Goal Congruency in Bimanual Object Manipulation

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In 3 experiments, the authors investigated the impact of action goals on the production of discrete bimanual responses. Similar to a bartender putting 2 glasses simultaneously on a shelf, participants placed 2 objects into either parallel or opposite orientations by carrying out either mirror-symmetrical or mirror-asymmetrical movements. In Experiment 1, performance was strongly affected by the congruency of the intended object orientations but was essentially unaffected by movement symmetry. Experiment 2 replicated this instrumental goal-congruency effect (and the absence of motor-symmetry effects) when actions were cued in advance. Experiment 3 revealed substantial motor-symmetry effects, provided the movements themselves became the action goal. The authors concluded that performance in bimanual choice reaction tasks is constrained by the creation and maintenance of goal codes rather than by properties inherent in the neuromuscular system that carries out these responses. These goals can relate to either body-intrinsic states or to body-extrinsic states according to the actor's current intentions.

In many everyday tasks people's hands have to operate in a coordinated manner to reach a certain goal, for example, when lifting a large object, placing a pair of shoes into a box, or eating with fork and knife. Experimental psychology has long been interested in the constraints that act upon such bimanual coordination. In a typical experiment, participants are instructed to simultaneously carry out simple hand or finger movements that vary with respect to spatial or temporal movement features. The main outcome of this research was that there is a tendency toward symmetrical movements (i.e., movements of symmetrical spatial or temporal features) and that symmetrical movements are easier to initiate. For example, mirror-symmetrical movements can be performed at a higher rate in synchrony with an external pacemaker (Haken, Kelso, & Bunz, 1985; Kelso, 1984). Also, simultaneous bimanual reaching movements over the same amplitude or in the same direction are initiated more quickly than movements of different amplitudes or directions (e.g., Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). Despite some exceptions, such as moving the arms asymmetrically when walking, it is fair to say that symmetrical movements are normally preferred. This symmetry preference is traditionally attributed to inherent properties of the motor system, such as a tendency for the activation of homologous muscles (Kelso, 1984; Swinnen et al., 1998), or a benefit of programming movements with identical motor parameters (Spijkers et al., 1997).

Recently, however, these widely acknowledged motor accounts have been challenged by the observation that performance in bimanual coordination is determined by the congruency of the movements' perceptual effects rather than by symmetry of muscles or motor commands. Mechsner, Kerzel, Knoblich, and Prinz (2001) found that mirror-symmetrical oscillatory finger movements (adduction and abduction of the index fingers) can be performed at a higher rate than parallel movements even if one hand is held palm up and the other hand is held palm down. Under these conditions, parallel (and not symmetrical) movements afford the activation of homologous muscles. Thus, perceptual congruency of the fingers seems crucial, independent of the muscles involved (cf. Mechsner & Knoblich, 2004). Moreover, very complex, mostly incommensurable movements can be performed simultaneously if the movements' feedback is congruent. Mechsner et al. (2001) explained these findings in an ideomotor framework of motor control, which basically holds that actions are represented and planned in terms of their sensory effects (Hommel, Müsseler, Aschersleben, & Prinz, 2001). Bimanual action control is thus concerned with the perceptual (tactile, proprioceptive, visual, etc.) movement effects rather than with the muscular activations that bring these effects about.

Goal congruency also facilitates the production of discrete bimanual responses. Unlike in continuous repetitive movements in which planning and execution of the movements are difficult to disentangle, discrete responses are mostly planned in advance of response execution. Therefore, bimanual interference occurs in advance of response onset and manifests in reaction times (RTs). Because we were mainly interested in the processes that precede movement execution, RT is the dependent variable on which we focused. In a study by Diedrichsen, Ivry, Hazeltine, Kennerly, and Cohen (2003), participants were asked to reach with both hands toward spatial locations on a table. The target locations of the hands were cued by dots of varying colors projected onto the table's surface. The colors used to signal the left- and right-hand movement were either identical or different. As a result, movements were initiated faster when signaled by identical colors rather than by different colors, independent of whether the movements'

target locations (and thus movement amplitudes and directions) were symmetrical or not. Again, congruency of the movement goals (the colors) rather than symmetry of the movement trajectories was crucial.

Altogether, these studies clearly showed that action goals play a considerable role in bimanual coordination. It is less clear, however, to which type of goal this role can be ascribed. This ambiguity relates to the lack of a crystal-clear definition of the term *goal*. In a broad sense, goals denote a future state that an actor intends to achieve. Yet, such goals can vary tremendously in terms of remoteness, ranging from "lifting a finger" to "tying a tie" or even "writing an acceptable scientific paper." In the above-mentioned studies on bimanual coordination, action goals were clearly from the proximal end of the remoteness continuum. For example, in the finger oscillation task, instructions directly relate to the performed movements and goal congruency must therefore arise at the level of body-intrinsic sensations from the oscillating fingers (Mechsner et al., 2001). Also, in reaching toward stimulated locations in the visual field, the goal locations are an integral part of the ultimately performed movement trajectory (Diedrichsen et al., 2003).

These tasks represent a relatively narrow sample of human goal-oriented action. Mostly we do not move for the sake of moving (as, perhaps, in dancing or aerobics), but we act to modify the body-extrinsic environment in a specific way. For example, reaching toward an object (e.g., a light switch) is not, of course, an uncommon task, but normally we do so with a more remote goal in mind (e.g., switching on a light). Remarkably, existing research has not systematically examined whether such remote goals that consist of forthcoming alterations of the body-extrinsic environment have the power to affect bimanual coordination as well. To investigate this idea was the main purpose of the present study.

To this end, we introduced a task inspired by the *object manipulation task* described in Rosenbaum et al. (1990). These authors asked participants to grasp and deposit a wooden object either in an upright or upside down orientation. The new feature of the present task was that two objects had to be manipulated simultaneously to end up in particular orientations (cf. Figure 1). The required object orientations were symbolically cued on a screen, and they could be either the same or different. To attain these orientations, participants performed either symmetrical movements (e.g., both hands turning outward) or asymmetrical movements (e.g., one hand turning outward and the other hand turning inward). In a sense, one can describe this as an *instrumental* bimanual task because the actions were carried out in service of an object-oriented manipulation. Similar instrumental tasks, such as opening a drawer and putting an object in it, have recently been used by Wiesendanger and colleagues (Perrig, Kazzenikov, & Wiesendanger, 1999; Serrien & Wiesendanger, 2000). These studies revealed a remarkable temporal synchrony of the hands at the target location. This suggests that the existence of an extrinsic goal allows for high temporal bimanual synchrony despite large timing differences of the individual hand movements. However, the individual goals of the left and right hand in these studies were always the same (e.g., the left hand always opened a drawer, and the right hand always put a small object in it). We were more interested to know whether the congruency of the hands' individual goals affected performance even when these goals were not functionally
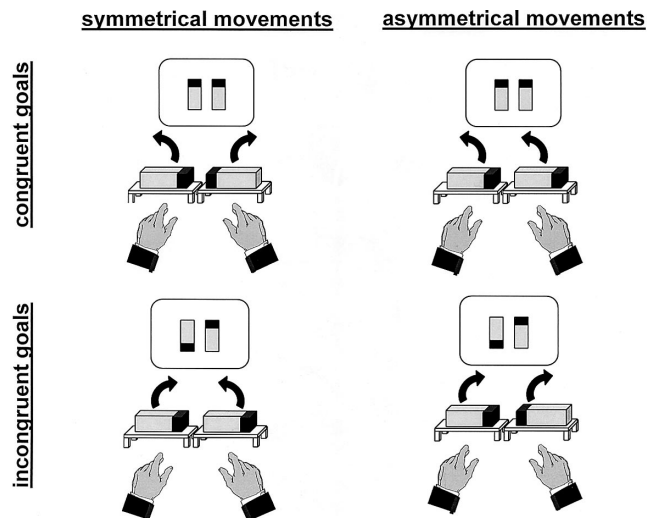

Figure 1. Illustration of the bimanual object manipulation task. Congruent or incongruent goal orientations afforded the execution of symmetrical or asymmetrical rotations of the hands.

related, and hence we varied the goals of the left and right hand independently.

Our second purpose, which we pursued in Experiment 2, concerned the time course of goal-congruency effects. Here we used a response-cuing paradigm in which participants had time to process the choice reaction stimuli and to prepare the bimanual responses in advance of a go signal (Rosenbaum, 1980, 1983). As we show, goal-congruency effects resist long preparation intervals. This renders an early locus of the goal-congruency effect that is related to the processing of the choice reaction stimuli unlikely. Rather, this result suggests that in our instrumental task, codes of intended goals remain activated up to the actual beginning of the action.

Our third purpose concerned traditional motor-symmetry effects, which can be construed as goal congruency regarding immediate movement-related action goals (cf. Mechsner et al., 2001). If this goal-based reinterpretation is correct, it should be possible to observe motor-symmetry effects in the object rotation task described above, provided that participants identify the movements themselves as action goals. To test this, we had participants in Experiment 3 perform movements physically identical to those in Experiments 1 and 2, but the instructions referred to the movements themselves rather than to the objects' orientation. This actually produced superior performance with symmetrical movements compared with asymmetrical movements, lending support to the proposal that motor symmetry might indeed be construed as congruency regarding body-related goals.

Experiment 1

In Experiment 1, we introduced our basic object manipulation task. Participants viewed two wooden building blocks, each with a blue mark on one end. Participants were instructed to grasp the blocks with an overhand grip and to rotate them from a given horizontal orientation into a specific vertical orientation that was symbolically displayed on a computer screen. The goal was thus

defined as a specific object manipulation. As seen in Figure 1, the experiment orthogonally combined congruent–incongruent manipulation goals with symmetrical–asymmetrical movements.

If movement symmetry benefits the coordination of bimanual actions, we should find better performance with symmetrical movements than with asymmetrical movements, irrespective of the goals pursued in the task. Alternatively, if goals determine the ease with which bimanual actions are carried out, we should find better performance with congruent goals than with incongruent goals, irrespective of movement symmetry. Of course, it might also be possible that goal congruency, as well as movement symmetry, both affect performance.

Method

Subjects.   Fourteen students (11 female and 3 male) aged 21 to 28 years from the Martin-Luther-Universität Halle–Wittenberg, Halle, Germany, participated for a payment of €6 ($8).

Apparatus and stimuli.   An IBM-compatible computer with a 17-in. VGA display was used for stimulus presentation and response sampling. Stimuli were presented in white on a black background, with a viewing distance of approximately 80 cm. The manipulated objects were two wooden building blocks (70 mm × 40 mm × 40 mm) marked with blue on one end (20 mm, cf. Figure 1). The blocks lay on small racks (100 mm × 100 mm × 15 mm), which were placed 300 mm in front of the display. The racks rested on four mechanical springs, which lifted the rack by 2 mm when the block was removed and thereby opened a microswitch. At the beginning of each trial, the blocks lay with their long sides on the racks. The task was to lift the blocks, align them according to the signaled goal orientation, and place them back on their racks. The participants were instructed to grasp and manipulate the blocks with an overhand grip (i.e., hold the blocks with the thumb at the blocks' front sides and the fingertips at the blocks' backsides). At the beginning of each trial, the participants' index fingers rested on microswitches (20 mm × 20 mm) that were separated by 150 mm and located 150 mm in front of the blocks. The participants were seated comfortably at the front side of the table. The experimenter sat at one long side of the table, so that an inspection of the participants' responses and a proper positioning of the blocks between experimental trials were possible. If the response was executed in a noninstructed manner (e.g., if the end orientations of the objects were incorrect or they were not grasped with an overhand grip), the experimenter entered this into the PC keyboard after each trial. No distinction between types of errors was made.

At the beginning of each trial, the experimenter placed the wooden blocks in randomly determined starting positions (i.e., with the head oriented to the left or right, respectively). The participant was told to carefully watch and realize this starting orientation of the blocks. When the participant felt prepared, he or she placed his or her index fingers on the home keys and told the experimenter to start the trial. The experimenter pressed the *Enter* key on the PC keyboard. Two thousand milliseconds later, the stimulus consisting of two symbolized bars (each bar was 25 mm × 15 mm) was presented until response initiation. The stimulus onset was accompanied by a 100-ms tone of 2000 Hz. RT was the interval between stimulus presentation and lifting of the index finger from the home key. *Approach time* (AT) was the interval between lifting the home key and lifting the object from its rack. ATs thus included approaching and grasping the objects as well as the initiation of their lifting. *Manipulation time* (MANT) was the interval from lifting the object and placing it back on its rack. These times were measured for each hand independently. If RT, AT, or MANT exceeded 1,000 ms, or either of these three times differed by more than 200 ms between the hands, a 1,500-ms visual error message (*Too slow* or *Too asynchronous*, in German) was given after completion of the response. If the experimenter judged the response as being incorrect, the message *Response not properly executed!* (in German) was displayed

for 1,500 ms on the screen. Then the wooden blocks were arranged for the next trial.

Procedure and design.   The participants received written instructions. They were instructed to bring the objects from the start orientation into the required end orientation as quickly as possible without making errors. After being demonstrated the required actions by the experimenter 5 to 10 times, they performed 24 practice trials. The experiment was run in 12 miniblocks consisting of 16 trials each. These 16 trials resulted from the orthogonal combination of 2 starting orientations of the left-hand block (leftward or rightward) × 2 starting orientations of the right-hand block (leftward or rightward) × 2 goal orientations of the left-hand block (upright or upside down) × 2 goal orientations of the right-hand block (upright or upside down). The order of trials was random. The participants had an opportunity for a brief rest after every second miniblock, in which error rates and the mean RTs of the preceding two miniblocks were displayed. The entire experiment took about 1 hr per participant.

Results

Data analysis.   Trials were excluded from the analysis if RT, AT, or MANT was below 100 ms or above 1,000 ms (3.2% of the data) or the movements were not performed simultaneously (i.e., RT, AT, or MANT for the two hands differed by more than 200 ms, or 2.7% of the data). In each individual trial, RT, AT, and MANT were averaged over the left and right hand and served as input for the analyses of duration of these intervals. These mean durations are listed in Table 1.

Preliminary data analysis revealed no influences of goal type (upright or upside down) or movement type (inward or outward rotations) on RTs. We therefore collapsed the data across these variables. For a full assessment of the results, the data are separated for these variables in Appendixes A, B, and C.

RTs.   The mean bimanual RTs were entered into an analysis of variance (ANOVA) with the variables of movement symmetry (whether homologous muscles were involved) and goal congruency (whether the afforded orientation of the blocks was the same or different) as repeated measures. Figure 2 shows the corresponding means from this analysis. There was a significant influence of goal congruency, $F(1, 13) = 12.8$, $p < .001$. No other effect approached significance.

ATs.   The hands approached the objects faster with intended congruent goal orientations than with incongruent goal orientation, $F(1, 13) = 20.84$, $p < .001$. No other effect approached significance.

MANTs.   The ANOVA of MANTs replicated the influence of goal congruency, $F(1, 13) = 4.95$, $p < .05$, whereas there was no influence of motor symmetry, $F(1, 13) = 2.18$, $p > .16$. In

Table 1

Mean Reaction Times (RTs), Approach Times (ATs), and Manipulation Times (MANTs) in Milliseconds and Percentages of Error (PEs) as a Function of Goal Congruency and Movement Symmetry in Experiment 1

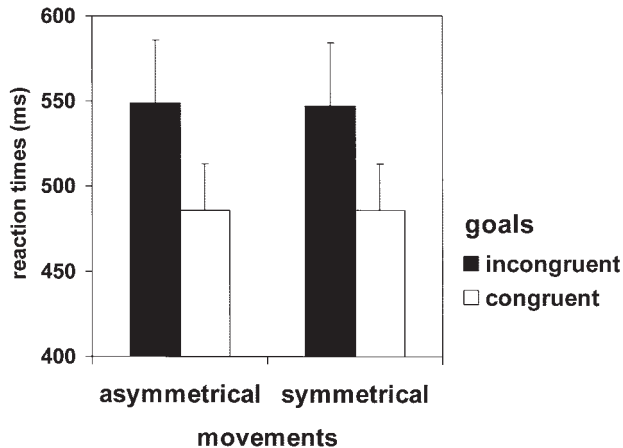| Goal	Symmetrical movement				Asymmetrical movement			
	RT	AT	MANT	PE	RT	AT	MANT	PE
Congruent	486	537	412	7.0	486	539	424	4.8
Incongruent	547	592	438	16.3	549	586	437	12.3

Figure 2. Mean reaction times (+ *SEM*) as a function of motor symmetry and goal congruency in Experiment 1.

addition, the interaction of goal congruency and motor symmetry reached significance, $F(1, 13) = 8.61$, $p < .05$, indicating particularly low MANTs when goals and movements were symmetrical at the same time.[1]

Movement offsets.   Sometimes bimanual interference manifests in an increase of movement offsets (i.e., asynchrony) rather than in an increase of movement duration. Such offsets could be systematic, resulting in an increase of mean offset, or they could be random, resulting in an increase of standard deviations. In each trial, we recorded the intermanual offsets of (a) releasing the homekeys, (b) lifting the blocks, and (c) depositing the blocks, and then computed the mean and standard deviation of these offsets for each participant and experimental condition. Negative mean asynchronies indicate that the left hand was on average faster than the right hand, whereas positive mean asynchronies indicated that the right hand was faster than the left hand. These offset data are listed in Table 2.

When averaged across conditions, none of the mean offsets of releasing the homekeys (-6.4 ms), lifting the objects (-3.8 ms), or depositing the objects (7.5 ms) differed significantly from zero (all ps > .20), indicating that there was no consistent leading hand in any segment of the movements. There were also no effects of goal congruency or motor symmetry on the mean offsets of releasing the homekeys or lifting the objects. Only the offset of the final movement segment (depositing the objects) was larger with asymmetrical movements (9.9 ms) than with symmetrical movements (5.0 ms), $F(1, 13) = 4.92$, $p < .05$. When averaged across conditions, the mean standard deviations of the offsets of releasing the homekeys, lifting the objects, and depositing them amounted to 16.3 ms, 29.6 ms, and 45.3 ms, respectively. The standard deviations of offsets of depositing the objects were higher with incongruent goals (48.8 ms) than with congruent goals (41.8 ms), $F(1, 13) = 13.6$, $p < .01$, and with asymmetrical movements (46.9 ms) than with symmetrical movements, (43.7 ms) $F(1, 13) = 4.8$, $p < .05$.

Errors.   A trial was counted as error if the movements were performed in a noninstructed manner (e.g., not using an overhand grip) or at least one of the objects was placed in a wrong goal orientation. The type of error (e.g., which object was misplaced)

was not recorded. Error rates were lower with congruent goals than with incongruent goals, $F(1, 13) = 24.70$, $p < .001$, and slightly higher with symmetrical movements than with asymmetrical movements, $F(1, 13) = 7.04$, $p < .05$.

Discussion

The congruency of the objects' intended orientations strongly affected RTs. Hence, goal-congruency effects extend beyond simple oscillation or reaching movements to situations in which goals comprise a body-extrinsic object modification. By contrast, movement symmetry had virtually no influence on RTs. There was an effect of motor symmetry in error rates, but it was in the opposite direction from the typically found benefit of symmetrical movements. Thus, put in a loose way, under the present conditions the "what" of the actions (the goals) was crucial, whereas the "how" (the motor patterns to achieve these goals) was not.

Goal congruency not only affected processes prior to response initiation (as revealed by RTs) but also processes following response initiation (as revealed by ATs and MANTs). Here we also found two hints for an influence of motor symmetry. First, motor symmetry interacted with goal congruency in the analysis of MANT duration. We find it unsatisfying to base any firm conclusion on this result for the reason explained in Footnote 1 and because this result was not replicated in Experiment 2. Second, the asynchrony of depositing the objects was on average lower and less variable with symmetrical movements than with asymmetrical movements. We see two possible explanations for these postinitiation effects. First, they might reflect execution-related interference, that is, interference from actually ongoing muscular activation (cf. Heuer, 1993). Second, these effects might reflect response specification processes that in principle can precede movement onset but, however, were postponed after response initiation and therefore manifested in measures after response onset (i.e., deposition of the blocks). We will return to this issue in the discussion of Experiment 2, which included conditions that allowed us to evaluate these alternatives more closely.

Experiment 2

We assume that goal-congruency effects in RTs arise from the mental representations of to-be-attained goal states. Yet, this might not be the only cause of the congruency effect. Note that congruent goals were signaled by stimuli that were congruent as well (cf. Figure 1). It seems intuitively plausible that congruent symbols could be identified more quickly than incongruent ones or that the required bimanual response alternative could be determined more

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[1] We are reluctant to interpret this interaction because it might be confounded with start symmetry (whether the start orientation of the bricks was symmetrical). As can be inferred from Figure 1, start symmetry was balanced with respect to the main effects of motor symmetry and goal congruency but not to their interaction (i.e., symmetrical and asymmetrical start orientations occurred equally often under each level of goal congruency and motor symmetry, but not under each combination of these factors). This design is known as a Latin square (with the factors goal congruency, motor symmetry, and start symmetry), in which interactions should generally not be considered (cf. Winer, Brown, & Michels, 1991).

Table 2
Means and Standard Deviations of Intermanual Offsets of Homekey Release, Object Lift, and Object Deposition (in Milliseconds) in Experiment 1

	Symmetrical movement			Asymmetrical movement		
Goal	Homekey release	Object lift	Object deposition	Homekey release	Object lift	Object deposition
Congruent						
M	−7.1	−8.3	6.8	−6.3	−2.1	6.9
SD	15.1	27.3	38.7	16.4	29.6	44.9
Incongruent						
M	−5.5	−3.7	3.1	−6.7	−1.5	13.2
SD	16.3	30.6	48.8	17.4	31.0	48.9

Note. Positive means indicate that the right hand was faster than the left hand. Negative means indicate that the left hand was faster than the right hand.

quickly with congruent stimuli. In other words, the congruency effects may have a stimulus-related origin.

To examine this possibility, we used a precuing technique (Rosenbaum, 1980, 1983). Participants were shown the stimuli long before (up to 1,500 ms) the presentation of an auditory go-signal that afforded the initiation of the required bimanual response. We assumed that by inserting a sufficiently long preparation interval, the stimuli can be identified prior to go-signal presentation, whereby the contribution of these perceptual processes to RT is abolished (cf. Schmidt & Lee, 1999, p. 81). To prevent participants from waiting to process the stimuli until presentation of the go-signal, the stimuli were removed after 200 ms. If goal congruency was entirely due to stimulus-related processes, the congruency effect in RTs should be abolished under these conditions (cf. Spijkers et al., 1997).

Method

Participants. Another 8 students (7 women and 1 man) aged 21 to 31 years from the Martin-Luther-Universität Halle–Wittenberg participated for a payment of €6 ($8).

Apparatus, stimuli, and procedure. The stimuli and apparatus were the same as in Experiment 1. Two alterations were made. First, the stimuli were presented by a randomly varying stimulus onset asynchrony (SOA) of 0 ms, 1,000 ms, or 1,500 ms prior to a beep (100 ms at 2000 Hz), which served as an auditory go-signal. The participants were instructed to prepare their responses according to the presented stimulus as efficiently as possible and to initiate the movement as quickly as possible when the auditory go-signal was presented. Second, the stimuli were removed after 200 ms to prevent participants from waiting to process them until presentation of the go-signal. Following 24 practice trials, participants performed 192 experimental trials that were divided into 4 miniblocks consisting of 48 trials each. Each miniblock resulted from the combination of 2 starting orientations of the left-hand block (leftward or rightward) × 2 starting orientations of the right-hand block (leftward or rightward) × 2 goal orientations of the left-hand block (upright or upside down) × 2 goal orientations of the right-hand block (upright or upside down) × 3 SOA levels.

Results

Trials were excluded from the analysis if RT, AT, or MANT was below 100 ms or above 1,000 ms (2.6% of the data) or the movements were not performed simultaneously (i.e., RT, AT, or

MANT for the left and right hand differed more than 200 ms, or 0.4% of the data).

RTs. The mean RTs were submitted to an ANOVA with the variables of motor symmetry (whether movements were performed with homologous muscles), goal congruency (whether the afforded orientation of the wooden blocks was the same or different), and SOA (delay between stimulus and go-signal, 0 ms, 1,000 ms, 1,500 ms, respectively) as repeated measures. The mean durations of the RTs, ATs, and MANTs from the orthogonal combination of these variables are listed in Table 3.

RTs decreased when SOA increased, $F(1, 7) = 61.92, p < .001$. In addition, responses were initiated more quickly with congruent goals rather than with incongruent goals, $F(1, 7) = 13.3, p < .01$. The goal-congruency effect was modified by SOA, $F(1, 7) = 18.3, p < .01$ (cf. Figure 3). It was more pronounced in the 0-ms SOA condition than in the 1,000-ms SOA conditions, $F(1, 7) = 15.6, p < .01$, and in the 1,500-ms SOA condition, $F(1, 7) = 28.7, p < .01$, whereas it did not differ between the 1,000-ms SOA condition and the 1,500-ms SOA condition, $F(1, 7) = 2.19, p > .18$. Single comparisons revealed a significant goal-congruency effect at each individual SOA level (all $ps < .025$). Hence, this data pattern can be summarized by saying that goal congruency was present even when there was a delay between stimulus and go-signal, but it was more pronounced when the stimulus and go-signal were presented simultaneously (i.e., with a 0-ms SOA). By contrast, motor symmetry exerted no reliable influence or interaction.

The preservation of goal-congruency effects in RTs with precuing might result from a minority of trials in which participants failed to use the preinformation provided by the stimulus (De Jong, 2000). For example, in some trials, stimulus identification may have started later than stimulus onset and was not completed when the go-signal came up. To test this possibility, we performed distribution analysis. We calculated the RT distributions for each participant, SOA level, and goal-congruency level. We rank ordered the RTs within these distributions and then divided them into five proportional bins such that each bin contained the same proportion (one fifth) of trials. Then the mean RTs within these bins were submitted to an ANOVA with the factors SOA, bin, and goal congruency. These data are shown in Figure 4. Neither the interaction of Bin × Goal Congruency nor the interaction of SOA × Bin × Goal Congruency approached significance (both

Table 3

Mean Reaction Times (RTs), Approach Times (ATs), and Manipulation Times (MANTs) in Milliseconds and Percentages of Error (PEs) as a Function of Goal Congruency, Movement Symmetry, and Stimulus Onset Asynchrony (SOA) in Experiment 2

	Symmetrical movement				Asymmetrical movement			
SOA and goal	RT	AT	MANT	PE	RT	AT	MANT	PE
SOA = 0 ms								
Congruent	589	418	353	2.5	559	407	352	1.5
Incongruent	680	478	374	23.6	660	481	367	15.3
SOA = 1,000 ms								
Congruent	364	425	364	6.3	357	433	367	3.9
Incongruent	411	461	366	6.3	394	448	357	3.9
SOA = 1,500 ms								
Congruent	332	435	365	1.5	323	443	374	2.4
Incongruent	359	454	378	3.1	358	451	370	4.7

ps > .25). Moreover, the goal-congruency effect was significant even in the fastest bin of the longest SOA (p < .05), in which with all likelihood the opportunity for preparation was in fact used. Hence, the preservation of goal congruency with precuing did not result from a proportion of trials in which stimulus identification was not completed in a timely manner.

ATs.   The hands moved faster toward the objects with congruent goals than with incongruent goals, $F(1, 7) = 13.6$, $p < .01$. This influence decreased with SOA, $F(1, 7) = 14.14$, $p < .01$, and was in fact statistically absent with an SOA of 1,500 ms ($p > .12$). No other effect approached significance.

MANTs.   There were no reliable effects in MANTs. Only the interaction of goal congruency and SOA approached significance, $F(1, 7) = 2.78$, $p = .10$, indicating that there was some influence of goal congruency with a 0-ms SOA, but no such influence with longer SOAs.

Movement offsets.   The means and standard deviations of the offsets of the movement segments are listed in Table 4. The mean offsets of releasing the homekeys (−2.1 ms), lifting the objects (3.7 ms), and depositing the objects (9.4 ms) were not significantly different from zero and not systematically affected by goal congruency or motor symmetry. The mean standard deviations of the offset of releasing the homekeys, lifting the objects, and depositing them amounted to 15.6 ms, 19.7 ms, and 32.7 ms, respectively. The standard deviations of the offsets of releasing the homekeys (i.e., the terminations of the RT interval) were higher with incongruent goals (17.7 ms) than with congruent goals (13.7 ms), $F(1, 7) = 6.93$, $p < .05$.

Error rates.   Error rates decreased with SOA, $F(1, 7) = 7.17$, $p < .01$. Movements were performed more accurately with congruent goals than with incongruent goals, $F(1, 7) = 10.05$, $p < .01$. This influence was most pronounced with a 0-ms SOA, producing a significant interaction of goal congruency and SOA, $F(1, 7) = 19.97$, $p < .001$. Finally, there was an influence of motor symmetry, but it was opposite to the influence normally observed, that is, symmetrical movements produced higher error rates than incongruent movements, $F(1, 7) = 9.54$, $p < .05$. This negative motor-symmetry effect declined as SOA increased, $F(1, 7) = 3.74$, $p = .05$. Both the effect of goal congruency and the effect of motor symmetry were absent with an SOA of 1,000 ms or 1,500 ms.

Discussion

In Experiment 2, we explored whether the congruency effects in the present task can be explained by stimulus-related processes such as the identification of response signals. The congruency effect was larger when stimulus identification was included in the RT interval than when it was removed. This suggests that part of the congruency effect relates to the processing of response signals. However, even when the stimuli were processed long before a go-signal that called for the signaled bimanual reaction, goal-congruency effects persisted in RTs, and they did so over the whole range of the RT distribution (cf. Figure 4). From this result, we conclude that stimulus-related processes alone cannot explain the congruency effect but that it is based substantially on codes of to-be-attained goal states (i.e., codes of to-be-reached object orientations).

The RT reduction with response preknowledge was massive (in fact, RTs were nearly cut in half, cf. Figure 3). It is therefore likely that not only the stimuli were identified but that also the required responses were prepared in advance of go-signal presentation. In other words, goal congruency had an impact on already selected
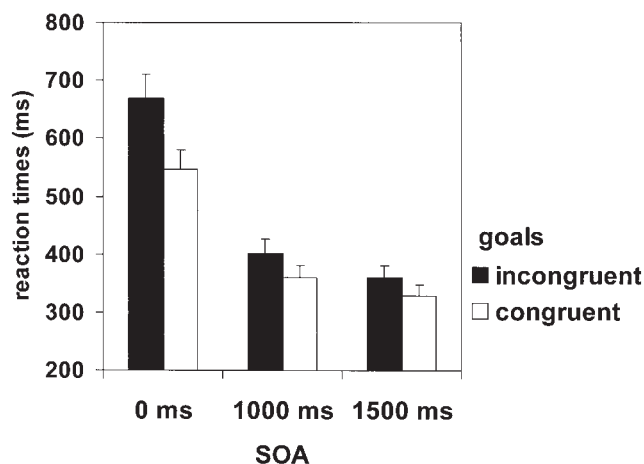

Figure 3.   Mean reaction times (+ *SEM*) as a function of stimulus onset asynchrony (SOA), motor symmetry, and goal congruency in Experiment 2.
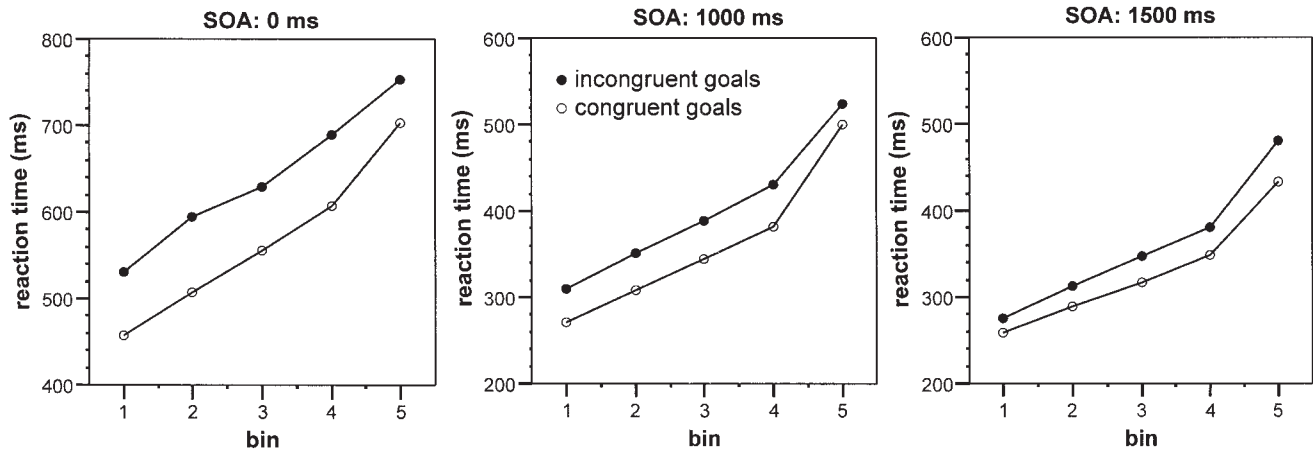
Figure 4. Mean reaction times as a function of stimulus onset asynchrony (SOA), reaction time bin, and goal congruency in Experiment 2.

responses that merely remained to be initiated on go-signal presentation.

This finding accords with similar observations with unimanual responses (e.g., Kunde, 2003; Kunde, Koch, & Hoffmann, 2004), and it concurs with an ideomotor framework of action control: If actions are in fact exhaustively coded in terms of intended goal states, these codes must be preserved up to the point of movement initiation, otherwise the mental representation of the response itself would be lost. Yet, such a long-lasting impact of goal codes beyond response selection does not fit so well to recent studies that

found goal effects to originate from "earlier processing stages such as those associated with stimulus identification or response selection" (Diedrichsen et al., 2003, p. 67). Remarkably, Diedrichsen, Hazeltine, Kennerly, and Ivry (2001), using a similar SOA manipulation as in the present study, found that goal effects were essentially removed after a precuing interval of 1–2 s. One reason for this discrepancy might relate to the different types of goals that the participants pursued. In the present study, the goals (i.e., the objects' end orientations) were a forthcoming outcome of the ultimately performed movement. These goals thus had to be re-

Table 4

Means and Standard Deviations of Intermanual Offsets of Homekey Release, Object Lift, and Object Deposition (in Milliseconds) in Experiment 2

SOA and goal	Symmetrical movement			Asymmetrical movement		
	Homekey release	Object lift	Object deposition	Homekey release	Object lift	Object deposition
SOA = 0 ms						
Congruent						
M	−2.7	5.3	5.9	−4.3	0.9	6.7
SD	14.6	15.8	30.1	13.9	19.1	33.9
Incongruent						
M	−1.1	3.2	14.1	−7.3	0.6	21.2
SD	22.1	23.9	36.3	15.7	21.3	37.9
SOA = 1,000 ms						
Congruent						
M	−2.3	4.8	3.6	−4.7	2.9	9.4
SD	11.7	18.9	30.7	13.0	23.4	32.5
Incongruent						
M	−0.5	2.4	6.8	0.9	5.5	7.1
SD	18.5	16.9	31.7	15.9	20.9	33.8
SOA = 1,500 ms						
Congruent						
M	−0.4	1.9	8.5	−1.0	12.6	5.7
SD	14.3	17.0	27.5	14.7	21.3	33.2
Incongruent						
M	−0.5	0.3	9.9	−1.0	6.4	14.9
SD	16.6	19.5	31.1	17.0	19.2	34.4

Note. Positive means indicate that the right hand was faster than the left hand. Negative means indicate that the left hand was faster than the right hand.

tained internally to govern the appropriate action. By contrast, in the studies by Diedrichsen and colleagues (Diedrichsen et al., 2001; Hazeltine, Diedrichsen, Kennerly, & Ivry, 2003) participants moved their hands to directly cued goal locations in space that were perceptible before and during the movement. This external aid might render the effort of retaining goal codes beyond the identification of these goals negligible in terms of RT costs. We warrant future research to clarify this issue.

A final noteworthy result is that with sufficiently long preparation time, influences of goal congruency (and motor symmetry) were nearly abolished in behavioral measures after response initiation (ATs and MANTs). This shows that a well-prepared movement in our task can unfold in a more or less ballistic manner, rendering dispensable a perpetuation of goal codes beyond movement initiation. Moreover, this result suggests that the presence of goal-congruency effects (and motor-symmetry effects) in the post-initiation measures in Experiment 1 was not an inevitable consequence of movement execution. Conceivably, these effects resulted from response specifications that were postponed after movement onset in Experiment 1 and which were now absorbed into the SOA.

Experiment 3

So far the results suggest that goal congruency has a strong and persistent influence on bimanual object manipulation, whereas the influence of motor symmetry (i.e., whether homologous muscles are used) is negligible. This leaves us with the question regarding why motor-symmetry effects have been so prominent in the majority of studies on bimanual coordination. A possible answer could be as follows: In these studies the goal was the movement itself. That is, participants were asked to produce certain movements with no other goal than carrying out the movement itself. It might therefore be possible to let motor symmetry effects reemerge even with the present paradigm, provided we declared the movements as goals themselves. To test this conjecture, we modified the task in the following manner. We removed the marks from the to-be-manipulated blocks as well as from the stimulus display. Participants then performed the same movements as in the preceding experiments with unmarked blocks to an arbitrarily assigned letter of the alphabet. The participants were instructed to perform the required movements without any goal beyond that. There was thus no external goal congruency but only congruency with respect to proximal (movement-intrinsic) effects.

Method

Participants.   Another 24 students (23 female and 1 male) aged 21 to 31 years from the Martin-Luther-Universität Halle–Wittenberg participated for a payment of €6 ($8).

Apparatus, stimuli, and procedure.   In this experiment, we used blocks without head marks, which were otherwise identical to the ones used in the previous experiments. Participants were instructed to grasp the blocks with an overhand grip and to place them back on their racks after carrying out one of the following bimanual responses: (a) turning the left and right hand clockwise, (b) turning the left and right hand counterclockwise, (c) turning the left hand clockwise and the right hand counterclockwise, or (d) turning the left hand counterclockwise and the right hand clockwise. These four movements were assigned to the letters *I*, *A*, *G*, and *M* (25 mm × 15 mm on the display, 200-ms presentation duration). These four letters were

selected because of their homogeneity of pairwise perceptual similarity (Mohr, 1982, p. 83). For half of the participants, the letters *I* and *A* signaled symmetrical movements of the left or right arm (*I*: pronation/pronation, *A*: supination/supination) and the letters *G* and *M* signaled asymmetrical movements (*G*: supination/pronation, *M*: pronation/supination). For the other half of participants the letters *I* and *A* signaled asymmetrical movements (*I*: supination/pronation, *A*: pronation/supination) and the letters *G* and *M* signaled symmetrical movements (*G*: pronation/pronation, *M*: supination/supination). By doing so, potential stimulus-related differences were counterbalanced between symmetrical and asymmetrical movements. In the beginning of the experiment, the experimenter demonstrated the movements. Following 24 practice trials, participants performed 8 miniblocks of 16 trials in which each of the 4 movements was repeated 4 times. The order of trials was random. A short break was possible after every second block.

Results and Discussion

Trials were excluded from the analysis if RT, AT, or MANT was below 100 ms or above 1,000 ms (2.8% of the data) or the movements were not performed simultaneously (i.e., RT, AT, or MANT for the two hands differed more than 200 ms, or 0.4% of the data). The dependent variables were analyzed as a function of movement symmetry.

RTs.   Symmetrical movements were initiated more quickly ($M = 480$ ms) than asymmetrical movements ($M = 494$ ms), $t(23) = 2.87$, $p < .01$.

ATs.   The hands approached the blocks nonsignificantly faster with symmetrical movements ($M = 559$ ms) than with asymmetrical movements ($M = 570$ ms).

MANTs.   MANT was shorter with symmetrical movements ($M = 420$ ms) than with asymmetrical movements ($M = 430$ ms), $t(23) = 2.59$, $p < .02$.

Movement offsets.   The means and standard deviations of the offsets of the movement segments are listed in Table 5. When averaged across conditions the mean offsets of releasing the homekeys (-3.9 ms) and lifting the objects (-2.8 ms) did not significantly differ from zero. The mean offset of depositing the objects was significantly larger than zero (13.7 ms), $t(23) = 3.97$, $p < .05$ (one sample), indicating that the right hand finished the object manipulation more quickly than the left hand. The mean offsets of releasing the homekeys tended to be lower with symmetrical movements (-3.2 ms) than with asymmetrical movements (-4.4 ms), $t(23) = -1.96$, $p = .06$, and the mean offset of depositing the objects was lower with symmetrical movements (7.4 ms) than with asymmetrical movements (20.1 ms), $t(23) = 4.01$, $p < .01$. The standard deviations of offsets of lifting the objects were smaller with symmetrical movements (14.9 ms) than with asymmetrical movements (17.5 ms), $t(23) = 2.20$, $p < .05$, and the standard deviations of offsets of depositing the objects were smaller with symmetrical movements (38.9 ms) than with asymmetrical movements (47.9 ms), $t(23) = 6.67$, $p < .01$.

Error rates.   The error rate was nonsignificantly lower with symmetrical movements ($M = 7.0\%$) than with asymmetrical movements ($M = 8.4\%$).

To assess whether the motor-symmetry effects in Experiment 3 were different from those in Experiments 1 and 2, we computed additional analyses with the between-subjects factor of experiment (1–3) and with motor symmetry for the dependent variables reported above. These analyses revealed between-experiment differ-

Table 5

Means and Standard Deviations of Intermanual Offsets of Homekey Release, Object Lift, and Object Deposition (in Milliseconds) in Experiment 3

Measure	Symmetrical movement			Asymmetrical movement		
	Homekey release	Object lift	Object deposition	Homekey release	Object lift	Object deposition
M	−3.2	−2.6	7.4	−4.4	−3.1	20.1
SD	15.6	14.9	38.9	16.9	17.5	47.9

Note. Positive means indicate that the right hand was faster than the left hand. Negative means indicate that the left hand was faster than the right hand.

ences of motor symmetry for RT duration ($p < .05$), mean offsets of lifting the objects ($p = .055$), standard deviations of offsets of depositing the objects ($p < .01$), and error rates ($p < .05$).

In Experiment 3, we removed extrinsic goals from the task. As a result, performance was considerably superior with mirror-symmetrical movements than with mirror-asymmetrical movements—an effect that played essentially no role when the intentions were directed toward goals beyond the movement itself (Experiments 1 and 2). That is, all segments of the movements were carried out more quickly and/or more synchronously with symmetrical than with asymmetrical movements. The overall level of ATs and MANTs was within the range of the preceding experiments, which suggests that at least within the analytical precision of our apparatus, the movements were carried out in a comparable manner.

On the methodological side, the observation of motor-symmetry effects reassures us that the present bimanual task is not special in the sense that motor-symmetry effects cannot be observed for principled reasons. On the theoretical side, the result suggests that congruency effects in bimanual coordination emerge with respect to currently intended goals. These goals may be either *extrinsic*, like the orientation of manipulated objects, or *intrinsic*, like the trajectory of the movements carried out.

General Discussion

In three experiments, we investigated the nature of interference in bimanual object manipulation. We hypothesized that this interference is determined by the congruency of intended action goals. In Experiment 1, participants had to simultaneously put two objects into congruent or incongruent goal orientations. Performance was strongly determined by the movement goals (whether congruent or incongruent) but unaffected by the specific movements performed (whether symmetrical or asymmetrical). From this we conclude that performance is not constrained by inherent features of the motor system but rather by codes of intended goal states. Obviously, such goal states need not be body related (like in previous studies), but they can relate to a body-extrinsic object manipulation as well (like in the present study).

In Experiment 2, we found that goal-congruency effects were preserved in RTs even when the stimuli were given a head start that should suffice to complete stimulus identification in advance of the RT interval. This renders an explanation of the congruency effect in terms of stimulus-related processes unlikely.

We note here that the response preknowledge in Experiment 2 was complete (i.e., all aspects of the response were known), suggesting that the responses were already selected at the point in time they were required. From the perspective of traditional stage theory, it might seem counterintuitive that goals had an impact even on the initiation of such selected responses (e.g., Sanders, 1980). Stage models suggest that all that remains to be done to initiate a selected response is to specify appropriate movement parameters (such as joint angles, movement speed, load forces).[2] It seems not obvious why codes of distal goals such as object orientations should affect such an apparently low-level motor process. However, if movements are, in fact, coded in terms of their intended consequences there would be no "level or stage in human motor control where coherent motor command or muscular activity patterns are organized as such" (Mechsner & Knoblich, 2004, p. 501). Rather, movement recruitment can be construed as a continuous increase of activation of motor-correlated effect codes with no qualitative distinction between stages in temporal terms. If the response is coded in terms of distal goals (object orientations), even codes of such distal goals have to be maintained until the actual response can replace its mental representation, that is, until the actual beginning of the action. Goal codes are assumed to be perceptual in nature (e.g., Hommel et al., 2001). There would thus be no need to discriminate different phases in terms of informational properties either. Hence, from an ideomotor point of view selecting and programming a movement (in stage terms) are both goal-related processes, and there are no principled reasons why action goals should affect the former but not the latter.

Importantly, one and the same motor pattern normally produces several sensory effects at the same time (proprioceptive, tactile, visual, etc.). Consequently, the same motor pattern might be cognitively represented by different effects, according to the actor's current intentions (cf. Wulf & Prinz, 2002). This, we propose, is the reason for the occurrence of apparent motor symmetry effects in Experiment 3, in which participants presumably coded their actions in terms of proximal movement-intrinsic reafferences. Such a recoding of movements in terms of different reafferences might also help to explain the inefficiency of spatial goal codes in

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[2] This stage is often labeled *response programming*. Mostly a distinction is made between response selection and response programming. Unfortunately, these labels are sometimes used interchangeably as well (cf. Klapp, 1995, for a discussion on this issue).

a recent study by Obhi and Haggard (2004). These authors found that interference of bimanual finger flexions or extensions was independent of the spatial direction of the finger movements (same or different) but was determined by the homology or nonhomology of muscles involved. Because there was no external goal the participants had to pursue, it seems possible that they actually coded their movements in terms of proprioceptive or tactile feedback, which naturally is congruent when homologous muscles are involved.

But why then is it easier to perform bimanual actions with congruent goals rather than with incongruent goals? We make two not mutually exclusive suggestions on this issue. First, mentally representing and maintaining a goal is conceivably not for free. It has been shown that generating and maintaining an image-like representation is harder the more different features these images encompass (cf. Kosslyn, Cave, Provost, & von Gierke, 1988). If we follow James's (1890/1981) introspective proposal that goals are represented as mental images, it is conceivably more demanding to prepare and retain goal-oriented actions the more different features the goal images encompass. This conjecture concurs with the observation that it is easier to switch from a prepared to an unprepared response when these responses produce identical instead of different action effects (Kunde, Hoffmann, & Zellmann, 2002). Second, goal-related interference could be due to an assignment problem (Diedrichsen et al., 2003). In case of goal incongruency, two goals have to be represented and assigned to the two hands, and attaining this assignment might be harder than with congruent goals in which an assignment of goals to individual hands is not necessary.

These issues certainly remain to be scrutinized in future studies. We are hopeful that these studies will further specify the main conclusion of the present study: The reconcilability of people's hands' activities is determined by the coherence of goals, not by the coherence of the muscles they use to reach these goals.

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Appendix A

Reaction Times (RTs), Approach Times (ATs), and Manipulation Times (MANTs) in Milliseconds and Percentages of Error (PEs) as a Function of Right Hand's Goal Orientation, Right Hand's Movement, Left Hand's Goal Orientation, and Left Hand's Movement in Experiment 1

	Right goal orientation															
	Upside down								Upright							
	Right movement inward				Right movement outward				Right movement inward				Right movement outward			
Left goal orientation and left movement	RT	AT	MANT	PE	RT	AT	MANT	PE	RT	AT	MANT	PE	RT	AT	MANT	PE
Upside down																
Inward	481	535	440	7.3	486	535	417	4.8	552	593	443	14.7	537	579	423	11.0
Outward	491	546	431	4.5	497	535	382	7.3	566	593	452	12.0	543	592	422	11.4
Upright																
Inward	541	608	477	28.6	559	603	444	14.6	493	550	435	7.4	487	546	425	6.9
Outward	532	577	436	11.0	552	585	422	11.2	483	530	428	3.1	475	530	393	6.1

Appendix B

Reaction Times (RTs), Approach Times (ATs), and Manipulation Times (MANTs) in Milliseconds and Percentages of Error (PEs) as a Function of Stimulus Onset Asynchrony (SOA), Right Hand's Goal Orientation, Right Hand's Movement, Left Hand's Goal Orientation, and Left Hand's Movement in Experiment 2

	Right goal orientation															
	Upside down								Upright							
	Right movement inward				Right movement outward				Right movement inward				Right movement outward			
Left goal orientation and left movement	RT	AT	MANT	PE	RT	AT	MANT	PE	RT	AT	MANT	PE	RT	AT	MANT	PE
0-ms SOA																
Upside down																
Inward	605	406	363	6.3	576	399	347	6.3	698	489	410	25.0	654	479	363	9.4
Outward	575	393	344	0.0	578	416	341	0.0	676	506	381	15.6	670	480	345	25.0
Upright																
Inward	688	489	413	32.3	664	493	372	17.7	582	429	376	3.1	553	433	371	0.0
Outward	628	456	369	17.7	666	464	359	15.6	533	415	350	0.0	597	421	325	0.0
1,000-ms SOA																
Upside down																
Inward	347	425	372	6.3	335	434	361	6.3	395	468	402	3.1	381	442	369	0.0
Outward	388	437	367	0.0	378	425	357	0.0	438	474	374	9.4	406	467	316	3.1
Upright																
Inward	416	455	387	3.1	390	445	353	0.0	356	431	385	6.3	345	425	362	6.3
Outward	375	437	335	6.3	437	458	366	15.6	356	436	380	3.1	375	421	340	12.5
1,500-ms SOA																
Upside down																
Inward	333	433	379	0.0	333	451	372	0.0	359	460	403	0.0	367	440	374	0.0
Outward	327	427	372	3.1	348	431	333	6.3	346	483	378	12.5	387	470	351	3.1
Upright																
Inward	345	449	386	3.1	367	451	376	3.1	318	435	387	3.1	315	454	380	0.0
Outward	352	433	353	3.1	346	436	371	0.0	321	442	376	6.3	328	439	359	3.1

(Appendixes continue)

Appendix C

Reaction Times (RTs), Approach Times (ATs), and Manipulation Times (MANTs) in Milliseconds and Percentages of Error (PEs) as a Function of Right Hand's Movement and Left Hand's Movement in Experiment 3

Left movement	Right movement							
	Inward				Outward			
	RT	AT	MANT	PE	RT	AT	MANT	PE
Inward	477	569	420	7.7	498	592	442	11.0
Outward	490	549	418	6.8	484	551	420	6.4