

Research Article

MOVING TO DIRECTLY CUED LOCATIONS ABOLISHES SPATIAL INTERFERENCE DURING BIMANUAL ACTIONS

Jörn Diedrichsen,¹ Eliot Hazeltine,² Steven Kennerley,¹ and Richard B. Ivry¹

¹University of California, Berkeley, and ²NASA-Ames Research Center

Abstract—*Interference is frequently observed during bimanual movements if the two hands perform nonsymmetric actions. We examined the source of bimanual interference in two experiments in which we compared conditions involving symmetric movements with conditions in which the movements were of different amplitudes or different directions. The target movements were cued either symbolically by letters or directly by the onset of the target locations. With symbolic cues, reaction times were longer when the movements of the two hands were not symmetric. With direct cues, reaction times were the same for symmetric and nonsymmetric movements. These results indicate that directly cued actions can be programmed in parallel for the two hands. Our results challenge the hypothesis that the cost to initiate nonsymmetric movements is due to spatial interference in a motor-programming stage. Rather, the cost appears to be caused by stimulus identification, response-selection processes connected to the processing of symbolic cues, or both.*

Humans possess a remarkable ability to coordinate the two hands while working on one task. However, as illustrated by the classic demonstration in which one attempts to simultaneously rub the stomach with one hand and pat the head with the other, the actions of the two hands are often not easily made independently. The psychological and neural mechanisms that constrain bimanual performance have been central to the study of coordination.

Coupling effects have been observed in both the temporal and the spatial domains. If the two hands reach for different goals, the movements tend to start and end at the same time, even when they differ in difficulty (Kelso, Southard, & Goodman, 1979; Marteniuk, MacKenzie, & Baba, 1984). Spatial coupling can also be quite pronounced during bimanual movements. For example, it is nearly impossible to draw a circle with one hand while simultaneously drawing a rectangle with the other. The two shapes will end up looking very similar to each other, resulting in something between a circle and a rectangle. Even simpler shapes, such as a line and a circle, will lead to severe cross talk between the two effectors (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Franz, Zelaznik, & McCabe, 1991).

These findings belie the fact that in many everyday tasks, the two hands can operate asymmetrically with little interference. For example, to pick up an object bimanually, the two hands do not need to follow symmetric trajectories. Why do people not experience interference in such situations given the great difficulty they have in the circle-square drawing task?

Investigations of this problem have focused on the level at which spatial-coupling effects arise. One possibility is that coupling reflects constraints associated with motor execution. For example, there may

be a preference for activating homologous muscles. Alternatively, spatial coupling might reflect cross talk during motor programming, arising when the motor system specifies the parameters of the movement (e.g., amplitude) before execution (Heuer, 1993; Rosenbaum, 1980; Spijkers, Heuer, Steglich, & Kleinsorge, 2000). By this hypothesis, movements involving different spatial characteristics should be performed with little interference when the programming can be completed prior to movement onset. Spijkers and Heuer (1995) showed that cyclical movements of different amplitudes for the two hands could be performed quite accurately if the required amplitude for each hand remained constant. In contrast, if one hand alternated between long and short movements, substantial cross talk was found.

If the time for motor programming is limited, there should be a difference in reaction time (RT) between situations in which the two hands make the same movement and situations in which different movements are required. Such a difference was found by Spijkers, Heuer, Kleinsorge, and van der Loo (1997), who used a task requiring lateral movements over amplitudes of 10 or 20 cm. The target amplitude for each hand was indicated by the German word for “long” or “short.” RTs were 170 ms longer when the two movements had different amplitudes than when the movements had the same amplitude. However, this difference disappeared when the participants had time to prepare the movements in advance of the imperative signal.

We propose that conditions employed in many of the bimanual-movement experiments place unusual demands on selection processes, an idea contrary to the motor-programming approach. The movements in these studies are usually cued symbolically—for example, a word indicates the target amplitude. However, in actions such as reaching for an object, there is no symbolic mediation. The distance between the hand and the object directly specifies the target amplitude. It is possible that many instances of spatial coupling result from processes involved in identifying the symbolic cues and translating these cues into specific actions.

A distinction between symbolically and directly cued actions was advanced by Goodman and Kelso (1980). They showed that the costs associated with specifying various movement parameters such as extent or direction (Rosenbaum, 1980) disappeared when the targets were cued directly. The question of whether interference observed during bimanual movements can be similarly abolished has not been examined.

To this end, we compared bimanual movements under conditions in which the two trajectories were either symbolically or directly cued (Fig. 1). In the symbolic condition, circles were present at all four possible target locations on each trial, and the letters “L” and “S” were used to specify the target amplitude, much as in the experiments by Spijkers et al. (1997). On each trial in the direct condition, circles were presented only at the two target locations for that trial. If the RT difference between movements involving the same and different amplitudes is due to motor programming, then this difference would be observed in both the direct and the symbolic conditions. If the cost for asymmetric movements is tied to processing symbolic cues, then it would appear only in the symbolic condition.

Address correspondence to Jörn Diedrichsen, Department of Psychology, University of California, Berkeley, CA 94720; e-mail: jdiedri@socrates.berkeley.edu.

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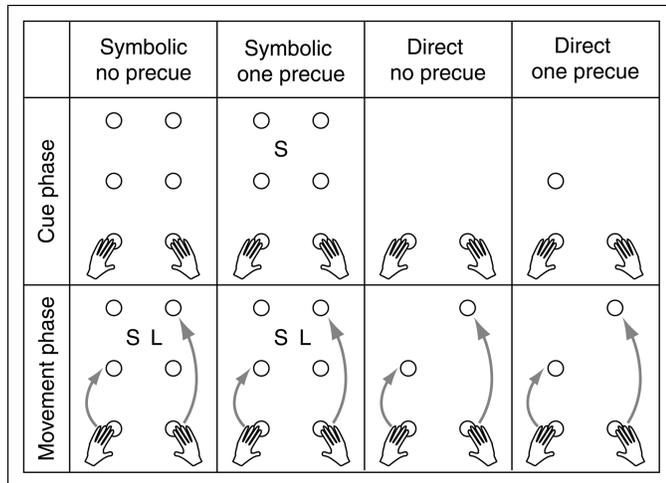


Fig. 1. The four experimental conditions for Experiment 1. The movement of each hand was either long or short. In the four examples illustrated here, a short movement was required for the left hand and a long movement was required for the right hand. In the symbolic conditions, circles at all possible target locations were presented, and the letters “S” (“short”) and “L” (“long”) indicated the required movements. In the direct conditions, circles indicated the target locations. For the no-precue conditions, the onset of the two letters (symbolic) or circles (direct) served as the imperative signal. In the one-precue conditions, one of the target locations was specified in advance in the cue phase.

We also included blocks in which the target for one hand was specified in advance of the imperative signal. The precue remained constant within a block to ensure that participants would use this information. A comparison between one-precue and no-precue conditions should reveal costs associated with specifying two amplitudes. If movements for the two hands can be planned in parallel with direct cues, then a precue should have minimal effect on RT.

EXPERIMENT 1

Method

Participants

Twelve undergraduate students (age: 18–20 years; 2 left-handed) from the University of California, Berkeley, participated in Experiment 1.

Apparatus and stimuli

Participants were seated at a table surface 75 cm high. They positioned their head in a chin rest with eye level set to approximately 43 cm above the table. Stimuli were presented from a video projector onto a rectangular screen (100 × 77 cm), which was 48 cm above the table surface. A mirror was mounted halfway between the screen and table, so that the stimuli appeared to be on the table surface. The participants could not see their limbs, but the positions of the tips of their index fingers were continuously indicated by two small dots (2-mm diameter). Unfilled circles (3.6-cm diameter) were used for both the starting circles and targets (Fig. 1). They were presented 7.6 cm to the left or right of the body midline, with the set of six circles spanning a

visual angle of $19^\circ \times 20^\circ$. The distance from the start position to the short and long targets was 10 and 20 cm, respectively. The letters “S” (for “short”) and “L” (for “long”) were 2×2.5 cm and were centered between the four possible target locations.

Procedure

To start each trial, the participants positioned their index fingers within the starting circles and remained in these circles during the variable-duration cue phase (1–2 s). In the direct, no-precue condition, only the starting circles were visible during the cue phase. In the corresponding one-precue condition, a circle was presented on one side, indicating the target location for that hand. In the symbolic conditions, all four possible target circles were presented during both the cue and the movement phases. In the symbolic, one-precue condition, a letter was presented on one side in the cue phase, again indicating the target location for that hand. The precued movement was held constant for each block of trials. The movement phase was initiated by the presentation of the remaining circle(s) or letter(s). The participants were told to move as quickly as possible after the appearance of these imperative signals. They were instructed to reach for each location with a single movement. A tone was played 500 ms after both hands stopped moving to indicate the end of the trial. The participants then returned to the starting circles to begin the next trial.

The four conditions were run sequentially in a counterbalanced order. For each condition, participants completed one practice block of 8 trials and four blocks of 24 trials. In the one-precue conditions, a different cued movement was used in each of the four blocks.

Data acquisition and analysis

Movements were recorded with an Ascension miniBIRD magnetic tracking system (130-Hz sampling rate). The recorded trajectories were smoothed by a Gaussian kernel with a width of 14 ms. The RT for each hand was taken at the time when the tangential velocity first exceeded 2 cm/s. The movement time (MT) was measured from this point until the velocity dropped again below 2 cm/s.

Results and Discussion

On 1.4% of the trials, the software prematurely determined that the movement was completed. We excluded these trials, as well as all trials in which either movement was initiated with an RT less than 100 ms (anticipations, 0.7% of the trials), the lag between the hands was more than 150 ms (0.1% of the trials), or the movement ended at the wrong target (1.6% of the trials, all in the symbolic conditions).

There were no differences in RT between long and short movements, so we collapsed the data over this factor and the two hands (see Fig. 2a). We conducted a 2 (congruency: same or different amplitude) × 4 (condition) repeated measures analysis of variance (ANOVA) on the RTs. Both main effects were significant: condition, $F(3, 33) = 58.93, p < .001$; congruency, $F(1, 11) = 16.38, p = .002$. Moreover, the Condition × Congruency interaction was reliable, $F(3, 33) = 8.73, p < .001$.

The results for the symbolic, no-precue condition replicate the findings of Spijkers et al. (1997). The RT difference between the same- and different-amplitude conditions was 55 ms, indicating bimanual interference when the two hands had to move different distances. When one of the movements was precued, a significant 92-ms decrease in RT was found, $t(11) = 7.00, p < .001$, and the congruency

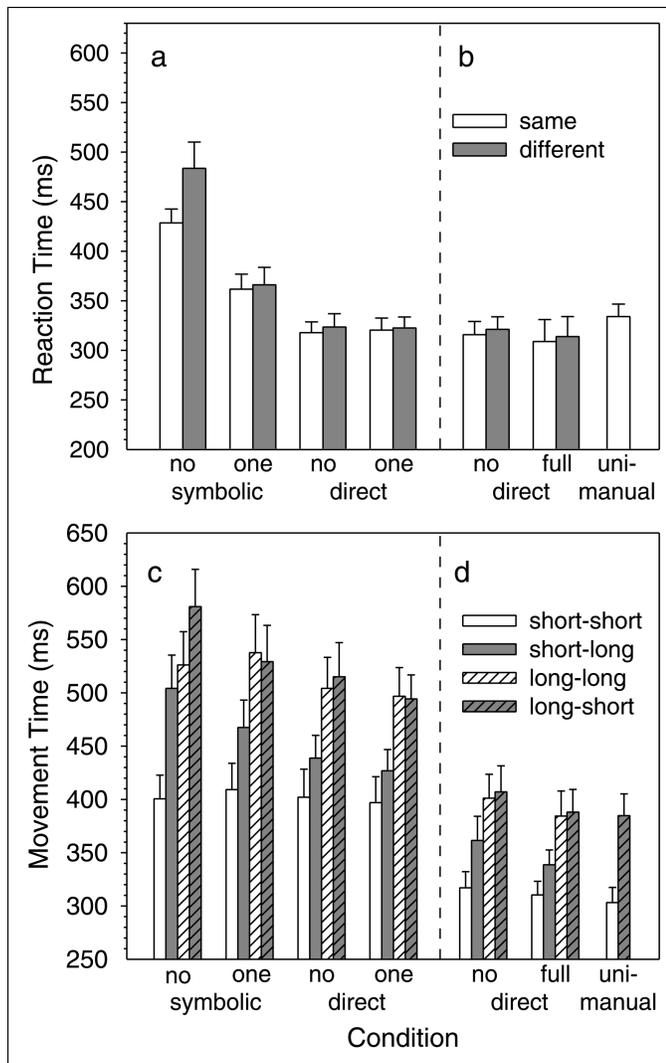


Fig. 2. Results of Experiment 1. The top panel shows reaction times, averaged across the two hands, when the movements of the two hands were either the same or different in amplitude, in the main experiment (a) and the control experiment (b). The bottom panel shows movement times for the main experiment (c) and control experiment (d); the amplitude of the depicted hand is given before the hyphen, and the amplitude of the other hand is indicated after the hyphen. Results for the main experiment are shown separately for the four cuing conditions (direct or symbolic, either with no advance information or with one precue). Results for the control experiment are shown separately for the no-precue, full-precue, and unimanual conditions. All of the movements in the control experiment were directly cued. Note that different participants participated in the main experiment and control experiment. Error bars indicate standard errors.

effect was abolished. The latter result is not consistent with a motor-execution account of bimanual interference because the movement requirements were similar for the one-precue and no-precue conditions. Rather, the interference arose during motor programming or during earlier processing stages.

A very different pattern was found for the direct conditions. In this case, there was no advantage in the precue condition, nor was there a

significant difference between the same- and different-amplitude conditions (6 ms), $t(11) = 1.59$, $p = .140$. Simultaneous motor programming can occur independently and without interference between the hands when the targets are presented directly. Thus, bimanual interference appears to result from processes involved in identifying symbolic cues or translating these cues into the appropriate motor commands.¹

Although we did not find any effect of coupling in the RT data, coupling could manifest itself in cross talk in the spatial aspects of the movements. Surprisingly, the long movements were 3.6 mm longer when coupled with a short rather than a long movement, whereas short movements were 0.6 mm shorter when coupled with a long rather than a short movement. Thus, the influence on the amplitude was opposite to the direction expected if there was cross talk between the hands. That is, coupling should have made the produced amplitudes for the two hands more similar to each other. Moreover, these effects were small compared with the average variable error of movement end points, which was 9.5 mm.

Could the absence of an RT cost in the direct-cue condition have resulted from deferred programming? Perhaps the participants focused on initiating the movements rapidly and started moving before the amplitude was fully specified. If programming was partially deferred to the movement period, then higher MTs would be observed for incongruent trials than for congruent trials. The MT data are shown in Figure 2c. The results are very similar for the three conditions for which there were no interference costs in the RT data: Consistent with the deferred-programming hypothesis, short movements in the direct conditions and the symbolic, one-precue condition were executed more slowly in the incongruent condition than the congruent condition. These results do not necessarily reflect deferred programming, however. An alternative explanation is that a short movement was performed more slowly when paired with a long movement so that the two movements terminated at approximately the same time (Kelso et al., 1979; Marteniuk et al., 1984). The fact that no difference was found between the congruent and incongruent trials for the long movements in the MT data for these three conditions lends support to this accommodation hypothesis.

A different picture emerged in the symbolic, no-precue condition. In this case, a long movement became slower when paired with a short rather than a long movement. The interaction among condition, amplitude of the movement, and amplitude of the other hand was significant, $F(3, 33) = 22.40$, $p < .001$. Thus, in this condition, on top of the normal accommodation effect (bias to move the hands synchronously), there was a congruency effect, with an overall slowing of MT for trials in which the hands moved different amplitudes.

Control Experiment

Although the MT results of Experiment 1 do not support a deferred-programming hypothesis, it is noteworthy that the MTs were generally longer than those in previous studies investigating amplitude specification of unimanual (Goodman & Kelso, 1980) or bimanual

1. The symbolic and direct conditions differed in that when the imperative signal appeared, all four possible targets were present in the former but only two targets were present in the latter. In subsequent studies, we have tested direct-cuing conditions in which circles appeared at all four locations and the targets were specified by their color. No congruency effect was observed with this form of direct cuing.

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(e.g., Spijkers et al., 1997) movements. This raises the possibility that for the direct, no-precue condition, costs associated with programming movements of different amplitudes were absorbed into the movement-execution phase. To address this issue, we conducted a control experiment with 10 new participants, modifying the instructions to emphasize movement speed. Two bimanual conditions were included: a replication of the direct, no-precue condition and a full-precue condition in which both targets were specified in advance of the imperative signal. For the no-precue condition, all four possible targets were initially visible for 0.8 s and then turned off for a variable period of 0.2 to 1.2 s. The onset of the two targets served as the imperative stimulus. For the full-precue condition, the timing of the trial events was identical, but only the two target locations were presented at the start of the trial. A comparison of these two conditions, one requiring amplitude specification for both hands and the other allowing full preparation before the imperative signal, provides a strong test for any costs associated with bimanual movement programming and execution that might be observed in either the RT or the MT data. We also included a unimanual condition to establish a baseline for evaluating such costs. In this condition, all four locations were initially visible, but only one randomly selected target location was presented as the imperative signal.

As expected given the change in instructions, the MTs were considerably faster in the control experiment than in the main experiment (see Fig. 2d). The pattern for the four movement combinations remained unchanged. Most important, there was no significant difference between the no-precue and full-precue conditions, $F(1, 9) < 1.0$, and the precue variable did not interact with the type of movement combination. Indeed, the MTs for the bimanual conditions were comparable to those observed in the unimanual condition. For the RT data (Fig. 2b), a 5-ms advantage was observed on congruent trials compared with incongruent trials. This difference was not significant, $F(1, 9) = 2.63, p = .139$, and was comparable for the no-precue and full-precue conditions. The bimanual RTs were similar to the unimanual RTs.

In summary, even when the movements were produced considerably faster than in the main experiment, no reliable costs were observed in the direct, no-precue condition when the two amplitudes were incongruent. Strikingly, when amplitudes were specified by direct cues, the no-precue condition produced no increase in RT or MT compared with conditions in which both required movements were precued or only one movement was required.

EXPERIMENT 2

In Experiment 2, we explored the generality of the findings from the previous experiment, looking at movements that followed parallel or orthogonal trajectories. Movements in this experiment could be either forward from the starting position or lateral, away from the midline. With this setup, deferring programming until after movement onset would lead to errors in the initial direction. Interference associated with programming movements in different directions would be manifest either in the RTs or in directional errors at movement onset.

Method

Twelve Berkeley undergraduates (age: 18–37 years; 1 left-handed) participated in Experiment 2. The starting circles were slightly closer to the midline (7.2 cm) than in Experiment 1. The target locations

were either 10 cm in front of the starting locations (forward movements) or 10 cm eccentric to the starting locations (lateral movements). The symbolic cues (“F” for “forward,” “S” for “sideways”) were presented between the starting circles, equidistant from the target locations. In all other respects, Experiment 2 was identical to Experiment 1. We also included a control experiment ($n = 10$) similar to the control experiment for Experiment 1, again emphasizing movement speed.

Results and Discussion

We excluded trials (3.3%) according to the criteria used in Experiment 1. On the basis of the findings of Experiment 1, we conducted a set of planned comparisons of the RT data (Fig. 3a). RTs were very fast for all of the direct conditions, with only a nonsignificant 4-ms effect of congruency in the direct, no-precue condition, $t(11) < 1$. Moreover, no advantage was found when one of the movements was precued, $t(11) < 1$. In contrast, in the symbolic, no-precue condition, RTs were 94 ms slower in the different- than in the same-direction condition, $t(11) = 5.28, p < .001$. Symbolic precuing for one hand was effective, reducing RTs by 106 ms, $t(11) = 10.13, p < .001$, and no congruency effect was observed in this condition.

Lateral movements were faster than forward movements (Fig. 3c), likely because of biomechanical factors (see unimanual MT data in Fig. 3d). The MTs for movements in a particular direction were slower when the other hand moved in an orthogonal direction, $F(1, 11) = 99.512, p < .001$. This effect did not differ among the four cuing conditions, $F(3, 33) = 2.51, p = .076$. If motor-programming costs had been deferred until the movement phase, then the MTs for incongruent trials should have been prolonged only in the uncued conditions.

Although the preceding analyses indicate that bimanual interference is essentially abolished when the movements are directly cued, the results of the control study qualify this conclusion. A significant 10-ms congruency effect was obtained in the direct, no-precue condition, $t(9) = 2.68, p = .025$ (Fig. 3b). This effect could reflect interference associated with programming bimanual movements along orthogonal directions, a cost that becomes evident only under instructions emphasizing movement speed. However, there are two arguments against such an interpretation. First, there was also a 7-ms congruency effect in the full-precued condition even though we assume motor programming was finished before the imperative signal in this condition. Second, the congruency effect was present only for the forward direction (18-ms congruency effect). No difference was found for the lateral direction (3 ms). It is likely that the small congruency effect for forward movements reflects a slower detection time in the incongruent than in the congruent condition. In the congruent condition for forward movements, the two targets were close together; in the incongruent condition, the targets were much further apart. In the case of lateral movements, the targets were not close together in either the congruent or the incongruent condition, which might explain the lack of a congruency effect for such movements.

Unlike in the control experiment for Experiment 1, precuing the direction for both hands led to an 80-ms decrease in RT, $t(9) = 8.34, p < .001$. Uncertainty about movement direction appears to entail an RT cost (Megaw, 1972). Interestingly, this cost seems equivalent regardless of whether the uncertainty is associated with two hands or one hand, as shown by the comparison between the direct, no-precue and unimanual conditions.

As expected, the MTs were faster in the control experiment than in the main experiment, but the patterns are similar (Fig. 3d). Although

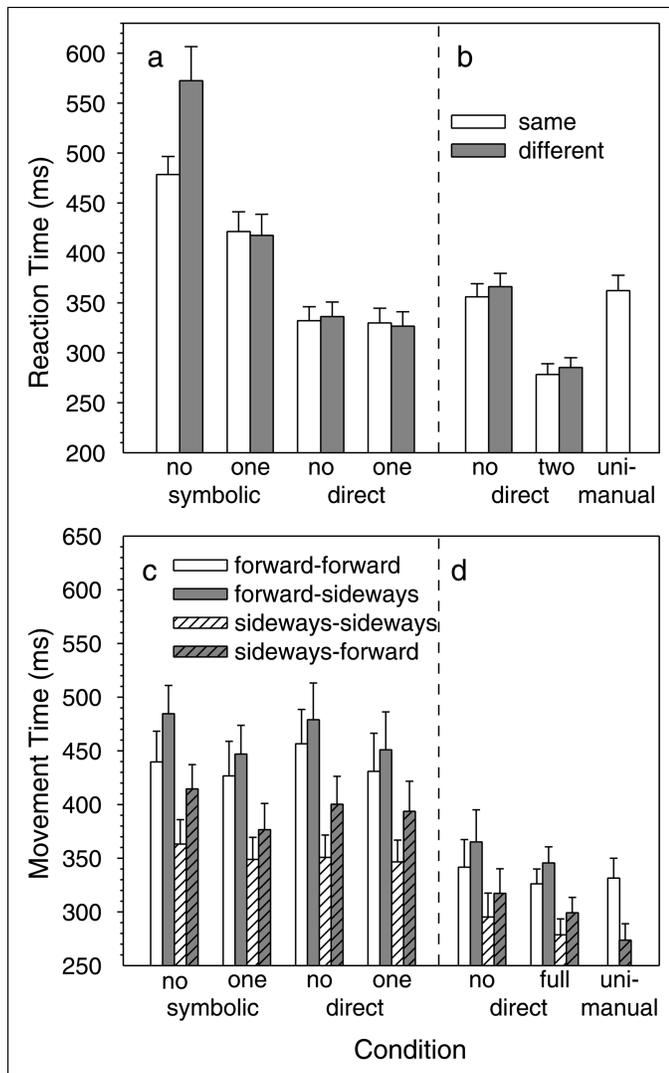


Fig. 3. Results of Experiment 2. The top panel shows reaction times, averaged across the two hands, when the movements of the two hands were either the same or different in direction, in the main experiment (a) and the control experiment (b). The bottom panel shows movement times for the main experiment (c) and control experiment (d); the direction of the depicted hand is given before the hyphen, and the direction of the other hand is indicated after the hyphen. Results for the main experiment are shown separately for the four cuing conditions (direct or symbolic, either with no advance information or with one precue). Results for the control experiment are shown separately for the no-precue, full-precue, and unimanual conditions. All of the actions in the control experiment were directly cued. Note that different participants participated in the main experiment and control experiment. Error bars indicate standard errors.

the mean for the no-precue MTs in the control experiment was slightly slower than the mean for the full-precue and unimanual conditions, neither of these differences was reliable.

The MT results do not support the hypothesis that programming costs may be deferred until after movement onset. Moreover, an analysis of the initial movement direction indicates that the participants specified the direction prior to movement onset. We determined the di-

rection traversed by the index finger over the first 150 ms of each movement. Surprisingly, the vectors could be unambiguously assigned to either the target location (correct direction) or the nontarget location (incorrect direction): There were essentially no initial trajectories that fell between these two directions. In the direct, precue and direct, no-precue conditions, the error rates were 0.2% and 0.7%, respectively. In contrast, the error rates in the symbolic conditions rose to 6.6% in the one-precue and 16.5% in the no-precue condition. In the latter condition, the majority of these errors occurred on incongruent trials, and were due to a misassignment in which each hand followed the target trajectory for the other hand. In the symbolic, one-precue condition, errors were equally likely for congruent and incongruent trials. On most error trials, the trajectory was adjusted in midflight so that the two hands ended up in the correct circle. However, the lack of errors in the direct-cue conditions indicates that the direction had been correctly specified before the movement started.

GENERAL DISCUSSION

These experiments demonstrate a striking dissociation between symbolically and directly cued actions in terms of the degree of spatial interference during bimanual movements. When the imperative signal directly indicated the target location, RTs were fast, there was no benefit from one precue, and there was no cost in programming nonhomologous movements for the two hands. The modest increase in MT on incongruent trials was limited to the short movements and likely reflects an accommodation effect. A very different pattern was found for the symbolic-cue conditions. When the movements were incongruent, substantial costs were observed for both RT and MT, and errors were much more frequent. Benefits were found for a symbolic precue, in terms of both an overall reduction in RT and an elimination of the costs on incongruent trials.

We assume that motor programming was necessary in all the conditions in which the actions could not be fully specified in advance. This requirement was present in the no-precue conditions regardless of whether the targets were specified symbolically or directly. Thus, these results provide strong evidence that the RT cost associated with producing asymmetric bimanual movements results from processes associated with translating symbolic cues into actions. Such costs are present even when highly compatible symbolic cues are used (e.g., bars of different lengths, which indicate the movement distance; Spijkers et al., 1997, 2000).

There are several possible loci for the interference effects in the symbolic conditions. The interference could arise during stimulus identification, with processing being faster when the display is composed of identical elements than when it is not (Posner, 1978). However, the magnitude of the interference was almost twice as large in Experiment 2 as in Experiment 1. Given that similar symbols were used, it is unlikely that the entire cost associated with asymmetric bimanual movements was due to stimulus identification. Alternatively, the cost could be associated with the translation of symbolic stimuli into response codes (e.g., Pashler, 1994). When the stimuli are different (and thus require nonidentical movements), an assignment problem might arise. The high number of confusion errors in the symbolic, no-precue condition of Experiment 2 supports this hypothesis.

Franz and her colleagues (Franz, 1997; Franz et al., 1991, 1996) have reported strong spatial coupling during bimanual movements. However, in all of these studies, the movements were symbolically cued, with the participants drawing shapes to match a template. Thus,

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the movement trajectories were internally generated rather than externally specified. We predict that the coupling effects in RTs, even for complex patterns such as those used in Franz's studies, would be strongly attenuated if the goals of the movements were directly specified. However, distortions of trajectories when movements are not symmetric may still be caused by cross talk during the programming of bimanual movements (Spijkers & Heuer, 1995).

Contrasting symbolically cued and directly cued movements is similar to an idea proposed in the neurophysiology literature, namely, that distinct neural systems are associated with internally guided and externally guided movements (Goldberg, 1985; Mushiake, Inase, & Tanji, 1991; see also Goodale & Milner, 1992). The internal-external distinction emphasizes a difference in reliance on visual guidance. In the symbolic condition of our experiments, potential targets were presented in all four locations, and the selection of the required movements depended on an internal translation process. Presenting only the targets in the direct condition bypassed this response-selection stage. Indeed, the lack of a benefit from a precue for one hand in the direct condition suggests that movements can be specified in parallel and without interference (see also Greenwald & Shulman, 1973).

Everyday behaviors rarely require people to produce movements of a particular trajectory or amplitude without reference to specific objects. When external goals are available, the two hands seem to be able to produce nonhomologous trajectories without difficulty. For example, catching a ball usually requires that the two hands traverse different paths to arrive at the same location. In this case, the spatial independence of motor programming for the two hands is essential for smooth performance. In contrast, for abstractly defined movements like drawing, spatial coupling can be very powerful, perhaps as a consequence of interference in the translation of symbolic information into motor commands.

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