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RESEARCH ARTICLE

Individual differences in motor planning during a multi-segment object manipulation task

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Abstract Research has demonstrated that people will adopt initially awkward grasps if they afford more comfortable postures at the end of the movement. This end-state comfort effect provides evidence that humans represent future posture states and select appropriate grasps in anticipation of these postures. The purpose of the study was to examine to what extent the final action goal of a task influences motor planning of preceding segments, and whether grasp postures are planned to optimize end-state comfort during a three-segment action sequence in which two objects are manipulated, and participants can select from a continuous range of possible grasp postures. In the current experiment, participants opened a drawer, grasped an object from inside the drawer, and placed it on a table in one of the three target orientations (0°, 90°, or 180° object rotation required). Grasp postures during the initial movement segment (drawer opening) were not influenced by the final action goal (i.e., required target orientation). In contrast, both the intermediate (i.e., object grasping) and the final movement segment (i.e., object placing) were influenced by target orientation. In addition, participants adopted different strategies to achieve the action goal when the object required 180° rotation, with 42 % of participants prioritizing intermediate-state comfort and 58 % prioritizing end-state comfort. The results indicate that individuals optimize task performance by selecting lower level constraints that allow for successful completion of the action goal and that the selection of these constraints is dependent upon contextual, environmental, and internal influences.

Keywords End-state comfort · Motor planning · Multi-segment action sequence · Object manipulation

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Introduction

A characteristic of successful motor performance is the ability to plan and execute movements so that everyday tasks can be accomplished. Although movement kinematics are highly influenced by the properties of the object, the intentions of the actor, and the goals of the task (Ansuini et al. 2008; Armbruester and Spijkers 2006; Jeannerod 1981, 1984; Marteniuk et al. 1987), there is remarkable similarity in the grasp postures which individuals select when manipulating objects.

The relative invariance in grasp postures was first described by Rosenbaum et al. (1990). In that study, participants grasped a horizontally arranged bar and placed either the left end or the right end of the bar into a target disk. Rosenbaum et al. (1990) found that the hand posture (overhand or underhand) used to grasp the bar depended on which end of the bar was to be inserted into the target disk—participants grasped the bar with an underhand posture when the left end of the bar was to be inserted into the target disk, and an overhand posture when the right end of the bar was to be inserted into the target disk. Stated a different way, participants always grasped the bar with an initial hand posture that ensured a comfortable posture at the end of the movement. Called the end-state comfort effect, this phenomenon indicates that future body states are represented and that individuals select initial grasps in anticipation of these future postures.

Motivated by these findings, Haggard (1998) investigated whether grasp posture planning extends to action sequences that require multiple movements. Participants grasped an octagonal object and performed a movement sequence composing of two, three, or five action steps. The movement sequences were identical except that participants had to move the object to one of the two critical target positions at the 2nd, 3rd, or 5th step in the sequence. When the movement sequences involving different target positions were compared, Haggard found that initial grasp postures differed depending on the specific movement sequence, which participants were instructed to perform for sequences consisting of up to three action steps. Based on these results, Haggard argued that people are able to plan an appropriate initial grasp posture when the multi-sequence movement consists of two or three action steps.[1] Haggard also found that differences in initial grasp posture were more likely to occur when the critical target occurred early on in the movement sequence, which he took as evidence that early steps in an action sequence are considered more compared to later steps (i.e., a gradient of grasp posture planning).

More recent research has examined whether motor planning extends to situations in where multiple objects are manipulated (Hesse and Deubel 2010b). In the study of Hesse and Deubel (2010b, Experiment 1), participants performed a pick-and-place action sequence that consisted of three movement segments and the manipulation of two different objects. In the first movement segment, participants reached and grasped an object (4-cm-diameter cylinder) located 20 cm to the left of the hand start position, and placed the object on a target circle (second movement segment). In the third movement segment, participants grasped a second object that was positioned in one of the three orientations and placed it in the middle of the workspace. The authors found that the orientation of the second object (i.e., the target bar) in the third movement segment influenced the grip orientation of the first and second movement segment (i.e., when grasping and when releasing the cylinder), suggesting that anticipatory motor planning extends to situations in which multiple objects are manipulated.

In sum, the results of Haggard (1998) and Hesse and Deubel (2010b, Experiment 1) indicate that individuals consider each element of a multi-segment action when planning their initial grasp postures and that initial grasp postures depend critically on task requirements in the final steps of a movement sequence. However, from these two studies, it is unclear what individuals planned in advance. One possibility is that people plan their grasp postures to ensure comfort at the end of a movement. The sensitivity toward comfortable end postures has been found to generalize to a number of experimental paradigms during two segment movement sequences (i.e., grasping and placing of a single object) and is a predominant grasp selection constraint in unimanual tasks (see Rosenbaum et al. 2006 for a review). But whether people plan their grasp postures to satisfy end-state comfort during an action sequence consisting of more than two segments has yet to be fully investigated. The present study built on this previous work and investigated motor planning during a multi-segment action sequence in which two objects are manipulated, and participants can select from a continuous range of possible grasp postures. Of particular interest was the extent to which the final action goal of the task influences the planning (i.e., grasp postures and movement times) of the preceding segments during a three step movement sequence, and whether grasp postures are planned to optimize comfort at the end of the movement.

To address these questions, participants were asked to perform a three-segment grasping and placing action sequence. In this task, participants opened a drawer (initial movement segment), grasped a cylindrical object from inside the drawer (intermediate movement segment), and placed the object on a table (final movement segment). The final action goal of the task was manipulated such that participants placed the object on a table in one of the three different target orientations (from the participants perspective: up [0° rotation], left [90° rotation], or down [180° rotation]).

Based on previous research (Haggard 1998; Hesse and Deubel 2010b, Experiment 1) indicating that individuals are able to plan the entire action sequence prior to movement initiation (i.e., before opening the drawer), it is expected that grasp posture and movement times during the first movement segment (i.e., drawer opening) would be influenced by the final action goal of the task (i.e., specific end orientation when placing the object on the target). However, given that participants do not have to maintain their initially selected grip during the entire action sequence, it is also possible that later movement segments would influence only the *immediately preceding*, rather than *all*, grasp postures in the movement sequence (a sequential planning strategy). That is to say, the final

[1] When participants made adjustments to initial grasp posture, they typically did so by changing the placement of the individual fingers, rather than rotating the whole hand.

goal of the movement would influence the grasp posture of the intermediate, but not the initial movement segment.

Moreover, previous research has shown that people plan their grasp postures to afford comfortable end-states (e.g., Rosenbaum et al. 1990). Thus, it is expected that individuals will grasp the object with a posture that results in similar final postures regardless of target orientation in the final movement segment. Thus, intermediate but not final grasp postures should differ as a function of object end orientation. However, there also exists the possibility that the ability to plan for comfortable end postures does not extend past the second segment in an action sequence. If this is the case, then it is expected that final grasp postures would differ as a function of object end orientation, but that intermediate grasp postures would be similar for all target orientations. Last, it is also possible that grasp comfort would be dispersed between the intermediate and final movement segments. If this is the case, then it is expected that both intermediate and final grasp postures would change as a function of object end orientation.

Methods

Grasping task

Participants

Twenty students from Bielefeld University took part in the experiment in exchange for experimental course credit. The data set from one participant was removed prior to the analysis as the participant was unable to follow instructions. The remaining 19 participants (mean age = 21.95, SD = 5.23, 3 men, 16 women) were classified as right-handed (mean = 81.6, SD = 16.5) as assessed by the Edinburgh Handedness Inventory (Oldfield 1971). Participants had normal or corrected to normal vision, did not have any known neuromuscular disorders, and were naïve to the purpose of the study. The experiment was conducted in accordance with local ethical guidelines and conformed to the declaration of Helsinki.

Apparatus

Figure 1 shows the set up of the experiment. The apparatus consisted of a drawer (8.5 × 20 × 30 cm) attached to a wooden platform. Affixed to the center of the drawer face was a cylindrical knob (7 cm in diameter, 4 cm in height). The drawer could be adjusted to participant's hip height by sliding the wooden platform up and down on four metal poles (each 2 m in height, 2 cm in diameter).

The manipulated object was a PVC cylinder (7 cm in diameter, 4 cm in height, and 215 g in weight) with a black mark (0.5 cm in width) on top, which extended from the center to the outer edge of the object. Located inside the drawer was a 7.2-cm-diameter socket (0.5 cm in depth) that served to house the object. A black mark (0.5 cm in width, 3.5 cm in length) extended from the socket toward the back of the drawer. The object was visible to the participants before the drawer was opened. At the start of each trial, the object was situated so that the marks on the object and socket coincided with one another.

The wooden target board (29 cm × 29 cm) was height adjustable and featured a centrally located socket (7.2 cm in diameter, 0.5 cm in depth). Radiating from the outside edge of the target well were three colored marks (blue, green, and red, 0.5 cm in width, 3.5 cm in length)[2] that indicated the three target orientations up, left, and down. These target orientations required the participants to rotate the object 0°, 90°, or 180°, respectively.

Motion capture

Kinematic data were recorded using an optical motion capture system (VICON Motion Systems, Oxford, UK) consisting of 12 MX-F20 CCD cameras with 200 Hz temporal and 0.25 mm spatial resolution. Retro-reflective markers (14 mm in diameter) were placed dorsally on the distal end of the third metacarpal (MCP), the styloid process of the ulna (WRP), the styloid process of the radius (WRT), the medial and lateral epicondyle of the humerus (ELM and ELL, respectively), the acromion process (ACR) of the right arm, the suprasternal notch (CLAV), the xiphoid process (STRN), the 7th cervical vertebra, and the 8th thoracic vertebra of the torso. In addition, a marker (10 mm in diameter) was placed on top of the object (2.5 cm from the center), and 3 markers (10 mm in diameter) were placed on the corners of the target board (top left, top right, and bottom right). These markers were used for the calculation of end orientation error (measured in degrees [°]).

Procedure

Upon entering the laboratory, the task was explained to the participants, and after any questions were answered, the participants completed the informed consent and handedness forms. Retro-reflective markers were placed on the appropriate anatomical landmarks, and arm length and hip height were measured, and the apparatus was adjusted. A stripe of tape was placed on the floor (at a distance of 75 % of participant's arm length from the face of the drawer) and

[2] In order to control for perceptual effects associated with target perception, the spatial arrangement of the coloured marks on target board was randomized.

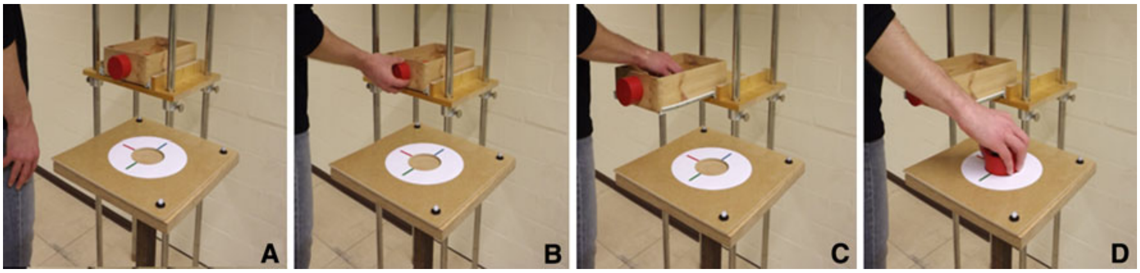

Fig. 1 Set up and procedure of the experiment. **a** At the start of the trial, the participant stood with the *right* arm by the side of the body. **b** After a signal from the experimenter indicating the required target orientation of the object, the participant opened the drawer by the knob (initial movement segment), **c** grasped the object from inside the drawer, **d** placed it on the target board in the predefined target orientation

served to mark where the participants should stand during the experiment.

At the start of the trial, participants stood slightly to the left of the drawer midpoint, with the right arm by the side of the body, so that the right shoulder was aligned with the center of the drawer knob (see Fig. 1a). At the start of each trial, the experimenter verbally instructed the target mark that the object should be placed to (e.g., "blue"). The participants then opened the drawer by the knob (see Fig. 1b), grasped the object from inside the drawer (see Fig. 1c), and placed it on the target board in the instructed target orientation (up, left, or down, requiring 0°, 90°, or 180° object rotation, see Fig. 1d). The participants then placed the arm back to the side of the body and waited for the next trial to begin. Participants were instructed that all fingers should contact the objects during manipulation. Furthermore, participants were informed that accuracy was of utmost importance and that they should move at a comfortable speed.

Each target orientation was repeated 12 times in a randomized order, yielding a total of 36 trials. The experimental session, including informed consent, took approximately 20 min.

Data analysis

The 3-D coordinates of the retro-reflective markers were reconstructed and labeled in VICON Nexus 1.4. Marker loss was minimal and interpolated using the gap fill procedure. The trajectories were low-pass filtered at a 5 Hz cutoff, using a second-order Butterworth filter. Calculations based on the kinematic data were conducted via custom written MATLAB scripts (R2008a, The MathWorks). Prior to kinematic analysis, the wrist joint center (WJC) and the elbow joint center (EJC) were calculated as the midpoint between WRT and WRP and as the midpoint between ELL and ELM, respectively. The shoulder joint center (SJC) was calculated as 50 mm below ACR. In addition, two direction vectors were calculated, one pointing distally from the WJC to MCP ($V1 = \text{MCP} - \text{WJC}$), and a second one passing through the wrist ($V2 = \text{WRP} - \text{WRT}$). The hand center (HC) was defined on a plane normal to $V1 \times (V2 \times V1)$, positioned palmar from MCP at a distance of (hand thickness + marker diameter)/2 in a way that (HC − WJC) and (HC − MCP) formed a right angle. The dependent variable of major interest was the hand orientation at each movement segment. Hand orientation was calculated as the angle (α) of the projection of the vector pointing distally from the WJC to the HC on the drawer face plane (for the initial movement segment) and on the drawer floor/target board plane (for the intermediate and final movement segment). Hand orientations with the fingers pointing up (12 o'clock position), left (9 o'clock position), right (3 o'clock position), and down (6 o'clock position) are defined as hand orientation angles 0°, 90°, −90°, and 180°, respectively (Fig. 2).

Recent research (Studenka et al. 2012) has shown that anticipatory adjustments during sequential tasks cannot only be observed at the end effector (i.e., the hand) but also at more proximal joints of the arm. Thus, in addition to hand orientation, we also calculated the configuration of the whole arm (i.e., the seven joint angles from the shoulder, elbow, and wrist). Based on the ISB recommendations on the definitions of joint coordinate systems for the upper

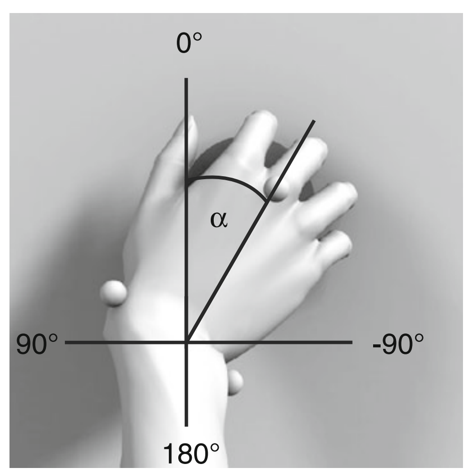

Fig. 2 Calculation of hand orientation angle α

body (Wu et al. 2005), four body segments were defined. Thorax coordinates were defined differently from Wu et al. (2005) in a way that the x axis of all segments was pointing from the back to the front of the body, the y axis from the finger tips to the shoulder, and the z axis pointing upwards, when participants assumed a zero position with the arm stretched toward the side and the thumb pointing upwards. Joint angles were calculated via Euler rotations between adjacent body segments. Euler rotations of the thorax to the upper arm yielded shoulder flexion/extension, shoulder horizontal flexion/extension, and shoulder internal/external rotation. Euler rotations of the upper arm to the lower arm yielded elbow flexion/extension and pronation/supination. Euler rotations of the lower arm to the hand yielded wrist flexion/extension and wrist abduction/adduction.

For each trial, the time series was divided into the three movement segments: (1) drawer opening (initial movement segment), (2) object grasping (intermediate movement segment), and (3) object placing (final movement segment). The initial movement segment (drawer opening) was defined as the time period between when the hand (WJC) left the body to the time the hand grasped the drawer knob. The intermediate movement segment (object grasping) was defined as the time period between when the hand left the drawer knob to the time the object was grasped. The final movement segment (object placing) was defined as the time period between when the object was lifted from the drawer to the time the object was placed to the target board. Movement onset of each segment was determined as the time of the sample in which the resultant velocity of the hand exceeded 5 % of peak velocity of the corresponding segment. Movement offset was determined as the time of the sample in which the resultant velocity dropped and stayed below 5 % of peak velocity of the corresponding phase. Initial movement time, intermediate movement time, and final movement time were defined as the time period between movement onset and offset of the corresponding segment. Initial, intermediate, and final hand orientation and joint angles values were extracted at movement offset of the corresponding segment.

Statistical analysis

Hand orientation angle was analyzed using repeated measures ANOVAs with the factor target orientation [up (0° object rotation), left (90° object rotation), down (180° object rotation)][3] at the end of each movement segment (opening the drawer, grasping the object, placing the object on the target board). Movement times and object placement error were analyzed using repeated measures ANOVA with the factor target orientation (up, left, down). Joint angles were analyzed using repeated measures MANOVAs with the factor target orientation (up, left, down) and the seven joint angles at the end of each movement segment as dependent variables.

Mauchly's test of sphericity was applied to test that the variance–covariance matrix of the transformed variables had covariances of 0 and equal variances. In the event that the sphericity assumption was violated, the Greenhouse–Geisser correction was applied and the associated p values are reported. All significant effects were examined using Bonferroni corrected post hoc analysis. Values are presented as mean ± SE.

Assessment of grasp comfort

To quantify comfortable grasp postures, we obtained an independent measure of grasp comfort at the end each movement segment (i.e., drawer opening, object grasping, object placing) using a separate pool of participants ($n = 14$, mean age = 26.36, SD = 2.37, 4 men and 10 women). Participants reported normal or corrected to normal vision and did not have any neurological or neuromuscular disorders. The experiments were conducted in accordance with local ethical guidelines and conformed to the declaration of Helsinki.

The experimental set up and motion capture analysis were identical to that used in the main experiment. At the start of each trial, the movement segment was specified verbally by the experimenter, and participants were told to reach out with their right hand and grasp the object with the most comfortable grasp posture. Following each response, the participant placed their hand back to the side of the body and waited for the next trial to begin. The participant performed 5 comfortable grasps in each movement segment, yielding a total of 15 trials. The entire session lasted approximately 10 min. The grasp postures of the Comfort group were analyzed and compared to the grasp postures adopted in the grasping task.

Results

Object placement error

In general, object placement error was very low (mean = 4.13°) and did not differ between the 0° (3.84 ± 0.31°), 90° (3.42 ± 0.52°), and 180° (5.14 ± 1.16°) object rotation conditions, $F(2,36) = 1.44$, $p = 0.251$.

Movement time

Analysis revealed that there was no effect of target orientation on initial movement time, $F(2,36) = 0.236$,

[3] The 0° rotation (up) condition was used as a baseline measure of grasp behavior.

Table 1 Mean movement times in ms (SEs) as a function of target orientation

	Initial movement time	Intermediate movement time	Final movement time
Target orientation (°)			
0	751 (33)	1,936 (77)	1,659 (79)
90	753 (30)	2,006 (84)	1,768 (104)
180	757 (29)	2,149 (106)	1,946 (128)

$p = 0.742$. In contrast, intermediate movement time and final movement time increased with the required degree of object rotation, $F(2,36) = 34.905$, $p < 0.001$ and $F(2,36) = 15.875$, $p < 0.001$, respectively (Table 1). For both the intermediate and the final movement segment, post hoc tests indicated that all conditions differed significantly from each other (all $p < 0.05$).

Hand orientation

As with movement times, hand orientation angles were similar regardless of target orientation when opening the drawer, $F(2,36) = 1.90$, $p = 0.165$. The finding indicates that the final action goal did not influence grasp choice during the initial movement segment (Fig. 3a).

In contrast, hand orientation angles when grasping the object from inside the drawer (intermediate movement segment) were influenced by target orientation [$F(2,36) = 13.16$, $p = 0.002$], indicating that participants changed their intermediate grasp posture depending on the required object end orientation. During movements to the 0° rotation target (up), participants grasped the object so that the middle finger pointed toward the 12 o'clock position (−2.69 ± 2.51°). Post hoc analysis revealed significant differences between the hand orientation angles for 90° (left) target orientation (−12.13 ± 2.13°, 1 o'clock) compared to the 0° (up) target orientation ($p < 0.001$), and compared to the 180° (down) target orientation (23.03 ± 8.59, 11 o'clock, $p = 0.002$), indicating that the object was grasped with the hand in a more adducted (i.e., with the wrist bent toward the pinkie side) hand orientation for the 90° (left) target orientation condition than for the 0° (up) and 180° (down) orientation condition. Hand orientation angles were also significantly different for the 0° (up) orientation condition than for the 180° (down) target orientation conditions. Specifically, the object was grasped with the hand in a more abducted (i.e., with the wrist bent toward the thumb side) hand orientation for the 180° (down) target orientation compared to the 0° (up) target orientation 0° ($p = 0.022$) (Fig. 3b).

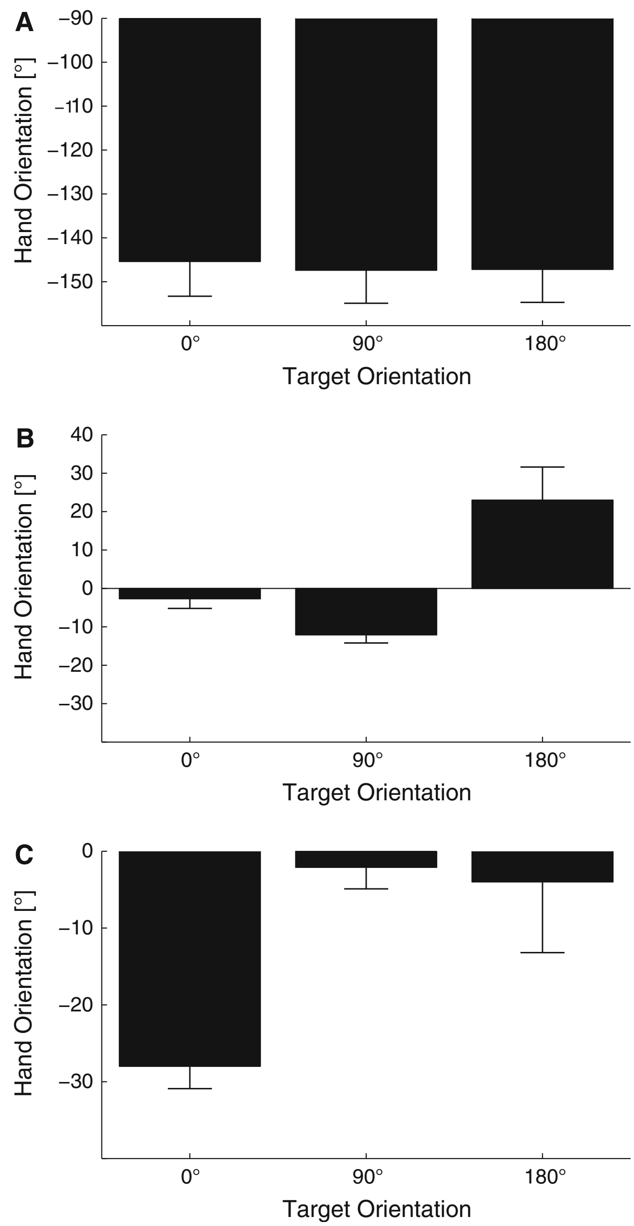

Fig. 3 Hand orientation as a function of target orientation for **a** initial movement segment (drawer opening), **b** intermediate movement segment (object grasping), **c** final movement segment (object placing)

As in the intermediate movement segment, there was an effect of target orientation on hand orientation angles at the end of the final movement segment, $F(2,36) = 6.96$, $p = 0.015$. Post hoc analysis indicated that the object was placed with the hand in a more abducted (i.e., with the wrist bent toward the thumb side) orientation for the 90° (left) condition (−2.11 ± 2.81°) compared to the 0° (up) condition (−27.99 ± 2.85°, $p < 0.001$). No other comparisons were significant (Fig. 3c).

Table 2 Mean (SE) joint angle values (°) for the different target orientation and *F* values of the separate ANOVAs

Joint angle	Target orientation			*F*
Intermediate movement segment				
Wrist	0°	90°	180°	
Flexion/extension	7.5 (1.1)	10.4 (1.1)	4.7 (2.2)	4.48*
Radial/ulnar deviation	23.7 (1.4)	28.5 (1.1)	9.6 (4.6)	15.01**
Elbow				
Flexion/extension	66.7 (1.8)	60.5 (2.5)	61.8 (3.0)	4.07*
Pronation/supination	145.0 (1.8)	148.8 (2.7)	148.8 (2.7)	1.58
Shoulder				
Flexion/extension	79.3 (1.6)	79.3 (1.6)	61.5 (5.3)	14.48**
Horizontal flexion/extension	23.6 (1.5)	25.5 (1.7)	33.7 (2.0)	49.58***
Internal/external rotation	23.3 (1.4)	22.4 (1.5)	36.5 (2.3)	29.05***
Final movement segment				
Wrist	0°	90°	180°	
Flexion/extension	8.5 (1.1)	2.1 (2.0)	−10.9 (5.0)	10.02**
Radial/ulnar deviation	4.2 (1.4)	−9.8 (1.0)	5.0 (3.7)	11.34**
Elbow				
Flexion/extension	65.8 (2.3)	61.2 (2.5)	56.4 (2.6)	29.25***
Pronation/supination	135.3 (1.4)	138.1 (2.0)	143.4 (4.4)	1.96
Shoulder				
Flexion/extension	51.2 (1.7)	33.7 (1.8)	36.0 (3.1)	19.70***
Horizontal flexion/extension	3.7 (1.3)	8.4 (1.3)	12.4 (1.4)	25.77***
Internal/external rotation	−5.2 (2.6)	19.4 (3.2)	25.1 (4.7)	24.39***

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Joint angles

Separate repeated measures MANOVAs on the seven joint angles revealed that final target orientation did not influence the joint angles when opening the drawer, $F(14,60) = 1.55$, $p = 0.12$. Final target orientation did, however, influence the joint angles when grasping the object and when placing the object on the target [$F(14,60) = 9.84$, $p < 0.001$ and $F(14,60) = 18.93$, $p < 0.001$, respectively]. To assess which joint angles contributed to the effects, separate repeated measures ANOVAs were conducted on each joint angle at the end of the intermediate and final movement segment.

Analyses revealed that for both the intermediate and the final movement segment, all joint angles but the pronation/supination angle were influenced by the target orientation (all $p < 0.05$) (Table 2). As with hand orientation angles, the results on joint angles indicate that the requirements of the final task (i.e., placing the object in a certain target orientation) influenced the intermediate (grasping the object) and final movement segments (placing the object), but not the initial movement segment (opening the drawer).

Given that the results obtained from the joint angle data were similar to the hand orientation angle data, the following analyses were restricted to the hand orientation angles.

An unexpected result to emerge from the current experiment was the presence of individual differences in the direction of object rotation for the 180° (down) target orientation condition. Eleven of the 19 participants predominantly rotated the object clockwise (in 81.8 % of the trials), whereas 8 or the 19 participants rotated the object counterclockwise (in 96.9 % of the trials).[4]

Given these individual differences, we examined whether the direction of object rotation for the 180° target orientation condition influenced the adopted hand orientation angles. Participants were separated into two groups (clockwise turner [CWT]) and counterclockwise turner [CCWT]), and only the trials in which the object was rotated according to group classification were included in the analysis. Differences in hand orientation angle at the end of the initial, intermediate, and final movement segment were assessed using separate mixed effect ANOVAs on the factors [(group: CWT, CCWT) and (target orientation: up, left, down)]. Differences in object placement error were examined using a 2 (group) × 3 (target orientation) mixed effects ANOVA. Separate independent *t* tests were conducted to compare differences between the two groups at each target orientation.

[4] Inspection of the data revealed that if the direction of object rotation differed from their typical strategy (e.g., rotating the object counterclockwise, when they typically rotated the object clockwise), this usually occurred in the first two trials. There were no observable differences in consistency between participants.

Analyses indicated that initial hand orientation angles were not influenced by target orientation [$F(2,34) = 2.25$, $p = 0.121$] or group, $F(1,17) = 0.016$, $p = 0.902$. The target orientation × group interaction was also not significant, $F(2,34) = 1.51$, $p = 0.235$ (Fig. 4a).

There were significant differences in intermediate grasp postures between target orientation [$F(2,34) = 88.05$, $p < 0.001$] and group, $F(1,17) = 86.72$, $p < 0.001$. Additionally, the target orientation × group interaction was significant, $F(2,34) = 139.70$, $p < 0.001$. Post hoc t tests revealed no differences in intermediate grasp postures between the groups for target orientation 0° (up) [CWT = −0.61 ± 3.30°, CCWT = −5.56 ± 3.87°, $p = 0.345$] and 90° (left) [CWT = −11.57 ± 2.88°, CCWT = −12.88 ± 3.38°, $p = 0.771$]. In contrast, for target orientation 180° (down), intermediate grasp postures of the CWT were oriented more counterclockwise (63.59 ± 2.43°, 10 o'clock) compared to the CCWT [−18.33 ± 2.84°, $p < 0.001$, Fig. 4b]. The same pattern of results emerged for final grasp postures. Analysis revealed significant differences dependent on target orientation [$F(2,34) = 59.25$, $p < 0.001$] and dependent on group, $F(2,34) = 43.87$, $p < 0.001$. The target orientation × group interaction was also significant, $F(2,34) = 176.83$, $p < 0.001$. Post hoc t tests indicated that final grasp postures did not differ between groups for target orientation 0° (up) [CWT: −27.59 ± 3.86, CCWT: −28.52 ± 4.52, $p = 0.877$] and 90° (left) [CWT: −2.87 ± 3.78, CCWT: −1.09 ± 4.43, $p = 0.763$]. In contrast, for target orientation 180° (down), grasp postures of the CWT were oriented more clockwise (−47.15 ± 3.39) compared to the CCWT (44.75 ± 3.98, $p < 0.001$ (Fig. 4c).

Object placement error was not influenced by group [$F(1,17) = 0.52$, $p = 0.480$], nor did the target orientation × group interaction reach significance, $F(2,34) = 2.36$, $p = 0.110$.

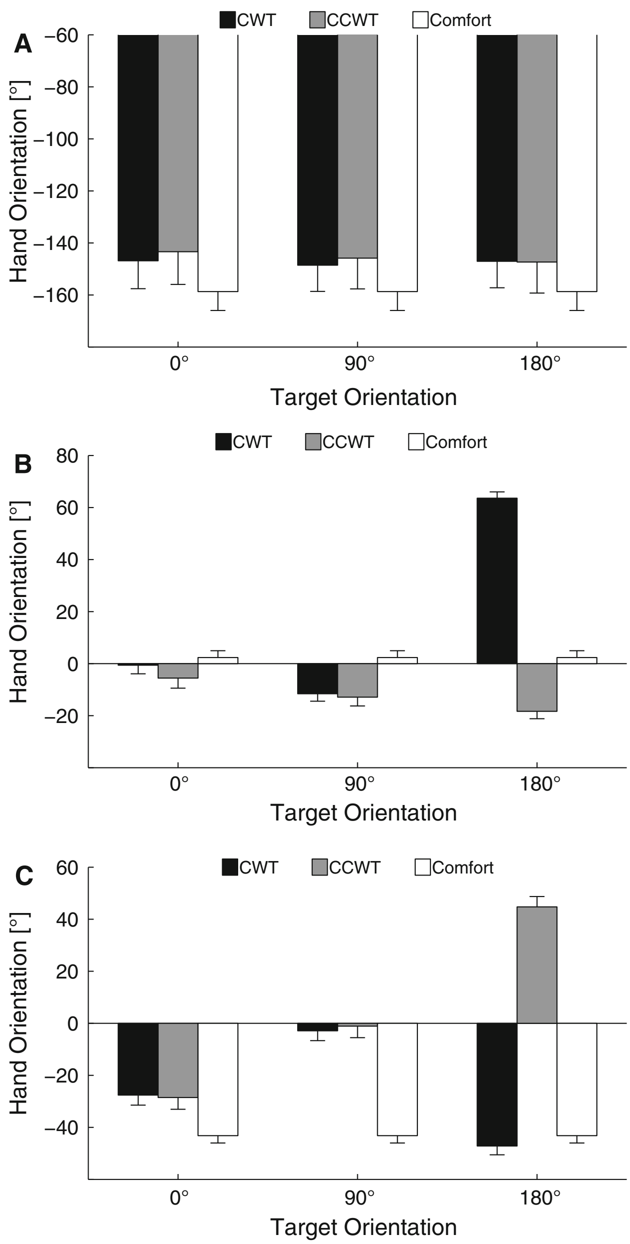

Fig. 4 Hand orientation as a function of target orientation for **a** initial movement segment (drawer opening), **b** intermediate movement segment (object grasping), **c** final movement segment (object placing). *Black bars* indicate hand orientation of clockwise turner (CWT), *gray bars* of counterclockwise turner (CCWT), and *white bars* of the Comfort group (comfort)

Grasp comfort

Analysis of grasp comfort (Comfort group) indicated that hand orientation angles of −158.69 ± 7.26° were considered as most comfortable during the initial movement segment (drawer opening). Hand orientation angles of 2.35 ± 2.61° (12 o' clock hand position) were considered as most comfortable during the intermediate movement segment (object grasping). Hand orientation angles of −43.17 ± 2.83° (2 o' clock hand position) were considered as most comfortable during the final movement segment (object placing).

In the current experiment, we were specifically interested in whether grasp postures are planned to optimize comfort at the end of the movement. To this end, we compared the hand orientation angles of the CWT and CCWT groups with the hand orientation angles obtained in the assessment of grasp comfort (Comfort) at each movement segment.[5] During the initial movement segment, hand orientation angles of CWT and CCWT were similar to the

[5] Because the assessment of comfortable hand orientation angles differed considerably from the assessment of grasp postures during the main experiment (i.e., different sample population, task, and instructions), the data are compared qualitatively, rather than quantitatively.

hand orientation angles of the Comfort group for all target orientations (Fig. 4a).

For the 0° target orientation, intermediate hand orientation angles were also similar for all groups, indicating that participants adopted comfortable intermediate postures for this condition. Final hand orientation angles of CWT and CCWT differed slightly from the Comfort group (mean deviation: CWT = 15.61°, CCWT = 14.68°, Fig. 4b, c).

Intermediate hand orientation angles of CWT and CCWR during the 90° target orientation deviated from intermediate hand orientation angles of the Comfort group by 13.97° for CWT and by 15.28° for CCWT. Final hand orientation angles between CWT and the Comfort group differed by 40.33° and between CCWT and the Comfort group by 42.11° (Fig. 4b, c). Thus, for the 90° target orientation, adopted grasp postures did neither strictly optimize comfort at the intermediate nor at the final movement segment.

For the 180° target orientation, intermediate hand orientation angles of both CWT and CCWT were different from the Comfort group. However, the magnitude of deviation was larger for CWT (61.19°) compared to the CCWT group (20.73°). Final hand orientation angles differed considerably between the CCWT and the Comfort group (mean deviation = 87.92°). In contrast, final hand orientations of CWT were very similar to the comfortable final hand orientation angles (mean deviation = 3.98°, Fig. 4b, c). In sum, for the 180° target orientation, the data indicate that participants who rotated the object clockwise (CWT) prioritized the end-state comfort, whereas participants who rotated the object counterclockwise (CCWT) prioritized the intermediate comfort over the end-state comfort.

Discussion

The aim of the present study was to investigate the anticipatory planning during a multi-segment object manipulation task. Based on previous literature (Haggard 1998; Hesse and Deubel 2010b), we hypothesized that grasp postures during both the intermediate (i.e., when grasping the object from the drawer) and initial movement segment (i.e., when grasping the drawer) would be influenced by the final action goal of the task (i.e., specific end orientation when placing the object on the target). Our findings, however, do not support this prediction. We found that the movement end-goal influenced grasp postures during the intermediate, but not the initial movement segment, indicating that participants did not plan the entire movement sequence holistically in advance.

Although there is a possibility that anticipatory planning is limited to a single object, the finding that motor planning extends to tasks in which multiple objects are manipulated (Hesse and Deubel 2010b, Experiment 1) indicates that such an explanation is unlikely. We hypothesize that the ability to plan for the entire movement was influenced by the degree of precision required during the final movement segment (see also Hesse and Deubel 2010a, b; Rand and Stelmach 2000; Haggard and Wing 1998; Alberts et al. 2002). For example, in Hesse and Deubel (2010b, Experiment 2), participants performed the same multi-segment movement sequence described in the introduction (Hesse and Deubel 2010b, Experiment 1), except that the precision demands of the second movement segment (i.e., placing the cylinder) were increased. Instead of placing the cylinder on a target circle, participants had to place the first object on a pin located in the center of the target circle. Hesse and Deubel found that the increased precision demands affected the planning process, such that the grip orientation in the early movement segments was no longer influenced by the orientation of the bar in the last movement segment. The authors argue that the higher task demands might have required more planning resources and thus prevented a holistic planning process.

The results of the current experiment support this proposition. After grasping the object from the drawer, participants had to align the black mark located on the top of the object (0.5 cm wide) with the appropriate colored mark (0.5 cm wide) located on the target board. We maintain that this action required a high level of precision at the end of the movement sequence. Thus, the high precision demands in the present task might have required vast cognitive costs associated with motor planning and programming. To mitigate these cognitive costs, participants might have adopted a sequential planning strategy. In other words, participants generated two different movement plans (one for the drawer opening and another for grasping and placing the object) to reduce the cognitive motor planning costs. One way in which this hypothesis could be tested is by reducing the precision demands at the final movement segment (e.g., double the width of the target marks). If the ability to plan in a holistic fashion is influenced by the high precision requirements, then one would expect to observe a shift from sequential to holistic performance when end point precision requirements are reduced, and the final target orientation would also influence initial grasp postures.

In this study, we examined whether individuals are able to plan their grasp postures to optimize end-state comfort during a three-segment action sequence in which they can select from a continuous range of possible grasp postures. Based on the comfort ratings, intermediate hand postures were defined by orientation angles of 2.35° (12 o'clock hand position), and comfortable final postures were defined by hand orientation angles of −43.17° (2 o'clock hand position). Comparison of the object manipulation task with the comfort ratings data indicated that participants selected a comfortable grasp posture (−2.69°, 12 o' clock hand position) when grasping the object from inside the drawer for the 0° target orientation condition. This grasp posture resulted in a final grasp posture (−27.99°, 1 o'clock position) that was slightly different from a comfortable final posture (mean deviation = 15.18°). In contrast, participants typically grasped the object from the drawer with an average hand orientation angle of −12.13° (1 o'clock position) for the 90° (left) target orientation condition, which resulted in average final hand orientation angles of −2.11° (12 o'clock position). Thus, comparing the hand orientation angles for the 90° rotation (left) and the 0° rotation (up) condition, intermediate grasp postures were less comfortable for the 90° rotation condition, indicating that participants sacrificed comfort when grasping the object from the drawer so that the hand could be placed in a more comfortable posture at the end of the movement. However, the deviation from comfortable hand orientation angles at the end of the movement (when placing the object on the target board) was larger for the 90° rotation condition (41.06°) compared to the 0° rotation condition (15.18°), suggesting that postures are not planned to strictly optimize end-state comfort.

At first glance, the results of the current experiment are incongruent with the corpus of work demonstrating that end-state comfort is a primary motor planning constraint (e.g., Rosenbaum et al. 1990, 1993; Short and Cauraugh 1999; Weigelt et al. 2006). However, the critical difference between previous research and the present study is that previous studies limited the range of possible hand orientations that could be adopted. In the aforementioned studies, participants had to choose between two distinct grasp postures (i.e., overhand vs. underhand grasp). A limitation of these dichotomous grip choice tasks is that they do not allow for moderate comfort at both the start and the end of the movement, instead forcing participants to sacrifice comfort at the start of the movement if they wish to satisfy end-state comfort.

More recent studies in which an object is to be rotated have indicated that the sensitivity toward comfortable end-states differs in tasks where participants can select from a continuous range of possible grasp postures (e.g., Herbort and Butz 2010, 2012). For example, Herbort and Butz (2010) asked participants to grasp a circular knob and rotate it 45°, 90°, or 135° in a clockwise or counterclockwise direction. They found that participants selected initial grasp postures to afford end-state comfort, but that the extent of end-state comfort sensitivity was strongly influenced by the direction of rotation, as well as the degree of object rotation. Thus, evidence from the present study as well as the studies of Herbort and Butz (2010, 2012) suggests that individuals plan their movements to afford moderately comfortable grasp postures at the intermediate and final movement segments, rather than for end-state comfort alone. Compared to grasp postures that optimize comfort at the end of the movement (which necessitate that participants sacrifice comfort at the start of the movement), this "weighted comfort" strategy negates extremely awkward and uncomfortable positions at discrete points in time (e.g., when placing the object on the target board). The results of the present study do not provide information about the precise distribution of the "weighted comfort" between the intermediate and final movement segments. It is possible that individuals distribute comfort between the two time periods equally. Conversely, the possibility exists that individuals weight comfort higher at one time point than at the other time point.

An interesting finding to emerge from the present study was the presence of individual differences for movements that required 180° rotation. We found that some participants preferred to rotate the object counterclockwise ($n = 8$), while others preferred to rotate the object clockwise ($n = 11$). Participants who preferred counterclockwise rotations typically grasped the object from the drawer with the hand in a 1 o'clock orientation (−18.33°), which resulted in final grasp postures (44.75°, 10 o'clock) that were considerably different from what was expected based on the comfort ratings data (−43.17°, 2 o'clock). In contrast, participants who rotated the object clockwise typically grasped the object from the drawer with the hand in a 10 o'clock orientation (63.59°), which resulted in final grasp postures (−47.15°, 2 o'clock) that were similar to the comfortable final postures. Thus, the data indicate that participants who preferred counterclockwise rotations prioritized comfort at the intermediate grasp over end-state comfort, while participants who preferred clockwise rotations weighted end-state comfort higher than comfort at the intermediate grasp.

Individual differences in selection of movement strategies have been reported before during unimanual (Hughes et al. 2012a; Rosenbaum et al. 1996) and bimanual synchronous movements (Fischman et al. 2003; Hughes and Franz 2008; Hughes et al. 2012b; Janssen et al. 2010). For example, in the study of Janssen et al. (2010), participants grasped two bars and placed them in target boxes with either the left end or the right end pointing down. Although the majority of participants adjusted their initial grips so that they could end the movement in a comfortable posture (i.e., thumb-up posture), there was a subset of participants who always grasped the bars with the same initial grips, irrespective of the required end orientation of the bars. The authors argue that the latter group weighted comfort at the start posture higher than end-state comfort and suggest that these participants might be "less proficient planners" (Janssen et al. 2010, p. 251).

Although it is certainly plausible that these participants were less efficient planners than the participants who planned for end-state comfort, we have an alternative explanation for these differences. In the present task, the instructions of the task emphasized accuracy, and participants were not only able to satisfy the action goals of the task, but were highly accurate in doing so. Thus, we postulate that some individuals prioritized comfortable start postures or averaged comfort, which in our opinion does not necessarily imply that these individuals have compromised motor planning abilities. The results of the current experiment do not allow us to determine whether this subset of participants prioritize start or averaged comfort, or have compromised planning abilities. One possible solution to dissociate between these two explanations would be to examine motor planning across a number of different tasks. If the participants in the present task who did not behave in accordance with end-state comfort are less proficient planners, they should also exhibit poor planning abilities across a range of tasks. In contrast, if these participants prioritize comfort at different stages in the action sequence, then we would expect that they would exhibit likewise behavior in similar tasks (i.e., prioritizing intermediate-state comfort), but that planning performance in other tasks would be comparable to the general population.

In sum, the results of the present study build on previous research from our laboratory (Hughes and Franz 2008; Hughes et al. 2011, 2012a, b; Seegelke et al. 2011) in which we advocate the perspective that movements are first planned with respect to the action goals of the task. These action goals, in turn, serve to guide lower level constraints, such as grasp posture planning. The process and selection of appropriate grasp postures are influenced by not only the task, but by the internal state of the individual. Specifically, each individual optimizes their own performance by selecting lower level constraints that allow for successful completion of the action goal, and the selection of these constraints is dependent upon contextual, environmental, and internal influences. The chosen constraints are then weighted relative to one another, forming a task-specific constraint hierarchy. As our results suggest, individual differences in task conceptualization and optimization lead some participants to prioritize end-state comfort, and other participants to prioritize comfort at the intermediate, rather than at the final, movement segment.

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