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RESEARCH ARTICLE

Goal-related planning constraints in bimanual grasping and placing of objects

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Abstract Our primary objective was to examine the possible interplay of the end-state comfort effect and bimanual temporal and spatial coupling constraints in a grasp-to-place task. Unimanual and bimanual grasping and placing tasks were employed with manipulations on initial comfort (by use of potentially interfering obstacles) and target goals (using various demands on end goal object orientations). Confirming previous temporal findings, incongruent bimanual tasks were considerably slower in initiation time and movement time than congruent ones, reflecting costs in conceptualizing, planning, and completion of the task. With respect to spatial constraints, when the same goal was present for both hands there was strong evidence of the influence of both end-state comfort and bimanual constraints. This was often not the case when the task demands differed for the two hands, although the primary task goals were still attained. We suggest that the implementation of constraints is not based on a strict hierarchy; rather, certain constraints become dominant depending on the task and situation.

Keywords Bimanual coordination · Grasping · Movement planning

Introduction

The ability to synchronize and regulate movements has been a subject of intense study in recent years. Specific emphasis has been placed on elucidating the cognitive organization of movement planning (Marteniuk et al. 1987; Rosenbaum et al. 1990; Rosenbaum and Jorgensen 1992). In a seminal experiment by Rosenbaum et al. (1990) participants were asked to grasp, using one hand, a horizontally placed cylinder and move it to either a left or right target. Reacting spontaneously, subjects used an overhand grip when placing the right end of the cylinder on either target, but used an underhand grip when placing the left end of the cylinder on the target. The idea is that people plan their movements so that the involved effectors end up in comfortable postures. This phenomenon is termed the end-state comfort effect and is clearly evident in everyday life. For example, a person unloading a dishwasher is likely to grasp a cup in an inverted (awkward) posture in order to set the cup down in a comfortable manner on a shelf located overhead. The end-state comfort effect is supported by other studies utilizing multifarious manipulanda and movement goals (Rosenbaum et al. 1993) and indicates that initial grip orientation is dependent on external (e.g., obstacles, object size) and internal (e.g., range of movement, injury) constraints on the system, as well as the movement goal. Importantly, this effect reveals that during movement planning, a subject can predict at least some of the properties of the final limb configuration.

Recent research has extended the end-state comfort effect to conditions that require both hands (Fischman et al. 2003; Weigelt et al. 2006) with somewhat mixed results. Fischman et al. (2003) found that while the end-state comfort effect still occurs in bimanual situations, it is not as pronounced as shown in previous unimanual studies and is strongly influenced by the absolute position of a movement end-goal (defined as being in a high or low location according to shelf height). In contrast, an investigation of the role goal-related planning exerts on

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initial grasp postures revealed that subjects are more likely to plan their movements to achieve the desired final posture regardless of movement goal congruency (Weigelt et al. 2006). In order to explain the strong preference for end-state comfort compliance, it might be that prior experience of musculoskeletal constraints on the limbs may affect a person's ability to tolerate uncomfortable end-states.

In addition to end-state comfort constraints, multi-effector movements reveal a number of other types of constraint, generally classified as temporal and spatial bimanual constraints. Across studies on inter-limb coordination, there is strong support for the claim that temporal synchronization of effectors is a predominant constraint (Marteniuk and MacKenzie 1980; Perrig et al. 1999; Serrien and Wiesendanger 2000; Tuller and Kelso 1989). In an influential experiment, Kelso et al. (1979a, b) studied human inter-limb coordination during upper limb movements using a modified Fitts's Law paradigm (Fitts 1954) in which the targets of the required movements varied in both amplitude and size depending on condition. Findings demonstrated in bimanual conditions a strong tendency for the hand with the easy index of difficulty movement to accommodate to the hand with the difficult index of difficulty movement more than vice versa.

In a later study, the authors (Kelso et al. 1983) added a clever manipulation to their earlier task by requiring one limb to navigate an obstacle while the other hand was free to maintain any trajectory course. The results of that study clearly illustrated that the limb with the obstacle in its path initiated movement before the other limb, and this early departure was offset by an increased movement time. In addition, the limb without the obstacle adjusted its velocity and acceleration to be more similar to the limb with the obstacle, and even showed some tendency to alter its spatial course as though hurdling, despite there being no physical barrier present for that hand. As in their earlier study, some adjustments were made in the movements of both hands so that they reached the end target in a more coupled manner than the unimanual trials would predict. As these experiments illustrate, at least some parameters associated with movement planning and execution are influenced by constraints such as obstacles, goal congruency, and the context of the motor task. How the different constraints work together, however, is less well understood.

In addition to temporal constraints, spatial constraints have also been described. For example, in a bimanual situation that involves two different movement tasks performed by the left and right hands (e.g., circles paired with lines or squares), each hand tends to take on some of the spatial characteristics of the other hand's movement, an effect referred to as spatial coupling (Franz 1997, 2003; Franz et al. 1996, 1991; Franz and Ramachandran 1998). One account of spatial coupling is that some degree of spatial interference in movements is due to tasks of the two hands being conceptualized separately; if conceptualized as one unified task, interference between the limbs diminishes relative to the dual-task situation (Franz et al. 2001). Extending this account, it might be the case that when two different movement goals are present, participants might naturally try to adopt postures that are in alignment with some common action goal or unified representation. However, there remains the possibility that the requirements of the two tasks are so disparate that certain distinctive characteristics of each hand's movement are maintained. In the present study, our primary manipulation on task goals was to instruct participants to place an object (or objects) in one of two orientations (upright or upside down) in unimanual and bimanual conditions. We predicted that in unimanual conditions the end-state comfort constraint discovered by Rosenbaum and colleagues would hold. In bimanual situations the question of primary interest was whether, in the goal incongruent situation, the easy movement hand (the one without the requirement to rotate/invert the object) would accommodate to the difficult movement hand (the hand that had to rotate the object from a normal to inverted orientation); this would provide evidence consistent with the temporal findings of Kelso and colleagues, and perhaps violate end-state comfort constraints found in unimanual situations. This finding would therefore suggest that the end-state comfort constraint was overridden by some form of bimanual coupling constraint. An alternate outcome would be that the difficult movement hand is constrained by end-state comfort (thereby adopting an awkward initial posture) while the easy movement hand maintains its normal initial posture. This outcome would suggest that the end-state comfort constraint for unimanual situations overrides the bimanual coupling constraint, given each hand would maintain allegiance to its own end-state comfort constraint.

In addition to manipulating postural requirements of the hands by levels of goal congruency, we borrow the idea from Kelso et al. of placing an obstacle in one or both movement paths. In our case, however, the primary purpose of this manipulation was to push to its limits the end-state comfort effect by further increasing the awkwardness of an already awkward initial posture of a hand. Of critical importance was again the bimanual situation in which an obstacle was in the way of one hand's movement but not the other. Using the same logic as posed above for goal congruency, the critical question was whether the presence of the obstacle would influence the planning and/or movement properties of the hand without the obstacle present. Depending on the outcome, it could be discerned whether the two hands are processed as a bimanual unified task in which one goal drives the outcome of both hands (e.g., conceptual unification of goals), or whether the requirements of the two hands are now so distinct that the individual hands maintain separate plans and movements.

Methods

Subjects

Twenty participants from Otago University (6 men, 14 women) with a mean age of 21 years (SD = 2.63) participated in exchange for $10.50 compensation for their time. Based on administration of the Oldfield (1971) inventory, handedness scores ranged from 0.3 to 1.0 with a mean of 0.72 (SD = 0.17) on a scale ranging from −1.0 (strongly left-handed) to 1.0 (strongly right-handed). The study was approved by the ethics committee of the Department of Psychology, University of Otago.

Apparatus

The apparatus consisted of a purpose-designed shelving unit (70 cm × 80 cm) situated on a countertop (75 cm in height) (see Fig. 1). The top of the shelving unit was about eye level of a typical subject, and the counter was located at the height of the typical subject's navel.

The shelving unit contained two movable obstacle boxes (38.5 cm × 32 cm). During conditions that required the presence of one or both obstacles, one or both boxes were positioned outside the shelving unit so that participants had to reach into the box(es) in order to grasp the cylinder(s). Two PVC cylinders (14 cm height × 6.5 cm diameter), each with a band of blue electrical tape (2 cm) wrapped around one end, and a band of yellow electrical tape (2 cm) wrapped around the other end, were used in the task.[1] The cylinders were positioned so that the blue band was always on the bottom and the yellow band on the top. Pictorial displays of the cylinder(s) in actual size were presented on cards at the onset of each trial to indicate what the final position(s) of the cylinder(s) should be. Hand position was recorded continuously using a Panasonic NV-DS60 digital video camera.

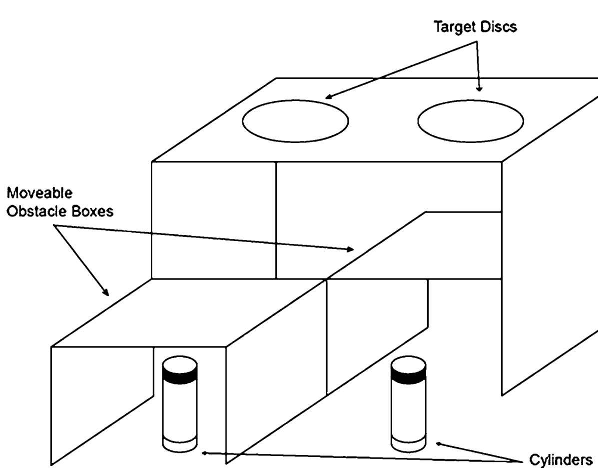

Fig. 1 Shelving unit with movable obstacle boxes

Design

There were 32 trials in total, made up of the 4 cylinder arrangements × 4 obstacle arrangements for bimanual trials, in addition to 8 unimanual control trials for each hand. Each trial was performed only once, given our interest in spontaneous performance uninfluenced by memory traces of a previously performed identical trial.

Procedure

After signing informed consent forms, participants were asked to stand on a rectangular footpad (45 cm × 32 cm) and face the apparatus with hands relaxed by their sides. The nature of the task was then explained, with instructions specifying that the left cylinder was to be moved to the left target using only the left hand, and the right cylinder was to be moved to the right target using only the right hand. No specific instructions were given about how to grasp the cylinders or how to couple the hands during bimanual conditions. We emphasized speed of responding and the requirement that final placement of the cylinders on the targets should replicate what was displayed on the card presented at the onset of each trial. However, we warned participants to avoid collisions with the apparatus. When the experimenter was certain that each participant understood the instructions, the 32 trials were administered in randomized order.

Each condition was displayed in pictorial form on a cue card held by the experimenter. Subjects were instructed that the cards displayed pictures of the movement goals (the way the cylinders should look after being successfully placed). In bimanual conditions, the movement goals were either congruent or incongruent for the two hands, and required movement of both cylinders. Unimanual control trials were identical to bimanual trials except that subjects were instructed to manipulate (with the appropriate hand) only the cylinder represented on the condition card and not the other cylinder (see Fig. 2a, b). Participants were informed that each trial would begin as soon as the

[1] While using an actual drinking cup or glass would have increased the ecological validity of the tasks, it may have biased subjects to act in a manner consistent with end-state comfort.

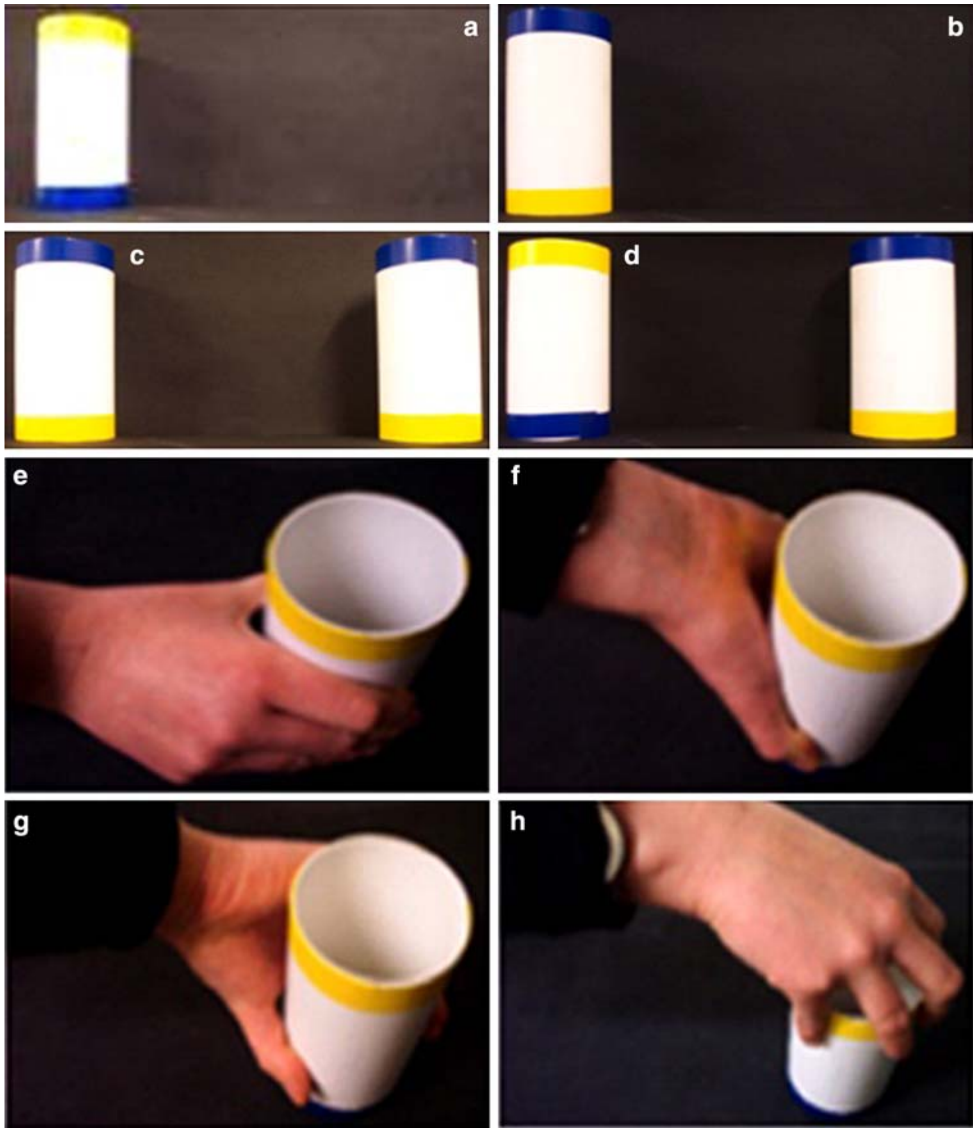

Fig. 2 Examples of condition cards: **a** unimanual left hand with no rotational requirement. **b** Unimanual left hand with rotational requirement. **c** Bimanual congruent with rotational requirement for both hands. **d** Bimanual incongruent with rotational requirement for only the right hand. Grasp postures typically used: **e** normal grip, **f** internal grip, **g** external grip, **h** top grip

condition card was displayed and they were instructed to return both hands to their sides after completion of the required movement and to wait for the next condition card to be displayed.[2]

Data analysis

Trials performed in a non-instructed manner (using both hands on a unimanual trial, and/or the wrong hand to manipulate a cylinder), or with an incorrect placement of one or both cylinders, were counted as errors and were not included in analysis. Given that the total numbers of rejected trials due to errors comprised <4% of the data (approximately equally distributed across subjects) condition mean substitution was used to replace missing values.

The behavioural data were analyzed with respect to end-state comfort in unimanual trials and coupling strategy in bimanual trials based on preset codes of grasp posture (see Fig. 2e–h for typical grasp postures used in unimanual trials). Adapted in-house interactive digitizer routines from our gesture studies (see Miller and Franz 2005) were used to determine movement onset and offset.

To analyze micro properties of the timing structure, we classified the dependent variables of interest into three basic types. The first type was associated with the timing structure of the trial. Variables in this type included initiation time (latency between condition card presentation and initial movement onset), and movement time (initial

[2] We realize that having only one cylinder displayed on the cue card in unimanual trials and two present in bimanual trials introduces higher demands on processing and interpreting the additional stimulus in the bimanual case (which would be expected to increase IT compared to the unimanual case). Indeed it is difficult to avoid this problem; importantly however, results suggest that number of cylinders displayed on the cue card alone cannot account for our primary effects.

movement onset to completion of movement). The second type of variable described bimanual temporal coupling. We computed the signed initiation time differences between the hands, and the absolute value of the initiation differences. The signed difference preserves information about which hand begins movement first. The absolute difference reveals the magnitude of the initiation difference between hands, irrespective of which hand begins first (following Shen and Franz 2005; Hughes and Franz 2007; Franz and Fahey 2007). The third variable refers to grasp posture. This variable is reported as percentage of trials (of the total) that subjects satisfied end-state constraints in unimanual trials, and for bimanual trials, the percentage of trials that subjects satisfied end-state constraints, bimanual constraints, or both types of constraint. To assess the end-state comfort effect of Rosenbaum and colleagues, Chi-square tests of independence were conducted on the factors movement goal and obstacle arrangement.

Results and preliminary discussion

Timing structure

Initially a *t*-test was conducted to examine whether there were significant differences for condition (unimanual vs. bimanual). Analysis of IT data revealed a significant effect of condition, $t(19) = 19.34$, $P < 0.001$, with bimanual trials taking longer to initiate than unimanual trials (means: unimanual 127, bimanual 170 ms). This pattern of results was similar for MT, $t(19) = 10.80$, $P < 0.001$ (means: unimanual 137, bimanual 169 ms). Based on these findings, ANOVAs were employed separately for unimanual and bimanual trials for IT and MT.[3]

Unimanual. For the unimanual trials, data were organized using a 2 × 2 × 2 ANOVA on the factors hand, rotational requirement, and obstacle presence. We found no significant effects of hand, rotational requirement, or obstacle presence on IT. However, as can be seen in Table 1, manipulations of obstacle presence and rotation revealed significant main effects on MT, [respectively, $F(1,7) = 28.65$, $P < 0.001$, $R^2 = 0.76$, and $F(1,7) = 7.71$, $P = 0.006$, $R^2 = 0.20$] suggesting that during unimanual movements, rotation and obstacle manipulations resulted primarily in an increase in movement time but not planning time.

Bimanual. To examine congruity effects in bimanual conditions, the same within-hand factors were used as above, in addition to factors indicating whether the two movements were congruent or not (for goal demands and for obstacle arrangements). As can be seen in Table 2, the main effect of goal congruency was highly significant for IT, $F(1,31) = 24.80$, $P < 0.001$, $R^2 = 0.58$, with bimanual incongruent goal conditions resulting in ITs that were on average approximately 31 ms longer than in congruent conditions.

As can be seen by the approximately 12 ms difference between incongruent and congruent (goal) trials (Table 2), the effect of goal congruency was also significant for MT, $F(1,31) = 18.41$, $P < 0.001$, $R^2 = 0.27$. In addition, the main effect of obstacle presence reached significance for MT, revealing a slightly longer MT when the reaching movement involved the requirement to reach into the obstacle boxes to grasp the cylinders compared to when no obstacles were present, $F(1,31) = 16.49$, $P < 0.001$, $R^2 = 0.24$. Furthermore, in conditions where the obstacle arrangement was incongruent for the two hands, MTs were approximately 6 ms longer than when obstacles were

Table 1 Mean and standard deviation (in ms) of initiation and movement time for unimanual movements (averaged across hands) under different conditions of movement goals and obstacle arrangements

	IT		MT	
	Mean	SD	Mean	SD
No cylinder rotation	128	48	132	26
Cylinder rotation	129	43	142	29
No obstacle presence	125	48	127	25
Obstacle presence	132	42	147	28

Table 2 Mean and standard deviation (in ms) of initiation and movement time in bimanual movements (averaged across hands) under different conditions of movement goals and obstacle arrangements

	IT		MT	
	Mean	SD	Mean	SD
Congruent movement goals				
No cylinder rotation	157	61	159	47
Both cylinder rotation	167	75	166	38
Incongruent movement goals				
Only left cylinder rotation	196	79	178	43
Only right cylinder rotation	191	95	172	47
Congruent obstacle arrangements				
No obstacles present	174	79	155	41
Both obstacles present	174	76	179	43
Incongruent obstacle arrangements				
Only left obstacle present	182	62	171	37
Only right obstacle present	181	99	175	51

[3] In addition to standard statistical reporting we provide R^2 values were appropriate. R^2 can be interpreted as the proportion of response variation explained by a variable of interest (Draper and Smith 1998).

identically arranged (congruent obstacle arrangement trials), $F(1,31) = 8.57$, $P < 0.004$, $R^2 = 0.12$. In sum, our findings (above) concerning the effects of goal congruency were very similar for IT and MT (although larger for IT), suggesting that the effects of planning extend into the movement portion as well. This effect does not apply to obstacle presence; thus, as in unimanual conditions, the presence of a potentially interfering obstacle placed at the beginning portion of the movement(s) affects only MT and not IT.

Bimanual coupling variables. Of primary importance were the effects of obstacle congruency and goal congruency on between-hand temporal coupling. As indicated above, two types of bimanual RT differences were defined: signed and absolute. For the signed IT differences, there were no significant main effects of either type of congruency, nor did the two types of congruency interact significantly, all $F(1,19) < 1.3$, all $P > 0.29$. The grand mean signed IT difference was approximately −9 ms (indicating a right hand lead, on average).

For the absolute bimanual IT difference, there was a significant interaction of obstacle arrangement congruency and movement goal congruency, $F(1,19) = 4.46$, $P = 0.048$. However, while there was not a reliable main effect of obstacle arrangement congruency alone, [$F(1,19) = 1.86$, $P = 0.19$], the main effect of movement goal congruency was significant, $F(1,19) = 6.61$, $P = 0.019$. This pattern of effects was very clear from the mean absolute IT differences, with a 15 ms difference between hands under conditions of obstacle arrangement congruency combined with movement goal congruency, compared to over 30 ms difference in conditions in which there was incongruency of at least one factor (particularly end-state goals). These findings clearly indicate that when both the obstacle arrangement and the cylinder arrangement were identical for the two hands, the onset of movement of the two hands was more closely coupled (on average) than when such congruence was not present (referring to bimanual onset coupling without reference to which hand leads).

A similar analysis on bimanual coupling was conducted for MT as for IT. The only meaningful and significant effect occurred in the absolute MT differences, with a significant interaction of rotation congruence × side of obstacle placement, $F(1,19) = 8.51$, $P = 0.01$. This interaction revealed that absolute MT difference was larger (by approximately 9 ms, on average) under goal incongruent compared to goal congruent conditions, but only when an obstacle was placed at the initial portion of movement of the right hand. However, given these results were on absolute MT difference and not signed MT difference, there was no clear pattern as to which hand's MT was generally longer or shorter, but only that they were on average, more different from one another under these situations (revealing less coupling in movement duration). Taken together, one can roughly conclude that goal congruency was a primary factor on the coupling of the movement onset time (IT) and MT of the two hands.

Grasp posture

Grip choice in unimanual trials. The proportion of total trials that satisfied end-state comfort was significantly higher when cylinder rotation was not required compared to required (93 vs. 68%), $\chi^2_{(df=2)} = 21.4$, $P = 0.001$ (Table 3). The left hand tended to satisfy end-state constraints more than the right hand (85 vs. 76%), however, this difference was not significant, $\chi^2_{(df=2)} = 2.14$, $P = 0.34$. End-state comfort satisfaction did not differ significantly depending on the presence or absence of an obstacle on unimanual trials, $\chi^2_{(df=2)} = 2.69$, $P = 0.261$.

Composite grip choice in bimanual trials. Here, we refer to the grip combination for the two hands in bimanual conditions as composite grip type. Composite grip types reported as percentages of total trials that satisfy end-state comfort and bimanual constraints are shown in Table 4. Chi square tests revealed that the overall relation between composite grip type and movement goal was highly significant, $\chi^2_{(df=9)} = 76.75$, $P < 0.01$. To assess specific differences based on movement goal congruency a Chi-squared contingency table was employed (Campbell 2007). Analyses revealed significant differences between movement goal conditions and composite grip type in congruent conditions [$\chi^2_{(df=2)} = 33.811$, $P < 0.01$] indicating that subjects tended to elect composite grip types that are in line with both bimanual and end-state comfort constraints. However, these differences did not extend as clearly to conditions involving incongruent movement goals, $\chi^2_{(df=2)} = 6.04$, $P = 0.11$. Both constraints appeared to influence movement outcome more often under congruent

Table 3 Percentages of total trials that satisfy end-state comfort in unimanual trials

	No cylinder rotation		Cylinder rotation	
	Satisfy end-state (%)	Movement errors (%)	Satisfy end-state (%)	Movement errors (%)
Left hand	100	4	69	4
Right hand	86	3	66	3

Table 4 Composite grip types (percentages of total trials) that satisfy end-state comfort and bimanual constraints in bimanual trials comprising different experimental conditions

Types of experimental conditions	Bimanual (%)	End-state (%)	Bimanual and end-state (%)	Movement errors (%)
Congruent movement goals				
No cylinder rotation	00	03	96	1
Both cylinder rotation	24	09	63	4
Incongruent movement goal				
Only left cylinder rotation	36	20	38	6
Only right cylinder rotation	24	16	55	5
Congruent obstacle arrangement				
No obstacles present	19	25	53	3
Both obstacles present	25	21	46	8
Incongruent obstacle arrangement				
Only left obstacle present	25	25	45	5
Only right obstacle present	15	28	55	2

compared to incongruent goal conditions [$\chi^2_{(df\,=\,2)} = 44.63$, $P < 0.01$]. It was clear from these results that bimanual constraints, end-state constraints, and the combination of both constraints did not regulate task outcomes according to any obvious hierarchy of constraints; however, the instructed goal (placing the objects in the correct orientations) tended to be achieved by subjects.

The overall relationship between obstacle arrangement congruency and composite grip type was not statistically significant [$\chi^2_{(df\,=\,6)} = 5.701$, $P > 0.45$], suggesting that neither constraint alone or in combination was influential in a consistent manner. Furthermore, Chi-square contingency tables revealed no significant effects on obstacle arrangement [respectively, $\chi^2_{(df\,=\,2)} = 1.53$, $P > 0.47$ and $\chi^2_{(df\,=\,2)} = 3.62$, $P > 0.16$ for congruent and incongruent arrangements].

Discussion

Timing structure

The pattern of results in variables associated with the timing structure clearly revealed a large effect of condition type, with bimanual trials considerably slower than unimanual. However, there did not appear to be any significant difference between hands for either IT or MT. In line with previous research (Kunde and Weigelt 2005) we found that bimanual trials with incongruent movement goals were significantly slower than bimanual trials with congruent movement goals. This effect was more pronounced for IT than for MT, suggesting that the effects reflect mainly movement planning. In contrast, there were no significant effects of congruency on initiation time for obstacle arrangement congruency. Thus, the primary effects on movement planning depended on manipulations of the movement goal in bimanual situations rather than on manipulations of obstacles. This is intriguing, given one might have expected that the obstacles (to be negotiated at the beginning portion of the movement) would have influenced planning variables. It is interesting to note, however, that the effects of obstacle arrangement congruency reached significance for movement time, with bimanually incongruent obstacle arrangement conditions yielding slower movement times than bimanual congruent obstacle conditions. This indicates that in the present study, the incongruency of obstacle arrangement did not increase the time it took to plan bimanual movements but rather, the time to manipulate the object(s) and carry out the movements.

A primary issue investigated in this study was whether temporal accommodation would occur in a bimanual object placing task when the difficulty of movement for each hand is manipulated by different goal requirements for the two hands. Our data are consistent with previous research demonstrating that the hand with the easy movement task (identified as the hand with no rotation requirement) slows its response to the level of the hand with the difficult movement task (identified as the hand with a rotational requirement present), so that they might reach the target simultaneously. Interestingly, while our findings demonstrate a strong tendency for the hands to respond closer together in time if one or both types of congruency are present (movement goal and obstacle arrangement), this effect is apparent in the absolute but not the signed bimanual differences, revealing that the effect does not depend on which hand leads. In other words, on some trials, one hand might lead and on other trials the other might lead, but overall, the magnitude of the temporal difference between hands is smaller when both conditions are congruent. Temporal coupling is enhanced, therefore, when spatial congruency is enhanced, and this form of enhancement seems to occur prior to the assignment of specific movements to the hands. Furthermore, during conditions of movement goal incongruency alone, the tendency toward synchrony of movement onset of the two hands also decreased. All in all, it appears that congruency of the movement goals is the primary factor in the coupling of bimanual movement onset, whereas obstacle arrangement congruency plays little role. This latter finding at first glance appears at odds with the seminal experiment by Kelso et al. (1983) which examined the influence of an obstacle on interlimb coordination and demonstrated that the presence of an obstacle in one limb's path disrupts the movement onset of the two limbs (Kelso et al. 1983, Experiment 2). We do note however, that in the present study subjects must navigate obstacles that may be arranged identically (congruent) or differently (incongruent) while completing a task for which there also may be identical or disparate movement goals. This added constraint may have neutralized the effect that a physical obstacle has on movement onset coupling. Another possibility is that in the Kelso et al. task, hurdling the obstacle might actually have been conceptualised as a primary movement goal; thus, according to our movement goal hypothesis (and the conceptual constraint hypothesis of Franz et al. 2001), one might reinterpret the results of Kelso et al. as reflecting an incongruence of goals.

Grip posture

With respect to unimanual movements, our data indicate that end-state comfort is a predominant constraint in reaching and grasping tasks, regardless of hand and obstacle presence. However, a considerable decrease in prevalence of the end-state comfort effect was apparent when subjects were required to rotate the cylinder (see Table 3). We hypothesize that in the present study uncomfortable end-states are not as uncomfortable as those required in previous tasks (in the present study subjects were asked to place a cylinder on a shelf that is within reaching distance). During rotation conditions, by adopting a grip that satisfies initial state comfort (characterized by utilizing a "normal" grip) the joints required to rotate the cylinder (shoulder, elbow, and wrist) stay within typical anatomical angles. This is in contrast to previous studies in which adopting a grip posture that satisfies initial comfort over end-state comfort places the joints in extreme angles (Rosenbaum et al. 1990; Weigelt et al. 2006). Indeed, our post-experiment surveys revealed that subjects unanimously ranked both unimanual tasks at the same difficulty level.

A corollary purpose of this study was to pit the constraints of end-state comfort (as described for unimanual movements), and constraints of bimanual coupling against one another in order to determine whether a constraint hierarchy is present. Additionally, we were interested in the bimanual coupling of spatial constraints, in particular, initial posture. Recall from the Introduction that we entertain two ideas: the first is that subjects might evoke a unified representation of the two movement goals; accordingly, both hands would adopt postures that are in alignment with a common goal (i.e., satisfy bimanual coupling). Alternatively, if each hand maintains allegiance to its own end-state comfort constraint we may take this as evidence that end-state coupling overrides bimanual coupling constraints. Interestingly, our findings reveal that with congruent movement goals subjects often adopt composite grip postures that are in line with both bimanual coupling and end-state comfort constraints. Furthermore, subjects often will adopt identical hand postures, in line with bimanual spatial coupling constraints. There are also examples in which subjects satisfy end-state and bimanual constraints when the movement goals are incongruent. One is highlighted by the condition depicted in Fig. 3. On 19% of total trials, both hands adopted a "top grip". By utilizing this grip posture subjects are able to achieve rotation by grasping the cylinder between the thumb and middle finger

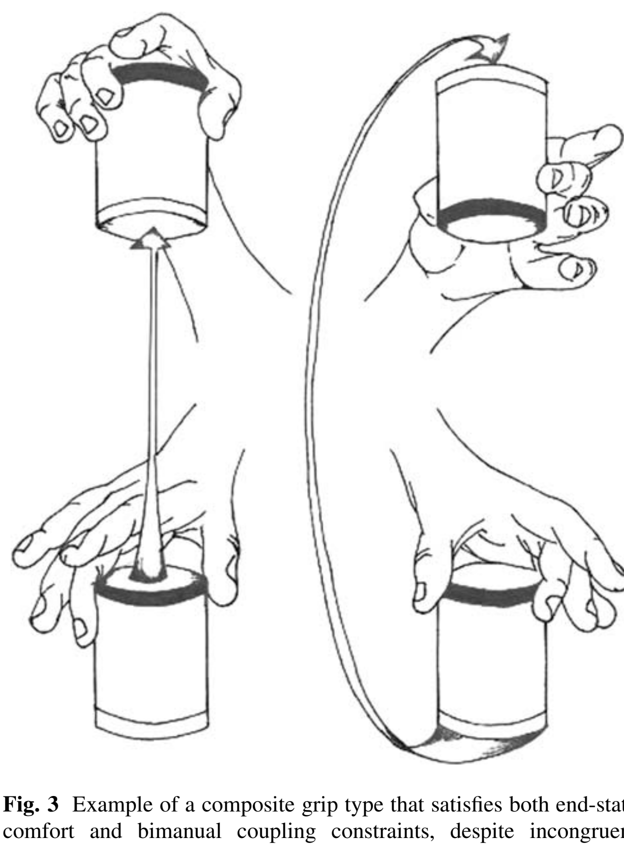

Fig. 3 Example of a composite grip type that satisfies both end-state comfort and bimanual coupling constraints, despite incongruent movement goals. Shown is the initial and ending composite grip posture in conditions when the rotational requirement is present for only the left hand (note the face-on view, with the left hand on the right of the figure)

and flicking or twirling the cylinder. This flicking or twirling method fits with the primary assumption of the end-state comfort effect; that is, to reduce awkward joint angles and ensure a comfortable posture at the end of the movement.

Aside from the example illustrated above, our data for trials with incongruent end goals (object placements) more generally reveal that subjects did not reliably elect composite grip strategies that are in line with both end-state comfort and bimanual constraints. A possible explanation for this result is based on dual task interference. In an initial study examining bimanual spatial coupling, subjects were asked to draw lines with one hand and circles with the other (Franz et al. 1991). The resultant spatial pattern demonstrated strong spatial interference revealed by circle-like lines and line-like circles. This type of finding has been extended to various experimental setups including circle-line tasks with different muscle sets, continuous movements with different amplitudes, circles paired with squares, and combinations of differently sized and shaped parts of rectangles (Franz 1997, 2003; Franz et al. 1996). In an investigation of spatial interference in amputees with vivid phantom limb sensation in the amputated limb, Franz and Ramachandran (1998) found that spatial coupling occurs even with the loss of the peripheral properties of the limb, indicating that it depends to some degree on central properties such as representation (see Franz 2003, for review). What is key, however, is that all of those studies required that two different (separate) tasks be produced at the same time. Additional research revealed that when a bimanual task is conceptualized more like a *single task,* at least some of the effects of interference between hands diminishes (Franz et al. 2001).

In the present study, when the hands were afforded identical movement goals, they tended to act in a concerted manner to achieve the primary (instructed) end-goal (i.e., place the cylinders on the target discs so that they match what is displayed on the cue card). However, during bimanual tasks with incongruent movement goals, while still able to satisfy the primary end-goal, subjects were less able to execute two different movement goals concurrently without flaw. We suggest that in those situations, the end-goal of the task is primary, and the more specific movement goals (subgoals) become subordinate and might not be achieved when attention is on attaining the end-goal (see Franz 2004 for a description of other research that supports this levels of constraint idea). This notion is also supported by gait studies examining foot placement during obstacle avoidance. Patla et al. (1999) demonstrated that alternate foot placements are based on specific factors or determinants (economy and response speed, stability, and forward progression), and they developed a decision algorithm describing the selection process that guides foot placement. A later study (Moraes et al. 2004) added specific spatial and temporal constraints to the task, revealing that changes in task difficulty can alter the decision-making process. Importantly, the selection and implementation of these determinants depend upon the difficulty of the task, and do not need to be satisfied to complete the end-goal. In our view, when attention is focused on the primary (instructed) goal (end-goal), other forms of constraint might become less influential. In this manner, there might be something akin to a flexible hierarchy of constraints determined by the allocation of attention to primary (in this case, spatial) goals (Franz 2004).

We also examined whether the addition of a physical obstacle at the initial portions of the grasp would alter the preference for a particular initial grip posture to be adopted. Again we found that subjects do not reliably satisfy end-state and/or bimanual coupling constraints. While it is possible that obstacles (in the initial portions of movement) do not affect initial grasp posture in grasping and placing tasks, we must also take into consideration the possibility that the presence of a physical obstacle, in our experiment, was likely not salient enough to be construed as an explicit goal and therefore impact observed grip behaviours. However, even though presence of a physical obstacle did not affect composite grip postures, as mentioned previously, it did affect movement time.

In sum, our findings suggest that in bimanual tasks with identical movement goals, end-state comfort satisfaction and spatial coupling in initial grasp postures can coexist. Findings also support the view that when subjects are unable to conceptualize bimanual incongruent movement goals as being unified, they take longer to plan and complete the dual task (than when such unification is possible). Finally, the end goal(s) is (are) often attained through a variety of means, often not revealing any fixed patterns of constraint hierarchy.

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