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Target-related coupling in bimanual reaching movements

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Abstract While bimanual interference effects can be observed when symbolic cues indicate the parameter values of simultaneous reaching movements, these effects disappear under conditions in which the target locations of two movements are cued directly. The present study investigates the generalizability of these target-location cuing benefits to conditions in which symbolic cues are used to indicate target locations (i.e., the end points of bimanual movements). Participants were asked to move to two of four possible target locations, being located either at the same and different distances (Experiment 1), or in the same and different directions (Experiment 2). Circles and crosses served as symbolic target-location cues and were arranged in a symmetric or non-symmetric fashion over the four target locations. Each trial was preceded by a variable precuing interval. Results revealed faster initiation times for equivalent as compared to non-equivalent target locations (same vs. different cues). Moreover, the time course of prepartion suggests that this effect is in fact due to target-equivalence and not to cue-similarity. Bimanual interference relative to movement parameter values was not observed. These findings suggest that cuing target locations can dominate potential intermanual interference effects during the concurrent programming of different movement parameter values.

Introduction

The coordination of two-handed actions is a fundamental aspect of human motor control. Tying shoelaces, opening a bottle of water, or unbuttoning a shirt are examples of bimanual tasks in which we have to skillfully coordinate our two hands. Most of the time, we perform these tasks effortlessly. Sometimes, however, limitations in performance can become obvious when we have to coordinate our two hands with high temporal and/or high spatial precision requirements. Polyrhythmic tapping and trying to thread a needle are two examples. Performance failures and action slips are frequently observed under these conditions. We experience great difficulty in producing a difficult tapping rhythm (e.g., 4:5) or we fail to keep our hands steady and are thus unable to thread the needle. Given these (casual) observations, questions about the nature of limitations in bimanual task performance arise. Previous research has investigated these limitations for the discrete and continuous coordination of two-handed actions. The present paper focuses on limitations during the coordination of discrete bimanual movements.

The specification of movement parameters

Factors constraining the preparation of discrete bimanual movements have been studied by Heuer, Spijkers, and colleagues (Heuer, 1993; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998; Spijkers & Heuer, 1995; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997), who claim that particular parameter values of the forthcoming action must be programmed before each movement can be initiated. These parameter values can relate to the amplitude (e.g., Spijkers et al., 1997) and the direction (Steglich, 2002) of a movement, as well as to the required muscle force activity (Rinkenauer, Ulrich & Wing, 2001; Steglich, Heuer, Spijkers, & Kleinsorge, 1999). Bimanual movements of similar parameter values are called symmetric and movements of different parameter values are called asymmetric. A critical assumption for the preparation of bimanual movements is that neuronal crosstalk influences the concurrent programming of movement parameters

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(Heuer, 1993; Cardoso de Olivera, 2002), resulting in strong effector coupling for symmetric movements, whereas programming interference arises for asymmetric movements. The coupling of similar parameter values is transient. Interference effects vanish when there is sufficient time for the programming of different movement parameters (Heuer et al., 1998; Spijkers et al., 1997).

Spijkers et al. (1997) tested this assumption by having participants perform bimanual movements over short (10 cm) and long (20 cm) amplitudes, as indicated by two, simultaneously presented, symbolic cues (i.e., words or vertical bars). Insofar, their bimanual task required the specification of symmetric (e.g., two short amplitudes) and asymmetric (e.g., one short and one long amplitude) movements. The results showed faster movement initiation under symmetric conditions in which the same amplitude was required, as compared to asymmetric conditions with different amplitudes. With increasing time for response preparation, the benefits for similar amplitude values vanished and movements over different amplitudes were initiated without much interference between the two hands. The authors interpreted these results as a support of the assumption that intermanual interference arises from the concurrent programming of different movement parameter values (Spijkers et al., 1997).

The selection of movement targets

This interpretation, however, has been challenged by Diedrichsen, Ivry and colleagues (Diedrichsen, Hazeltine, Kennerly, & Ivry, 2001; Diedrichsen, Ivry, Hazeltine, Kennerly, & Cohen, 2003; Hazeltine, Diedrichsen, Kennerly, & Ivry, 2003). These authors argued that the use of symbolic cues in studies like Spijkers et al.'s (1997) "places unusual demands on selection processes... involved in identifying the symbolic cues and translating these cues into specific actions" (p. 493). At the same time, they suggested that any preparation process should benefit from situations in which the target location is presented directly to the actor. In their experiment, Diedrichsen et al. (2001) contrasted the use of direct and symbolic cues. In symbolic cuing conditions, the letters "S" and "L" were used to indicate movements over short and long amplitudes (using a similar experimental design as Spijkers et al., 1997). In direct cuing conditions, the target locations of the movements were projected directly onto the table surface. Hence, symbolic cuing required the translation of symbols into actions, whereas no such translation was needed under direct cuing. Their results for symbolic cuing replicated the results obtained by Spikers et al. (1997), showing an advantage for symmetric movements. The advantage of movement symmetry was, however, absent under direct cuing, with no differences between two movements over the same and different amplitudes. Diedrichsen et al. (2001) concluded that the interference effects observed in discrete bimanual coordination may not relate to the concurrent programming of two movements, but rather to the processes involved in the handling of symbolic cues (such as stimulus identification and/or response selection).

Recently, Diedrichsen et al. (2003) followed up on their earlier study (Diedrichsen et al., 2001) by having participants reach target locations that were specified by colored dots. Under different conditions, two target locations were either cued by the same or different colors. The results showed that participants initiated their bimanual movements faster to target locations of the same color than to different colors, irrespective of whether this required the preparation of symmetric or asymmetric movements. Thus, selecting target locations with similar features (i.e., colors) enhanced participants‘ performance in a bimanual coordination task. Diedrichsen et al. (2003) elaborated on this notion by proposing that the "primary constraint in bimanual reaching is associated with target selection" (p. 76).

The present study

In a recent overview on the constraints affecting the preparation of two-handed actions, Irvy, Diedrichsen and colleagues stated that "spatial interference effects, at least in terms of response planning, are limited to situations in which the movements are symbolically cued" (Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004, p. 290). The experiments by Diedrichsen et al., (2001, 2003), however, do not fully support this statement, because their manipulation differed relative to previous studies (e.g., Spijkers & Heuer, 1995; Spijkers et al., 1997) in two ways: First, the form of cuing was direct instead of symbolic, and second, the cues indicated target locations instead of movement parameters. Therefore, the question remains if a similar target-location cuing-effect (such as a benefit for similar target features) can be found when symbolic cues (instead of direct cues) are used to indicate target locations, but not movement trajectories. If so, directing any preparation process to the target of a movement should enhance bimanual coordination in situations where similar target locations have to be selected, even if this involves the identification of symbolic cues. The present study aims at providing further support for the notion of target-location cuing-benefits (over movement-symmetry benefits) while using symbolic cues to specify the target locations of bimanual movements.

Experiment 1

We arranged for a task in which participants performed bimanual reaching movements to two of four possible target locations over the same and different amplitudes. In each trial, the bimanual responses were cued symbolically by a combination of circles and crosses (target-location cues), which specified the target locations for the left and right hand, respectively. The target-location cues could either be the same (e.g., two crosses, one for each hand) or different (e.g., a cross for the left hand and a circle for the right hand). Importantly, however, different mappings of cues to target locations applied in different parts of the experiment (mapping). We thereby created a situation in which, dependent on mapping, given pairs of cues triggered different pairs of movements and, at the same time, given pairs of movements were triggered by different pairs of cues. For instance, a pair of same target-location cues could indicate symmetric or asymmetric movements, depending on the rule applicable for mapping cues to target locations. Likewise, symmetric movements (e.g., two movements over same amplitudes) could either be specified by a pair of same or different target-location cues. Hence, the paradigm provides a full dissociation between the symbolic equivalence of target locations (same vs. different cues) and the physical similarity of movements (symmetric vs. asymmetric). This should help us to decide if target-location cuing-effects can also be found when symbolic cues indicate the end points of bimanual movements.

It is inherent to the present experiment, however, that the equivalence of two target locations is confounded with similarity of symbolic cues. Hence, stimulus similarity could present an advantage for the processing of similar cues, whereas processing different cues may be hampered. In order to demonstrate target-location cuing-effects, we must, therefore, ensure that any benefits observed cannot fully be explained by an advantage of processing similar symbolic cues. To this end, we used the response precuing technique and stimulus masking in the forthcoming experiment. The response precuing technique, as proposed by Rosenbaum (1980, 1983), provides the actor with additional time to prepare each response, before a go-signal (i.e., a tone) triggers the response onset after a variable interval [Stimulus onset asynchrony (SOA)]. The degree to which each response can be prepared in advance depends on the delay of the response onset. We assume that by providing participants with sufficient time to prepare their responses, all combinations of symbolic cues can be identified prior to the presentation of the go-signal, abolishing possible confounding effects of early visual processing on response preparation (cf. Schmidt & Lee, 1999, p. 81). In addition, to ensure that participants start processing the symbolic cues immediately, we combined response precuing with backward masking by structure, occluding both cues 200 ms after their appearance. To our knowledge, Rosenbaum's precuing technique has not been combined with stimulus masking in bimanual research, leaving open the question whether stimulus symmetry effects influenced the results of previous studies (e.g., Heuer et al., 1998; Spijkers et al., 1997). Further, the present procedure should provide a window into the transient nature of potential target-location cuing-effects, with the benefits for similar target locations vanishing as the time to prepare the bimanual movements increases.

Method

Participants

Fourteen students (age: 20–31 years, 1 left- and 13 right-handed) participated in Experiment 1. They were each paid 12 Euros for participation.

Apparatus and stimuli

Participants were seated at a table (surface 75 cm high) in front of a response board, a computer monitor (Phillips, 17 T), and two loudspeakers (positioned to the left and right of the monitor). The response board's dimensions were 50×35 cm. Square keys (4 cm side length) were used both for the starting positions and movement targets. Six keys were arranged in two parallel columns (3 keys each) with their centers spaced 15 cm apart. The first key of each column served as the starting key for the left and right hand, respectively. The remaining two keys for each column served as target keys at a distance of 10 and 20 cm in the fronto–lateral direction relative to the starting keys for the left and right hand.

A drawing of the response board was displayed as a default picture on the screen. Circles and crosses (size: 2.5×2.5 cm) served as symbolic cues on the computer screen and were centered between the two home keys, indicating the target location for each hand. Any combination of two symbols indicating two target locations was possible. Throughout the remainder of the article we refer to *same target locations* when the same symbolic cues are used for the response and to *different target locations* for different symbolic cues. Symmetric mappings (e.g., second row: circle/circle and third row: cross/cross) and diagonal mappings (e.g., second row: circle/cross and third row: cross/circle) were instructed in different parts of the experiment. Thus, a given pair of target-location cues could trigger movements over the same and different amplitudes. Likewise, a given pair of movements could be triggered by the same and different target-location cues. Figure 1 illustrates the different conditions under different mappings. Here, it is important to note, that the instructed cue to target location mappings had to be learned by each participant before the testing, as the symbols were only presented on the computer screen, but not drawn on the response board.

Task and procedure

Participants were asked to react as quickly as possible while performing bimanual reaching movements to the target locations. At the beginning of each trial, they placed their hands on the starting position for the left and right hand, while a default picture of the response board was presented for a fixed interval of 2,000 ms on the computer screen. Then, two symbolic cues were simultaneously presented, indicating the target location

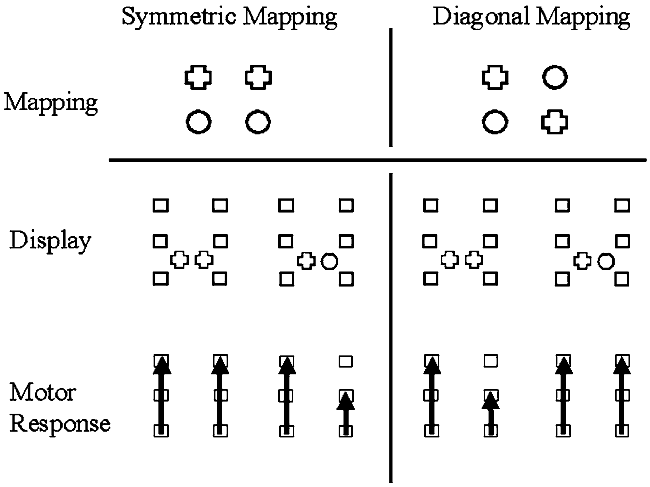

Fig. 1 Schematic depiction of the task with symmetric (e.g. *second row* circle/circle and *third row* cross/cross) and diagonal (e.g. *second row* circle/cross and *third row* cross/circle) mappings. Participants were tested in both, symmetric and diagonal mappings (order counter balanced). The task required movements to symbolically cued target locations. *Circles* and *crosses* served as symbolic cues, specifying the response for each hand separately (but were presented simultaneously)

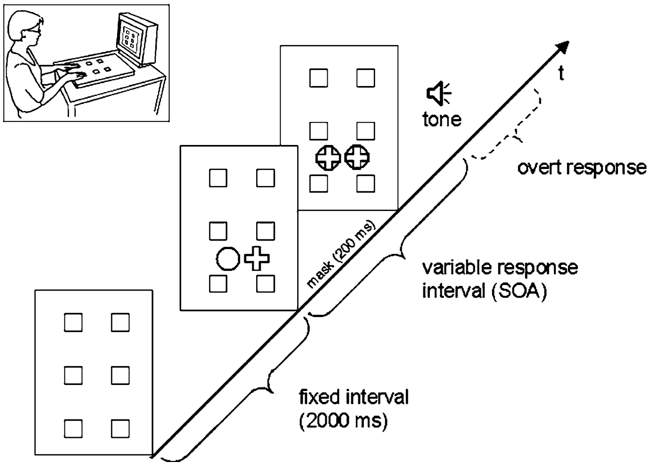

Fig. 2 Succession of events within a trial in Experiment 1: (1) Participants placed their hands on the two home keys; (2) A fixed interval followed for 2,000 ms, in which the default picture was displayed; (3) After the fixed interval, two symbolic cues were presented indicating the target locations for the left and right hand, respectively; (4) Both symbolic cues were masked after 200 ms; (5) A tone served then as the imperative signal following variable stimulus onset asynchronies (SOAs: 0, 250, 500, 1,000 and 1,500 ms); (6) Participants executed the bimanual response

for each hand separately. Masks appeared 200 ms after the appearance of the target cues, fully obstructing the cue's structural features. After a varying SOA of either 0, 250, 500, 1,000, or 1,500 ms, a tone served as the go-signal (a 1,000 Hz tone, presented for 100 ms), indicating the response onset. The bimanual response was then carried out by the participants and the mask disappeared as soon as both target locations were reached. The next trial started after participants had moved back to the starting positions. A depiction of the task and procedure can be seen in Fig. 2.

All combinations of two cues to two target locations for the different SOAs were possible. Different mappings were applied in different parts of the experiment. For the first part of the experiment, participants were instructed either in a symmetric or a diagonal cue to target location mapping and practiced the task for about 40 trials before the actual testing began. For the second part, participants switched to the other, remaining mapping and performed another 40 practice trials (order counterbalanced across participants). During testing, every target-location cueing × response onset combination was randomly presented an equal number of times within each of four blocks (100 trials each) in the two mapping conditions, resulting in a total of 800 trials. The whole experiment lasted for about 1.5 h.

Data acquisition and analysis

Data were collected with the response board, which was connected to the parallel port of a personal computer (PC). Reaction time (RT) was assessed as a function of home key release following the onset of the response cue (tone). Movement errors (ME) were analyzed for movements in which at least one of the hands terminated at the wrong target location. Movement time (MT) was calculated as the average time when the target keys were pressed minus RT.

To analyze movement preparation and target-location specification for the different response intervals, separate 5 (SOA: 0, 250, 500, 1,000, and 1,500 ms)×2 (mapping: symmetric vs. diagonal)×2 (target-location cueing: same vs. different) repeated measures analyses of variance (ANOVAs) were conducted on RT and ME. To analyze movement execution, a single 5 (SOA: 0, 250, 500, 1,000, and 1,500 ms)×2 (target-location cueing: same vs. different)×3 (movement pair: short–short vs. long–long vs. different) repeated ANOVA was conducted on MT.

Results

A total of 9.09% of the trials were excluded from the analysis of RT and MT for the following reasons: (1) a time lag between the two hands greater than 100 ms (0.94% of the trials); (2) RT less than 100 ms (anticipations, 0.30% of the trials); (3) RT greater than 1,200 ms (1.44% of the trials); (4) MT greater than 600 ms (3.20% of the trials); and (5) movements that went to wrong target locations (2.70% of the trials). Movements to wrong target locations were analyzed separately as ME.

We report RT averaged across hands throughout the article, because both, the starting times and the ending times for the two hands were always strictly coupled. Also, there was no influence of cue type (circles and crosses) and there was no difference between movement pairs (short–short vs. long–long and short–long vs. long–short) across conditions. We therefore reorganized the data for symmetric (collapsing short–short and long–long movement pairs) and asymmetric movements (collapsing short–long and long–short movement pairs), as well as for cue type (collapsing the combinations of circles and crosses for same and different symbols). The RT analysis then included the factors SOA, mapping, and target-location cuing. This was different for the MT data: While there was no significant difference between symmetric (243 ms) and asymmetric (237 ms) mappings across conditions, there was a significant difference between movement pairs. We, therefore, collapsed the data over the factor of mapping, while including SOA, target-location cuing, and movement pair into the MT analysis.

Movement preparation–reaction time

The results for RT can be seen in Fig. 3. The ANOVA revealed a significant main effect for SOA, $F(4,52) = 80.466$, $p < 0.001$, reflecting the fact that RT became shorter with longer precuing intervals: SOA 0 (525 ms), SOA 250 (388 ms), SOA 500 (332 ms), SOA 1,000 (290 ms), and SOA 1,500 (285 ms) (no difference between SOA 1,000 and SOA 1,500, all other p's < 0.05, pairwise comparisons between successive SOAs). The main effect for cueing, $F(1,13) = 10.917$, $p < 0.01$, and the interaction of SOA × cueing, $F(4,52) = 7.130$, $p < 0.001$, were both significant. The main effect for mapping was not significant, but the interaction of SOA × mapping, $F(4,52) = 15.560$, $p < 0.001$, reached significance. A potential effect of movement symmetry on response preparation would manifest itself in the interaction of mapping × cueing [$F(1,13) = .356$, $p = .561$] and/or in the three-way interaction of SOA × mapping × cueing [$F(4,52) = 0.085$, $p = .987$]. Both interactions were not significant, showing that movement symmetry had virtually no effect on the preparation of the bimanual responses in the present experiment. To analyze both, the significant interaction of SOA × cueing and the significant interaction of SOA × mapping, a series of one-way ANOVAs was conducted separately for each SOA. Significant differences showing faster RTs for same versus different cues, were found for SOA 0 (difference = 42 ms), SOA 250 (difference = 44 ms), and SOA 500 (difference = 26 ms) (all ps < 0.05). A tendency was still observable for SOA 1,000 (difference = 6 ms, $p = 0.072$), while there were no differences for SOA 1,500. Significant differences showing an RT advantage for symmetric over diagonal mappings were detected for SOA 0 (difference = 65 ms) and SOA 250 (difference = 35 ms) (both p's < 0.05). There were no significant effects of mapping for SOA 500, SOA 1,000 and SOA 1,500.

Target specification–movement error

The main effects for SOA, $F(4,52) = 6.545$, $p < 0.001$, and mapping, $F(1,13) = 6.299$, $p < 0.05$, were both significant, and so was their interaction, $F(1,13) = 4.665$, $p = 0.05$. Post hoc analyses of the interaction showed that participants committed fewer MEs under symmetric mappings for the SOA 0, with the symmetric-mapping benefit being 2.4% ($p = 0.05$). The main effect for target-location cueing and the other interactions were not significant.

Movement execution–movement time

The MT data are listed in Table 1. The ANOVA revealed a significant main effect for SOA, $F(4,52) = 6.241$, $p < 0.001$, showing that after an initial tendency of MT to decrease after the shortest SOA 0 ($p = 0.069$), MT did not differ at intermediate SOAs (p's > 0.05), but rose significantly at the longest SOA 1,500 ($p < 0.05$). The overall means are: SOA 0 (246 ms), SOA 250 (235 ms), SOA 500 (234 ms), SOA 1,000 (234 ms), and SOA 1,500 (239 ms). The main effect for movement pair, $F(2,26) = 122.973$, $p < 0.001$, was significant. Accordingly, two short movements (198 ms) were always executed faster than two long movements (262 ms) and two different movements (253 ms) (ps < 0.001). The

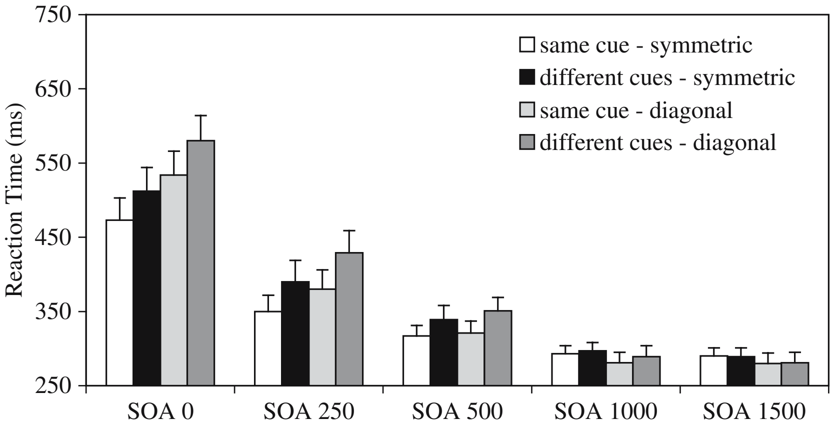

Fig. 3 Results for the RT analysis of Experiment 1. The *bars* show participant's mean RT for same and different cues, under symmetric and diagonal mappings, and over variable stimulus-onset asynchronies (*SOA*). *Error bars* indicate between-participant standard errors

Table 1 Experiment 1. Mean movement times (MT) as a function of movement pair, target-location cueing, and stimulus-onset asynchrony (SOA) (between-participant standard errors, SE, in parentheses)

Target cueing	Movement pair		
	Short–short MT (SE)	Long–long MT (SE)	Different MT (SE)
SOA = 0 ms			
Same	195 (13)	262 (16)	268 (13)
Different	212 (14)	274 (14)	264 (15)
SOA = 250 ms			
Same	196 (13)	253 (16)	244 (14)
Different	202 (12)	261 (15)	252 (16)
SOA = 500 ms			
Same	197 (14)	258 (15)	244 (12)
Different	198 (9)	255 (14)	252 (16)
SOA = 1,000 ms			
Same	201 (13)	267 (16)	246 (13)
Different	185 (12)	255 (14)	251 (17)
SOA = 1,500 ms			
Same	203 (14)	275 (17)	248 (13)
Different	191 (10)	260 (14)	259 (17)

difference between two long movements and two different movements was also significant, with faster MT for two different movements ($p < 0.01$). The main effect for target-location cueing was not significant. Both, the interaction of SOA × target-location cueing, $F(4,52) = 6.221$, $p < 0.001$, as well as the interaction of SOA × movement pair, $F(8,104) = 3.480$, $p = 0.001$, reached significance, and so did the three-way interaction of SOA × target-location cueing × movement pair, $F(8,104) = 4.031$, $p < 0.001$. The interaction of target-location cueing × movement pair was not significant. For a better post hoc inspection of the three-way interaction, we calculated the same-cue-benefit, as denoted by the difference between using the same cue versus different cues for each movement pair combination at the different response intervals. The analysis of these same-cue-benefit values revealed that the pattern of MT varied drastically for the different movement pair combinations depending on the response time interval. Both movement pair combinations over the same amplitude (two short and two long movements) initially benefited from using the same cue at SOA 0. This same-cue-benefit, however, vanished with longer time for preparation and even completely reversed at the longest SOA 1,500 (*T*-test between SOAs for each movement pair separately; ps < 0.05). A very different pattern emerged for movement pair combinations over different amplitudes (one short and one long movement). Here, participants displayed a negative value for the same-cue-benefit at SOA 0, but this effect reversed into a positive value at SOA 1,500 ($p < 0.05$).

Discussion

Experiment 1 investigated if the previously observed benefits for cuing target locations (Diedrichsen et al., 2001, 2003) can also be found under conditions in which symbolic cues are used to indicate the end points of bimanual movements. The RT pattern across different SOAs revealed significant target-location cuing-effects for precuing intervals of up to 500 ms, with the general finding being that two movements were always initiated faster when the same symbolic cues indicated the responses, as opposed to different symbolic cues. This finding cannot be explained by an advantage of processing similar symbolic cues, because introducing response precuing and the masking procedure should have minimized any effects of stimulus similarity early on in the preparation process. With significant effects for the SOA 500, a stimulus similarity interpretation of the present findings seems, therefore, implausible. Rather, the findings appear to relate to the symbolic equivalence of two target locations. Moreover, the target-location cuing-effects were independent of whether the symbols afforded the preparation of symmetric or asymmetric movements. This shows that the benefits of cuing target locations are not restricted to direct cuing paradigms (as suggested by Ivry et al. 2004), but can also be observed when symbolic cues are used to indicate the end points of bimanual movements.

The effects of target-location cuing vanished with increasing time for response preparation, with the differences between same and different targets absent at longer SOAs (i.e., SOAs of 1,000 and 1,500 ms). This pattern of results suggests that transient coupling, observable under situations in which two responses have to be prepared simultaneously, may not relate to the concurrent specification of motor parameters, as suggested by Heuer, Spijkers and collgeaues (Heuer et al., 1998; Spijkers et al., 1997), but to the selection/specification of target locations. Further, RT benefited from symmetric cue-to-target-location mappings under short precuing intervals (i.e., up to 250 ms), but not thereafter. It may be that mapping symbolic cues to target locations in a symmetric fashion across the two hands led to better maintenance of these associations than in diagonal mappings. This notion was supported by lower error rates for symmetric mappings under conditions in which there was not enough time for the responses to be prepared in advance.

The MT results suggest that target-location cuing-effects are not only limited to the preparation of bimanual movements (as revealed by the RT data), but also influence their execution. Two symmetric movements (e.g., two short or two long amplitudes) initially benefited from the same symbolic cues, as they were executed quicker under these conditions. These cuing effects selectively affected symmetric movements, as the execution of asymmetric movements (e.g., short and long amplitudes) did not initially benefit from the same symbolic cues. It may be reasoned, however, that the difference in cuing was due to deferred programming which arose for symmetric movements when different symbolic cues were used to indicate these responses. With additional time for response preparation (and with the stimuli being masked at SOA 250) no effects of cuing on MT were observed, suggesting that any deferred programming of symmetric movements vanished quickly. Further, it is worth noting that in the present experiment, asymmetric movements showed the typically observed assimilation effect, where the spatio-temporal pattern of the short amplitude adjusts to the pattern of the long amplitude (Kelso, Southard, & Goodman, 1979; Marteniuk, MacKenzie, & Baba, 1984). That is, the execution of short amplitudes took longer when these were paired with long amplitudes of the other hand. In this regard, the execution of the present bimanual movements did not differ from previous observations.

Experiment 2

Experiment 2 investigates if the target-location cuing-effects for symbolic cues found in Experiment 1 generalize to bimanual movements that have to be performed in the same or different directions. We expect the results of the present experiment to replicate the ones obtained in Experiment 1. Hence, we predict that target-location cuing-effects will dominate potential motor-symmetry effects when using the same symbolic cues to indicate the end points of bimanual movements. Further, the target-location cuing-effects should be transient, with the benefits for using the same symbolic cues vanishing as the time for response preparation increases.

Method

Participants

Sixteen students (age: 20–34 years, 1 left- and 15 right-handed) participated in Experiment 2. They were each paid 12 Euros for participation. Two participants were excluded from the analysis due to a malfunctioning in data recording.

Apparatus and stimuli, task and procedure

The experimental set-up and procedure for Experiment 2 were similar to those of Experiment 1. The only exception was that this time a response board that allowed us to investigate bimanual movements in the same and different directions was used. The response board's dimensions were 30×20 cm. Square keys (4 cm side length) were used both for the starting positions and the target locations. While the centers of two home keys were arranged 7.5 cm to the left and right of the body midline in a first row, four target keys were arranged in a second row. Here, the centers of the two inner target keys were 3.5 cm and the two outer target keys were 10.5 cm to the left and right. The distance from the home keys to the associated target keys was held constant at 10 cm and an angle of either 45 or −45 degrees to the sagittal plane.

Circles and crosses (as in Experiment 1) served as symbolic cues on the computer screen and were centered between the two home keys, indicating the end point of the movements for the left and right hand, respectively. Symmetric and parallel cue-to-target-location mappings were specified by instructions. In symmetric mappings, symbols were mapped in a symmetric fashion (e.g., circle/cross/cross/circle) over the four target locations. In parallel mappings, the order was repetitive (e.g., circle/cross/circle/cross). As a result, the two movements performed on a given trial could either form a symmetrical pattern (inward or outward movements of both hands) or an asymmetrical pattern (one hand moves inward and the other hand moves outward). As in Experiment 1, this design allows for the full dissociation between the symbolic equivalence of target locations (same vs. different cues) and the physical similarity of movements (symmetric vs. asymmetric). In all other respects (including the response precuing and masking procedure), Experiment 2 was identical to Experiment 1.

Results

A total of 8.22% of the trials were excluded from the analysis of RT and MT for the following reasons: (1) a time lag between the two hands greater than 100 ms (0.27% of the trials); (2) RT less than 100 ms (anticipations, 0.31% of the trials); (3) RT greater than 1,200 ms (0.85% of the trials); (4) MT greater than 600 ms (1.06% of the trials); and (5) movements that went to wrong target locations (5.02% of the trials). Movements to wrong target locations were analyzed separately as ME.

Movement preparation–reaction time

The results for RT can be seen in Fig. 4. There was no influence of cue type (circles and crosses), and no difference between movement pairs (inside–inside vs. outside–outside and inside–outside vs. outside–inside) across conditions. We, therefore, re-organized the data for movements pairs (symmetric and asymmetric) and cue type (same vs. different symbols). Participants' RT was then analyzed in a 5 (SOA: 0, 250, 500, 1,000, 1,500 ms)×2 (mapping: symmetric vs. parallel)×2 (target-location cueing: same vs. different) ANOVA. The main effects for SOA, $F(4,52) = 91.190$, $p < 0.001$, mapping $F(1,13) = 5.731$, $p < 0.05$, and target-location cueing, $F(1,13) = 10.748$, $p < 0.01$, were significant. The interaction of SOA × mapping, $F(4,52) = 14.024$, $p < 0.001$, and the interaction of SOA × target-location cueing, $F(4,52) = 16.414$, $p < 0.001$, were both significant. Like in Experiment 1, potential movement symmetry effects on response preparation would manifest themselves in the interaction of mapping × cueing [$F(1,13) = .234$, $p = .637$]

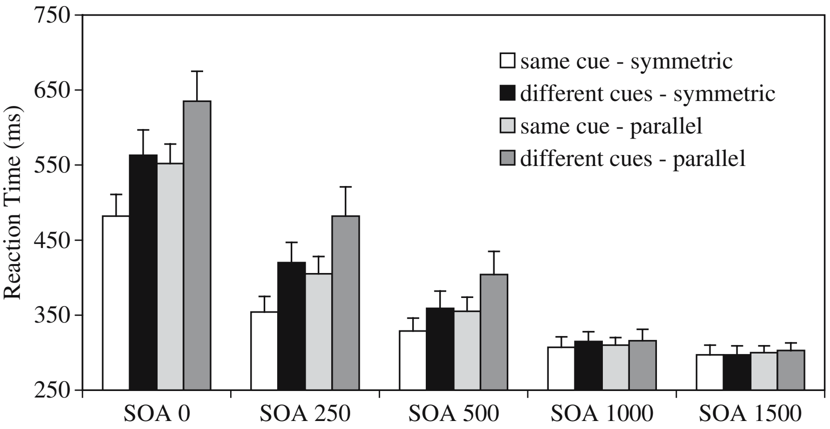

Fig. 4 Results for the RT analysis of Experiment 2. The *bars* show participant's mean RT for same and different cues, under symmetric and parallel mappings, and over variable stimulus-onset asynchronies (*SOA*). *Error bars* indicate between-participant standard errors

and/or in the three-way interaction of SOA × mapping × cueing [$F(4,52) = .476$, $p = .753$]. Both interactions were not significant. The main effect for SOA reflects that RT became shorter with longer precuing intervals, with the mean RTs being: SOA 0 = 558 ms, SOA 250 = 415 ms, SOA 500 = 362 ms, SOA 1,000 = 312 ms, and SOA 1,500 = 299 ms [no difference between SOA 1,000 and SOA 1,500; all other ps < 0.05 (pairwise comparisons between successive SOAs)]. To analyze the SOA × target-location cueing interaction, a series of comparisons between the same vs. different cues, separately for each SOA, revealed significantly faster responses with the same cues for SOA 0 (82 ms), SOA 250 (71 ms), and SOA 500 (40 ms) (*T*-tests; all p's < 0.05). There were no significant target-location cueing-effects for SOA 1,000 and SOA 1,500. Follow-up analyses of the SOA × mapping interaction revealed a significant advantage for symmetric mappings for the SOA 0 (71 ms), SOA 250 (57 ms), and SOA 500 (35 ms) (*T*-tests, all ps < 0.05). There were no significant mapping effects for SOA 1,000 and SOA 1,500.

Target specification–movement error

The main effects for SOA, $F(4,52) = 4.378$, $p < 0.01$, and target-location cueing, $F(1,13) = 5.016$, $p < 0.05$, were significant. The main effect for SOA indicates that ME decreased with longer time for response preparation: SOA 0 (5.5%), SOA 250 (4.9%), SOA 500 (3.9%), SOA 1,000 (2.8%), and SOA 1,500 (2.9%), respectively. The main effect for target-location cueing demonstrates that participants committed fewer MEs when the same cues were used (3.0%) to specify the target locations, as compared to different cues (5.0%). No other main effect and none of the interactions were significant.

Movement execution–movement time

The MT data are listed in Table 2. While there was no significant difference between symmetric (192 ms) and asymmetric (197 ms) mappings across conditions, there was a significant difference between movement pairs. We, therefore, conducted a 5 (SOA: 0, 250, 500, 1,000, and 1,500 ms)×2 (target-location cueing: same vs. different)×3 (movement pair: inside vs. outside vs. parallel) ANOVA on MT. The main effect for SOA was significant, $F(4,52) = 6.398$, $p > 0.001$, showing that MT steadily decreased after the first precuing interval: SOA 0 (202 ms), SOA 250 (196 ms), SOA 500 (189 ms) (pairwise comparisons with SOA 0; all p's < 0.05), and then remained stable at SOA 1,000 (191 ms) and SOA 1,500 (191 ms). The main effect for movement pair was also significant, $F(2,26) = 8.797$, $p = 0.001$, demonstrating that outside movements (188 ms) were always executed faster than inside movements (196 ms) and parallel movements (196 ms) (ps < 0.05). There was no significant difference between inside and parallel movements. The main effect for target-location cueing fell short of significance, $F(1,13) = 4.092$, $p = 0.064$, but the interaction of SOA × target-location cueing, $F(4,52) = 4.768$, $p < 0.01$, reached significance, indicating that the effect of target-location cueing was modulated by the precuing interval. Post hoc inspection of the MT data revealed

Table 2 Experiment 2. Mean movement times (MT) as a function of movement pair, target-location cueing, and stimulus-onset asynchrony (SOA) (between-participant standard errors, SE, in parentheses)

Target cueing	Movement pair		
	Inside MT (SE)	Outside MT (SE)	Parallel MT (SE)
SOA = 0 ms			
Same	195 (15)	186 (14)	205 (14)
Different	215 (12)	211 (11)	203 (16)
SOA = 250 ms			
Same	193 (16)	183 (15)	196 (12)
Different	200 (10)	200 (10)	201 (14)
SOA = 500 ms			
Same	190 (14)	179 (13)	192 (11)
Different	191 (9)	188 (10)	191 (13)
SOA = 1,000 ms			
Same	194 (13)	183 (12)	193 (10)
Different	196 (9)	187 (10)	194 (13)
SOA = 1,500 ms			
Same	194 (13)	182 (10)	196 (8)
Different	196 (9)	184 (8)	193 (12)

SCBs for movement execution under SOA 0 (14 ms) and SOA 250 (10 ms) (p's < 0.05). Target-location cueing did not affect the remaining precuing intervals, SOA 500, SOA 1,000, and SOA 1,500, respectively. None of the other interactions were significant.

Discussion

Experiment 2 was conducted to ascertain whether the effects of target-location cuing generalize to situations in which participants have to perform movements in same and different directions. The results of the present experiment replicated those obtained in Experiment 1. Responses were prepared faster (lower RT values) when the same symbolic cues indicated the end points of bimanual movements. The advantage of using the same symbolic cues was transient, the effects diminished as the time for response preparation increased (significant cuing effects for the SOAs 0, 250, and 500), and no significant differences were observed for longer precuing intervals (SOAs 1,000 and 1,500). This finding was corroborated by lower error rates (less ME) for similar cues. When there was sufficient time to prepare the responses, movements to different symbolic target locations were prepared equally well. Movement symmetry did not benefit response initiation at any time. Target-location cuing affected the execution of symmetric and asymmetric movements in the present experiment, which was revealed by slightly faster MT values when using the same symbolic cues in short precuing intervals (up to 250 ms). Thus, the programming of symmetric and asymmetric movements may have been initially deferred with different cues.

General discussion

The present study aimed to provide support for the notion of target-location cuing-benefits while using symbolic cues to specify the target locations of bimanual movements. The results of both experiments demonstrated that cuing target locations enhances the coordination of bimanual movements. This is supported by the finding that the bimanual responses were always initiated faster when the same symbolic cues were used to indicate the target locations, independent of whether this afforded symmetric or asymmetric movements. More specifically, target-location cuing benefited response preparation also under conditions, in which different movements had to be specified, dominating potential effects of bimanual interference during the concurrent programming of different motor parameter values of the forthcoming responses. Importantly, target-location cuing affected participants' performances for trials with precuing intervals of up to 500 ms. A stimulus similarity interpretation of this result seems rather implausible, because both cues (being same or different) must have been fully processed by this time. This was ensured by introducing stimulus masking to Rosenbaum's response precuing technique (1980, 1983), preventing participants from delayed processing of the stimuli. We, therefore, assume that the benefits observed relate to the symbolic equivalence of two target locations. The present findings are consistent with a number of studies by Diedrichsen et al. (2001, 2003). They extend these studies, however, by showing that target-location cuing-benefits are not limited to direct cuing paradigms, but can also be found when symbols are used to cue target locations.

The RT pattern across the different precuing intervals confirmed the transient nature of target-location cuing, showing that the benefits for similar target locations vanish as the time to prepare the bimanual responses increases. With sufficient time for response preparation processes to take place, movements to different target locations can be initiated as quickly as movements to the same target locations. Again, this pattern of results was independent of whether participants were required to prepare symmetric or asymmetric movements. This result is inconsistent with previous studies demonstrating that transient coupling arises relative to the concurrent programming of movement parameter values (e.g., Heuer et al.1998; Spijkers et al. 1997). However, these studies confounded cue similarity with movement symmetry, because two identical cues always indicated the preparation of similar parameter values. When this was unconfounded in the present experiments, any transient coupling effects related to the selection/specification of target locations, but not to the programming of movement parameters.

We propose that it should be always easier to coordinate the two hands under situations in which they simultaneously reach for the same target location. This notion shifts the focus onto the factors constraining discrete bimanual movements to the final states of the required actions, according with frameworks that view action control largely in terms of goal anticipations (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1997). Two recent studies can be taken as further support of this notion: in an object manipulation study, Kunde and Weigelt (2005) demonstrated that participants prepare their reaches for two objects faster under conditions in which the instructed final orientation of the two objects is the same. Further, Weigelt, Kunde, and Prinz (2005) showed that, when end-state comfort can be achieved for the two hands through the coordination of different actions, the anticipation of these goal states dominates potential intermanual interference arising from the concurrent coordination of different movements. The limitations observed for the coordination of bimanual movements to different target locations (or goal states, respectively) may thereby either relate to a selection problem (e.g., the difficulty to select two different target locations at the same time) or to an assignment problem (e.g., the difficulty to assign different target locations to the required movements) (Diedrichsen et al., 2003; Hazeltine et al., 2003).

Together the present experiments demonstrate the benefits of cuing target locations (i.e., the end points of movements) upon the coordination of discrete bimanual movements. With regard to the previously reported advantage of using direct cues over symbolic cues for the preparation of bimanual movements (e.g., Diedrichsen et al., 2001, 2003; Ivry et al. 2004), we assume that the limitations in bimanual coordination may relate predominantly to the selection/specification of target locations, rather than to the methods used to indicate these target locations. This assumption, however, must be substantiated in further experiments.

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