolically using movement direction specifying letters (e.g., "L" or "R") or by directly illuminating the targets. These latter two conditions were chosen to replicate, as closely as possible, the cueing conditions used in the studies of Diedrichsen et al. (2001, 2003). Furthermore, the object end-orientation conditions were split into two categories. The first category included conditions in which participants could (1) satisfy end-state comfort for one hand, (2) grasp the objects with identical initial postures (indicative of bimanual spatial coupling), or (3) concurrently satisfy bimanual coupling and end-state comfort for both hands. This category allowed us to examine whether both bimanual coupling and end-state comfort are predominant motor planning constraints. The second category included conditions in which participants could (1) satisfy end-state comfort or (2) grasp the objects with identical initial postures. From the results of this category, we were able to ascertain whether one constraint dominated the other (e.g., end-state dominates bimanual coupling, or bimanual coupling dominates end-state).

In our previous studies, the stimuli were cued in a semi-symbolic fashion (Hughes et al. 2011a, b). Based on this work, we hypothesized that participants in the semi-symbolic cueing group would select initial grasp postures that allowed them to satisfy both end-state comfort and bimanual coupling during congruent object end-orientation conditions. In contrast, during incongruent conditions, participants would not reliably (i.e., above chance levels) satisfy both end-state comfort and bimanual coupling. Further, during conditions in which bimanual coupling and end-state comfort are pitted against one another, we hypothesized that participants would satisfy end-state comfort (at the expense of bimanual coupling) during congruent object end-orientation conditions. However, during incongruent conditions, it is expected that neither end-state comfort nor bimanual coupling would emerge as the predominant posture planning constraint.

With respect to the symbolic cueing conditions, we hypothesized that cueing the movement goals in a symbolic fashion would result in conflicts related to the translation of symbolic cues into response codes during incongruent conditions. During conditions in which participants could satisfy end-state comfort for one hand, bimanual coupling, or end-state comfort and bimanual coupling, we expected that participants would be able to concurrently satisfy both end-state comfort and bimanual coupling during congruent conditions. However, during incongruent conditions, the conflict associated with translating the symbolic cues into two different actions would result in an inability to concurrently satisfy both end-state comfort and bimanual coupling. Further, when end-state comfort and bimanual coupling were pitted against one another, we hypothesized that end-state comfort would emerge as the predominant constraint during congruent conditions, but that the proportion of trials satisfying end-state comfort and bimanual coupling would be similar for incongruent conditions.

We also hypothesized that cueing the movement end-goals in a direct fashion would minimize the problems associated with the translation and response assignment. Thus, regardless of object end-orientation congruency, we expected that participants would satisfy both end-state comfort and bimanual coupling (when possible), and end-state comfort for both hands when bimanual coupling and end-state comfort are pitted against one another.

A corollary purpose of the present study was to examine whether the translational demands associated with symbolic cues extend to the level of movement execution during bimanual grasping and placing. Specifically, we examined the degree of interlimb coupling at the start (absolute onset) and end (absolute offset) of both the reach-to-grasp and grasp-to-place phases of the movement. Based on the work of Diedrichsen et al. (2001, 2003), one might expect that interlimb coupling should be lower for incongruent conditions (relative to congruent conditions) when the movement end-goals are cued symbolically, but similar when the movement end-goals are cued directly.

However, there is convincing evidence from recent studies (Blinch et al. 2011; Heuer and Klein 2006), demonstrating that costs in visuomotor translation are limited to movement preparation. For example, Blinch et al. (2011) examined interlimb coupling during both movement preparation (i.e., reaction time) and movement execution (i.e., movement time) during a bimanual reaching task to congruent or incongruent targets, which were symbolically or directly cued. They found that reaction times, movement times, and movement amplitudes for the two hands were more coupled during movements to congruent targets than movements to incongruent targets, independent of stimulus cueing technique. Thus, an alternate hypothesis is that interlimb coupling would be lower for incongruent conditions, compared with congruent conditions, irrespective of the manner in which the movement end-goals are cued.

Methods

Participants

Forty-five right-handed individuals were randomly assigned to either the symbolic cueing (mean age = 24.3, SD = 4.0, 7 men and 8 women), semi-symbolic cueing (mean age = 25.4, SD = 4.4, 9 men and 6 women), or direct cueing group (mean age = 25.4, SD = 4.4, 7 men and 8 women). Participants had normal or corrected-to-normal vision and did not have any known neuromuscular disorders. The experiments conformed to local ethical guidelines and the declaration of Helsinki.

Apparatus

Participants stood in front of a custom-built placement board (2.0 m × 0.4 m) braced by two legs (Fig. 1a). The placement board was adjusted to shoulder height, and the center of the board was oriented so that it coincided with the midline of the participant. On each side of the board were four white target circles[1] (10 cm in diameter). The target circles indicated how the object(s) should be oriented on the board at the end of the movement, and required 0° rotation, 90° internal rotation, 180° rotation, or 90° external rotation. The manipulated objects were two square wooden objects (17.8 cm × 17.8 cm × 3.8 cm) that had a 3.8 cm square protruding from one of the sides. The objects had a handle (17.5 cm length, 3.5 cm diameter) affixed to the center of the main body that allowed participants to use either an underhand or overhand grip. The objects were placed on a small rack (50 cm × 15 cm × 5 cm) located 40 cm in front of the computer display and positioned so that the protrusions always faced upwards.

[1] Viewed from the participant's perspective, these were 12 o'clock for both hands, 3 o'clock for the left hand and 9 o'clock for the right hand, 6 o'clock for both hands, and 9 o'clock for the left hand and 3 o'clock for the right hand.

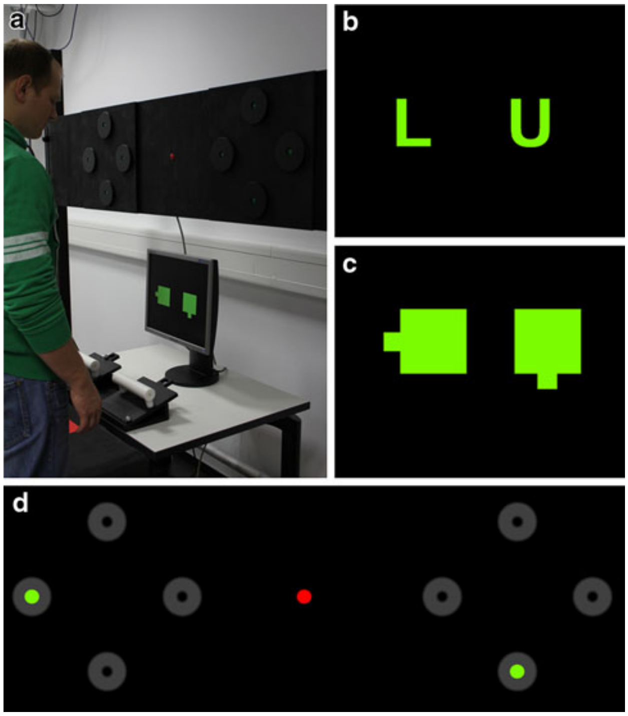

Fig. 1 **a** *Side view* of the experimental setup. Exemplar of the stimuli during **b** symbolic, **c** semi-symbolic, and **d** direct cueing conditions. Depicted are the stimuli for an incongruent condition that required 90° external rotation with the *left hand* and 180° rotation with the *right hand*

The stimuli were displayed symbolically, semi-symbolically, or directly (Fig. 1b–d). In the symbolic condition, the required object end-orientations for the two objects were cued using the first letter of the German word used to specify the movement direction. Thus, movements to the left object end-orientation target were cued using the symbol "L" (links), movements to the right object end-orientation target were cued using the symbol "R" (rechts), movements to the top object end-orientation target were cued using the symbol "O" (oben), and movements to the right object end-orientation target were cued using the symbol "U" (unten). In the semi-symbolic condition, the stimuli consisted of 2D images of the objects indicating the required end-orientations of the objects. In the direct cueing condition, a red light was embedded in the center of the placement board, which served as a preparatory signal. Green lights were embedded in the center of the targets at each object end-orientation, and served to cue the required object end-orientations for each trial.

Procedure

After signing informed consent forms, participants were asked to stand in front of the apparatus with hands relaxed by their sides. The nature of the task was then explained, with instructions specifying that movements with the left hand were always performed with the object and targets located directly in front of the left hand, and movements with the right hand were always performed with the object and targets located directly in front of the right hand. Participants were told to perform the task with the two hands simultaneously. However, no specific instructions were given about how to grasp the objects. We informed participants that movement accuracy was of utmost importance, but that they should also perform the task as quickly as possible.

In the symbolic and semi-symbolic cueing conditions, the beginning of the trial was signaled by the word "Achtung" (German for attention) displayed on the computer monitor. After a random interval (ranging from 1,500 to 2,500 ms), the stimuli were displayed in green, signaling that the participants could initiate their movements. In the direct cueing condition, the beginning of the trial was signaled by the red preparatory signal. After a random interval (ranging from 1,500 to 2,500 ms), the green lights at the corresponding target locations were presented, and participants were allowed to initiate their movements. After the stimuli were displayed, participant grasped and transported the objects to the instructed end-orientations on the placement board. After holding the objects on the board for 2 s, participants brought their hands back to the start position and waited for the next trial to begin. Participants performed five trials in each of the 16 conditions, yielding a total of 80 trials. The 16 conditions were presented in a randomized order. The entire testing session lasted approximately 45 min.

Three-dimensional movement kinematics was recorded at 200 Hz using an optical motion capture system (VICON Motion System, Oxford, U.K.), consisting of ten Bonita cameras. Three retro-reflective markers were placed on each object, and on the distal end of dorsal third metacarpal (MCP), the styloid process of ulna (WRP), and the styloid process of radius (WRT) of the left and right hand. Each trial was recorded using a Basler Pilot DV camera (Basler AG, Ahrensburg, Germany) that was placed above the apparatus and provided a bird's eye view of the apparatus and the participant. The digital video camera was synchronized with the VICON motion capture system and was used to record initial grasp postures and identify any movement errors.

Data analysis

Trials in which the object(s) were placed to the incorrect object end-orientation were counted as errors and not included in analysis. The total number of rejected trials due to errors was less than 1 % of the data, and was equally distributed across conditions and participants. Given the low error rate, mean substitution was used to replace missing values.

Grasp behavior

End-state comfort satisfaction was defined in accordance with recent studies in our laboratory, using a similar experimental setup (Hughes et al. 2011a, b). Specifically, end-state comfort satisfaction was defined by initial underhand grasp postures for movements that required 90° internal rotation and 180° rotation, and by initial overhand grasp postures for movements that required 0° rotation and 90° external rotation. Bimanual coupling was defined by the adoption of identical initial grips (i.e., overhand or underhand for both the left and right hands), irrespective of whether the grips satisfied end-state comfort.

To measure potential differences in initial grasp posture behavior as a function of object end-orientation congruency, stimulus cueing, and constraint satisfaction, the grasp posture data were first separated into congruent and incongruent object end-orientation conditions (Hughes et al. 2011a, b). During congruent object end-orientation conditions, the objects required the same degree of rotation and were mirror symmetric or identical with respect to global coordinates.[2] In contrast, during incongruent object end-orientation conditions, the objects required different degrees of rotation. The data were then separated into two categories. The first category included the individual conditions where it was possible for the hands to (1) satisfy end-state comfort for one hand, (2) satisfy bimanual coupling, or (3) satisfy both bimanual coupling and end-state comfort for both hands. The second category included the conditions where it was only possible to (1) satisfy bimanual coupling or (2) satisfy end-state comfort for both hands. The first category (satisfaction of end-state comfort for one hand, bimanual coupling, or bimanual coupling and end-state comfort for both hands) allows us to examine whether both bimanual coupling and end-state comfort are predominant motor planning constraints, whereas the second category (satisfaction of bimanual coupling or end-state comfort for both hands) allows us to ascertain whether one constraint dominates the other (e.g., end-state dominates bimanual coupling, or bimanual coupling dominates end-state). For both categories, the proportion of trials in which both bimanual coupling and end-state comfort were satisfied was determined for each participant and normalized using an arcsine transformation.[3]

Kinematics

The 3D coordinates of the reflective marker placed on the protrusion of the object were reconstructed, and missing data were interpolated using a cubic spline. All kinematic variables were calculated using custom written MatLab programs (Mathworks, Version 7.0). The marker coordinates were low-pass filtered at a 5 Hz cutoff, using a second-order Butterworth filter. The wrist joint center (WJC) was calculated as the midpoint between WRT and WRP.

For each trial, the time series was divided into the reach-to-grasp phase and the grasp-to-place phase. The reach-to-grasp phase was defined as the time period between when the hand (WJC) left the body to the time the hand (WJC) contacted the object. The grasp-to-place phase was defined as the time period between when the object was lifted from the start position to the time the object contacted the placement board. Movement onset for each phase was determined as the time of the sample in which the resultant velocity of the hand (WJC) exceeded 5 % of peak velocity of the corresponding phase. Movement offset was determined as the time of the sample in which the WJC resultant velocity dropped and stayed below 5 % of peak velocity of the corresponding phase.

Movement time of the reach-to-grasp phase was defined as the time period between reach-to-grasp phase onset and reach-to-grasp phase offset. Movement time of the grasp-to-place was defined as the time period between the grasp-to-place phase onset and offset. Movement velocity for the approach and transport phase was calculated using a first-order central difference technique, and time normalized to 100 data points prior to calculation of peak velocity and time to peak velocity.

The degree of interlimb coupling was calculated at the start (absolute onset) and end of the movement (absolute offset; following Hughes and Franz 2007, 2008; Hughes et al. 2011a). Absolute onset was determined by subtracting the movement onset of the left object from the movement onset of the right object. Absolute offset was determined by subtracting the time of left-hand contact from the time of right-hand contact on the placement board. For both absolute onset and offset, the absolute difference for each trial was calculated, and these individual trials were then averaged to provide a mean value for each condition. Large values indicate that the performance of the two hands was not in close synchrony. In contrast, values close to zero indicate a tight coupling between the two hands.

[2] Analysis revealed no significant differences between egocentric and allocentric congruency ($\chi^2_{(1)} = 0.024$, $p = 0.878$); thus, the data were collapsed across congruency.

[3] Because the grasp posture data did not meet the assumptions of parametric statistical tests (i.e., homogeneity and normal distribution), arcsine transformation was employed to transform the data prior to statistical analysis.

Results

Grasp behavior

General analysis

Differences in grasp posture were examined using a 3 × 2 mixed effects repeated measures analysis of variance (RM ANOVA) with the factors stimulus cueing (symbolic, semi-symbolic, direct) and object end-orientation congruency (congruent, incongruent). The grasp posture data were separated into two categories.

The proportion of trials in which participant's satisfied both end-state comfort for both hands and bimanual coupling are illustrated in Fig. 2a. During congruent conditions in which both constraints could be satisfied, the proportions in which both end-state comfort and bimanual coupling were satisfied were lower for both the symbolic (60 %) and direct cueing groups (75 %), compared with the semi-symbolic group (87 %). However, during incongruent conditions, the proportion of trials in which both constraints were satisfied was similar irrespective of stimulus cueing (symbolic = 60 %, semi-symbolic = 61 %, direct = 60 %). Analysis indicated that bimanual coupling and end-state comfort satisfaction was higher for congruent (74 %), compared with incongruent conditions (57 %), $F(1,42) = 62.047$, $p < 0.001$, $\eta_p^2 = 0.596$. There was also a statistically significant effect of stimulus cueing, $F(2,42) = 7.032$, $p = 0.002$, $\eta_p^2 = 0.251$. Bonferroni-corrected post-hoc analysis revealed significant differences in the proportion of trials satisfying both constraints between the symbolic (55 %) and semi-symbolic (74 %) groups, $p = 0.002$. In addition, the interaction between congruency and stimulus cueing reached significance, $F(2,42) = 4.148$, $p = 0.023$, $\eta_p^2 = 0.165$. The proportion of trials satisfying both constraints was higher for congruent object end-orientation conditions for all three stimulus cueing groups. However, this was more pronounced for the semi-symbolic group (congruency difference = 26 %) than for the symbolic (congruency difference = 11 %) and the direct cueing group (congruency difference = 14 %).

The proportion of trials in which participants satisfied end-state comfort for both hands is illustrated in Fig. 2b. During congruent forced-choice conditions (trials in which participants could either adopt identical initial grips or satisfy end-state comfort, but not both), participants in the semi-symbolic group satisfied end-state comfort in 82 % of total trials. However, the proportion of trials in which participants satisfied bimanual coupling (symbolic = 49 %, direct = 51 %) or end-state comfort for both hands (symbolic = 47 %, direct = 49 %) was similar for both the symbolic and direct groups. Furthermore, the proportion in which end-state comfort was satisfied during

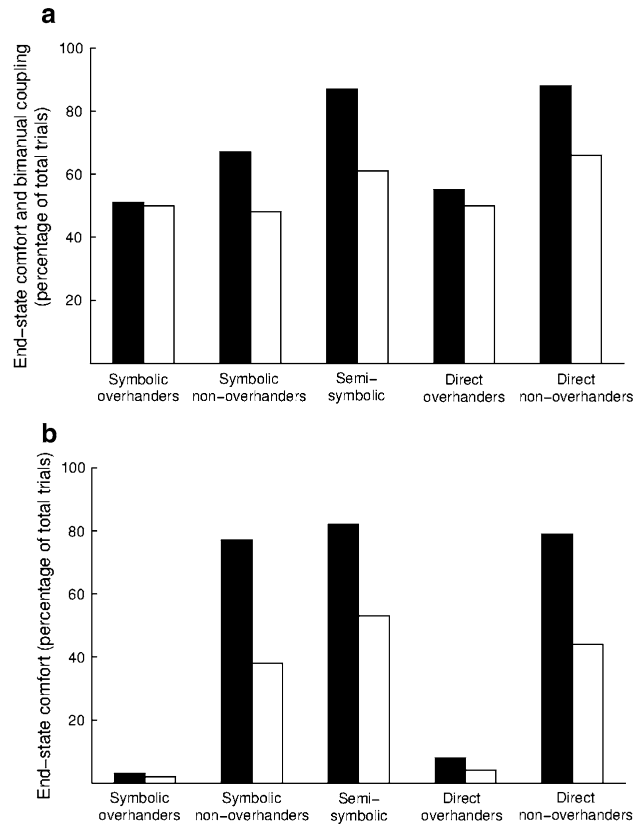

Fig. 2 **a** Percentage of trials in which participants satisfied end-state comfort and bimanual coupling, and **b** end-state comfort for both hands. *Black bars* refer to congruent object end-orientation conditions. *White bars* refer to incongruent object end-orientation conditions

incongruent conditions was much lower for the symbolic (29 %) and direct cueing groups (31 %), compared with the semi-symbolic group (53 %). Analysis indicated that end-state comfort satisfaction was higher for congruent (60 %), compared with incongruent object end-orientation conditions (35 %), $F(1,42) = 41.458$, $p < 0.001$, $\eta_p^2 = 0.497$. A significant main effect of stimulus cueing was also observed, $F(2,42) = 5.250$, $p = 0.009$, $\eta_p^2 = 0.200$. Post-hoc analysis revealed that end-state comfort satisfaction was higher for the semi-symbolic group, compared with both the symbolic and direct cueing groups, $p < 0.05$.

Although the results of the semi-symbolic group replicate our previous findings, the results of the symbolic and direct groups were strikingly different to those we had observed in our previous examinations of end-state comfort (Hughes et al. 2011a, b). When the data were examined in closer depth, there were observable individual differences in the symbolic and direct groups. In these groups, there was a subset of participants (40 %) that grasped both objects using an overhand grasp in all conditions. These participants were classified as "overhanders," whereas the participants who acted in accordance with our previous results were classified as "non-overhanders."

Analysis of individual differences

Given these individual differences, we then examined potential differences in grasp posture behavior using a 5×2 RM ANOVA with the factors stimulus cueing (symbolic overhander, symbolic non-overhander, semi-symbolic, direct overhander, direct non-overhander) and object end-orientation congruency (congruent, incongruent).

During conditions in which participants could satisfy both end-state comfort and bimanual coupling, there was a significant main effect of congruency, with a larger proportion of trials satisfying both constraints during congruent object end-orientation conditions (68 %), compared with incongruent object end-orientation conditions (54 %), $F(1,40) = 40.159$, $p < 0.001$, $\eta_p^2 = 0.501$. There was also a significant main effect of stimulus cueing, $F(4,40) = 7.486$, $p < 0.001$, $\eta_p^2 = 0.428$. Post-hoc analysis revealed significant differences between symbolic non-overhanders and symbolic overhanders (56 vs. 50 %), direct overhanders and direct non-overhanders (52 vs. 72 %), semi-symbolics and symbolic overhanders (76 vs. 56 %), semi-symbolics and symbolic non-overhanders (76 vs. 50 %), and semi-symbolics and direct overhanders (76 vs. 52 %; all ps < 0.01). In addition, there was a significant interaction between congruency and stimulus cueing, $F(4,40) = 4.482$, $p = 0.004$, $\eta_p^2 = 0.310$. Post-hoc analysis revealed that the proportion of trials satisfying both constraints was higher for congruent than for incongruent trials for symbolic non-overhanders (congruent = 67 %, incongruent = 48 %), semi-symbolics (congruent = 87 %, incongruent = 61 %), and direct non-overhanders (congruent = 88 %, incongruent = 66 %; all ps < 0.01). Not surprisingly, the proportion of trials in which both constraints were satisfied for symbolic overhanders and direct overhanders was similar for both congruent and incongruent conditions ($p > 1.0$).

When initial grasp postures could satisfy only one constraint, end-state comfort satisfaction was higher for congruent (32 %), compared with incongruent object end-orientation conditions (17 %), $F(1,40) = 31.012$, $p < 0.001$, $\eta_p^2 = 0.437$. In addition, a significant main effect of stimulus cueing was observed, $F(4,40) = 26.395$, $p < 0.001$, $\eta_p^2 = 0.725$. Post-hoc analysis indicated that end-state comfort satisfaction was higher for symbolic non-overhanders than for symbolic overhanders (54 vs. 0.4 %), for symbolic non-overhanders than for direct overhanders (54 vs. 2 %), for direct non-overhanders than for direct overhanders (60 vs. 2 %), for semi-symbolics than for symbolic overhanders (59 vs. 0.4 %), and for semi-symbolics than for direct overhanders (59 vs. 2 %; all ps < 0.001). End-state comfort satisfaction did not differ between the symbolic non-overhanders, semi-symbolics, and direct non-overhanders ($p > 1.0$).

Kinematics

Given the observed individual differences in grasp behavior between the symbolic and direct cueing groups, potential differences in reach-to-grasp times and grasp-to-place times were examined using separate mixed effects ANOVA's with the factors stimulus cueing (symbolic overhander, symbolic non-overhander, semi-symbolic, direct overhander, direct non-overhander), hand (left, right), and object end-orientation congruency (congruent, incongruent). Mean movement time values for congruent and incongruent object end-orientation conditions during the reach-to-grasp and grasp-to-place phase of the movement are displayed in Fig. 3.

Differences in interlimb coupling during the reach-to-grasp and grasp-to-place phases of the movement were examined using separate mixed effects ANOVAs with the factors stimulus cueing and object end-orientation congruency. Significant results were followed up using post hoc paired comparisons (Bonferroni corrected). Mean interlimb coupling and standard error (in parentheses) values for congruent and incongruent object end-orientation conditions during the reach-to-grasp and grasp-to-place phases are displayed in Table 1.

Reach-to-grasp phase

Reach-to-grasp times were shorter for movements to congruent (742 ms) compared with incongruent object end-orientations (832 ms), $F(1,40) = 59.124$, $p < 0.001$, $\eta_p^2 = 0.596$. In addition, movements performed by the non-dominant left hand (779 ms) were significantly shorter than movements performed by the dominant right hand (795 ms), $F(1,40) = 4.507$, $p = 0.04$, $\eta_p^2 = 0.101$. There was also a significant congruency by group interaction, $F(4,40) = 6.068$, $p = 0.001$, $\eta_p^2 = 0.378$. Post hoc analysis revealed that the difference between incongruent and congruent conditions was significant for symbolic non-overhanders (congruency difference = 108 ms), semi-symbolics (congruency difference = 172 ms), and direct non-overhanders (congruency difference = 111 ms; all ps < 0.001). In contrast, there was no effect of congruency for symbolic overhanders (congruency difference = 43 ms) and direct overhanders (congruency difference = 17 ms; respective p values = 0.165 and 0.609).

Interlimb coupling at the start of the reach-to-grasp phase was similar irrespective of stimulus cueing, $F(4,40) = 0.691$, $p = 0.603$, $\eta_p^2 = 0.065$. In contrast, interlimb coupling was influenced by object end-orientation congruency, with smaller absolute onset values during movements to congruent

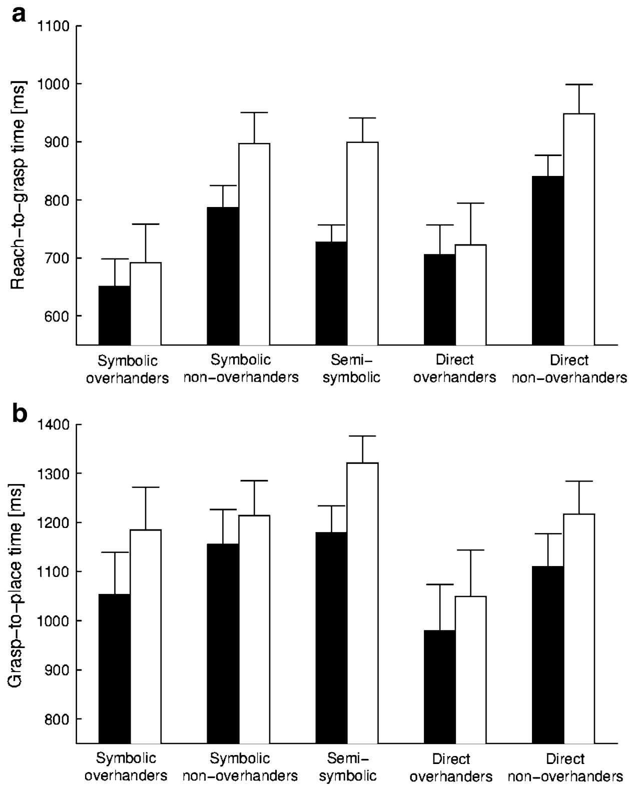

Fig. 3 Mean reach-to-grasp time (**a**) and grasp-to-place time values (**b**) for movements to congruent and incongruent object end-orientations. *Black bars* refer to movements to congruent object end-orientations. *White bars* refer to movements to incongruent object end-orientations (mean ± SE)

(32 ms) object end-orientations, than those during movements to incongruent (46 ms) object end-orientations, $F(1,40) = 5.071, p = 0.03, \eta_p^2 = 0.113$. A similar pattern of results was obtained for reach-to-grasp phase absolute offset, with similar interlimb coupling values regardless of stimulus cueing, $F(4,40) = 1.123, p = 0.360, \eta_p^2 = 0.101$. There was, however, a significant main effect of congruency, with smaller absolute offset values for congruent (33 ms) than for incongruent (69 ms) conditions, $F(1,40) = 17.913$, $p < 0.001, \eta_p^2 = 0.309$.

Grasp-to-place phase

Grasp-to-place times were similar regardless of stimulus cueing (symbolic overhanders = 1,119 ms, symbolic non-overhanders = 1,184 ms, semi-symbolic group = 1,249 ms, direct overhanders = 1,014 ms, direct non-overhanders = 1,164 ms), $F(4,40) = 1.333$, $p = 0.275$, $\eta_p^2 = 0.118$. In contrast, movements performed by the left hand (1,113 ms) were significantly shorter than movements performed by the right hand (1,180 ms), $F(1,40) = 10.811$, $p = 0.002$, $\eta_p^2 = 0.213$. In addition, a significant main effect of object end-orientation congruency was observed, with shorter grasp-to-place times for congruent (1,095 ms) compared with incongruent (1,197 ms) conditions, $F(1,40) = 100.8$, $p \leq 0.001$, $\eta_p^2 = 0.716$. The interaction between group and congruency was also significant, $F(4,40) = 3.065$, $p = 0.027$, $\eta_p^2 = 0.235$. Post hoc analysis indicated significant congruency differences for symbolic overhanders (132 ms), symbolic non-overhanders (59 ms), semi-symbolics (142 ms), the direct overhanders (70 ms), and direct non-overhanders (107 ms), all $ps < 0.01$.

Discussion

Replicating previous works in which the movement goals were cued in a semi-symbolic fashion (Hughes et al. 2011a, b), participants selected initial grasp postures that allowed them to satisfy both end-state comfort and bimanual coupling during congruent object end-orientation conditions (87 %). However, the proportion of trials in which both constraints could be satisfied was significantly lower (61 %) for movements to incongruent object end-orientations. Furthermore, when bimanual coupling and end-state comfort were pitted against one another, participants typically elected to satisfy end-state comfort (82 %) during congruent object end-orientation conditions. In contrast, during incongruent conditions, the proportion of trials in which end-state comfort and bimanual coupling were

Table 1 Mean interlimb coupling and standard error (in parentheses) values for congruent and incongruent object end-orientation conditions during the reach-to-grasp and grasp-to-place phases

	Reach-to-grasp				Grasp-to-place			
	Absolute onset		Absolute offset		Absolute onset		Absolute offset	
	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
Symbolic overhander	19 (10)	22 (20)	34 (7)	58 (24)	21 (5)	37 (12)	211 (37)	298 (43)
Symbolic non-overhander	35 (8)	61 (17)	36 (6)	100 (20)	23 (4)	51 (10)	236 (30)	294 (35)
Semi-symbolic	25 (6)	51 (13)	33 (5)	85 (15)	21 (3)	40 (7)	251 (24)	348 (27)
Direct overhander	37 (11)	43 (22)	30 (8)	31 (26)	14 (5)	17 (13)	156 (41)	179 (47)
Direct non-overhander	42 (8)	52 (16)	32 (6)	71 (19)	29 (4)	50 (9)	211 (29)	328 (34)

satisfied was not statistically different (53 and 45 % respectively).

With respect to the symbolic and direct cueing groups, we hypothesized that direct cueing would minimize interference in goal selection, such that participants would satisfy both end-state comfort and bimanual coupling, regardless of object end-orientation congruency. Our results, however, do not support this hypothesis. During conditions in which participants could satisfy both constraints, there was no advantage in cueing the object end-orientations directly (compared with cueing the movement end-goals in a symbolic or semi-symbolic fashion). Furthermore, when end-state comfort and bimanual coupling were pitted against one another, end-state comfort was much lower for the symbolic (24 %) and direct (28 %) cueing groups than for the semi-symbolic cueing group (53 %) during incongruent object end-orientation conditions.

Closer inspection of the data indicated that the decrease in end-state comfort satisfaction in the symbolic and direct cueing groups could be attributed to individual differences in grip behavior. Although the majority of participants performed the task in a similar fashion to the semi-symbolic group, there was a subset of participants (40 %) in both the symbolic and direct cueing groups who grasped the two objects using an overhand grip in virtually all trials, regardless of condition. Individual differences in end-state comfort sensitivity have been reported in previous studies (Fischman et al. 2003; Janssen et al. 2010; Rosenbaum et al. 1990, 1996), and as in those previous studies, the mechanisms that influenced the individual differences in movement strategies cannot be readily explained by personal factors. Specifically, the age of the participants and proportions of males and females were similar regardless of the chosen planning strategy.

Previous research has suggested that individuals who do not plan their grasps in accordance with end-state comfort may have compromised motor planning abilities (Janssen et al. 2010). In the study of Janssen et al. (2010), participants grasped two bars and placed them into target boxes with either the left end or the right end of the bars pointing down. Although the majority of participants ($n = 10$) adjusted their initial grips so that they could end the movement in comfortable postures for both hands (left hand = 90.0 %; right hand = 98.3 %), there was a subset of participants ($n = 7$) who always grasped the bars with the same initial grips, irrespective of the required end-orientation of the bars (end-state comfort satisfaction: left hand = 21.4 %, right hand = 40.5 %). The authors argue that this subset of participants optimized comfort at the start of the movement, and speculate that these participants might be less proficient planners than individuals who plan their movements to afford comfortable end-states.

An alternate possibility is that the cognitive costs associated with visuomotor translation are higher during symbolic and direct cueing conditions and that participants adopt different grasp posture strategies to comply with the task demands (see De Jong and Sweet 1994 and Meyer and Kieras 1997 for similar findings). We speculate that when the movement end-goals are presented as two-dimensional images of the object (semi-symbolic cueing), the goal states (i.e., object end-orientations) are known prior to movement initiation, and participants plan their initial grasp postures based on the goal states indicated by the stimuli. In contrast, when the movement end-goals are symbolically and directly cued, the stimuli indicate the location in which the protrusion of the object should be oriented toward on the board, but do not provide information about the intended goal states (i.e., the specific object end-orientations). In these situations, participants must first extract information from the stimuli in order to generate and maintain an image-like representation of the objects (Kunde et al. 2009), and then plan the appropriate grasp postures for the left and right hand. We hypothesize that the additional cost of generating and maintaining two distinct object representations increases the cognitive demands associated with motor planning. In our opinion, individuals who grasped the two objects using an overhand grip in virtually all trials (i.e., overhanders) mitigated these cognitive costs by selecting a planning strategy that was less cognitively demanding (i.e., bimanual coupling).

Support for this hypothesis comes from the reach-to-grasp time data. In general, reach-to-grasp times were shorter for congruent (compared to incongruent) movements for symbolic non-overhanders, semi-symbolics, and direct non-overhanders. In contrast, there was no reach-to-grasp time congruency difference for symbolic and direct overhanders.[4] The observation that reach-to-grasp movements were similar for both congruent and incongruent conditions for overhanders in the symbolic and direct cueing groups indicates that these individuals planned their grasp postures prior to stimulus presentation. This strategy minimizes the amount of planning an individual has to engage in when the stimulus appears. In contrast, non-overhanders planned their postures based on the specific demands of the task (e.g., externally rotate the left object 90°, and rotate the right object 180°). Thus, this grasp posture strategy required that they wait for the stimulus to appear before planning the appropriate grasp posture for each hand. The data from the debriefing interviews also support the claim that individuals used different grasp

[4] Although there were differences in reach-to-grasp times based on grasp posture strategy, interlimb coupling during the reach-to-grasp phase did not differ between cueing conditions and grasp posture strategy.

posture strategies. All of the participants, who adopted an overhander strategy, stated that they did so because it was "easier" to grasp both of the objects with overhand grips, rather than grasping the objects with different postures that afford comfort at the end of the movement.

Thus far, we have suggested that the observed individual differences in grasp posture strategy might arise from differences in motor planning abilities or the strategies participants employ in order to comply with task demands. How can one delineate between these two hypotheses? One possibility is to use a within-subjects design, such that participants perform the task when the object end-orientations are cued symbolically, semi-symbolically, and directly. If the individual differences observed in the present study are due to general compromised motor planning abilities (as suggested by Janssen et al. 2010), then we would expect that participants would adopt an identical overhand grasp posture strategy irrespective of stimulus cueing condition. However, if our results are due to increased cognitive costs during the symbolic and direct cueing conditions, then grasp posture strategy would differ depending on the cueing condition. Participants would adopt an identical overhand grasp posture strategy for both congruent and incongruent movements during symbolic and direct cueing conditions. In contrast, when the movement end-goals are cued semi-symbolically, grasp posture behavior would be similar to previous research (Hughes et al. 2011a, b). During congruent movements, participants would satisfy both end-state comfort and bimanual coupling, when possible, and end-state comfort when the two constraints are pitted against one another. However, during incongruent movements, neither end-state comfort nor bimanual coupling would emerge as predominant constraints.

A corollary purpose of the present study was to examine whether the costs of visuomotor translation associated with symbolic cues during bimanual grasping and placing can be observed during movement execution (Diedrichsen et al. 2001, 2003), or are limited to movement preparation (Blinch et al. 2011). In general, average reach-to-grasp and grasp-to-place times were significantly longer for movements to incongruent (than for congruent) object end-orientations, regardless of how the movement end-goals were cued (symbolic, semi-symbolic, direct). Further, in line with Blinch et al. (2011) and Heuer and Klein (2006), we found that interlimb coupling during both the reach-to-grasp and grasp-to-place phases of the movement was lower during movements to incongruent targets and that this congruency difference was observed irrespective of how the movement end-goals were cued.

The finding that interlimb coupling was not affected by cueing condition indicates that the decrease in interlimb coupling during the reach-to-grasp and the grasp-to-place phases does not result from interference in response selection. Rather, the observed congruency effects likely arise from the specification of movement parameters specific to planning and execution of bimanual movements (Heuer 1993), or neuronal cross-talk in efferent pathways (Franz et al. 1996). Although our results indicate that the interference associated with incongruent movements is not influenced by the manner in which the movement end-goals for the two hands were cued, given that reaction time was not measured, there exists the possibility that interference effects related to cue type are limited to early stages of movement preparation (i.e., reaction time). Furthermore, our results should not be taken as evidence that bimanual interference can only occur at the motor programming level. It is our conjecture that bimanual interference in planning and execution can occur at multiple levels of the central nervous system and that the locus of interference differs based on movement characteristics and task requirements (see Spijkers and Heuer 1995 for a similar argument).

Summary

Taken together, our results demonstrate that limitations in grasp posture planning do not arise from conflicts in response selection. In contrast to our original hypothesis, we found that end-state comfort satisfaction was much lower for the symbolic and direct cueing groups, compared with the semi-symbolic group. Furthermore, approximately 40 % of participants in the symbolic and direct cueing groups grasped both objects with initial overhand postures. The observed individual differences in grasp posture strategy might arise from differences in motor planning abilities, or the strategies participants employ in order to comply with task demands. We also found that interlimb coupling was similar regardless of stimulus cueing, suggesting that interference in the execution of bimanual grasping and placing tasks is not due to response selection conflicts.

References

Albert NB, Weigelt M, Hazeltine E, Ivry RB (2007) Target selection during bimanual reaching to direct cues is unaffected by the perceptual similarity of the targets. J Exp Psychol Hum Percept Perform 33:1107–1116

Blinch J, Cameron BD, Franks IM, Chua R (2011) Bimanual reaches with symbolic cues exhibit errors in target selection. Exp Brain Res 212:541–554

De Jong R, Sweet JB (1994) Preparatory control of visual perception in overlapping tasks. Percept Psychophys 55:731–750

Diedrichsen J, Hazeltine E, Kennerley S, Ivry RB (2001) Absence of bimanual interference during directly cued actions. Psychol Sci 7:493–498

Diedrichsen J, Ivry RB, Hazeltine E, Kennerley S, Cohen A (2003) Bimanual interference associated with the selection of target locations. J Exp Psychol Hum Percept Perform 29:64–77

Diedrichsen J, Grafton S, Albert N, Hazeltine E, Ivry RB (2006) Goal-selection and movement-related conflict during bimanual reaching movements. Cereb Cortex 16:1729–1738

Fischman MG, Stodden DF, Lehman DM (2003) The end-state comfort effect in bimanual grip selection. Res Q Exerc Sport 74: 17–24

Franz EA, Zelaznik HN, McCabe G (1991) Spatial topological constraints in a bimanual task. Acta Psychol 77:137–151

Franz EA, Eliassen J, Ivry RB, Gazzaniga MS (1996) Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. Psychol Sci 7:306–310

Hazeltine E, Diedrichsen J, Kennerley SW, Ivry RB (2003) Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. Psychol Res 67:56–70

Heuer H (1993) Structural constraints on bimanual movements. Psychol Res 55:83–98

Heuer H, Klein W (2006) The influence of movement cues on intermanual interactions. Psychol Res 70:229–244

Heuer H, Kleinsorge T, Spijkers W, Steglich C (2001) Static and phasic cross-talk effects in discrete bimanual reversal movements. J Mot Behav 33:67–85

Hughes CML, Franz EA (2007) Experience-dependent effects in unimanual and bimanual reaction time tasks in musicians. J Mot Behav 39:3–8

Hughes CML, Franz EA (2008) Goal-related planning constraints in bimanual grasping and placing of objects. Exp Brain Res 188: 541–550

Hughes CML, Haddad JM, Franz EA, Zelaznik HN, Ryu HR (2011a) Physically coupling two objects in a bimanual task alters kinematics but not end-state comfort. Exp Brain Res 211: 219–229

Hughes CML, Reißig P, Seegelke C (2011b) Motor planning and execution in left- and right-handed individuals during a bimanual grasping and placing task. Acta Psychol 138:111–118

Janssen L, Craje' C, Weigelt M, Steenbergen B (2010) Motor planning in bimanual object manipulation: two plans for two hands? Mot Control 14:240–254

Kunde W, Krauss H, Weigelt M (2009) Goal congruency without stimulus congruency in bimanual coordination. Psychol Res 73:34–42

Marteniuk RG, MacKenzie CL (1980) A preliminary theory of two hand co-ordinated control. In: Stelmach GE, Requin J (eds) Tutorials in motor behavior. North-Holland, Amsterdam, pp 185–197

Meyer DE, Kieras DE (1997) A computational theory of executive control processes and human multiple-task performance: part 2. Accounts of psychological refractory-period phenomena. Psychol Rev 104:749–791

Rosenbaum DA, Marchak F, Barnes HJ, Vaughan J, Slotta JD, Jorgensen MJ (1990) Constraints for action selection: overhand versus underhand grips. In: Jeannerod M (ed) Attention and performance XIII. Motor representation and control. Lawrence Erlbaum, Hillsdale, pp 211–265

Rosenbaum DA, van Heugten CM, Caldwell GE (1996) From cognition to biomechanics and back: the end-state comfort effect and the middle-is-faster effect. Acta Psychol 94:59–85

Rosenbaum DA, Cohen RG, Meulenbroek RG, Vaughan J (2006) Plans for grasping objects. In: Latash M, Lestienne F (eds) Motor control and learning over the lifespan. Springer, New York, pp 9–25

Spijkers W, Heuer H (1995) Structural constraints on the performance of symmetrical bimanual movements with different amplitudes. Q J Exp Psychol [A] 48:716–740

Spijkers W, Heuer H, Kleinsorge T, van der Loo H (1997) Preparation of bimanual movements with same and different amplitudes: specification interference as revealed by reaction time. Acta Psychol 96:207–227

Van der Wel R, Rosenbaum DA (2010) Bimanual grasping planning reflects changing rather than fixed constraint dominance. Exp Brain Res 205:351–362

Weigelt M (2007) Re-examining structural constraints on the initiation of bimanual movements: the role of starting locations, movement amplitude, and target locations. Hum Mov Sci 26: 212–225

Weigelt M, Kunde W, Prinz W (2006) End-state comfort in bimanual object manipulation. Exp Psychol 53:143–148