End-State Comfort in Bimanual Object Manipulation

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Abstract. The present experiment investigated the sensitivity for end-state comfort in a bimanual object manipulation task. Participants were required to simultaneously reach for two bars and to place the objects' ends into two targets on the table. The design of the experiment allowed to dissociate the relative roles of initial means (e.g., the selection of grips) and final postures (e.g., the anticipation of end-states). The question of interest was whether affording different grip patterns for the two hands would introduce a bias away from reaching end-state comfort. Results revealed a strong sensitivity for end-state comfort, independent of the required grip patterns. In particular, end-state comfort was preferred even if this meant selecting different initial means (i.e., different grips) for the two hands. Hence, end-state oriented action planning appears to dominate interaction costs that may result from motor-related, intermanual interference. We infer that movement planning is constrained by action goals (e.g., a comfortable end-posture for both hands), but largely unaffected by the type of motor actions necessary to achieve these goals.

Keywords: bimanual coordination, motor planning, prehension, end-state comfort effect

Introduction

The ability to grasp and manipulate objects in a purposeful way is essential to solve everyday tasks, such as using a knife to spread butter over bread or operating a corkscrew to open a bottle of wine. Given the seemingly endless number of situations in which we have to grasp and manipulate objects, it is astonishing that we appropriately select our grip postures nearly every time we perform a particular action, without having to spend much thought on it. From a behavioral perspective, the selection of grip postures provides an interesting field of study for researchers interested in the principles and mechanisms underlying human action control.

In a sense, every voluntary body movement is a goal-oriented action at the same time. Even if one has nothing else in mind than just moving (i.e., when dancing), there has to be a representation of what the movement should look like, feel like, and sometimes even sound like. If we accept this notion, then we must assume that the generation of action goals always comes before the specification of efferent motor commands needed to satisfy these goals. The model of "posture-based movement planning" nicely illustrates this point (e.g., Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995). According to this model, movements are planned relative to the final state of an action, as long as the actor is free to choose the necessary motor maneuver. Consider a study by Rosenbaum et al. (1990), in which participants were asked to reach for a bar that was horizontally supported by a stand and to place one marked end into a target disc on the table. In this task, almost all participants chose their reaches in a way that allowed them to finish the action in a comfortable grip posture (e.g., holding the bar with the thumb pointing up), even if this meant to initiate the action out of an awkward grip posture (e.g., underhand grip). This sensitivity to avoid awkwardness at the final position has been termed the "end-state comfort effect" (Rosenbaum et al., 1990) and has been replicated for a number of similar transport tasks (Cohen & Rosenbaum, 2004; Rosenbaum & Jorgensen, 1992; Short & Cauraugh, 1997). From our point of view, end-state comfort provides an excellent example of goal-related planning in human motor control, where means (e.g., efferent motor commands) are instantaneously specified to reach desired ends (e.g., comfortable final positions). This idea accords with ideo-motor approaches to motor control, which hold that movements are exhaustively coded in terms of their various reafferences (visual, proprioceptive, auditory), and that specifying some intended reafference is all that needs to be done (and actually all that can be deliberately done) to plan the forthcoming action (James, 1890). The necessary "motor activity of, sometimes extreme formal complexity, is spontaneously tuned in" (Mechsner, Kerzel, Knoblich, & Prinz, 2001, p. 72).

However, it is certainly debatable whether the specification of goal-satisfying efferent motor commands occurs so effortlessly and encapsulated as suggested by ideo-motor approaches, because there is much evidence that utilizing different means (i.e., different patterns of muscle activation) can substantially affect performance. Some of the most impressive demonstrations of means-related influences can be found in research on bimanual coordination. Here, it has been shown that the simultaneous specification of asymmetrical motor patterns for the left and right hands can result in massive intermanual interference (such as when initiating a forceful response with the one hand while initiating a weak response with the other hand; Steglich, Heuer, Spijkers, and Kleinsorge, 1999; for overviews, see

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Heuer, 1993, or Swinnen & Carson, 2002). This interference is assumed to reflect interaction costs that arise when different efferent motor commands have to be simultaneously specified (e.g., Heuer, 1993) and/or carried out (Carson, Riek, Smethurst, Lison, & Byblow, 2000). Hence, potential interaction costs should affect performance under situations in which the two hands are simultaneously engaged in solving goal-related tasks.

In the present study, we explored to what extent goal-related action planning (indicated by end-state comfort effects) is affected by means-related processes (indicated by intermanual cross-talk effects) when the two hands reach for two objects simultaneously. To this end, we extended Rosenbaum et al.'s (1990) object transport task to a bimanual situation. Participants were asked to simultaneously grasp two bars (horizontally supported by two stands) and to position them into two targets on a table (see Figure 1). Both bars were painted black on one end and white on the other end. The critical manipulation in the present task was that the two bars were either positioned in the same orientation (e.g., both black ends pointing to the right) or in different orientations (e.g., one black end pointing left and the other black end pointing right). Importantly, the two bars could either be grasped with similar (bimanual overhand or bimanual underhand) or different (one overhand and one underhand) initial grips, which in turn afforded a rotation of the forearms toward and/or away from the body midline. For bimanual forearm rotations, it has been shown that performance degrades with asymmetrical forearm rotations (one arm rotating inward and the other arm rotating outward) in comparison to symmetrical forearm rotations (both arms rotating inward or outward), presumably due to manual interference arising from non-homologous muscle activations (Byblow, Chua, & Goodman, 1995; Carson et al., 2000). The present task provides for a situation in which the two hands rotate either in a symmetrical or asymmetrical fashion before grasping the objects and/or during the following transport phase.

The manipulation of initial object orientation allows to dissociate the relative roles of initial means (the way objects are grasped at the beginning of the movement) and final postures (the way hands are placed at the end of the movement). Here, similar means (e.g., both hands use an overhand grip) may lead to different ends (e.g., one hand holding the bar with the thumb pointing up and the other with the thumb pointing down), and, at the same time, similar ends (e.g., both thumbs pointing up) can be achieved through different means (e.g., one hand uses an overhand grip and the other an underhand grip). The question of interest is whether participants prefer to select similar means (i.e., grasp-related similarity), while tolerating differences in end-state comfort, or similar ends (i.e., end-state—related similarity), while flexibly selecting different means.

Figure 1 illustrates the conditions that help to decide between these alternatives. In the upper panel, means-related and ends-related accounts make identical predictions (i.e., both preferring an overhand grip for the two hands). More interesting are conditions of the type depicted in the lower panel. Here, a tendency for similar means will result in the selection of identical grips for both hands (i.e., both hands use an overhand grip), while producing a comfortable end-state in one hand but not in the other (i.e., right thumb pointing up but left thumb pointing down). Conversely, a sensitivity for comfortable end-states will result in the selection of different grips (i.e., underhand grip for the left hand but overhand grip for the right hand), while producing comfortable end-states for both hands (i.e., both thumbs pointing up).

Experiment

Method

Participants

Twelve students from the University of Munich participated in the experiment. There were eight women and four men. All participants gave their informed consent prior to the experiment, and none of them had experienced the task before. There was no financial benefit for participation.

Apparatus

Figure 1 depicts the apparatus. Two bars, each 20 cm long and 2 cm in diameter, rested horizontally on two supports. Each bar was painted black on one end and white on the other end. The two supports were spaced 20 cm apart and held the bar 25 cm above the table (75 cm above the floor). Two white cubes (dimensions: length = 10 cm, width = 10 cm, and height = 5 cm) served as movement targets and were placed on the table, about 20 cm in front of each support. Each cube further consisted of a round hole (2.5 cm diameter), in which one end of the bar could be inserted. Also, a taped line, approximately 150 cm away from the table, yielded the starting position that had to be taken up before each trial. A video camera recorded the whole experiment with the prior consent of each participant.

Task and Procedure

The experiment consisted of two parts: In the first part, participants were asked to reach for the bar with either their left or right hand and to place one end (black or white) into the target. For these *unimanual* trials, only one bar was positioned on the support to the left or right, respectively. Each bar end (black and white) was put down one time for left- and right-hand reaches, resulting in a total of four unimanual trials (Tasks 1–4). The order for hand (left vs. right), color (black vs. white), and bar orientation (the black end pointing to the left vs. to the right) was counterbalanced across the participants. In the second part of the experiment, participants were asked to reach for the two bars with both hands simultaneously and to place their ends into the two targets. For these trials, two bars were positioned on the two supports. The two bars were either in the same orientation (Tasks 5–8; e.g., both black ends pointing

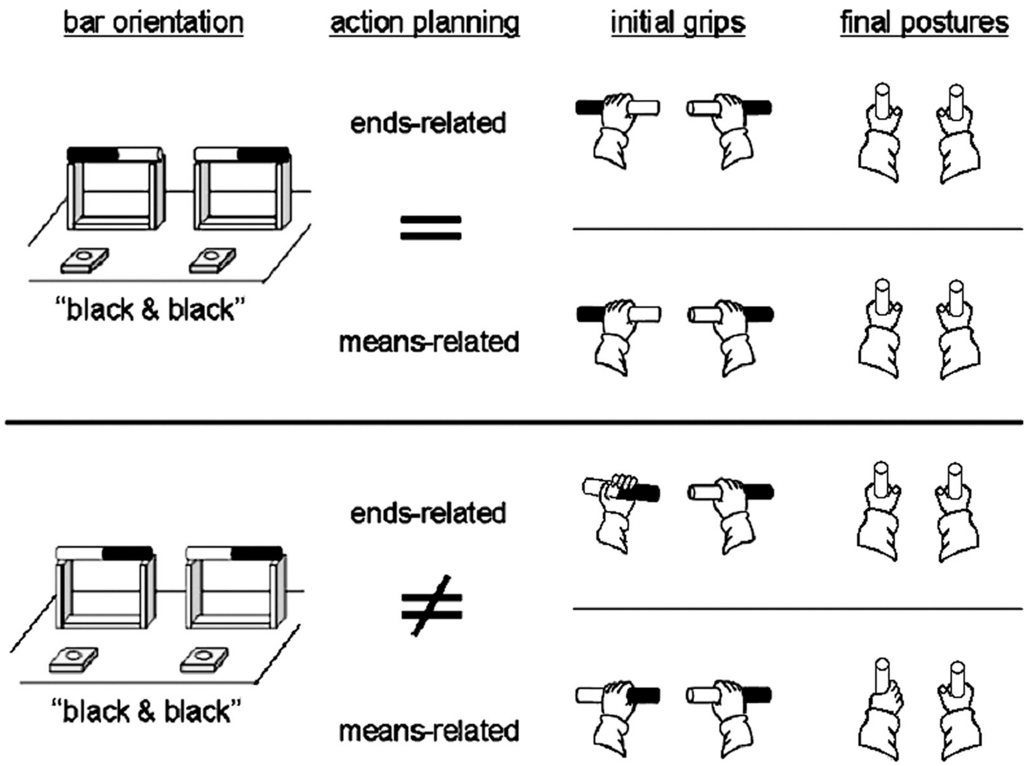

Figure 1. Depiction of the bimanual bar transport task. The upper and lower panels illustrate the predictions according to means-related and ends-related influences on action planning for the initial grip selected and the final posture obtained in two sample conditions. When similar ends are instructed, different predictions arise depending on the orientation of the bars (same vs. different) in Task 10 (upper panel) and Task 5 (lower panel).

to the right) or different orientations (Tasks 9–12; e.g., one black end pointed to the left and one to the right). Each combination of colors for the two ends (black and white) was required one time for each bar orientation, resulting in a total of eight bimanual trials. The order for bar orientation (same vs. different) was blocked and counter-balanced across the participants, while the order of color combination (black vs. white) was variable within these blocked conditions.

Participants began each trial behind the starting line, where they were instructed by the experimenter which bar end had to be placed into the target. Then, participants were asked to step toward the bar, pick it up, and place the instructed bar end squarely into the target. After keeping the hand fixed in the final position for about 2–3 seconds, they returned the bar to its starting position. The experimenter noted on an experimental spreadsheet the initial grip at the beginning and the final posture at the end of each trial. For future reference, each task was videotaped with the participant's prior consent. The procedure was equivalent for bimanual trials. The whole experiment lasted about 20 minutes. Please note at this point that we tried our utmost to replicate the apparatus used, task exploited, and procedures undertaken as closely as possible to the Rosenbaum et al. (1990) study mentioned above. The design of the present study was altered only to include bimanual conditions.

Results

Table 1 should be consulted for a summary of the different conditions and the number of successful reaches (i.e., the hands finishing in end-state comfort) for unimanual and bimanual trials.

Unimanual Trials

During right-hand trials (Trials 1–2), all 12 participants used an overhand grip when the right end of the bar had to be placed down, ensuring a comfortable final posture. However, when the left end had to be placed down, 11 out of 12 participants spontaneously adopted an underhand grip, which in turn led to the same result—a comfortable final posture. During left-hand trials (Trials 3–4), essentially the same pattern of results was obtained. Participants used an overhand grip when it led to end-state comfort (for all 12 participants), but they spontaneously adopted an underhand grip in situations in which the overhand grip would not have sufficed (11 out of 12). Thus, participants chose their grips in a way that replicated the end-state comfort criterion (Rosenbaum et al., 1990). To evaluate this outcome statistically, we analyzed the grip preference data across hands with Cochran's Q test (Siegel, 1956, pp. 161–165). The grip preference differed significantly from chance: $Q = 71.167$, $p < .001$, ($df = 7$).

Table 1. Summary of conditions and results.

Task	Action	Orientation	Color	Grip	Observed
1	uni	- □■	right: black	right: overhand	12
2	uni	- □■	right: white	right: underhand	11
3	uni	□■ -	left: black	left: underhand	11
4	uni	□■ -	left: white	left: overhand	12
5	bim	same	right: black	right: overhand	12
		□■ - □■	left: black	left: underhand	11
6	bim	same	right: white	right: underhand	12
		□■ - □■	left: white	left: overhand	12
7	bim	same	right: black	right: overhand	12
		□■ - □■	left: white	left: overhand	12
8	bim	same	right: white	right: underhand	12
		□■ - □■	left: black	left: underhand	12
9	bim	different	right: black	right: overhand	12
		■□ - □■	left: black	left: overhand	12
10	bim	different	right: white	right: underhand	12
		■□ - □■	left: white	left: underhand	12
11	bim	different	right: black	right: overhand	12
		■□ - □■	left: white	left: underhand	12
12	bim	different	right: white	right: underhand	12
		■□ - □■	left: black	left: overhand	12

Note. All task descriptions assume the right bar pointing with the black end to the right (in the experiment, however, bar orientation was counter-balanced between participants). *Action* denotes unimanual (uni) and bimanual (bim) trials. *Orientation* is the relative position of two bars on the supports as being the same or different. *Color* provides the instructed end for the right and left bar. *Grip* gives the initial grip needed to reach end-state comfort for the right and left hand. *Observed* provides the number of participants finishing in a thumb-up posture (max = 12).

Bimanual Trials

With regard to bar orientation and bar ends instructed, four different conditions can be differentiated: (1) When the two bars were placed into the *same* orientation *and* the *same* end colors were instructed, 11 out of 12 participants selected different grips for the two hands (Tasks 5–6). (2) When the two bars were placed into the *same* orientation *but different* end colors were instructed, all 12 participants selected the same grip for the two hands (Tasks 7–8). (3) When the two bars were placed into *different* orientations *but* the *same* end colors were instructed, all 12 participants selected the same grip for the two hands (Tasks 9–10). (4) When the two bars were placed into *different* orientations *and different* end colors were instructed, all 12 participants selected different grips for the two hands (Tasks 11–12). To summarize, participants chose their bimanual grips to ensure a comfortable posture for the two hands at the end of the movement under all conditions. To evaluate this outcome statistically, we analyzed the grip preference data across all bimanual conditions with Cochran's Q test. The grip preference differed significantly from chance: $Q = 173.125$, $p < .001$, ($df = 15$).

Discussion

In the present experiment, we sought to find out whether the notion of posture-based movement planning and end-state comfort (e.g., Rosenbaum et al., 1990, 1995) holds for tasks in which the two hands reach for two objects simultaneously. The question of interest was whether affording different grip patterns (while introducing potential intermanual interaction costs) for the two hands would impose a bias away from reaching end-state comfort. If so, participants should have displayed a tendency to select similar initial grips while tolerating differences in end-state comfort for the two hands. This, however, was never the case. That is, participants aimed at reaching comfortable end-states under all conditions, even when this meant to select different initial grips and to specify different efferent motor commands. Two task conditions are especially noteworthy in this respect: In the first one, participants spontaneously adopted an awkward grip in the beginning of the action (e.g., grasping both bars with an underhand grip), in order to maximize comfort at the end (Tasks 8 and 10). The second one is even more compelling. Here, participants flexibly adopted different initial grips (e.g., one overhand and one underhand grip), so that the two hands finished the bimanual action in a comfortable end-state (Tasks 5–6 and Tasks 11–12)—that is, despite previous research showing performance difficulties during the simultaneous production of asymmetrical forearm rotations (Byblow et al., 1995; Carson et al., 2000), as was the case under the latter task condition. Hence, the sensitivity to reach a comfortable end-state in one hand appears to be largely unaffected by the type of efferent activation (e.g., a different motor command) taking place in the other hand.

These results highlight the influence of intended goal states on the selection of appropriate movements (Jeannerod, 1999; Prinz, in press), while supporting the notion that means (e.g., initial grips) are prepared relative to desired ends (e.g., comfortable hand postures). The present experiment revealed the tendency to minimize awkwardness for both hands at the end of bimanual object manipulations, even under conditions in which end-state comfort could only be achieved through different grips and motor actions. We propose that the preparation processes involved in generating bimanual end-state comfort dominate processes related to the selection of hand grips and trajectory planning, where the anticipation of a common action goal (e.g., comfortable end-postures) determines the production of efferent motor commands (e.g., patterns of muscle activation) with little efferent interference between hands. Converging evidence for this notion comes from another recent study by Kunde and Weigelt (2005). These authors demonstrated that under time pressure, selecting congruent goal positions for two objects enhances the preparation of bimanual responses—independent of the motor demands required to achieve these goals.

With respect to the motor demands of the task, it may be argued that the methods used in the present experiment were not sensitive enough to show interaction costs between the two hands. That is, the potential manual interference effects arising when movement trajectories for the two hands differ (e.g., during asymmetric rotations of the bilateral forearms) may be too small when compared to the larger variations in end-state comfort. Further, it seems reasonable to assume that interaction costs related to the anticipation of goal states (e.g., manual end-state comfort), the selection and programming of movements (e.g., hand grips), and the coordination of overt manual behavior (e.g., during the reaching, grasping, and manipulation of objects) all have different origins within the sensory-motor system. If true, this notion has implications for different brain functions, which will be discussed below.

It is known that the control of actions involves a number of distributed systems that can be functionally linked to action planning, movement selection and preparation, and movement execution (Gazzaniga, Ivry, & Mangun, 1998). For instance, action goals are generated in the association cortex, while the appropriate movements necessary to reach these goals are selected in the supplementary motor area and the premotor cortex. Once a movement has been selected, the basal ganglia and the lateral cerebellum are involved in the preparation of the movement, while the motor cortex activates a particular muscle pattern to realize the action. In this context, bimanual tasks can provide insight into the relative contribution of goal- and motor-related processes for the control of actions. That is, in these tasks, potential interaction costs arise because of neuronal cross-talk between the two brain hemispheres (Cardoso de Oliveira, 2002). Does neuronal cross-talk affect these processes, and thus distinct brain regions, differently? From the present study it can be cautiously inferred that interaction costs have a greater effect on brain areas involved in the generation of action goals, but less effect on brain areas involved in the selection and preparation of movements (for a similar view, see Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004).

Further research using neuroscience methods is certainly needed to substantiate this notion. Here, event-related fMRI, measuring the bold signal of neural activity during the simultaneous production of two-handed actions, has already been proven to be a useful tool in revealing possible brain areas involved in the control of bimanual coordination (for an overview of related studies, see Swinnen & Wenderoth, 2004). We conclude that, when grip selection is unconstrained by task requirements, bimanual action planning aims to generate comfortable end-states for both hands, flexibly adjusting for the required movement trajectories. An interesting question is whether common goal states determine grip selection even if one hand is (a priori) fixed in an awkward position. To plan for common goal states under such conditions, the other hand would end in an uncomfortable posture as well. We are currently conducting such experiments.

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