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ORIGINAL ARTICLE

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Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters

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Abstract Simultaneous reaching movements made with the two hands can show a considerable increase in reaction time (RT) when they differ in terms of direction or extent, compared to when the movements involve the same direction and extent. This cost has been attributed to cross-talk in the specification of the motor parameters for the two hands. However, a recent study [Diedrichsen, Hazeltine, Kennerley, & Ivry, (2001). *Psychological Science, 12,* 493–498] indicates that when reaching movements are cued by the onset of the target endpoint, no compatibility effects are observed. To determine why directly cued movements are immune from interference, we varied the stimulus onset asynchrony for the two movements and used different combinations of directly cued and symbolically cued movements. In two experiments, compatibility effects were only observed when both movements were symbolically cued. No difference was found between compatible and incompatible movements when both movements were directly cued or when one was directly cued and the other was symbolically cued. These results indicate that interference is not related to the specification of movement parameters but instead emerges from processes associated with response selection. Moreover, the data suggest that cross-talk, when present, primarily shortens the RT of the second movement on compatible trials rather than lengthening this RT on incompatible trials.

Introduction

The study of compatibility effects has had a major impact on our understanding of the architecture of human cognition. Compatibility can exist between distinct features of the stimulus display (S-S compatibility) or between features of the stimuli and features of the responses (S-R compatibility) (Kornblum, 1992). Both S-S and S-R compatibility can affect reaction time (RT) (see Hommel & Prinz, 1997; Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990; Proctor & Reeve, 1990; Ridderinkoff, 2002), although there remains considerable controversy regarding the degree of overlap between the mechanisms underlying these forms of compatibility (De Jong, 1994; Hommel, 1997; Kornblum, 1994).

Compatibility can also exist between two simultaneous or nearly simultaneous responses, termed R-R compatibility (see Heuer, 1995). R-R compatibility has been invoked to account for some findings from choice-RT experiments (e.g., Lien & Proctor, 2000), but its importance has been especially emphasized in bimanual movement studies. In these experiments, researchers measure the performance cost when an individual makes simultaneous movements of different amplitudes or in different directions with respect to the primary axis of the body (incompatible movements) compared to when the movements entail the same amplitude and direction (compatible movements). When the movements are incompatible, RTs are longer and spatial assimilation effects are observed (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Franz, Zelaznik, & McCabe, 1991; Heuer, 1995). Moreover, the difference between compatible and incompatible conditions is diminished or absent when the desired trajectories are designated by precues, provided the participants are given sufficient time (e.g., 1 s) to prepare for the movements (Spijkers, Heuer, Steglich, & Kleinsorge, 1997). Thus, the compatibility costs in RT have been attributed to transient cross-talk between motor programming processes for the two limbs

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(Spijkers et al., 1997; Spijkers, Heuer, Steglich, & Kleinsorge, 2000).

At present there is a theoretical divide between hypotheses that account for compatibility effects observed in button-press experiments and bimanual movement experiments. Compatibility effects on RT are robust in both types of studies. In bimanual movement studies, compatibility effects are attributed to the specification of movement parameters. However, in button-press experiments, the effects are generally attributed to the processing of irrelevant stimulus information and its concomitant influence on response selection processes. For example, in a series of button-press experiments by Logan and Schulkind (2000), participants categorized pairs of visually presented stimuli. One character was responded to with the right hand and the other with the left hand. When the two stimuli were presented close together in time, RTs for both hands were shortened when the stimuli belonged to the same category compared to when they belonged to different categories. This advantage was interpreted as reflecting parallel retrieval of the stimulus categories for the two response selection processes.

Compatibility effects observed in bimanual reaching studies may also reflect interactions arising at a response selection stage. However, to the best of our knowledge, this possibility has yet to be explored (see Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, in press). The differing theoretical biases likely stem from the more complex motor requirements associated with the movements used in the bimanual studies. Bimanual tasks are presumed to place greater demands on motor processes. Indeed, in addition to the increases in RT found on incompatible trials, interference is also observed in the trajectories of the movements. This latter measure is not applicable in discrete response tasks. Moreover, discrete response tasks often involve more complex displays in which particular properties of the stimuli serve as distractors and must be ignored.

Identifying the locus of interference during bimanual reaching

In the present study, we seek to link these two literatures by focusing on RT effects and using the psychological refractory period (PRP) procedure during a bimanual reaching task. In PRP studies, the stimuli for the tasks are presented sequentially. The interval between the two stimuli, termed the stimulus onset asynchrony (SOA), is varied, typically from near-simultaneous presentation ($\sim$0 ms SOA) to 1 s. Instructions emphasize that the first response should be produced as fast as possible, and indeed, participants are able to heed these instructions as evidenced by the fact that reaction times (RT1) for the first task are relatively independent of SOA. However, there is a systematic effect of SOA on performance of the second task with RT2 increasing as SOA is reduced. The PRP effect has been attributed to the constraint imposed by a central process that is shared by both tasks and operates in a serial manner, either due to a structural limitation in the cognitive architecture (Pashler, 1994) or reflecting the strategic use of executive control processes (Meyer & Kieras, 1997).

While the tasks used in most PRP studies involve discrete responses, Spijkers et al. (2000) adopted a similar procedure to examine the dynamics of coupling during bimanual movement tasks. In their experiments, symbolic stimuli signaled the required amplitude for reversal movements of the left and right hands. RTs for the second hand were much longer at the shorter SOAs, suggesting that the two tasks shared common processes. Moreover, the effects of compatibility were much stronger at the shorter SOAs than at the longer SOAs. This result was interpreted as transient coupling of motor programming processes associated with the two hands. That is, prior to the production of the movements, movement parameters (e.g., amplitude and direction) are specified, and cross-talk associated with the specification processes diminishes as the processes are separated by longer intervals of time (Spijkers et al., 2000).

Recent evidence suggests that this cross-talk may be dependent on factors other than the specification of movement parameters. Diedrichsen, Hazeltine, Kennerley, and Ivry (2001) reported that the costs associated with incompatible reaching movements are abolished when the movement goals are directly cued by the presentation of the movement endpoints themselves. Rather than requiring the participants to move their hands across a boundary line and back, Diedrichsen et al. used unidirectional reaching movements. Under these conditions, RT and movement time (MT) were essentially identical for compatible and incompatible conditions. In contrast, when symbolic cues (letters) were used to indicate the appropriate movements, a substantial RT difference was observed between compatible and incompatible conditions. Because the movements were identical in the two cue conditions, the results suggest that the specification of movement parameters is not the primary source of interference during bimanual performance.

To examine the difference between directly cued and symbolically cued movements more closely, we adopted the cueing procedures of Diedrichsen et al. (2001) in the PRP experiments reported below. Participants made two reaching movements on each trial. In one condition, the movements were directly cued by presenting a visual signal at the target locations; in the other, the target locations were symbolically cued by letters. For both conditions, five different SOAs were used, ranging from 50 ms to 1 s. This procedure allowed us to evaluate three hypotheses concerning the lack of compatibility effects for directly cued movements.

One possibility is that directly cued movements are exempt from compatibility effects because they bypass the central processes required to translate stimuli into appropriate responses. According to this hypothesis, directly cued movements do not engage the set of cognitive processes that are susceptible to intermanual cross-talk. Previous research suggests that tasks involving highly compatible S-R associations may place minimal demands on response selection processes, thereby avoiding conflicts with other ongoing tasks (Greenwald & Shulman, 1973; but see Lien, Proctor, & Allen, 2002). Given that response selection processes are likely the locus of compatibility effects (McCann & Johnston, 1992), bypassing these processes may account for the lack of bimanual interference observed between directly cued movements. With direct cues, the stimuli share critical features with the environmental consequences of their associated responses (see Elsner & Hommel, 2001; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Mechsner, Kerzel, Knoblich, & Prinz, 2001). Under such conditions, there is little need for the S-R translation processes invoked by symbolic cues. We term this proposal the excluded-stage hypothesis.

An alternative hypothesis supposes that the two movements in the directly cued condition form a unitary, grouped response. In the experiments of Diedrichsen et al. (2001) RTs in the directly cued conditions were not reduced when the movement for one hand was precued; participants responded as quickly to the onsets of two direct cues as they did to one direct cue. In contrast, precueing had a significant influence on RTs in the symbolically cued conditions. While this phenomenon is consistent with the excluded-stage hypothesis, it is also possible that the simultaneous presentation of two endpoint locations causes the perception of a single object that is to be grasped with both hands. In effect, the direct cues may allow for the bimanual reaches to be planned and executed as a single task. We term this proposal the grouped-response hypothesis.

A third account of the lack of compatibility effects with direct cues focuses on the considerable differences in the RTs for the two types of cues. In the experiments of Diedrichsen et al. (2001), the mean RT for symbolically cued movements on compatible trails was about 475 ms (and increased to about 575 ms on incompatible trials), whereas the mean for directly cued movements was less than 350 ms. It is possible that, given the high S-R compatibility with direct cues, movements are initiated before cross-talk from one hand has time to influence performance with the other hand. We term this proposal the outraced-interference hypothesis.

Because both the stimuli and responses for the two tasks will occur sequentially when the SOA is greater than 0, participants should no longer be able to group their responses. Thus, assuming participants follow the task instructions, the PRP procedure should be sufficient to eliminate response grouping, providing a strong test of the grouped-response hypothesis: Compatibility effects should reemerge when the tasks are staggered even if both movements are directly cued. The same prediction is also derived from the outraced-interference hypothesis. If cross-talk arises too late during directly cued movements with a 0-ms SOA (as in Diedrichsen et al., 2001), then introducing a delay between the two movement onsets should provide an opportunity to observe compatibility effects in the second response. In contrast, the excluded-stage hypothesis predicts that compatibility effects should be unchanged by the addition of the SOA manipulation.

We also included a third condition in which the responses for Task 1 were symbolically cued and the responses for Task 2 were directly cued. Having directly cued movements follow shortly after symbolically cued movements provides a second means to evaluate the three hypotheses. If the excluded-stage hypothesis is correct, no interference should be observed in this hybrid condition; the directly cued responses for the second task bypass performance-limiting central processes. In contrast, if the grouped-response hypothesis holds, compatibility effects should return when directly cued movements are paired with symbolically cued movements. If one movement is directly cued and the other requires a translation process, the two should not be combined into a common, grouped response. A similar result is predicted if the outraced-interference hypothesis is correct: delaying the directly cued task until after the symbolically cued task should cause critical processing for the second task to occur after the activation of the source of interference. Thus, compatibility effects should be observed.

Experiment 1

In Experiment 1, participants made reaching movements with their left and right hands in a sequential fashion. All movements were made to one of three locations, each at an identical distance from the hand's starting position. The order of the two stimuli was fixed, with the cue for the left hand always appearing first. However, the interval between the cues varied from trial to trial. The relative onsets of the two stimuli were determined by five equally probable SOAs (50, 150, 250, 400, 1,000 ms).

The cues in this experiment were of two types (Fig. 1). The symbolic cues were letters, presented to the left or right of fixation. The lateralized letters indicated the target location for the ipsilateral hand. The target locations were visible as circles prior to the onset of the cues and remained visible for the entire duration of the trial. The direct cues consisted of the onsets of target circles. These circles were identical to those used with the symbolic cues, but their onsets signaled the appropriate movements.

The three conditions of Experiment 1 differed in terms of their combinations of direct and symbolic cues. In the S-S condition, the movements of both hands were cued symbolically (Fig. 1, column A). In the D-D condition, the cues for both the left- and right-hand movements were directly cued (Fig. 1, column B). In the S-D condition, the left hand movement was symbolically cued, but the right hand movement was directly cued

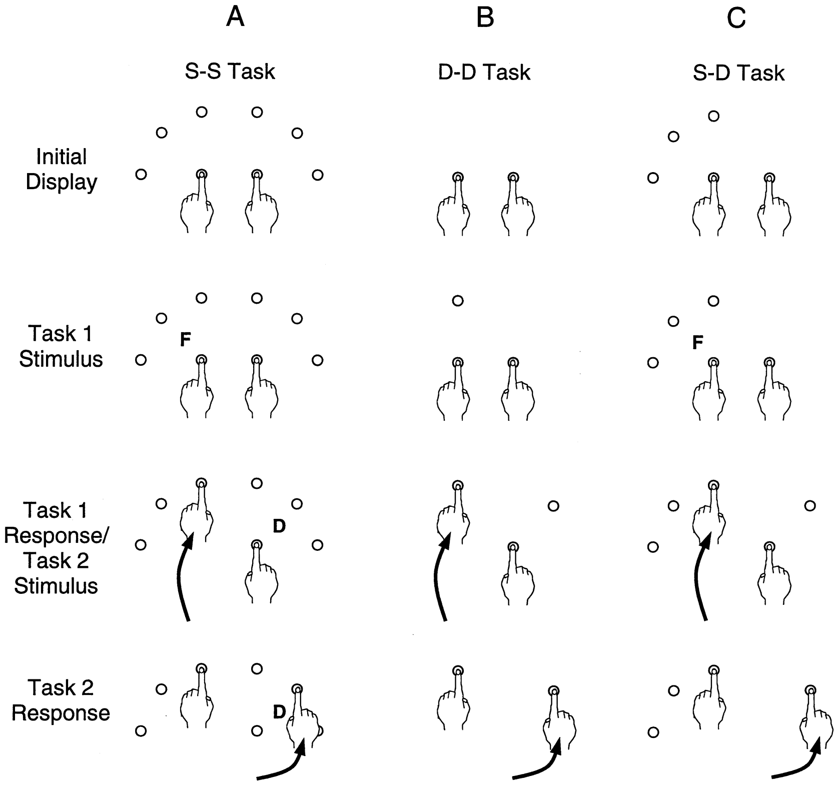

Fig. 1 Schematic depiction of the three conditions of Experiment 1. The onset of the cues (symbolic, S, or direct, D) served as imperative signals

(Fig. 1, column C). The three conditions were run in separate blocks so that participants always knew which type of cues to expect for each hand.

Method

Participants

Eight college-aged undergraduates performed a 1-h session. They were paid a flat rate plus a bonus depending on both the speed and accuracy with which they performed the task.

Apparatus and stimuli

A virtual projection system was used to present the stimuli (see Diedrichsen et al., in press). Participants were seated at a table (height 75 cm) with the head restrained by a chin rest such that their eye position was approximately 43 cm above the table. A mirror (100×77 cm) and a screen (same size) were mounted parallel to and 24 cm or 48 cm above the table surface, respectively. All stimuli were presented on the screen from a downward projecting Plus UP 800 computer projector mounted 160 cm over the table. The participants viewed the screen through the mirror, yielding the impression that the stimuli were presented on the table surface.

All movements were produced just above and along the table surface. The participants could not see their limbs. A magnetic tracking system (Ascentech mini-bird) was used to record the movements. Two small antennas (15×7×7 mm) were taped to the tip of the participants' index fingers. The system recorded the position of the two antennas at a sampling rate of 140 Hz. An IBM-compatible 486 PC was used for data collection and stimulus presentation. The computer presented a small dot (diameter of 2 mm) at the position on the screen corresponding to the position of each antenna, thus giving the participants veridical information about the position of the limbs.

Circles with a diameter of 3.6 cm were used to indicate the starting positions and target locations. The starting circles were located 25 cm from the border of the table and separated by 14 cm. The three possible targets were located 10 cm from the starting circle, either forward, outward, or at a 45° diagonal from the starting circle. The letters "F", "D" and "S" were used as symbolic cues, indicating forward, diagonal or outward (S, sideways) movements, respectively. The dimensions of the letters were approximately 2.5×2.5 cm. The letters were presented 1.5 cm from the starting circles, along the 45° diagonal away from the participant.

Procedure

The onset of each trial was signaled by the presentation of the two starting circles. The participant moved each index finger into the respective starting circle and was required to remain within it for 1 s. Then, if the cue for both hands were symbolic, all six possible target positions were presented. If the cue was symbolic for the left hand, but direct for the right hand, only the left three targets were presented. If both cues were direct, no targets were presented.

In the symbolic cue condition, three target circles appeared on the screen indicating the possible movement endpoints. After a fore period of random length between 1 and 2 s, a letter appeared near the starting circle (see above). All movements were made towards one of the target circles. In the direct cue condition, no target circles appeared until the target location was indicated by the onset of a single target circle after the random delay. The symbolic or direct cue for the right hand appeared after an SOA of 50, 150, 250, 400, or 1,000 ms following the presentation of the left-hand cue.

The instructions emphasized that movements should be made as fast as possible, while maintaining a high accuracy. After each block, participants received feedback about the mean time it took them to complete the responses (RT + MT) and the percentage correct, separated by hand. While the participants were instructed to make their first response to the left-hand stimulus, a monetary bonus system based on the performance of both hands was devised to keep the participants motivated. Bonus money could be earned for maintaining accuracy on a level higher than 80% and for achieving a shorter average time to reach the target.[1]

The three cueing-conditions (S-S, S-D and D-D) were run sequentially. Each condition started with a practice block of 18 trials (two of each possible movement combination) to familiarize the participant with the procedure. Then, three blocks of 45 trials each were run in each condition. One of three condition orders was randomly selected for each participant: S-D, S-S, D-D; S-S, D-D, S-D; or D-D, S-D, S-S. Within each block, the 45 combinations of the 5 possible SOAs, the 3 possible movements of the left hand, and the 3 possible movements of the right hand occurred once.

Results and discussion

Reaction time

RT was defined as the interval between the onset of the stimulus and the time at which the relevant hand achieved a velocity of 2 cm/s. The end of the movement was defined as the point in time at which the velocity dropped below this threshold. RTs were only analyzed from trials in which the responses for both hands were correct. Trials were also eliminated when the RT for either hand was less than 150 ms or greater than 1,200 ms, or the movement time for either response was greater than 1,200 ms. These trimming procedures eliminated less than 4% of the data. To assess the effects of the differently cued actions, the data were submitted to a three-way ANOVA, with condition (S-S, D-D and S-D), compatibility (compatible vs incompatible), and SOA (50, 150, 250, 400, 1,000) as factors[2]. RTs for the two hands were analyzed separately.

Task 1

The left hand always responded to the first stimulus (RT1). The ANOVA revealed a significant main effect of condition [$F(2, 14) = 98.60$; $P < 0.0001$] and post-hoc comparisons (Student-Newman-Keuls tests) indicated that the responses to direct stimuli (D-D condition, mean RT 351 ms) were faster than responses to symbolic stimuli in the S-S and S-D condition ($P < 0.01$ for both comparisons). Moreover, within the two symbolic conditions, RT1 was faster when the symbolic cue was paired with a direct cue (S-D condition 525 ms) compared to when the symbolic cue was paired with a second symbolic cue (S-S condition 582 ms). Having to respond to two different types of cues did not slow participants as much as having to respond to two symbolic cues.

The only other reliable effect was the interaction between condition and SOA [$F(2, 14) = 2.81$; $P < 0.05$]. Follow-up ANOVAs conducted on the three conditions separately indicated that SOA had an effect on RT1 in the D-D condition with RT1 increasing from the 50-ms SOA (332 ms) to the 1-s SOA (374 ms). RT1 remained flat across SOA in the S-S and S-D conditions.

Task 2

Given the significant effect of condition on RT1, the RT2 data were segregated according to condition, and separate two-way ANOVAs were performed, with Compatibility and SOA as factors.

The ANOVA for the S-S condition revealed a significant effect of compatibility [$F(1, 7) = 29.62$; $P < 0.001$], SOA [$F(4, 28) = 15.79$; $P < 0.0001$], and their interaction [$F(4, 28) = 7.29$; $P < 0.0005$]. As depicted by the circles in Fig. 2, a large PRP effect was observed for the S-S condition, and this effect was larger for the

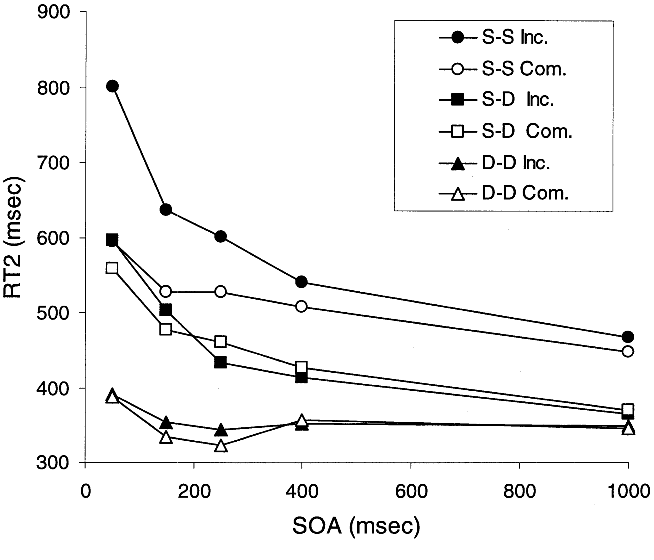

Fig. 2 RTs for the second reaching movement in Experiment 1 as a function of SOA according to whether the movement was compatible or incompatible with the first movement (*RT* reaction time, *SOA* stimulus onset asynchrony, *Inc.* incompatible, *Com.* compatible)

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[1] If the participants accuracy was greater than 80%, the participant received an extra 40 cents on that block. If the accuracy was greater than 90%, the bonus was increased to 55 cents. If the accuracy was less than 75%, 10 cents was subtracted from their bonus. RTs also produced bonuses. If participants were performed a block 80 ms faster than their best time for that condition (established for block 1 during the practice block), then they received a bonus of 55 cents. If their RTs were better than their best time by less than 80 ms, then the bonus was 40 cents. If the RTs were worse than the best time by less than 80 ms, then the bonus was 5 cents. If they were worse by more than 80 ms, 10 cents were subtracted from the bonus. For each block, combined bonuses that summed to less than 0 cents were changed to 0 cents so that participants could not lose money on a block.

[2] As pointed out by an anonymous reviewer, using a compatibility factor with two levels in the analysis may have weakened our power, given that the effects due to incompatibility may change when the movements differ by 45° compared to when they differ by 90°. Therefore, for both Experiments 1 and 2, we performed additional ANOVAs on the RT, MT, and accuracy data. These ANOVAs were identical to the reported ANOVAs except that the compatibility factor contained three levels, compatible, near (i.e., separated by 45°), and far (i.e., separated by 90°). The significant effects revealed by these ANOVAs were identical to those obtained in the ANOVAs with just two levels of compatibility.

incompatible (333 ms) trials than for the compatible trials (146 ms). Put another way, the effect of compatibility was 207 ms at the shortest SOA and 20 ms at the longest, consistent with the findings of Spijkers et al. (2000). As noted above, Spijkers et al. attributed the attenuation of the compatibility effect to a transient component of cross-talk associated with the specification of the movement parameters.

However, for the two conditions in which the right-hand responses were made to direct cues, only the main effect of SOA was significant [D-D: $F(4, 28) = 2.94$; $P < 0.05$; S-D: $F(4, 28) = 19.02$; $P < 0.0001$]. In D-D and S-D conditions, neither Compatibility nor the SOA by Compatibility interaction were significant (see Fig. 2). That is, when one of the movements was directly cued, there was no effect or interaction involving compatibility. This result provides further evidence against the hypothesis that compatibility costs during bimanual reaching movements are due to conflicts that arise during motor programming (Diedrichsen et al., 2001). Given that the movements are essentially the same for both symbolically and directly cued conditions, it is reasonable to assume that the specification of the movement parameters is similar.

The magnitude of the compatibility effect observed in Experiment 1 is considerably larger than those reported by Spijkers et al. (2000). In their first experiment, the shortest SOA was 100 ms and the compatibility effect was 61 ms. In comparison, the compatibility effect in Experiment 1 was 206 and 109 ms for the 50-ms and 150-ms SOAs, respectively. There are several candidate reasons for this disparity. First, Spijkers et al. used a two-choice task and the imperative signals were long or short horizontal bars, mapped to long or short movements, respectively. As we expand upon below, the time required by processes involved in S-R translation are likely reduced when S-R compatibility is high, and this likely reduces the costs associated with producing incompatible responses. Second, Spijkers et al. had the participants make reversal movements that differed in amplitude but not direction. This procedure may have allowed participants to initiate movements before completely programming them, given that the initial portions of the long and short movements were likely similar. Third, the participants in the Spijkers et al. study were more practiced than those in the present experiment, performing the task for approximately 3.5 h.

Despite these differences, the findings from both studies are consistent with the excluded-stage hypothesis: the compatibility effects were limited to the S-S condition. Moreover, the data from the present study are inconsistent with the grouped-response and the outraced-interference hypotheses. RT2 was not affected by compatibility at any SOA when the second task was directly cued, even if the first task was cued symbolically. It appears that the directly cued movements are not susceptible to cross-talk from processes involved in specifying another movement.

It should be noted that a variant of the grouped-response hypothesis may be consistent with the present data. A grouping strategy need not imply simultaneous responses. Sequential responses would be produced if the strategy was to generate both responses as a pair, but with one hand leading the other. Thus, the fact that two responses in the S-D and D-D conditions were initiated over 100 ms apart does not preclude the possibility that responses were grouped in these conditions. It is possible that at the shorter SOAs, the responses were grouped in these conditions and in this manner, cross-talk was eliminated.

However, we see two difficulties for this hypothesis. First, it is unclear why grouping would occur during incompatible trials in the S-D condition but not the S-S condition. Second, in the D-D condition, 69% of the Task1 responses were initiated before the onset of the Task2 stimulus at the 400-ms SOA. On this subset of trials, there was no evidence of any cross-talk [Incompatible RT2 = 345 ms; Compatible RT2 = 361 ms; $t(7) = 1.05$; $P > 0.3$], even though response grouping would not be possible. In the S-D and S-S conditions, participants consistently responded to Task 1 after the onset of the Task 2 stimulus at the 400-ms SOA, making it impossible to analyze the corresponding subsets of trials. However, even though it was theoretically possible for most responses to be grouped at the 400-ms SOA, there was a 74-ms compatibility effect for the S-S condition. Thus, this modified version of the grouped-response hypothesis does not provide a straightforward account of the RTs.

Although the data support the excluded-stage hypothesis, a PRP effect was observed in both conditions involving direct-cues (i.e., D-D and S-D): RT2 became slower as SOA decreased. To obtain an estimate of the PRP effect, we subtracted the RT2 at the longest SOA from the RT2 at the shortest SOA. By this crude measure, the PRP effect was 43 ms for the D-D condition and 211 ms for the S-D condition. Had directly cued movements been completely free from dual-task costs, no such effects should have been observed. Nonetheless, while there is a PRP effect in the D-D condition, the cost to RT2 even at the shortest SOA does not appear to be associated with processes affected by the compatibility manipulation. Rather, the persistent PRP effect may reflect a response execution bottleneck (De Jong, 1993) or a strategic delay voluntarily imposed by subjects to demonstrate adherence to the task instructions (Meyer & Kieras, 1997). We return to this issue in the general discussion.

Movement time

For the analysis, only movement times for trials in which both responses were correct were included. MT1 was 382, 361, and 365 ms for the S-S, D-D, and S-D conditions, respectively. These values did not differ significantly [$F(2, 14) = 1.25$; $P > 0.3$]. However, MT2 was 357, 319 and 327 ms for the S-S, D-D, and S-D conditions, respectively, which reflected a significant effect of condition [$F(2, 14) = 9.74$; $P > 0.005$]. Symbolically cued movements were performed an average of 34 ms slower than directly cued movements for Task 2. To further evaluate the factors influencing MT, separate two-way ANOVAs were performed on the two MTs for each of the three conditions with Compatibility and SOA as factors.

Task 1

The analyses of movement times for the left-hand (Task 1) responses revealed that in the S-S condition, the main effect of compatibility was significant [$F(1, 7) = 8.55$; $P < 0.05$]. MT1 was 21 ms faster for compatible movements than incompatible movements. In the D-D condition, there were no significant main effects, but the interaction between SOA and compatibility did achieve significance [$F(4, 28) = 4.50$; $P < 0.01$]. However, the interaction reflected a complex pattern in which at the shortest SOA, MT1 was actually shorter for incompatible trials than compatible trials by 27 ms, whereas at the longest SOA MT1 was nearly equivalent for the two types of stimuli. This interaction is not consistent with compatibility effects predicted by either grouped-response or avoided-interference hypotheses. There were no significant effects in the S-D condition.

Task 2

The analyses of movement times for the right-hand (Task 2) responses in the S-S condition revealed a significant effect of compatibility [$F(1, 7) = 29.03$; $P < 0.001$], with compatible movements being made 57 ms faster than incompatible movements. No other effects achieved significance. In the D-D condition, there were no significant effects. In the S-D condition, there was a significant effect of SOA [$F(4, 28) = 9.64$; $P < 0.0001$], indicating that MT2 was 53 ms slower at the shortest SOA than at the longest. In other words, there was an indication of a PRP effect in MT2 as well as RT2 for this condition. In short, as with RT, compatibility effects in MT occurred only when both movements were symbolically cued.

Accuracy

Movements were scored as correct when the movement ended within the target circle. Our criterion of using a velocity-based termination rule was adopted to minimize the effects of corrective movements. For Task 1, the mean proportions correct for the S-S, D-D and S-D conditions were 0.87, 0.89, and 0.86, respectively. There was a significant effect of SOA in the S-D [$F(4, 28) = 5.47$; $P < 0.005$] and D-D [$F(4, 28) = 8.18$; $P < 0.0005$] conditions, but not in the S-S condition [$F < 1$]. For both the S-D and D-D conditions, the effect of SOA reflected the fact that accuracy increased with SOA (S-D: 0.83–0.93; D-D: 0.79–0.95). This effect may reflect the interfering influence of the onset of a new target within the first movement at short SOAs. Neither the main effect of compatibility nor the Compatibility × SOA interaction approached significance for any of the conditions.

For Task 2, the mean proportions correct for the S-S, D-D and S-D conditions were 0.84, 0.85, and 0.80, respectively. There were no significant main effects in any of the conditions. However, the SOA × Compatibility interaction was significant for the S-S condition [$F(4, 28) = 2.97$; $P < 0.05$]. Consistent with the RT2 data, participants were generally less accurate on incompatible trials at the shorter SOAs (50 ms: 0.73 correct) than at the longer SOAs (1,000 ms: 0.82 correct). This pattern was not observed on compatible movements (50 ms: 0.85 correct; 1,000 ms: 0.81 correct). Therefore, the overadditive effect of compatibility observed in RT2 was not the product of a speed-accuracy tradeoff.

Initial heading

To verify that motor programming was taking place during the RT interval – that is, before the movement was initiated – we analyzed the initial heading of each movement by computing its direction during the first 100 ms. For Task 1, 94% of the accurate movements had an initial heading within 25° of the direction of the target. For Task 2, the percentage was 92%. Given that the targets were 45° apart, it is apparent that, on most trials, the movement's direction was programmed before it was initiated. The proportion of movements with the appropriate initial heading was not affected by either compatibility or SOA, except for the Task 2 movements in the S-S condition, in which congruent trials had higher proportion of appropriate initial headings than incongruent trials [0.95 vs 0.70; $F(1, 7) = 33.45$; $P < 0.001$]. This effect did not interact with SOA and is consistent with the effect of compatibility observed in MT. Excluding the trials in which a movement began in a direction more than 25° from the target did not affect the pattern of RTs.

In sum, Experiment 1 indicates that compatibility effects between the two hands are present only when both responses are cued symbolically. This observation is most apparent in the RT data for Task 2, but is also supported by the MT data and accuracy results. There was no evidence of any interference, as measured by compatibility effects, when one or both responses were directly cued. As outlined in the introduction, these results fail to conform to predictions derived from the grouped-response and outraced-interference hypotheses. Rather, they are consistent with the excluded stage hypothesis. By this account, a directly cued movement can be selected, planned, and produced without engaging processes that are subject to cross-talk from similar processes associated with planning and executing a movement by the other hand.

Despite the absence of cross-talk, measured by the difference between compatible and incompatible movements, the PRP effect was not eliminated. In fact, for the S-D condition, the difference in RT2 between the shortest and longest SOAs was over 200 ms. These results indicate that whatever processes are excluded when at least one of the movements is directly cued, they are not solely responsible for the PRP effect. The residual bottleneck effects may relate to abbreviated response-selection processes associated with directly cued movements (that are not susceptible to cross-talk), a response execution bottleneck (e.g., De Jong, 1993), or strategies adopted by the participants (e.g., Ivry, Franz, Kingstone, & Johnston, 1998; Meyer & Kieras 1997).

Experiment 2

The results of Experiment 1 indicate that bimanual interference arises from processes that are invoked during symbolically cued movements but not during directly cued movements. In symbolically cued action, the appropriate response has to be selected based on an abstract mapping from cue to response. Cross-talk occurs when this mapping has to be performed for two separate movements. This selection process does not appear to be necessary for directly cued movements; we have called this the excluded-stage hypothesis.

The inter-dimensional condition (S-D) of Experiment 1 showed that a directly cued movement is not susceptible to interference from a preceding, symbolically cued movement. There are at least two possible explanations for this finding. First cross-talk during the preparation of two actions might only occur when both engage similar response-selection processes. If one of the actions is directly cued, the response-selection stage is skipped, bypassing the possibility for interference effects due to cross-talk. Second, symbolically cued movements may require complex mapping processes that can be influenced by distracting information concerning the characteristic of a preceding or simultaneous movement. By this logic, we would expect to observe compatibility effects when symbolically cued movements follow directly cued movements. Directly cued movements, while not susceptible to cross-talk themselves, may influence response selection processes required by subsequent symbolically cued movements. Experiment 2 was designed to evaluate these two hypotheses.

Method

Participants

Eight college-aged undergraduates performed a 1-h session for Experiment 2. Payment followed the same scheme as in Experiment 1.

Apparatus and procedure

The apparatus, stimuli and procedure were identical to those in Experiment 1. The only difference was that the D-D condition in Experiment 1 was replaced with a condition in which the left (first) hand was cued directly and the right (second) hand was cued symbolically (D-S). As in Experiment 1, participants were randomly assigned to one of three possible condition orders: S-D, S-S, D-S; S-S, D-S, S-D; or D-S, S-D, S-S.

Results and discussion

Reaction time

The same trimming procedures were used as in Experiment 1, resulting in the elimination of less than 3% of the data. As before, only correct responses were included in the analyses.

Task 1

As in Experiment 1, the RT data for each hand were submitted to a three-way ANOVA, with Condition (S-D, D-S, or S-S), Compatibility, and SOA as factors. For the first (left) hand, there was a main effect of Condition [$F(2, 14) = 9.38$; $P < 0.005$], but no other effects or interactions achieved significance. The RT1 means were 527, 458, and 607 ms for the S-D, D-S, and S-S conditions, respectively. RT1 was not only dependent on how that response was cued (direct or symbolic), but it was also affected by how the second response was cued.

Task 2

The RT2 data (right hand responses) were segregated according to Condition and submitted to separate two-way ANOVAs with Compatibility and SOA as factors (Fig. 3). The effect of SOA was highly significant for all three conditions [S-D: $F(4, 28) = 25.69$; $P < 0.0001$; D-S: $F(4, 28) = 12.37$; $P < 0.0001$; S-S: $F(4, 28) = 12.97$; $P < 0.0001$], but in the two conditions involving direct cues, neither compatibility nor its interaction with SOA was significant. In contrast, in the S-S condition, there was a significant effect of Compatibility [$F(1, 7) = 18.78$; $P < 0.005$] and a significant Compatibility × SOA interaction [$F(4, 28) = 8.24$; $P < 0.0005$]. Thus, a PRP effect was observed in all conditions. However, only when both hands were cued symbolically was there an effect of Compatibility, and the effect diminished as SOA increased.

As in Experiment 1, the significant Compatibility × SOA interaction in the S-S condition indicated that the cost of incompatible movements was overadditive. Across the five SOAs, 50, 150, 250, 400, and 1,000 ms, the compatibility effect was 242, 188, 121, 59, and 20 ms, respectively.

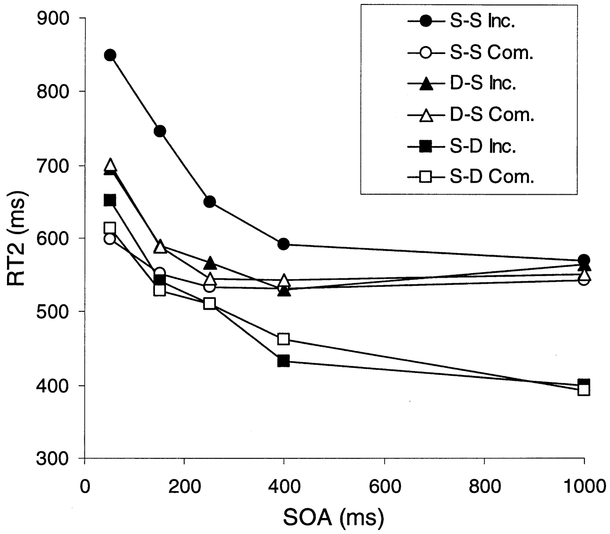

Fig. 3 RTs for the second reaching movement in Experiment 2 as a function of SOA according to whether the movement was compatible or incompatible with the first movement

Movement time

The mean MT1 for the first (left) hand was 445, 455, and 460 ms for the S-D, S-S, and D-S conditions, respectively. These did not differ significantly. For the second (right) hand, MT2 was 365, 390, and 405 ms, for the three conditions, with slower movements times obtained when the responses were cued symbolically [$F(2, 14) = 4.07$; $P < 0.05$].

Task 1

For the analyses of movement times for the left-hand responses, neither the S-D nor D-S conditions produced any significant effects or interactions. However, in the S-S condition, there was a small but significant effect of Compatibility [$F(1, 7) = 10.19$; $P < 0.05$], reflecting the fact that compatible movements were made 24 ms faster than incompatible movements. This effect is nearly identical in magnitude to the compatibility effect observed in Experiment 1 for this condition.

Task 2

For the analyses of movement times for the right-hand responses, the S-D condition produced a significant effect of SOA [$F(4, 28) = 4.11$; $P < 0.01$]. MT2 was 59 ms slower for the shortest SOA compared to the longest SOA. For the S-S condition, there was a significant effect of Compatibility [$F(1, 7) = 11.14$; $P < 0.05$], with compatible movements being produced 60 ms faster than incompatible movements. There were no significant effects for the D-S condition.

Accuracy

For Task 1, the mean proportions correct for the S-D, S-S and D-S conditions were 0.92, 0.92, and 0.93, respectively. Significant effects of SOA were found for both the S-D and D-S conditions [S-D: $F(4, 28) = 4.11$; $P < 0.01$; D-S: $F(4, 28) = 3.97$; $P < 0.05$], but not for the S-S condition [$F < 1$]. In both cases, the effect of SOA reflected the fact that participants were between 8 and 10% more accurate at the longer SOAs. For Task 2, the mean proportions correct for the S-D, S-S and D-S conditions were 0.89, 0.86, and 0.86, respectively. There were no significant effects or interactions in any of the conditions.

Initial heading

For Task 1, 93% of the accurate movements had an initial heading within 25° of the direction of the target. For Task 2, the percentage was 80%. As in Experiment 1, a significant effect of compatibility was observed in the S-S condition for both Task 1 [0.94 vs 0.88; $F(1, 7) = 16.95$; $P < 0.005$] and Task 2 [0.92 vs 0.61; $F(1, 7) = 40.48$; $P < 0.0005$]. Excluding the trials in which a movement began in a direction more than 25° from the target did not affect the pattern of RTs. No effect of compatibility or SOA was observed on the measure of heading in the D-S and S-D conditions.

The results from Experiment 2 replicate and extend the findings from Experiment 1. In short, although robust PRP effects were observed in all conditions, compatibility effects were only observed in the S-S condition. Moreover, the lack of a compatibility effect in both hybrid conditions, D-S and S-D, suggests that interference only arises when the two action engage similar S-R translation processes.

Interference or facilitation?

RT differences between symbolically cued, incompatible and compatible bimanual movements have generally been attributed to interference during incompatible movements rather than facilitation during compatible movements (e.g., Franz et al., 1996; Heuer, 1995; Spijkers et al., 1997, 2000). This conclusion is based, in part, on the observation that overall RTs tend to be slower in compatible bimanual conditions compared to unimanual movement conditions. However, the unimanual conditions do not provide an ideal comparison, because the task demands are quite different during unimanual and bimanual trials. While there may be some cross-talk during compatible bimanual movements, it is also possible that the increase in RT on bimanual trials reflects general preparatory processes or the fact that more S-R combinations are possible in the bimanual conditions (see Goodman & Kelso, 1980).

The present case, in which the same bimanual reaches were made under one set of conditions without evidence of any compatibility effect (D-S) and under another set of conditions resulting in pronounced compatibility effects (S-S), provides an opportunity to evaluate whether the cross-talk provides facilitation or interference. Directly comparing RT2 in the D-S and S-S conditions can be misleading, because Task 1 differs, which can result in distinct carry-over effects on Task 2 performance. Therefore, we adopt an approach that has been developed in the PRP literature (McCann & Johnston, 1992) in which each task is divided into three critical stages, each of which may entail many cognitive processes (Fig. 4). Stage A, often characterized as stimulus categorization, includes all of the processes occurring before the central stage (Stage B). Stage A is assumed to operate in parallel with other stages, such that processing within Stage A for Task 2 can overlap with processing at any stage for Task 1. In fact, the only constraint on Stage A is that it cannot begin until the appropriate stimulus has been presented.

Greater processing constraints exist for Stage B: This stage cannot begin until all processing within Stage A is complete. Moreover, and critical to the central bottleneck model, Stage B processing for Task 2 must be delayed until Task 1 processing at this stage is completed (Pashler, 1994). Stage C is assumed to operate with the same minimal constraints as Stage A and can proceed as soon as Stage B is completed.

In sum, the model assumes that there exists a processing stage that is shared by both tasks and can only operate in a sequential manner. Note that there may be multiple operations subject to this constraint; the model takes the simplified approach of lumping these operations into a single, performance-limiting stage. The model is designed to account for how RT2 will vary as a function of SOA. With long SOAs, B1 is presumably completed before A2. As such, RT2 will simply be determined by the sum of its three component stages, or

$$RT2_{\mathrm{Long}\,SOA} = A2 + B2 + C2 \tag{1}$$

However, at short SOAs, B2 is delayed until the completion of B1. RT2 will now be determined by the duration of stages from both tasks, including both Stages B, or

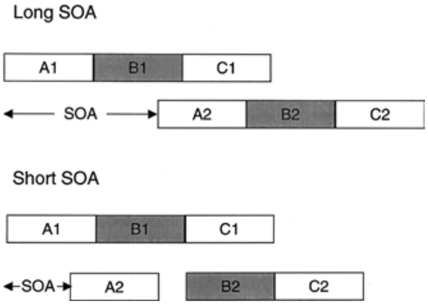

Fig. 4 Source of lengthened reaction times at shorter SOAs in the PRP paradigm (*PRP* psychological refractory period)

$$RT2_{\mathrm{Short}\,SOA} = A1 + B1 - SOA + B2 + C2 \tag{2}$$

Unlike RT2, RT1 is assumed to be determined by the sum of its three component stages (A1, B1, and C1) regardless of the SOA, and indeed, the task instructions emphasizing that Task 1 be given priority are designed to ensure that this assumption is not violated. In the current experiments, RT1 was largely unaffected by SOA in both experiments. Therefore, subtracting RT1 from RT2 produces difference scores that reflect different sets of processes at the long and short SOAs. At long SOAs, where we assume no overlap at Stage B, the score simply reflects the difference between the sum of Task 1 stages and the sum of Task 2 stages. At short SOAs, where we assume there is always overlap at Stage B, the score reflects the difference between post-bottleneck stages of both tasks (which, given the similarity between the two movements, is likely to be small) plus the time required for Stage B2.

$$RT2 - RT1_{\mathrm{Long}\,SOA} = A2 + B2 + C2 - A1 - B1 - C1 \tag{3}$$

$$RT2 - RT1_{\mathrm{Short}\,SOA} = B2 + C2 - C1 - SOA \tag{4}$$

To gain further insight into the effects of compatibility on stage B processes, we subtracted the measured Task 1 RT from the Task 2 RT at the shortest and longest SOAs for the two conditions using symbolic-cues on Task 2. First, consider the RT differences at the longest SOA (Fig. 5, top panel). The model predicts that the difference should be determined by the length of the all three stages for both tasks (Eq. 3). Accordingly, the S-S and D-S conditions produce different values. The difference scores are negative in the S-S condition, reflecting the fact that initiating the second movement was faster than the first at the longest SOA. This is clearly not the case for the D-S condition, for which the scores are positive; participants responded to the direct cues more quickly than the symbolic cues. However, these differences do not indicate which stage components are shorter for the two tasks.

A different pattern of results is obtained for the difference scores at the shortest SOA (Fig. 5, bottom panel). The three-stage model predicts that the RT difference at this SOA should be determined only by the duration of Stage B2 and the difference between stages C1 and C2 (Eq. 4)[3]. That is, rather than reflecting differences between all of the components of the two tasks, the scores are predominantly determined by the time required on Task 2 at the bottleneck stage. The congruent movements for the S-S condition produce the smallest scores at the shortest SOA. The most reasonable account of this effect is that it reflects a repetition

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[3] Given the strong similarity between the two movements, C1 and C2 are likely to be very similar. Thus, the y-intercept of the difference function may provide an estimate of the duration of stage B2.

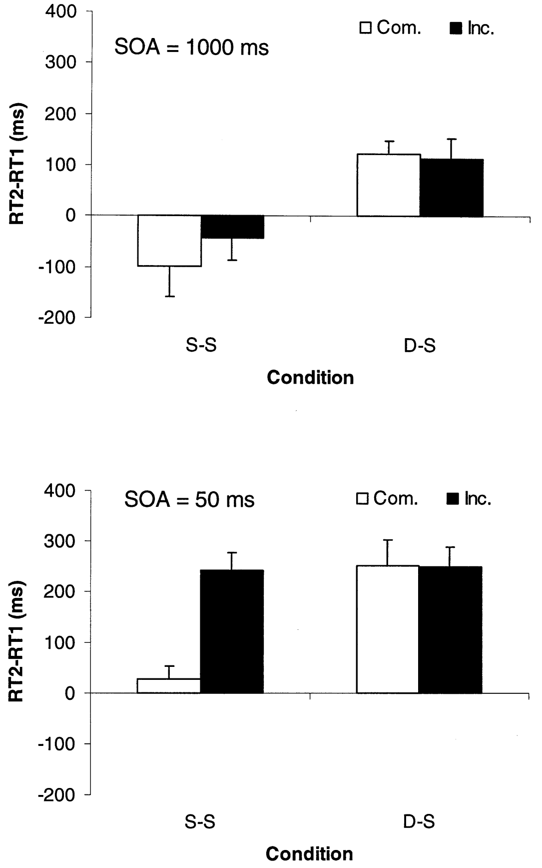

Fig. 5 Mean reaction times of the second movements minus mean reaction times of the first movements for the two conditions in which the second movement was symbolically cued. The *upper panel* depicts the difference for the 1,000 ms SOA. The *lower panel* depicts the difference for the 50 ms SOA

benefit. Stage B2 is dramatically shortened when the symbolic stimulus for Task 2 is the same as that which had been presented for Task 1 (e.g., "F" for both left and right hand movements).

The difference scores for both the compatible and incompatible D-S conditions are similar to that obtained for incompatible trials in the S-S condition. This result suggests that Stage B2 is constant across these three trial types. The difference scores for the D-S condition provide estimates of the duration of Stages B2 and C2 for symbolically cued movements under dual-task conditions without compatibility effects. The score for the S-S incompatible movements is nearly identical to these estimates. The implication from this result is that the difference between compatible and incompatible movements in the S-S condition stems from a shortening of processes for the compatible movements, not a lengthening of processes for the incompatible movements. In short, facilitation, not interference, is responsible for the compatibility effect. Specifically, the cross-talk effects observed during symbolically cued bimanual movements appear to be largely related to performance benefits in association with repetitions of S-R combinations (e.g., Pashler & Baylis, 1991). However, unlike the standard stimulus-repetition effect, the benefit observed with compatible movements is short-lived, diminishing rapidly in the first 400 ms after the initial stimulus.

Alternative interpretations

It is possible that the small RT2-RT1 score in the S-S compatible condition stems from participants grouping their responses on some proportion of trials when they perceive two identical stimuli. An indication of grouping is given by whether or not RT1 is lengthened at short SOAs. This should occur as participants, observing the stimulus for Task 2, withhold the Task 1 response until ready to simultaneously produce the Task 2 response. Contrary to this prediction, RT1 was not longer on the short SOA trials. In sum, there is no evidence to support a grouping account of the reduced RT2-RT1 difference for the S-S compatible trials.

A second possibility is that the similarity between the RT differences for the S-S incompatible trials and the D-S trials results from tradeoffs between the durations of the component stages. For example, if Stage C for symbolically cued movements is longer than for directly cued movements, then Stage B for incompatible movements in the S-S condition could be longer than for Stage B for the second task in the D-S condition (Eq. 4). This hypothesis can be tested with the results from Experiment 1. Unlike Stages A1 and B1, the duration of Stage C1 does not get passed on to RT2 at the shortest SOAs (Eq. 2). Therefore, a factor extending the duration of C1 should cause a greater increase in RT1 than in RT2 at the shortest SOA. In Experiment 1, a directly cued Task 2 was paired with both a directly and a symbolically cued task 1 (D-D and S-D conditions), providing a comparison in which neither condition incurs compatibility effects. The average difference between the symbolically and directly cued Task 1 RTs at the 50-ms SOA was 166 ms (499 vs 333 ms). At the same SOA, the average difference in RT2 for these two conditions was 188 ms (578 vs 390 ms). This value did not differ significantly from the RT1 difference [$t(7) < 1$], and was in the opposite direction as predicted by an increased in the duration of Stage C1.

A third possibility is that a set-shifting operation is required for Task 2 in the D-S condition but not the S-S condition. When individuals have to switch rapidly from responding to one set of stimuli to another, as in the D-S condition, RTs for the second task can be inflated, presumably reflecting the operation of executive control processes that may be needed to instantiate the new S-R mappings or optimize resource allocation for task performance (Allport, Styles, & Hsieh, 1994). However, there is reason to believe that set-shifting costs are not incurred with the present combination of tasks. First, distinct stimuli are used for the symbolic and direct cues. Such conditions minimize set-shifting costs, although they do not always eliminate them (e.g., Rogers & Monsell, 1995). Furthermore, RT2 is nearly identical for the D-S and S-S conditions at the longest SOA. Set-shifting is generally associated with an "exogenous" component that persists at even longer intervals (Allport et al., 1994; Mayr & Kliegl, 2000). That no such costs were observed in the D-S condition suggests that set-shifting costs are not incurred with the present combination of tasks.

In sum, the data are most consistent with facilitation rather than interference being the primary source of the compatibility effects. In other words, processing the symbolic cue for Task 1 confers a benefit for Task 2 when the same symbolic cue is used for both responses.

General discussion

Numerous studies have shown that humans are often limited in their ability to produce independent bimanual movements (e.g., Heuer, 1995; Spijkers et al., 1997, 2000). The current studies were designed to identify the source of a compatibility effect, the cost observed when the movements traverse non-parallel axes compared to when they follow parallel axes. Using a PRP task in which the two movements were cued in close succession, robust compatibility effects were observed when both movements were symbolically cued, similar to the previous report of Spijkers et al. (2000). In contrast, compatibility effects were abolished when both of the movements were directly cued. Moreover, no compatibility effects were found when a directly cued movement was combined with a symbolically cued movement, regardless of whether the directly cued movement was made first or second. This pattern of results is consistent with the hypothesis that directly cued movements do not engage processes that are subject to bimanual cross-talk, an idea that we have referred to as the excluded-stage hypothesis.

There are several candidate reasons as to why the symbolically cued movements induced cross-talk but the directly cued movements did not. Most obvious, the symbolically cued trials involved the presentation of a letter which had to be translated into the appropriate movement. However, there were other potentially important differences. With the symbolically cued movements, the possible target endpoints are displayed before the actual movement is known, allowing for partial preprogramming of the response during the interval before the appearance of the letter cue. In addition, the unselected target endpoints remained visible throughout the trial, potentially serving as distractors. Finally, the inclusion of a symbolic cue introduces an additional location that must be attended. Having to attend to the cue may detract from the salience of the target locations. None of these conditions existed with the directly cued movements.[4] The present experiments do not allow us to determine which factors are responsible for the cross-talk.

Nonetheless, these characteristics of the symbolically cued movements are similar to those found in button-pressing experiments, which have provided an extensive literature on S-R compatibility. In this way, we provide a link between two previously separate literatures, bimanual movement studies and dual-task performance. The literature concerning simultaneous bimanual movements has generally focused on the idea that the difficulty in initiating non-symmetric bimanual movements is related to cross-talk in processes associated with the specification of movement parameters (e.g., Franz et al., 1996; Heuer, 1995). However, if the motor programming hypothesis was correct, compatibility effects should have only depended on the interval between the successive responses and not the type of cues. The lack of compatibility effects when at least one of the movements was directly cued, even when the actual movements overlapped, argues against hypotheses that emphasize cross-talk during motor programming. Instead, the results indicate that the source of interference associated with the initiation of bimanual movements is related to S-R translation. This conclusion matches studies that have minimized response requirements (e.g., button presses).

In attempting to link the two literatures, we have focused our analyses on RT effects. It is possible that the forms of bimanual interference reported in other studies (e.g., Heuer, 1995; Spijkers et al., 1997, 2000) – for example distortions in the movement trajectories – may be based on interference of motor programming and/or execution. Moreover, unlike many of the previous studies of bimanual interference, the present experiments required participants to make reaches to visible targets rather than reversal movements across boundaries and back. It remains possible that reversal movements place higher demands on motor programming and thus may be more susceptible to interference. While our findings do not rule out the existence of cross-talk at the motor level, they do indicate that a major component is restricted to response selection.

The proposal that direct and symbolic cues engage different sets of processes bears some resemblance to the influential theory of Milner and Goodale (1995) concerning the functional roles of the dorsal and ventral visual processing systems. According to their proposal, the dorsal system is prominent in sensorimotor control, while the ventral system is prominent in object recognition and conscious perception. One line of evidence cited in support of this distinction is research showing that the ventral pathway is influenced by extraneous information to a greater extent than the dorsal pathway (e.g., Haffenden & Goodale, 1998). With respect to the current experiments, it might be postulated that the symbolic cues require input from the ventral pathway to be decoded into the appropriate movements, whereas the directly cued movements can be performed by the dorsal pathway alone. The fact that only symbolically

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[4] We thank two anonymous reviewers for pointing out these differences.

cued movements are subject to cross-talk is similar to the proposal that the ventral system is more susceptible to visual illusions induced by irrelevant stimuli (but see Carey, 2001).

The representational nature of bimanual cross-talk

We have argued that compatibility effects arise from S-R translation processes necessary for translating the symbolic cues into the appropriate responses. An alternative hypothesis centers on upstream processes associated with the stimulus codes. According to this account, the compatibility effect is based on interactions between representations of the two stimuli. The two hypotheses differ in that the former supposes that cross-talk involves representations that include information about the intended response.

This issue has been the focus of intense discussion in the dual-task literature (e.g., Hommel, 1998; Lien & Proctor, 2000). For instance, the Logan and Schulkind (2000) study described in the introduction involved a series of PRP experiments in which Tasks 1 and 2 required participants to categorize sequentially presented stimuli. The categorization tasks either involved the same rule or different rules. An advantage for same-category responses, strongest at short SOAs, was observed despite the fact that the exact stimulus never repeated from Task 1 to Task 2. In addition, the assignments of the keys to the categories was counterbalanced so that for half the participants, identical-category responses meant button presses with homologous fingers, whereas for the other half, identical-category responses meant button presses with non-homologous fingers. Therefore, the repetition effect they observed could not be attributed to cross-talk between pure stimulus codes or pure movement parameters.

Further evidence against a pure stimulus-based account comes from the PRP studies reported in Lien and Proctor (2000). Although there was no obvious overlap between their two tasks, RTs for both tasks were smaller when they required corresponding button presses (e.g., left button for Task 1 and left button for Task 2). The effect did not interact significantly with SOA, but there was a consistent trend in this direction, with the advantage for corresponding button presses largest at the shortest SOA. Such results make clear that compatibility effects between distinct responses do not require stimulus repetitions – in short, the compatibility effect is not simply a version of a stimulus repetition effect.

Because the Lien and Proctor (2000) experiments used two tasks with distinct sets of stimuli and, therefore, distinct S-R mappings, it appears that the compatibility effect must be based on representations of the responses. However, the current experiments provide evidence that processes associated with motor programming are not a major source of interference. One way to reconcile these findings is to assume that the interference emerges from abstract representations of the responses. That is, interference involves cross-talk between conceptual codes for the responses, and these codes mediate response selection processes.

We propose that the compatibility effects observed when two reaching movements are cued symbolically relates primarily to interactions between the internal codes for the potential responses. With the symbolic cues in the present experiments, the three possible movements were made to identical visual targets, visible throughout the trial, that differed only in terms of location. These conditions required that the participants develop internal codes for each movement and associate these with the symbolic cues. Incompatible cues required the activation of distinct translation processes, one for each movement. Presumably, compatible symbolic cues did not separate translation processes, because, under the present task conditions, the internal codes for the two movements are highly similar (e.g., 'S'→"outward movement"). In contrast, for the direct cues, only the relevant target endpoints appeared on each trial and the participants did not need to employ internal codes to differentiate the possible responses. In this manner, they were able to bypass much of the translation processes and thus, interference between the two tasks was eliminated.

The exact composition of these internal codes remains a topic for further research. One candidate form of representation is the action concept, as described by Hommel and colleagues (Elsner & Hommel, 2001; Hommel, 1998; Hommel et al., 2001; Stoet & Hommel, 1999). Action concepts combine sensory information, including the environmental consequences consequent to the completion of the action. The representations of responses are conceptualized as integrated codes that facilitate response selection by virtue of being commensurate with stimulus representations. Such representations have been invoked to explain other forms of compatibility effects such as the Simon effect (Hommel, 1993), interactions between successive responses (Hazeltine, 2002; Ziessler & Nattkemper, 2002) and even bimanual coupling effects on movement trajectories (Mechsner et al., 2001).

The inclusion of stimulus information makes the action concept imminently capable of accounting for the compatibility effects observed when both movements were symbolically cued. The action concepts for the symbolically cued movements may include semantic information, such as forward or outward, posing potential benefits for other movements involving related concepts. In contrast, the action codes for the directly cued movements may specify only the target without reference to *relative* location, and, thus, the amount of conflict would be identical for compatible and incompatible movements.

Cross-talk as facilitation

Further analysis of the data suggested that facilitation rather than interference was the primary source of the compatibility effect when both targets were symbolically cued. That is, the primary effect of cross-talk was a benefit observed during the compatible movements rather than a cost associated with incompatible ones. Although preliminary, the proposal that cross-talk primarily serves to facilitate selection when the targets are compatible rather than impose costs when the targets are incompatible represents a significant departure from previous proposals. The term cross-talk implies the transmission of unwanted information across channels to the detriment of performance. In contrast, the present results suggest that cross-talk can be beneficial when there is overlap between the two tasks in terms of S-R translation processes.

It is important to bear in mind that the movements in the present study, unlike those in many other bimanual cross-talk experiments, were sequential rather than simultaneous. Even in the 50-ms SOA trials, the onsets of the movements in the S-S condition were separated by more than 200 ms, indicating that any processes specific to simultaneous movements were likely not engaged during the present experiments. However, Diedrichsen et al. (2001) have reported highly similar patterns of compatibility effects for S-S and D-D conditions when the movements were made simultaneously.

Locating cross-talk within S-R translation processes makes some intuitive sense given the relative ease with which people perform bimanual actions. When climbing a tree or grabbing different parts of a large object, the two hands often move in distinct trajectories in a highly coordinated fashion. In these cases the two actions subserve a common goal (see Franz, Zelaznik, Swinnen, & Walter, 2001; Mechsner et al., 2001). Only one response has to be selected, thus preventing substantial interference. In contrast, situations in which the hands have distinct goals, such as driving a standard transmission car with one hand steering and the other hand shifting gears, are extremely challenging for novices.

Summary

The principal finding from these experiments is the absence of compatibility effects when people initiate bimanual reaching movements to directly cued targets. The exemption from compatibility effects likely reflects the manner in which these actions are represented and how these representations engage response selection processes. Because the lack of interference was observed across a range of SOAs and stimulus conditions, compatibility effects that occur with symbolically cued movements do not appear to be related to processes associated with motor programming. Moreover, if the two movements were made in rapid succession, symbolically cued movements were initiated at a nearly constant interval after the first response except when the symbolic cue was repeated for the second response. When repetitions occurred, the interval was much shorter. This result suggests that interactions between the two actions are primarily related to a benefit afforded to symbolic cues that overlap along critical features. In other words, the compatibility effect may best be characterized as facilitation between similar responses rather than interference between dissimilar ones. This account emphasizes that a major limitation in human performance is the ability to initiate two goal-directed behaviors at the same time rather than the ability to coordinate distinct groups of muscles. Put simply, we shouldn't blame the hands for a limitation in our heads.

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