Bimanual Interference Associated With the Selection of Target Locations

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Four experiments were conducted to identify the locus of interference observed during the preparation of bimanual reaching movements. Target locations were specified by color, and the right-hand and left-hand targets could be either the same or a different color. Movements of different amplitudes (Experiment 1) or different directions (Experiment 2) to targets of the same color were initiated more quickly than symmetric movements to targets of different colors. These results indicate that costs observed during bimanual movements arise during target selection rather than during motor programming. Experiments 3 and 4 further examined the interference associated with target selection. Reaction time costs were found with unimanual movements when the target was presented among distractors associated with responses for the other hand. Interference observed during bimanual reaching appears to reflect difficulty in segregating the response rules assigned to each hand.

We typically use our two hands in a coordinated fashion to achieve a common goal. When we are unscrewing a bottle or tying a knot, the actions of the two hands have to be finely tuned in relation to each other. Constraints on bimanual performance become apparent when we use our hands to achieve different goals at the same time. Consider, for example, the task of picking out good cherries among rotten ones from a tray in the supermarket, with either one or two hands. If our hands could work independently, we should be able to pick out many more cherries with two hands than with one hand. This, however, is not the case. This limitation may be due to our inability to plan or execute independent movements with the two hands at the same time. Alternatively, we may have problems in selecting and maintaining the goals for the two movements. The present article aims to determine the processing stage that gives rise to performance limitations during bimanual reaching movements.

In the laboratory, constraints on bimanual performance have been studied with tasks that require the simultaneous production of two movements with either symmetric or differing spatial characteristics. In comparison with symmetric movements, movements with different spatial characteristics require longer initiation times

(Franz, Eliassen, Ivry, & Gazzaniga, 1996; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997) and result in significant distortions of spatial trajectories (Franz, Zelaznik, & McCabe, 1991; Kelso, Putnam, & Goodman, 1983; Sherwood, 1990; Spijkers & Heuer, 1995).

Spijkers and his associates (Spijkers et al., 1997; Spijkers, Heuer, Steglich, & Kleinsorge, 2000) have explored the source of these constraints in a series of studies. In these experiments, participants were required to execute fast lateral reversal movements (outward and back). Two bars were presented on the computer screen, one to the left of fixation and one to the right. The size of the bar indicated whether the target amplitude for the corresponding movement was short or long. Reaction times (RTs) were nearly 100 ms longer when the two movements were incongruent (i.e., one short and the other long) than when the two movements were congruent (i.e., both short or both long). The authors proposed that this increase reflected interference at the stage of motor programming (see Rosenbaum, 1980; Rosenbaum & Kornblum, 1982). Programming was fast when the only unknown parameter, movement amplitude, was set to the same value for each hand. When different parameters needed to be specified, cross talk was hypothesized to occur between the programming processes required for the right arm and those required for the left arm. This cross talk presumably led to the increase in RT on incongruent trials.

The programming hypothesis has been called into question by a recent study in which the target locations were directly specified (Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001). Symbolic cues such as bar length were not used; rather, visual stimuli were projected onto a table surface, and participants were instructed to move as quickly as possible to these target objects. Under these conditions, no differences were found in RT between congruent and incongruent movements. Indeed, the RT on bimanual trials with direct cues was as short as that on unimanual trials. These findings indicate that bimanual interference is unlikely to result

from either motor programming or execution, assuming that these processes are essentially the same for direct and symbolically cued movements. Instead, the interference visible in the RT data is probably due to a processing stage associated with identification of the stimulus or selection of the appropriate response.

Although rarely discussed as such, bimanual reaching tasks can be considered a form of a dual task. Limitations in dual-task performance have been one of the central topics in cognitive psychology and have played a critical role in the development of analytic tools for specifying processing stages across a range of tasks (Pashler, 1998b). One example centers on the psychological refractory period (PRP; McCann & Johnston, 1992; Pashler, 1994; Telford, 1931). In PRP studies, participants have to respond to two stimuli in rapid succession. When the stimulus onset asynchrony (SOA) between the tasks is short, the RT for the second task is delayed. This limitation has been attributed to a response selection bottleneck (but see Meyer & Kieras, 1997; Pashler, 1984, 1998a). By this view, it is assumed that stimulus identification and response execution for the two tasks can occur in parallel; the limitation in performance is hypothesized to arise as a result of overlapping demands of the two tasks on a common response selection process. Response selection for one task must be completed before this operation can be performed for the other task. With short SOAs, this delay will appear as an increase in RT for the second task.

Spijkers et al. (2000) used a PRP paradigm with bimanual reversal movements involving the same or different amplitudes. At short SOAs, the initiation of the second movement was considerably delayed when the amplitudes were different. The authors interpreted their results as interference of temporally overlapping motor programming processes. However, given their use of symbolic cues, the RT costs could have resulted from the demands associated with processing nonidentical cues on incongruent trials or from the fact that nonidentical "abstract" movement codes had to be selected. As a means of testing the first hypothesis, a control condition was included in which participants simply had to identify the first stimulus on a random subset of the trials; speeded responses were only required to the second stimulus. Participants showed similar RTs on congruent and incongruent trials, arguing against the perceptual hypothesis. The authors dismissed the selection hypothesis because "the distinction between response selection and amplitude specification is inappropriate for our experimental paradigm. . . . As argued by Rosenbaum (1983), selection of a movement is equivalent to specifying its parameters" (Spijkers et al., 2000, p. 1103).

This argument may be valid when the movements are not directed toward specific targets but rather are characterized by symbolically specified movement parameters. Under these conditions, the movements are probably represented in terms of task-defined movement parameters. That is, when participants are told to make a long or short reversal movement in response to the letter L or S, they probably represent the action as "long movement" or "short movement." Response selection will be based on these codes, and interference is likely to arise when the two actions are associated with different codes. With symbolic cues, the codes for response selection and response parameterization overlap.

In contrast, when movements are directly cued, response selection may well be in terms of characteristics of the goal of the movement rather than in terms of movement parameters. For example, imagine that you want to retrieve a tool from a cluttered drawer. Response selection would involve deciding which object you wanted to pick up. The location of that object and its orientation would then dictate the motor programming requirements, a process that would follow selection. In this way, the selection of the movement goal and the specification of the movement parameters are separated.

This distinction suggests two possible loci for bimanual interference. If cross talk arises during response selection, the pattern of interference should depend on how the actions are represented. If cross talk arises during the specification of motor parameters, then interference should be determined by the kinematic properties of the movements. In Experiment 1, participants were instructed to select a target object for each hand and then reach for the two objects. The resulting movements required either the same or different amplitudes. We sought to determine whether interference should be attributed to early stages of processing (stimulus identification and response selection), as hypothesized in the PRP literature and our earlier direct reaching study (Diedrichsen et al., 2001), or later stages (motor programming and motor execution), as assumed in most bimanual reaching studies.

Experiment 1

The experiment was conducted with an apparatus that allowed participants to reach directly for visually presented targets (Figure 1). Four possible target locations were defined on each trial by the presentation of four colored circles that formed the corners of an invisible rectangle (see Figure 2). The participants' task was to execute bimanual reaching movements, with the left hand moving to one of the two left-side targets and the right hand moving to one of the two right-side targets. The actual target locations were
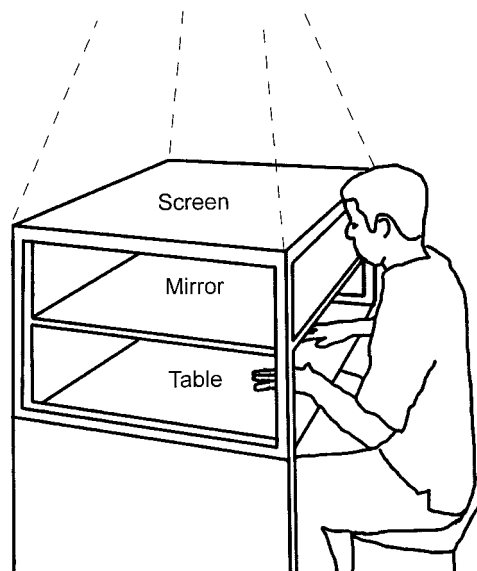
Figure 1. Apparatus used in all four experiments. The participant was seated in front of a table and looked onto a mirror. A computer projector displayed visual stimuli on the screen (dashed lines). Because the mirror was equidistant between the screen and table, the stimuli appeared to be presented on the table surface. Although the mirror blocked the participant's view of his or her hands, the position of the tip of both index fingers was projected as a small dot at corresponding locations on the screen.
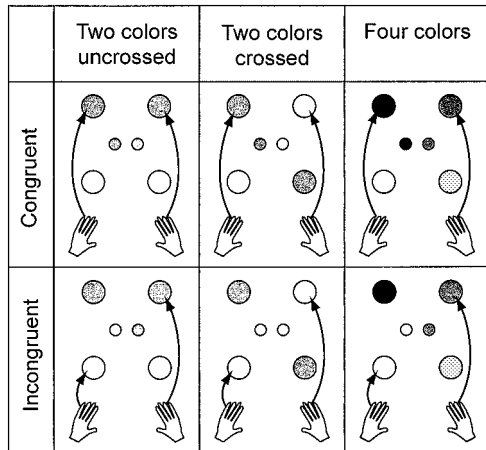
Figure 2. Experimental conditions in Experiment 1. Four colored circles indicated the possible target locations. After a delay interval, two smaller colored circles appeared in the center and served as the cues. Participants were instructed to reach with each hand to the target location that matched the color of the cue on that side of the display. The amplitudes of the two movements could be either identical (congruent, top row) or different (incongruent, bottom row). Three conditions were tested. Left: The target colors for the two sides were in spatial correspondence in the uncrossed condition. Middle: The target colors for the two sides were spatially crossed in the crossed condition. Right: The two targets and two distractors were all different colors in the four-color condition. The actual colors were green, red, blue, and yellow, here represented through shading and pattern.

specified by the presentation of two small, colored circles (cues) near the center of the display. The color of each of these cues matched the color of one of the two target circles on the corresponding side, thereby indicating the target location for that trial. The onset of the cues also served as the imperative signal. For example, if the colors of the cues on the left and right were blue and yellow, respectively, then the participant would reach to the blue target location on the left and the yellow target location on the right.

There were three conditions. In the *four-color condition*, unique colors were used for the four target locations. In the other two conditions, only two colors were used, with each color appearing at one of the two target locations on each side. In the *two-color uncrossed condition*, one color was used for both far target locations, and the second color was used for both near target locations. In the *two-color crossed condition*, one color was used for the target locations along one diagonal, and the other color was used for the target locations along the other diagonal.

The experiment was designed to determine the locus of interference during planning of bimanual movements of unequal amplitude. Consider first the four-color condition. The target colors for the two hands were always different in this condition. If interference reflects competition at the stage of stimulus identification or response selection, we should expect similar performance for all of the movement combinations. This is because, on every trial, two different cues must be identified and targets of different colors must be selected. However, if interference arises at the stage of motor programming, then we should observe a movement congruency effect. That is, when participants have to execute movements of the same amplitude (either short–short or long–

long), movement initiation should be faster than when the movements have different amplitudes (short–long or long–short).

Next consider the two-color conditions. For these conditions, the two target colors were the same on half of the trials and different on the other half of the trials. In the uncrossed condition, identical target colors indicate movements of the same amplitude (both short or both long). Thus, for this condition, congruent movements should be initiated more quickly than incongruent movements, independent of the locus of interference, because the former involve identifying the same color, selecting targets defined by the same color, and programming movements of identical amplitudes. In contrast, early and late models of interference make opposite predictions for the crossed condition. When the cues and colors of the target locations are identical, stimulus identification and response selection should be facilitated, because only one color needs to be evaluated. Programming should be difficult, however, because the required movements are of unequal amplitude. The reverse holds for the situation in which the target colors are different, thus requiring movements of equal amplitude. In this case, stimulus identification and response selection should be difficult, but programming should be easy.

In summary, the contrast between same- and different-target color trials in the two-color conditions provides a strong comparison of models that attribute bimanual interference to early stages (stimulus identification–response selection) and late stages (response programming or execution). The early-stage model would be supported if performance were fastest when the cues and colors of the target locations were identical, regardless of whether these targets involved movements of equal or unequal amplitude. The late-stage model would be supported if performance were fastest when the movements were of identical amplitude, regardless of whether the targets were specified by the same or different colors. It is, of course, possible that interference can arise at all stages. If so, we would expect to find performance influenced by both target color correspondence (same or different target colors) and target amplitude (same or different movement amplitudes).

Method

Participants. Ten participants were recruited from the University of California, Berkeley, community. All were right-handed and had normal color vision (self-reported); participants ranged in age from 18 to 28 years.

Apparatus and stimuli. A mirror-reflecting system was used for the presentation of all stimuli (Figure 1). This system consisted of a computer projector (Plus UP 800) and three parallel surfaces (each 100×77 cm): a table surface along which movements were made, a projection surface onto which the stimuli were presented, and a mirror surface that reflected the stimuli onto the table surface. The table surface was situated at a height of 75 cm. The projection surface was positioned 48 cm above the table, and the mirror was placed halfway between the projection and table surfaces. With this arrangement, stimuli displayed onto the projection surface appeared to be presented on the table.

A three-dimensional movement recording system (Ascentech mini-bird system) was used to monitor the positions of the two hands. Small antennas ($15 \times 8 \times 8$ mm) were taped to the tip of each index finger. These antennas responded to magnetic signals generated by a transmitter and provided an output signal of current position (*x*-, *y*-, and *z*-coordinates). The sampling rate was 140 Hz, and the average spatial resolution was 0.5 mm.

Filled colored circles were used to indicate the four target locations. Circles were 3.6 cm in diameter and were displayed at the vertices of an imaginary rectangle. The width of the rectangle was 15.4 cm (16.7°), and the length was 10 cm (11.3°). The cues were presented near the center of

the rectangle. Each cue was a circle 1.2 cm in diameter, with a distance of 3.8 cm between the two cues. In addition, two unfilled white circles were displayed at the start of each trial to indicate the starting position for each index finger. These circles were 3.6 cm in diameter and were 10 cm from the center of the nearest target locations. Thus, the movements for each hand could be either 10 cm or 20 cm. The mirror screen prevented the participants from seeing their hands, but the position of each index finger was continuously monitored and displayed as a small dot (2-mm diameter) on the table surface. An exact match of visual stimulus and hand position was ensured by a manual calibration of a three-parameter transformation from space to screen coordinates. The participants' impression was that they were moving in the dark with only the tips of their fingers visible as they approached the colored target locations. Head position was stabilized by a chin rest.

Procedure. Each trial began with the illumination of the two starting circles. The left and right index fingers were then moved into these circles. After the starting position had been maintained for 1 s, the four possible target locations were presented.

In the four-color condition, the clearly distinguishable colors green, red, blue, and yellow were randomly assigned to the circles at these four locations. In the two-color conditions, two of these colors were randomly selected and assigned to the circles at the four locations in an uncrossed or crossed fashion. Each color combination was presented an equal number of times over the course of the experiment. After a variable time delay of 1–2 s, two cues appeared at the center of the imaginary rectangle. Participants were instructed to move their fingers as fast as possible to the circle that matched the color of the cue on the corresponding side. They were instructed to initiate the movements of the two hands simultaneously. The trial ended 100 ms after the velocity for both fingers had remained below 5 cm/s for a continuous 80-ms epoch. At this time, all stimuli were turned off, and an intertrial interval of 500 ms was imposed before the reappearance of the starting circles marked the onset of the next trial.

The experiment began with a practice block of 36 trials, after which each participant completed eight blocks of 36 trials each. There were 12 different trial types created by the factorial combination of three experimental conditions (four colors, two colors crossed, and two colors uncrossed) and four movement combinations (short–short, long–long, short–long, and long–short). Each combination occurred three times within a test block. The trial types were randomly ordered within a block, and, across blocks, all possible color combinations were counterbalanced for each trial type. After each block, the participants received feedback indicating mean RT, mean movement time (MT) and the percentage of trials in which the movement terminated inside the target location.

Data analysis. For the purposes of data analysis RTs and MTs were calculated offline with a lower threshold than the online calculations for immediate feedback. The recorded trajectory for each hand was smoothed by a Gaussian kernel 14 ms in width. Then the velocity and acceleration profile was calculated, and the acceleration function was further smoothed by a 25-ms-wide Gaussian kernel. The RT for each hand was defined as the point at which the tangential velocity of the receiver exceeded 2 cm/s for the first time and stayed above this velocity for at least 100 ms. The end of the movement was defined as the point at which the velocity dropped below this same threshold, and MT was calculated as the difference between this point and the movement onset. As a result of different thresholds for online control and offline analysis, some trials had to be excluded because the recording program terminated sampling before the offline criterion was fulfilled. The acceleration function of each hand was used to determine possible subcomponents of the movements. A subcomponent was defined as a phase in which acceleration reached at least 100 cm/s^2 for 20 ms followed by a subsequent deceleration phase.

Results and Discussion

Trials were excluded from the analyses if (a) the recording was terminated before the offline criterion for a terminated movement

was fulfilled (4%), (b) the movements were not performed simultaneously (operationalized as a difference in movement onset time for the two hands of greater than 150 ms; 5.8%), or (c) one of the hands terminated the movement near the incorrect target (2%). Mean RTs are shown in Figure 3, with separate bars displayed for responses in which the movement amplitudes were the same (congruent) or different (incongruent). Throughout the article, we report RTs averaged across hands, because the starting times for the two hands were always strictly coupled. A series of planned comparisons directly tested the motivating hypothesis. In the uncrossed condition, RTs on congruent trials were 185 ms shorter than RTs on incongruent trials, $t(9) = 5.39$, $p < .001$. Strikingly, this effect was completely reversed in the crossed condition, in which RTs on incongruent trials were 185 ms shorter than RTs on congruent trials. Note, though, that the color of the cues and target locations was identical on incongruent trials in the crossed condition.

Thus, the results fail to support the hypothesis that interference on bimanual reaching tasks is due to conflicts that arise during motor programming. Rather, they strongly indicate that, with the current design, interference arises at earlier processing stages such as those associated with stimulus identification or response selection. The results from the four-color condition provide further support for this hypothesis. First, no effect of congruency was found in this condition, $t(9) = 0.38$, $p = .71$. Second, the mean RTs in the four-color condition were comparable to those observed in the two-color conditions in which the two cues involved different colors. On all trials in the four-color condition, target selection required the analysis of two different colors.

As noted, RTs were shortest when the color cues were identical and targets of identical color had to be selected. We can ask whether there was an additional effect of congruency. When the two colors were the same, RTs in trials requiring movements of the same amplitude (uncrossed condition) were 33 ms shorter than RTs in trials requiring movements of different amplitude (crossed condition), $t(9) = 4.01$, $p = .003$, suggesting that there was a
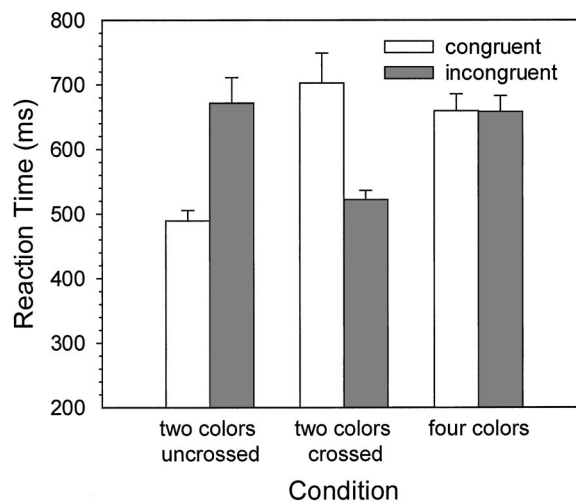

Figure 3. Reaction times in Experiment 1. Results are shown for the three conditions as a function of whether the two movements were congruent (same amplitude) or incongruent (different amplitude). Error bars indicate between-subjects standard errors.

congruency effect. However, when the two colors were different in the two-color conditions, a 32-ms advantage was again found for the uncrossed condition relative to the crossed condition, $t(9) = 2.85$, $p = .019$, even though the movements in the former condition were now incongruent. This suggests that there was an overall cost associated with the crossed condition. The data did not provide any evidence of a congruency effect related to programming movements of either the same or different amplitude.

The MTs (Table 1) in the four-color condition showed a typical assimilation effect. More time was needed to complete a short movement when that movement was paired with a long movement than when it was paired with another short movement, $t(9) = 4.00$, $p = .003$. No significant difference was observed in the MT data between long movements paired with another long movement and long movements paired with a short movement, $t(9) = 1.77$, $p = .11$. The pattern here reflects the tendency of the participants to synchronize both the onset and offset of the two movements (Kelso et al., 1983; Kelso, Southard, & Goodman, 1979).

A different pattern was found in the two-color conditions. In the uncrossed condition, congruent movements were executed more quickly than incongruent movements, $t(9) = 6.14$, $p < .001$. The reverse was observed in the crossed condition: Incongruent movements were executed more quickly than congruent ones, $t(9) = 3.82$, $p < .001$. This pattern is similar to what was seen in the RT data. It is likely that, at least on some trials, the movements were initiated before the response was fully selected and prepared. The conditions that had the longest RTs also had the longest MTs. As with the RT data, no evidence was found to suggest that MTs increased on trials involving movements of unequal amplitudes.

The slow MTs and the effect of target selection on MTs make it likely that part of the process of target selection and motor programming was deferred until after movement onset. The analysis of movement components further supports this hypothesis. Nearly 30% of the movements showed more than one acceleration phase, indicating that the movement consisted of multiple subcomponents. In 26.2% of all short movements, a second subcomponent began close to the near target. In another 2.7% of the short movements, a second subcomponent began close to the far target. In these latter trials, the participants made the initial mistake of moving to the far target and then reversed direction toward the close target. For long movements, a second component began near the close and far targets on 17.0% and 7.8% of the trials, respectively.

Given that some aspects of target selection or programming might be deferred to the movement phase on trials with second

Table 1
Movement Times (in Milliseconds) in Experiment 1 by Experimental Condition, Type of Movement, and Type of Movement Simultaneously Executed by the Other Hand

	Movement type[a]			
Condition	Short/short	Short/long	Long/short	Long/long
Uncrossed	531	785	825	758
Crossed	731	665	731	1,005
Four colors	580	690	761	799

Note. Results are shown averaged across both hands.
[a] Type of movement/type of movement simultaneously executed by the other hand.

acceleration components, we performed two post hoc analyses of the data. Neither exclusion of all trials with more than one movement component on either hand nor a median split according to MTs (within-participant–within-movement combination, yielding an average MT of 563 ms for the faster half) altered the pattern of RT results. Specifically, the reversal of the congruency effect between the crossed and uncrossed conditions remained complete, and there was no congruency effect in the four-color condition for these more limited data sets.

As a final assessment of interference associated with motor programming and execution, we considered the spatial characteristics of the movements. Endpoint accuracy, measured as the average distance of the movement endpoint from the center of the target circle, was 0.85 cm on average. Neither the effect of condition, $F(2, 18) = 1.14$, $p = .339$ nor the effect of movement congruency, $F(1, 9) = 1.75$, $p = .218$, was significant, and their interaction was nonsignificant as well, $F(2, 18) = 1.66$, $p = .215$. In addition, we measured the coupling of the produced amplitudes for the two movements. The amplitude of the movement for one hand was modulated by the amplitude of the movement for the other hand, $F(1, 9) = 15.63$, $p = .003$, and the effect interacted with movement amplitude, $F(1, 9) = 8.82$, $p = .016$. However, the direction of this modulation was opposite what would be expected if the two amplitudes were coupled. The amplitude of the other movement did not influence the amplitude of a short movement. The amplitude of a long movement, however, became 3 mm longer when the other movement was short. The modulation here, although small, had the effect of increasing the difference between the two movement amplitudes.

Experiment 2

The results of Experiment 1 demonstrate that the constraints associated with the initiation of bimanual movements need not reflect interference associated with motor programming. Rather, the limitations we observed seem to be connected to processes upstream of motor programming (e.g., processing cues of different colors or selecting target locations defined by these colors). However, two methodological weaknesses were associated with Experiment 1.

First, because of the long MTs and the substantial percentage of movements containing more than one submovement, it is likely that motor programming was not complete before movement initiation. It is probable that, on some trials, the participants deferred at least a portion of their planning until after the movement had started (Meegan & Tipper, 1998).

Second, the results may be specific to the manner in which the participants selected the target locations. For each response, the participants performed a matching task. They had to move to the target location that was presented in the same color as the target stimulus. Perhaps the advantage found when the targets were the same color reflected a benefit in perceptual grouping (Wertheimer, 1923). In the fastest experimental conditions, the cues and target locations were the same color and thus may have formed a single perceptual group allowing for rapid identification and selection. When the colors of the cues and target locations were different, two perceptual groups would be created, one on the left and one on the right. RTs are likely to be longer when two groups have to be processed. It remains to be seen whether a congruency effect

would emerge if the target locations could not be selected through a matching process.

To address the first issue, we chose movements with a lower index of difficulty, by reducing the movement amplitude of all movements to 10 cm. We also offered a monetary reward based primarily on fast MTs. Furthermore, we arranged the four target circles such that the movements always required the same amplitude of displacement but could involve different directions (Figure 4). If participants were deferring planning until after movement onset, adjustments should be easy to observe in the trajectory data.

In response to the second concern, we modified the selection rule. Rather than have color cues that varied from trial to trial, each participant was given a fixed rule at the beginning of each block indicating the color of the target locations for that block of trials. In the same-color condition (see Figure 4), a single color served as the goal for the two movements. For example, the participant might be told to always move to the yellow circles, and the distractor circles were always blue. In the different-color condition, different colors served as the goal for each movement. For example, the participant might be told to move to the red target location with the left hand and the green target location with the right hand. In the latter condition, the color of the distractor was always the color of the target on the other side, as in the crossed condition in Experiment 1. The appearances of the colored circles at target and distractor locations served as the imperative signals. In comparison with the task of Experiment 1, this task more closely matched natural conditions under which individuals reach for objects that satisfy internal goals in a field of distractors.

Method

Participants. Seven undergraduate students (18–36 years of age) from the University of California, Berkeley, participated in the experiment. They were paid $6 per session along with a performance-dependent bonus.

Procedure. The procedure and setup differed from Experiment 1 in two respects. First, the distance to each target from the starting circles was

Figure 4. Experimental conditions in Experiment 2 which demanded movements of different directions rather than amplitudes. In the same-color condition (left), participants were instructed to move with both hands to targets of one color (here gray). In the different-color conditions, two colors were used, one for the left-hand target and one for the right-hand target (here black on the left side, dotted on the right). The movements either were symmetric (congruent, upper row) or differed in terms of their direction (incongruent, lower row). The actual colors were red, green, blue, and yellow, here represented through shading and pattern.

10 cm, either in the forward direction or along a 45° diagonal. Second, the cues were eliminated, with the target colors specified in advance.

The same- and different-color conditions were performed sequentially, with each phase composed of nine 32-trial blocks, the first of which was considered practice. Three of the participants started with the same-color condition, and 4 started with the different-color condition.

The colors red, green, blue, and yellow were used, with the assignment of target colors counterbalanced across participants. The target color or colors used in the first phase of the experiment were always different from the target color or colors used in the second phase.
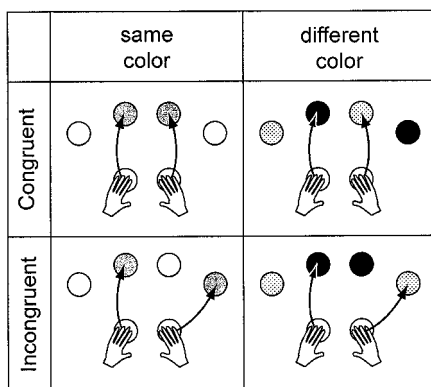
To initiate a trial, the participant placed his or her fingers in the starting circles and held this position for 1 s, after which the starting circles dimmed to alert the participant that the targets would soon appear. After a variable foreperiod of 1–2 s, four colored circles appeared. The participants were instructed to move, with each hand, as fast as possible to the two circles matching the target color for the respective hand. The instructions emphasized that the participants should move smoothly and directly to the targets, and the program was modified such that the trial was terminated as soon as the velocity in the direction of the target dropped below 4 cm/s. This procedure was adopted to discourage participants from making correctional movements.

At the end of each block, the participants received feedback on RT, MT, and accuracy. They also saw a score indicating their monetary bonus for the block. The bonus was designed such that payments would be highest if the movements were completed rapidly, as long as accuracy stayed above 85% correct.

Results and Discussion

Excluded from the analysis were trials in which the onset asynchrony was greater than 150 ms (1%) or in which one or both hands moved to the wrong target (0.1% in the same-color condition and 6.7% in the different-color condition). To ensure that the RT results reflected the full process of response selection and motor programming, we measured directions over the first 85 ms of movements to ensure that the movements were within ±20° of the target directions. This strict criterion resulted in the exclusion of an additional 13.7% of the trials.

To analyze RTs (Figure 5), we performed a two-factor analysis of variance (ANOVA) in which the independent variables were condition (same- vs. different-color condition) and combined left-hand–right-hand movement direction (forward–forward, sideways–sideways, forward–sideways, or sideways-forward). Mean RTs were much longer in the different-color condition (582 ms) than in the same-color condition (357 ms), $F(1, 6) = 77.67$, $p < .001$. This result is in accord with the findings of Experiment 1 and suggests that selection processes were the principal locus of cross talk in these experiments. There was also a significant effect of left-hand–right-hand movement directions, $F(3, 18) = 41.17$, $p < .001$. However, it is not likely that this effect was due to interference during motor programming, because the longest RTs were observed for the congruent condition in which both movements were in the diagonal direction. A more likely interpretation is that the participants' focus of attention at the start of each trial was closer to the forward than to the diagonal targets. Furthermore, the overall 7-ms advantage for congruent movements in the same-color condition was not significant, $t(6) = 2.00$, $p = .09$, and it was more than an order of magnitude smaller than the congruency effect reported by Spijkers et al. (1997). The congruent sideways–sideways movement was initiated with an especially long delay in the different-color condition, leading to
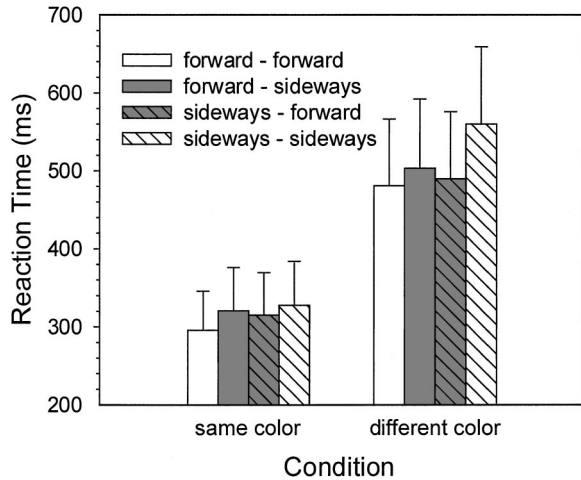
Figure 5. Reaction times in Experiment 2. Results are shown for the same-color and different-color conditions as a function of the movement directions of the left and right hands. Congruent movement directions appear in white; incongruent movement directions appear in gray. Error bars indicate between-subjects standard errors.

a Condition × Movement Direction interaction, $F(3, 18) = 14.03$, $p < .001$. This interaction also indicates a reversal of the congruency effect in the different-color condition.

The modifications of task difficulty, instructions, and bonus criteria yielded a considerable reduction in MTs (see Table 2). MTs did not differ significantly between the same- and different-color conditions, $F(1, 6) = 2.58$, $p = .16$. Forward movements were completed more slowly (320 ms) than diagonal movements (285 ms), probably reflecting biomechanical factors. Given the lack of difference between the same- and different-color conditions, as well as the required early specification of movement direction, it is highly unlikely that the participants deferred target selection and motor programming until after movement onset. That is, we can be fairly certain that the RT data reflect the combined costs of these two processes.

On average, the movement ended 0.97 cm from the center of the targets. This measure of spatial accuracy did not differ significantly between the same- and different-color conditions, $F(1, 6) = 0.36$, $p = .57$, nor did it differ between congruent and incongruent movements, $F(1, 6) = 0.01$, $p = .93$.

In summary, Experiment 2 shows that even when the specification of the movement has to be complete at movement onset, no programming costs are observed for movements of different directions when the target locations are directly cued (Diedrichsen et al., 2001). Moreover, although the procedure of Experiment 2 eliminated cue identification, we again observed substantially longer RTs when the targets were defined by two different colors than when a single color was used for both targets. Taken together, the results of Experiments 1 and 2 point to a substantial cost associated with response selection.

Experiment 3

In the next two experiments, we investigated the nature of the costs associated with response selection during bimanual reaching. The difference between the same-color and different-color condi-

tions of Experiment 2 may have not only reflected the cost of selecting targets with different rather than the same characteristics but also costs associated with the processing of the distractors (Meegan & Tipper, 1998; Tipper, Lortie, & Baylis, 1992). In the same-color condition, not only the targets but also the distractors were of identical color, whereas in the different-color condition the distractors were different in color. It may be easier to ignore identically colored distractors than differently colored distractors. Furthermore, the task relevance of the distractors was quite different for the two conditions. In the same-color condition, the distractor colors were always irrelevant; the colors were never used to indicate a target location. In contrast, in the different-color condition, the color of the distractor on each side was the same color as that used to indicate the target location for the other hand. Thus, participants not only had to select target locations defined by two different colors, they also had to ignore distractors that were task relevant (for the other hand).

To unconfound the costs of target selection and distractor relevance, we included two types of same-color and two types of different-color conditions in Experiment 3. In the same-color, no-distractor condition (Figure 6), only two target locations were presented, one on each side. Thus, participants in this condition could react to the onset of a stimulus and did not have to select between two target locations. Diedrichsen et al. (2001) found no congruency effect in RT, MT, or accuracy measures when target locations appeared without distractors. In fact, for directly cued targets requiring forward movements, bimanual RTs were no different from those observed during unimanual reaching. Thus, this condition provides a baseline for performance when there is no limitation associated with the selection of bimanual movements.

In the same-color, irrelevant-distractor condition, colored distractors appeared at the nontarget locations on each side. Different colors were used for the two distractors, and neither color was ever used to indicate a target location. Given our assumption that target selection is minimal (interference free) when only the targets are present in the same-color, no-distractor condition, an increase in RT in the same-color, irrelevant-distractor condition will provide an estimate of the time required to select two locations of the same color when these targets appear along with irrelevant and heterogeneous distractors. This comparison is reminiscent of the distinction that has been made in the visual attention literature between onset detection and pop out in visual search (Egeth & Yantis, 1997; Yantis & Jonides, 1984).

We also included a different-color, irrelevant-distractor condition. If bimanual interference reflects, at least in part, costs asso-

Table 2

Movement Times (in Milliseconds) in Experiment 2 by Experimental Condition, Type of Movement, and Type of Movement Simultaneously Executed by the Other Hand

	Movement type[a]			
Condition	Forward/ forward	Forward/ sideways	Sideways/ forward	Sideways/ sideways
Same color	308	311	278	265
Different color	333	325	293	303

Note. Results are shown averaged across both hands.
[a] Type of movement/type of movement simultaneously executed by the other hand.

distractor condition, the blocks alternated between the different-color, relevant-distractor and different-color, irrelevant-distractor conditions. Half of the participants started with the same-color session, and the other half began with the different-color session.

As a means of minimizing possible carryover effects across sessions, the target color or colors used in the first session were not included in the second session. To meet this criterion, a fifth color, gray, was included in the set of colors. For example, if blue and green were the targets for the different-color condition in the first session, gray would be the target color during the second session, and the distractors were always red and yellow.

Results and Discussion

Trials in which the recording was terminated prematurely (2.7%, again based on the different criteria for movement termination in online and offline analysis) or in which movement onset times were more than 150 ms apart (0.5%) were excluded from the analyses. Trials were scored as errors when the movement for one or both hands ended at a point closer to the distractor circle than to the target circle (for conditions in which four target locations were presented). None of these errors occurred in the same-color conditions. In the different-color, irrelevant-distractor condition, this type of error occurred on 1.3% of the trials. In the different-color, relevant-distractor condition, the error rate increased to 8.4%, with both hands ending up at the incorrect target on 10% of these trials. The error trials were excluded from further analyses.

The RT results show the different degrees of difficulty for the four conditions (Figure 7). Again, we used planned comparisons to assess the significance of each of the proposed sources of interference. As expected, the shortest RTs were observed in the same-color, no-distractor condition (mean RT, 303 ms). On the basis of our previous findings (Diedrichsen et al., 2001), we assume that response selection demands are minimal in this condition. The mean RT for the same-color, irrelevant-distractor condition was significantly longer, by 20 ms, $t(7) = 2.87$, $p = .024$. Thus, there was a modest cost associated with selection of targets of the same color in the presence of nonhomogeneous distractors. RTs increased much more dramatically when participants reached for targets defined by different colors. RTs for the different-color,
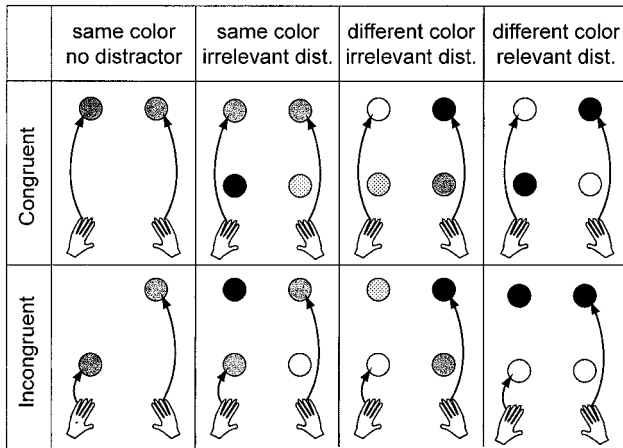

Figure 6. Experimental conditions in Experiment 3. In the same-color, no-distractor condition (first column), only the two target circles were present. Irrelevant distractors were present in the same-color, irrelevant-distractor condition (second column) and the different-color, irrelevant-distractor condition (third column). The colors indicating irrelevant distractors were different from those used for the targets. In the different-color, relevant-distractor condition (last column), the color of the distractor on one side matched the color of the target on the other side. The movements either had identical amplitudes (congruent, upper row) or differed in terms of their amplitude (incongruent, lower row). dist. = distractor.

ciated with response selection, we would expect RTs to be longer in this condition than in the same-color, irrelevant-distractor condition. This prediction is based on the assumption that response selection is facilitated when the target locations are defined by the same color, whereas there is a cost associated with selecting targets defined by different colors.

The fourth condition of Experiment 3 was the different-color, relevant-distractor condition, in which selection must be based on two colors and the distractor colors are a potential source of interference. The four conditions allowed us to ask three questions about the source of interference in preparation of bimanual reaching movements. First, is there a cost in selection when the targets are presented along with nonhomogeneous distractors? Second, what is the cost associated with selecting targets defined by two colors relative to one color? Third, how much of the interference is associated with filtering out distractors that are task relevant?

Method

Participants. Eight undergraduate students (18–36 years of age) from the University of California, Berkeley, participated in the experiment. They were paid $10 per session along with a performance-dependent bonus.

Procedure. The target layout was identical to that of Experiment 1, requiring movements of different amplitudes rather than directions. Otherwise, the procedure was identical to that of Experiment 2. The experiment was conducted in two sessions taking place, on average, 1 week apart. In one of the sessions, a single color was designated as the target for all movements. The session started with one practice block of 32 trials in the same-color, irrelevant-distractor condition. Next, eight test blocks of 32 trials each were administered, alternating between the same-color, no-distractor and same-color, irrelevant-distractor conditions. In the other session, the participants were instructed to move with their left hand to targets of one color and with their right hand to targets of a different color. After one practice block of 32 trials in the different-color, irrelevant-
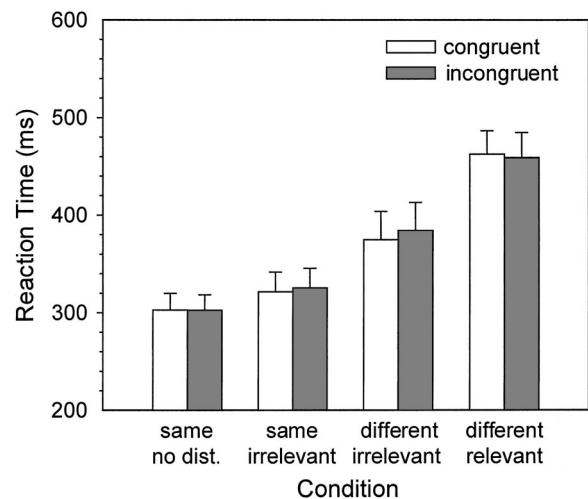

Figure 7. Reaction times in Experiment 3 as a function of experimental condition and movement congruency (same or different amplitude). Error bars indicate between-subjects standard errors. dist. = distractor.

irrelevant-distractor condition were 57 ms longer than the RTs for the same-color, irrelevant-distractor condition, $t(7) = 2.44$, $p = .045$. These costs could reflect processes required to shift from selection based on one color to selection based on the second color (Allport, Styles, & Hsieh, 1994). Moreover, there could be a cost associated with keeping track of the color–hand assignments. That is, there might be confusion as to which rule applies to which hand. Finally, the slowest latencies were observed in the different-color, relevant-distractor condition, with the mean RT here 81 ms longer than the RT in the different-color, irrelevant-distractor condition, $t(7) = 6.42$, $p < .001$. We consider the possible reasons for this dramatic cost in Experiment 4.

In correspondence with the results of Experiments 1 and 2, RTs did not differ between trials in which the two movements were of the same amplitude and trials in which they were of different amplitudes. If programming incongruent movements led to delayed initiation, we would expect this effect to become especially apparent in the same-color, no-distractor condition, in which the demands on target selection were low. However, there was no reliable effect of movement congruency, $F(1, 7) = 0.75$, $p = .41$, nor was there a Condition × Congruency interaction, $F(3, 21) = 1.46$, $p = .25$.

To assess the stability of these results over the course of a session, we conducted a secondary analysis that included block number as an additional factor. Surprisingly, the effect of block was not significant, $F(3, 21) = 2.14$, $p = .126$, and this factor did not interact with condition type, $F(9, 63) = 0.40$, $p = .928$.

As in Experiment 1, short-amplitude movements were completed more quickly than long-amplitude movements, $F(1, 7) = 226.00$, $p < .001$ (Table 3). Overall MTs were much shorter than in Experiment 1, again probably reflecting the emphasis in the instructions and the monetary reward. Short movements were 26 ms longer and long movements 2 ms shorter when they were combined with a movement of incongruent amplitude, $F(1, 7) = 19.80$, $p = .003$. MTs differed across conditions, $F(3, 21) = 6.94$, $p = .002$, with the changes in MTs paralleling those found in the RT data.

The number of movements with multiple acceleration phases was lower than in Experiment 1. Overall, 18% of the movements consisted of two or more subcomponents. The percentage was lowest in the same-color, no-distractor condition (12%) and highest in the different-color, irrelevant-distractor condition (26%).

Table 3
Movement Times (in Milliseconds) in Experiment 3 by Experimental Condition, Type of Movement, and Type of Movement Simultaneously Executed by the Other Hand

	Movement type[a]			
Condition	Short/short	Short/long	Long/short	Long/long
Same color				
No distractor	298	330	389	391
Irrelevant distractors	300	332	402	399
Different color				
Irrelevant distractors	305	332	408	401
Relevant distractors	333	347	444	462

Note. Results are shown averaged across both hands.
[a] Type of movement/type of movement simultaneously executed by the other hand.

The percentage was 17% in the two other conditions. Again, exclusion of trials that contained movements with more than one component did not change the reported RT results qualitatively. The same held true when we performed a median split on the MTs within each participant, condition, and movement combination (average MT for faster half: 333 ms). Although the RT advantage for congruent movements in the different-color, irrelevant-distractor condition rose here from 9 ms to 14 ms, in no other condition did a difference between congruent and incongruent movements become apparent, as one would expect if this effect were due to cross talk during motor programming.

The average distance from the target was 0.96 cm in the same-color, no-distractor condition, and this distance increased monotonically up to 1.11 cm in the different-color, relevant-distractor condition, giving rise to a significant effect of condition, $F(3, 21) = 4.24$, $p = .017$. Neither the effect of movement congruency, $F(1, 7) = 0.70$, $p = .431$, nor the Congruency × Condition interaction, $F(3, 21) = 1.03$, $p = .398$, reached significance.

In summary, Experiment 3 provides converging evidence that difficulties in initiating bimanual movements of unequal amplitude cannot be attributed to motor programming. Although we found some cost of the presence of nonhomogeneous distractors (Tipper et al., 1992), more substantial costs were observed when response selection demands increased. We hypothesize that each color in the different-color condition must engage the selection process separately. Moreover, the selection hypothesis provides a parsimonious account of the results for the two types of different-color conditions. Although the targets were the same in both the irrelevant- and relevant-distractor conditions, RTs were considerably longer in the relevant-distractor condition, in which the distractor color was the same as the target color for the other hand. We attribute this cost to interference between the selection processes for the two targets.

Experiment 4

In Experiment 4, we further examined the interference observed when the distractor color for one hand matched the target color for the other hand. We considered two hypotheses. First, the presence of another object of the target color might cause confusion for the selection process. For example, consider a situation in which the target color for the left hand is green. When the distractor on the right side is another color (i.e., irrelevant distractor), the selection process must simply identify the location of the green circle. However, when the distractor on the right side is green (i.e., relevant distractor), selection may be difficult because it requires information about both color and position. Given that spatial selective attention is not perfect (Eriksen & Eriksen, 1974), the distractor from the right side may disrupt the selection process. According to this spatial attention hypothesis, the interference in the relevant-distractor condition is due to competition within the operation of response selection for each hand.

An alternative hypothesis centers on the idea that the interference reflects confusion concerning the mapping between target colors and the two hands. In the relevant-distractor condition, both a circle of the target color for the left hand and a circle of the target color for the right hand appear on the left side. Such an arrangement is susceptible to confusion regarding color–hand assignment. According to this assignment hypothesis, the added cost in the

relevant-distractor condition reflects competition between the arbitrary stimulus–response rules.

The present experiment was designed to evaluate these two hypotheses. In all conditions, two target colors, one for each side, were specified for the entire experiment. The color of the distractor was either irrelevant (different from the target for the other side) or relevant (identical to the target color for the other side). We included a manipulation of the horizontal separation between the circles of the two sides (Figure 8). If the spatial attention hypothesis holds, we would expect to observe a larger cost in the relevant-distractor condition when the distance is small; that is, interference should be greatest when the target locations on one side are relatively close to the target locations on the other side. The reasoning here is based on previous results showing that magnitude of distractor interference is influenced by interobject distance (e.g., Eriksen & Eriksen, 1974).

In contrast, the assignment hypothesis predicts that the distance manipulation should have no effect, because interference in the selection process of each side is caused by the distractor appearing on that side. The presence of a task-relevant distractor activates the competing response rule. Because the distance between the target and distractor on each side is constant, no differences should be observed between the two bimanual conditions.

We also included a unimanual condition as a second test of the assignment hypothesis. Here only two circles were presented on each trial, both on the left or both on the right. The participants were instructed to move only the corresponding hand on these trials. Because they did not know the side of the target in advance, it was necessary to actively maintain the color-based selection rules for both hands. If the distractor color in the relevant-distractor conditions induces rule confusion, we should observe a cost even on unimanual trials.
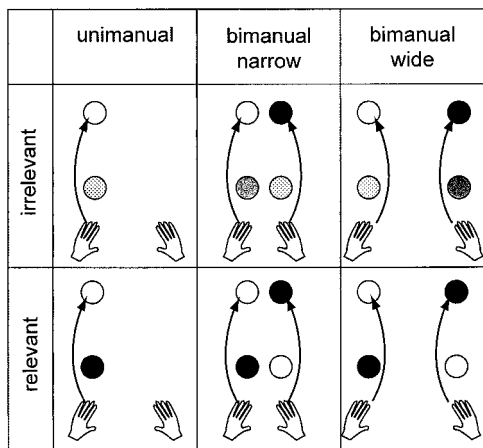

Figure 8. Experimental conditions in Experiment 4. Movements to circles of different colors had to be made with the left and right hands (here white on the left, black on the right). The target colors for each hand remained constant for the entire session, and the distractor colors were either irrelevant (never targets) or relevant (target for the other hand). In the unimanual condition, a target and distractor appeared on only one side, selected at random. In the bimanual conditions, targets and distractors on the two sides could be separated by a wide or narrow gap. Movement amplitudes could be either congruent or incongruent (not shown).

Method

Participants. Seventeen undergraduate students (19–26 years of age) participated in a 1-hr session for course credit or a $10 reimbursement.

Procedure. The participants were instructed to move with their left hand to a circle of one color and with their right hand to a circle of a different color. The designation of target and distractor colors was counterbalanced across participants. The target colors for each hand remained constant for the entire experiment.

Three conditions (see Figure 8)—unimanual, bimanual–narrow, and bimanual–wide—were tested in separate blocks. The bimanual conditions were identical to the different-color, irrelevant-distractor and different-color, relevant-distractor conditions of Experiment 3. In the bimanual–narrow condition, the horizontal distance between the left and right circles was 10 cm (12°); in the bimanual–wide condition, the distance was 19.5 cm (22°). In the unimanual condition, a single target, presented on either the left or right side, demanded either a long or a short unimanual movement. One distractor was presented on the same side. The color of the distractor was either relevant (the color used as the target for the other hand) or irrelevant (not the target color for either hand).

The experiment started with 3 practice blocks of 16 trials each, one for each condition; participants then completed 12 test blocks of 32 trials each. The conditions alternated across blocks, and the order was counterbalanced between participants. After each block, participants received feedback on average response time (RT + MT) and percentage of correct movements. They were encouraged to move as fast as possible, as long as accuracy did not drop below 85%. All other aspects of the procedure were identical to those of Experiment 3.

Results and Discussion

The data from 2 participants were excluded from the analyses. One participant failed to initiate the two movements in a synchronized fashion, exhibiting an interonset latency difference of greater than 150 ms on more than 60% of the trials. The other participant's data were excluded because the effect of distractor type was more than 5 standard deviations greater than that found for all of the other participants. This participant's responses were 130 ms (unimanual condition) and 262 ms (bimanual conditions) faster when the distractors were irrelevant than when they were relevant. Among the remaining 15 participants, 6.7% of trials were excluded because the trial was aborted prematurely, 1.6% were excluded because the asynchrony was more than 150 ms, and 4.6% involved an error in which the movement for one of the hands terminated closer to the distractor circle.

We analyzed the RT data (Figure 9) for the two bimanual conditions with an ANOVA in which the factors were distractor type, distance condition, and movement congruency. Similar to Experiment 3, the effect of distractor type was significant, $F(1, 14) = 21.03$, $p < .001$. On average, RTs were 43 ms longer when the distractor was relevant than when it was irrelevant. The distance manipulation did not affect RT, $F(1, 14) = 1.25$, $p = .28$, and, most important, did not interact with distractor type, $F(1, 14) = 0.59$, $p = .455$. Given that the distance between the pair of objects did not produce a significant effect on performance, the results fail to support the spatial attention hypothesis. Rather, the results are consistent with the hypothesis that the relevant distractors create interference during response selection owing to confusion between the rules in terms of color–hand assignments. A reliable 12-ms effect of distractor type was also found in the unimanual condition, $t(14) = 2.79$, $p = .014$. This finding provides additional support for the assignment hypothesis. Although only one target had to be selected in this condition, the presence of a
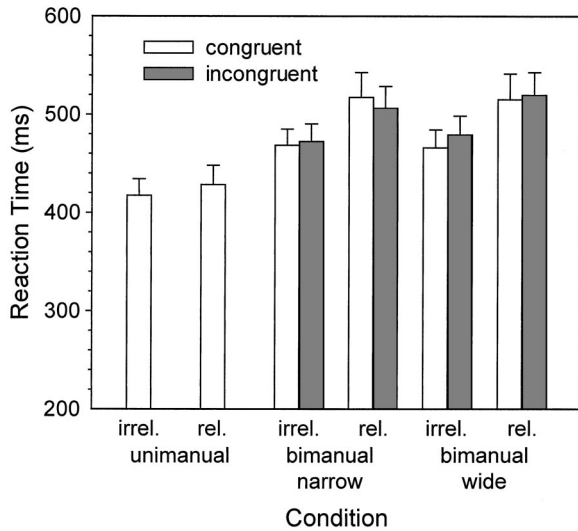
Figure 9. Reaction times in Experiment 4 as a function of condition and movement congruency (same or different amplitude). Note that congruency was not applicable in the unimanual condition. Error bars indicate between-subjects standard errors. irrel. = irrelevant; rel. = relevant.

color associated with targets on the other side induced some interference. Note that the distractor effect in the unimanual condition was small and less than half the size of the effect in the bimanual condition. It does not appear that the interference observed in the bimanual condition was simply due to the additive effects found for each hand treated individually.

As in the preceding experiments, no effect of movement congruency was found in the bimanual condition, $F(1, 14) = 0.19$, $p = .66$. Also, we found no congruency effect when we excluded all movements containing more than one submovement (43%) or performed a median split of MTs, focusing on the faster half of the movements in each condition.

An ANOVA in which distractor type, movement length, distance condition, and movement congruency were variables revealed that MTs (Table 4) were longer in the relevant-distractor condition, $F(1, 14) = 13.75$, $p < .001$, and this increase was more pronounced for long movements than short movements, $F(1, 14) = 6.98$, $p = .019$. MTs in bimanual conditions were influenced by the combination of amplitudes, $F(3, 42) = 85.74$, $p < .001$, reflecting the assimilation effect observed in Experiments 1 and 3; short movements increased from 449 to 470 ms and long movements decreased from 600 to 589 ms when they were combined with a movement of the other length. There was a reliable effect of the distance manipulation, with MTs being 18 ms longer in the wide condition, $F(1, 14) = 5.76$, $p = .031$. Relevant distractors led to an overall prolongation of movements of 45 ms, $F(1, 14) = 28.21$, $p < .001$. This effect was similar for the narrow and wide conditions, $F(1, 14) = 0.50$, $p = .49$.

The average spatial accuracy in this experiment was 1.2 cm. Accuracy was slightly worse in the bimanual–wide condition (1.24 cm) than in the bimanual–narrow condition (1.15 cm), $F(1, 14) = 5.73$, $p = .031$. No other accuracy effects were significant.

In summary, the results of Experiment 4 fail to support the spatial attention account. The magnitude of interference from task-relevant distractors was similar for the near and far condi-

tions. In contrast, the results are in accord with the predictions of the assignment hypothesis. This hypothesis attributes the interference to competition related to the assignment of the target colors to the two hands. We assume that this competition, or confusion, occurs because the distractor color activates the response rule associated with the other hand. This interference remains constant over distance and is even present, although attenuated, on unimanual trials. Thus, interference does not require competition between a distractor on one side and a target on the other side. Rather, it appears to occur at a processing level involved in maintaining the stimulus assignments for each hand across trials.

General Discussion

Numerous studies of bimanual coordination have shown that symmetric movements are easier to perform than asymmetric movements (Franz et al., 1991, 1996; Heuer, 1993; Kelso et al., 1983). For example, it is easier to initiate movements of the same amplitude than movements of unequal amplitude, what we have referred to as a movement congruency effect. Previous studies have generally emphasized a motor programming explanation of the congruency effect (Spijkers et al., 1997, 2000). The assumption has been that it is easier to specify a common movement parameter (i.e., distance) for both hands than to specify different parameters (i.e., two distances), or, at a less abstract level, it is easier to produce similar muscular commands than asymmetric commands. Using reversal movements, which are characterized in terms of their amplitude, these studies have confounded the demands associated with response selection with those associated with motor programming. To dissociate these processing stages, we used a goal-oriented reaching task in which target locations were specified on the basis of their color.

Experiment 1 demonstrated that the congruency effect can be reversed when movements of unequal amplitudes are made to targets of the same color relative to when movements of equal amplitudes are directed to targets that differ in color. We also failed to find congruency effects for movements of the same or a different direction in Experiment 2. These results strongly argue against the motor programming account of the congruency effect.

Table 4

Movement Times (in Milliseconds) in Experiment 4 by Experimental Condition, Type of Movement, and Type of Movement Simultaneously Executed by the Other Hand

Condition	Movement type[a]			
	Short/short	Short/long	Long/short	Long/long
Unimanual				
Irrelevant distractors	377			502
Relevant distractors	388			530
Bimanual–narrow				
Irrelevant distractors	416	447	567	560
Relevant distractors	447	469	600	630
Bimanual–wide				
Irrelevant distractors	435	463	583	572
Relevant distractors	477	487	617	658

Note. Results are shown averaged across both hands.
[a] Type of movement/type of movement simultaneously executed by the other hand.

Instead, they are consistent with the idea that the congruency effect arises at earlier processing stages.

In Experiment 2, the target colors were specified in advance of each block, thus reducing the demands on stimulus identification. Nonetheless, the results showed that the cost associated with selecting targets defined by different colors remained. We conclude that although the costs associated with stimulus identification may have contributed to the results of Experiment 1, the main source of interference in the preparation of bimanual movements is associated with selecting the targets of the reaches.

Limitations in this selection process were examined in Experiments 3 and 4. A primary source of RT cost centers on the task relevance of the distractor color. RTs were consistently elevated when the distractor color was also the target color for the other hand. The results of Experiment 4 indicate that this cost is due to competition between the response rules associated with the two hands, or what we called the assignment hypothesis. We infer that when the distractor color is task relevant, it engages the mapping rule for the other hand, creating interference in the selection process. Indeed, this cost was observed even on unimanual trials.

How Are Movements Selected?

In the experiments of Spijkers et al. (1997, 2000), symbolic cues specified the target amplitude of fast reversal movements. For example, the German word for *short* or *long*, or a short or a long bar indicated the target amplitude of the movements. Because these movements were not directed toward a target location, it is likely that they were represented in terms of their amplitude parameter (e.g., as a "long" or "short" movement). In the present experiments, the selection was based on the color of the target object; for example, the goal was to move to the red or green circle. We propose that this influenced how the possible movements were represented. When targets are selected as a red or green circle, there appears to be no explicit representation of the required amplitude. This hypothesis can account for the lack of an advantage of initiating movements of the same amplitude relative to movements of different amplitudes (or directions).

By this view, the congruency effect is based on the manner in which the actions are represented. Indeed, in our previous work (Diedrichsen et al., 2001), we observed no interference during incongruent bimanual movements when the two targets were presented without any distractors. Under such conditions, the movements are selected in terms of a target location, and there is no need for intermediate representations. The target locations themselves specify the necessary movement parameters. In contrast, many psychological studies require keypresses that are arbitrarily assigned to stimuli as responses. When responses are selected on the basis of the relative location of a key, interference between two actions is based on exactly this code (Hommel, 1998; Lien & Proctor, 2000).

Our emphasis on how actions are represented is related to the common coding theory developed by Prinz and colleagues (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1990). The theory stresses that the observed consequences are integrated into the representation of the action that caused them. This can, for example, dramatically influence the way in which irrelevant stimuli interfere with the selection of an action (e.g., Hommel, 1993).

Focusing on how a movement is represented and selected can also shed light on the debate concerning the validity of the movement precuing task (Rosenbaum, 1980; Rosenbaum & Kornblum, 1982). Reaching tasks have been widely used to test the processes involved in the specification of movement parameters. For example, in an experiment conducted by Rosenbaum (1980), participants made one of eight movements following the presentation of a colored circle. Each color represented a unique combination of three binary dimensions: hand (left or right), direction (forward or backward), and amplitude (short or long). On some trials, letter precues were presented to specify in advance the hand, direction, or extent of the movement for the forthcoming trial. From the pattern of benefits observed across the various cuing conditions, it was concluded that although the sequence of parameter specification was flexible, information about the hand was more beneficial than specification of movement direction, which in turn was more beneficial than specification of amplitude.

The characterization of these benefits in terms of advance specification of motor parameters has been questioned. Goodman and Kelso (1980) used the same precuing logic. However, instead of using letters as precues, they illuminated the possible target positions. For example, to indicate that the trial would involve a right-hand movement, the four possible target positions on the right were illuminated. In a similar manner, the target location was directly indicated by the illumination of that single location. With these direct cues, the differences between the types of precues were eliminated, and the benefits of cuing were based solely on the number of stimulus–response alternatives (see also Reeve & Proctor, 1984, 1985).

The difference between symbolic and direct cues in the precuing task provides further evidence that response selection is strongly influenced by the underlying representational codes. With symbolic cues, participants probably learn the responses in a symbolic form; for example, the green circle indicates a "long, forward movement with the left hand." Assuming that response selection works on these codes, a precue indicating one of the movement parameters would reduce the demands on the selection process. In contrast, with the direct cues, the movements are coded as potential locations for the response. Under this condition, precues indicating particular movement parameters are no longer helpful, because these parameters are not part of the representation and cannot be used to guide selection (Goodman & Kelso, 1980; Reeve & Proctor, 1984). Similarly, the interference connected to the execution of two movements of different amplitudes disappears.

Locus of Bimanual Interference

The proposal that target selection provides a limiting constraint to the performance of bimanual movements suggests an intriguing link between the present results and those obtained in dual-task experiments. Perhaps most relevant are studies proposing that dual-task performance is constrained by a bottleneck associated with response selection. If such a bottleneck exists, this process can operate only on one task at a time (Pashler, 1998b). In the context of bimanual reaching, the same-color condition might engage response selection only once, with the two target locations being chosen in a unified manner given their shared input status. In contrast, the different-color condition would have to engage the response selection process twice, once for each color.

However, a response selection bottleneck, on its own, is insufficient to account for the finding that relevant distractors produce greater interference than irrelevant distractors. The increased in-

terference from relevant distractors suggests that the selection process for each hand interacts with the selection process for the other hand. One account for the costs associated with relevant distractors posits that cross talk can occur when different rules are assigned to the two hands. That is, selection processes can be influenced and slowed by other activated codes. The presence of distractors that match the target color of the other hand activates the other response rule and increases uncertainty. As shown in Experiment 4, even in the absence of a second target, a distractor stimulus that activates the task rule for the other hand can induce a substantial cost. People have difficulty maintaining conflicting agendas for the two hands. Fortunately, such situations rarely arise in normal environments.

Other Sites of Interference and Cross Talk in Bimanual Performance

The current studies have focused on interference effects that arise during response or target selection and are apparent in the initiation times of movements. There is abundant evidence that interactions of different movement parameters also emerge during the planning and execution of bimanual movements. Much of this interaction occurs in the temporal domain. For example, actions of the two hands tend to synchronize with each other (Kelso et al., 1979, 1983), even when the movements are directly cued (Diedrichsen et al., 2001). However, interactions are also seen in the spatial domain. When the trajectory for one hand has to be modified as a result of the presence of an obstacle, the trajectory for the other hand is also altered (Kelso et al., 1983). Similarly, spatial assimilation effects are seen when people are asked to draw two different shapes, such as circles with one hand and lines with the other (Franz, 1997; Franz et al., 1991), or produce fast reversal movements of different amplitudes (Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998; Marteniuk, MacKenzie, & Baba, 1984; Sherwood, 1994). Heuer and colleagues (Heuer, 1993; Heuer, Kleinsorge, Spijkers, & Steglich, 2001) have distinguished between static and transient spatial cross talk by varying the time available to plan the movements. In summary, there is considerable evidence that there exist multiple kinds of movement coupling at stages other than response selection.

At present, we hypothesize that the interference observed in the RT data is primarily determined by how the movements are conceptualized. It remains to be seen whether a similar framework can account for interference observed in kinematic measures during movement execution. A recent study conducted by Mechsner, Kerzel, Knoblich, and Prinz (2001) suggests that, even here, the manner in which the movements are conceptualized is more important than aspects of the movements themselves. In this study, the stability of bimanual movements did not depend on the patterns of muscular activation but, rather, depended on the spatial characteristics of the movements. Similarly, if the two movements are conceptualized as serving a common goal, spatial interference between the movements is greatly reduced (Franz, Zelaznik, Swinnen, & Walter, 2001).

Nonetheless, we believe that it remains possible to dissociate interference associated with response selection from that associated with movement planning and execution. Our studies with callosotomy patients have provided dramatic examples of such dissociations. Although callosotomy patients show temporal decoupling during continuous circle-drawing movements, they re-main tightly temporally coupled when the movements are initiated discretely (Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002). We attribute the coupling observed during the circling movements to interactions between abstract spatiotemporal patterns, interactions that appear to depend on interhemispheric communication across the corpus callosum. The persistent coupling during discrete movements appears to reflect a different process, such as a gating process that constrains movement initiation for both hands (Ivry & Richardson, 2002).

Conclusion

Interference during the performance of bimanual actions may occur at different processing stages. Returning to the example introduced earlier, there may be various constraints limiting our ability to use the two hands to simultaneously pick out the good cherries and avoid the rotten ones. We explored three possible constraints on performance: (a) limits in selecting one target object at a time, (b) interference when different movement parameters have to be specified for the two hands, and (c) cross talk in the trajectories of the two actions when movements of different length or direction have to be executed. The results from the current experiments strongly favored the first explanation, that the primary constraint in bimanual reaching is associated with target selection. This process may become especially demanding if different rules govern the actions of each hand and if distracting information creates ambiguity as to which rule should be applied.

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