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Bimanual interference with compatible and incompatible tool transformations

Cristina Massen [a,*], Christine Sattler [b,1]

[a] Leibniz Research Centre for Working Environment and Human Factors, Ardeystr. 67, D-44139 Dortmund, Germany
[b] Department of Psychology, Max-Planck-Institute for Human Cognitive and Brain Sciences, Stephanstrasse 1A, 04103 Leipzig, Germany

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ABSTRACT

The present study investigates bimanual interference in a tool-use task, in which two target locations had to be touched concurrently with two tools, one for each hand. Target locations were either in the same, or in different directions for the two hands. Furthermore, the tools implemented either a compatible or an incompatible relationship between the direction of target locations and the direction of associated bodily movements. Results indicated bimanual interference when the tools had to be moved to targets in different directions. Furthermore, this interference was much more pronounced when the tools required body movements that were spatially incompatible to the cued target locations as compared to when they were compatible. These results show that incompatible relationships between target directions and bodily movement directions can aggravate bimanual interference in tool use.

Humans have a remarkable capability to coordinate the movements of both hands in order to achieve desired effects in the environment. Perhaps even more fascinating is the fact that they are likewise able to coordinate both hands when two tools are used concurrently. Consider the example of a laparoscopic surgeon, who has to coordinate two endoscopic tools inserted into the patient's body. Here, the difficulty is to generate the adequate hand movement for each required tool movement and at the same time coordinate the movements of the two tools. Up to now, comparatively little is known about how bimanual coordination with tools is accomplished and what factors determine its difficulty. The present study focused on two such factors, the symmetry of the tool movements involved, and the difficulty of the tool transformations.

In research on bimanual coordination, it has often been demonstrated, that asymmetric movements of both hands (e.g., in terms of amplitude or direction) can lead to interference, when they have to be executed concurrently (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Franz, Zelaznik, & McCabe, 1991; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997; Heuer, Spijkers, Steglich, & Kleinsorge, 2002; Swinnen, Dounskaia, Levin, & Duysens, 2001). Different explanations concerning the level at which this interference arises have been proposed (cf. Heuer, 1993). For instance, the interference could arise at the level of motor programming, when different parameters have to be specified for the movements of both hands. Consistent with this proposal, Spijkers et al. (1997) (see also Spijkers, Heuer, Steglich, & Kleinsorge, 2000; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 1998) demonstrated that lateral hand movements of either 10 cm or 20 cm amplitude are initiated about 170 ms faster when the amplitude of both movements is the same than when it is different. Importantly, this difference disappears when participants are given enough time to prepare for the movements in advance of the imperative stimulus, showing that the interference in *RT* is associated with the planning of the movement, rather than with movement execution itself. This programming hypothesis has been challenged, however, by the work of Diedrichsen and colleagues (Diedrichsen, Hazeltine, Kennerly, & Ivry, 2001; Diedrichsen, Ivry, Hazeltine, Kennerly, & Cohen, 2003; Hazeltine, Diedrichsen, Kennerly, & Ivry, 2003, see also Kunde & Weigelt, 2005; Weigelt, Rieger, Mechsner, & Prinz, 2007). According to these authors, the interference that arises in *RT* during spatially asymmetric bimanual movements is mainly due to the use of symbolic cues (e.g., the word SHORT for a short amplitude movement and the word LONG for a long amplitude movement) instead of direct movement cues in most of the studies. Symbolic cues require an additional translation stage in which the required response for each cue has to be determined, a process that may cause substantial interference when different cues for both hands have to be selected and processed concurrently. Consistent with this view, Diedrichsen et al. (2001) were able to show that bimanual interference disappears when target locations for both hands are directly (rather than symbolically) cued. According to these authors, the use of symbolic cues thus introduces artificial environmental conditions that produce interference effects on their own (cf. Goodman & Kelso, 1980).

Heuer and Klein (2006) further investigated the influence of cue–response translation on intermanual interactions. They used either

* Corresponding author. Tel.: +49 2311084311; fax: +49 2311084340.
E-mail addresses: massen@ifado.de (C. Massen), sattler@cbs.mpg.de (C. Sattler).
[1] Tel.: +49 3419940145.

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symbolic or direct cues and presented them either on a monitor, thus introducing a separation between visual and motor space, or directly at the target locations on the table, with an alignment of visual and motor space. When cues are presented on a monitor, participants are forced to code movements in terms of allocentric amplitudes and directions, whereas with an alignment of motor and visual space, movement specification in terms of egocentric target locations is possible. The general hypothesis was, that interference should be stronger when the links between cues and movement characteristics are only indirect (as is the case when symbolic cues are used or when there is a separation of visual and motor space). The results confirmed that bimanual interference was larger with symbolic cues as compared to direct cues. However, in contrast to the results by Diedrichsen et al. (2001), direct cues did not abolish interference in *RT* completely. Furthermore, a separation of visual and motor space had no significant impact on the magnitude of the interference effect, that is the *RT* difference between congruent and incongruent movements of the two hands was roughly the same for movement cues presented on the table and movement cues presented on the monitor.

In tool use, there is also a separation of visual and motor spaces in the sense that the goal of the action (e.g., the location to which the endoscopic tool is moved) and the position to which the body movement is executed, are spatially separated. Hence, when the goal of a tool-use action is directly cued, the body movement is not directed towards this goal location, but has to be executed to another location in space instead. In contrast to the study by Heuer and Klein (2006), both the cued (goal) location and the motor endpoint are usually in the same plane and can be coded egocentrically. Therefore, the first question addressed in this study was whether bimanual interference is found when two concurrent tool-use actions have to be executed to directly cued goal locations.

A second, related question concerns the role of the tool transformation for bimanual interference in tool use. For some tools, the relationship between the direction in which the tool moves and the direction in which the hand moves is incompatible. Consider again the example of an endoscopic tool inserted through an aperture in the patient's body. Here, the aperture serves as a pivot that inverts the hand movement direction into an opposite movement of the tool: If the surgeon moves the hand to the left, the distal end of the endoscopic tool moves to the right and vice versa. This inversion of movement is also known as the “fulcrum effect” and has been suspected to contribute to an increased rate of operative injuries, especially in novice surgeons (Savader, Lillemoe, & Prescott, 1997; Crothers, Gallagher, McClure, James, & McGuigan, 1999). Other tools (e.g., a hammer) implement a compatible relationship between the direction of hand movement and the direction of the corresponding movement of the tool. For unimanual reactions, several studies (e.g., Kunde, Müsseler, & Heuer, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008; Massen & Prinz, 2007) have shown, that an incompatible relationship between the movement of a tool's distal end and the associated bodily movement produces performance costs as compared to a compatible one (but see Proctor, Wang, & Pick, 2004). Such compatibility effects are usually attributed to an increased difficulty of stimulus–response translation when the relationship between stimuli and responses is incompatible (e.g., Hasbroucq, Guiard, & Kornblum, 1989; Hasbroucq, Mouret, Seal, & Akamatsu, 1995; Adam, 2000). Therefore, the question addressed in this study was whether incompatible tool transformations would increase interference in bimanual tool use.

We investigated this issue using a lever paradigm (cf. Herwig & Massen, 2009), in which participants touched near and far target locations in space with two levers, one for each hand. In experiment 1, the pivotal points of the levers were located in such a way that either a compatible relationship resulted between the direction of target locations and the direction of bodily movements, or an incompatible relationship. In experiment 2, the pivotal points of the levers were constant, but the target locations were varied in such a way that either a compatible or an incompatible relationship resulted between the direction of target locations and the direction of bodily movements. The first question was whether it would be more difficult to reach to spatially asymmetric target locations (i.e. one lever movement to the far target location and the other to the near target location) as opposed to initiating two lever movements to spatially symmetric target locations. The second question was whether the magnitude of this interference effect would be modulated by the spatial compatibility between the direction of target locations and the direction of associated bodily movement directions.

1. Experiment 1

In experiment 1, participants had to operate two horizontal levers, one with the left and the other with the right hand (see Fig. 1). The handle of the left lever was on its left side and the handle of the right lever was on its right side.

The task was to touch two target points with the levers (one with each lever) by moving the handles in the appropriate direction (towards or away from the body). The target points were located in different distances in front of the participant, either between the lever and the participant (near target point) or on the other side of the lever (far target point). We used two different kinds of levers in different experimental blocks. In the first lever type, the pivotal points of the levers were between the target points and the lever handles (Fig. 1, first and second rows). In these conditions, the handles have to be moved away from the body (i.e. arm extension was required) to touch the near target points and towards the body (i.e. arm flexion) to touch the far target points. This results in an incompatible relationship between the direction of a target point and the direction of the corresponding bodily movement to reach it. In the second type of lever, the pivotal points of the levers were situated at the (distal) ends of the levers (Fig. 1, third and last rows). In these conditions, the handles have to be moved away from the body to touch the far target points and towards the body to touch the near target points. This results in a compatible relationship between the direction of a target point and the direction of the corresponding bodily movement to reach it. The lever type used was always the same for both hands and within an experimental block, whereas target direction was varied between trials and hands.

1.1. Method

1.1.1. Participants

24 right-handed participants from the subject pool of the Max-Planck-Institute in Leipzig served as participants (12 female, mean age = 25.2 years). They were paid 7 Euro for their participation.

1.1.2. Apparatus

The apparatus consisted of a pair of metal, horizontal levers, that were mounted on two plastic plates each (34.4 cm × 45.0 cm). For each lever, two possible target points (wired, elastic pins with a light diode on top of it), which were situated orthogonal (at a distance of 6.9 cm) to the lever, were mounted on the plate. The lever had to be rotated by about 20° to touch one of these targets. At the end of the movement, the lateral end of the handle was in a distance of 4 cm (in the *y*-dimension) to its starting position when the pivotal point of the lever was near the handle (incompatible condition), and it was in a distance of 13.8 cm (in the *y*-dimension) to its starting position when the pivotal point was situated at the distal end of the lever (compatible condition).

The apparatus was controlled by a standard IBM-compatible computer and connected to it via the serial and parallel port. The light diodes could be turned on and off by signals from the computer. Furthermore, it was possible to lock and unlock each lever with the experimental software by activating magnets attached beneath it. The

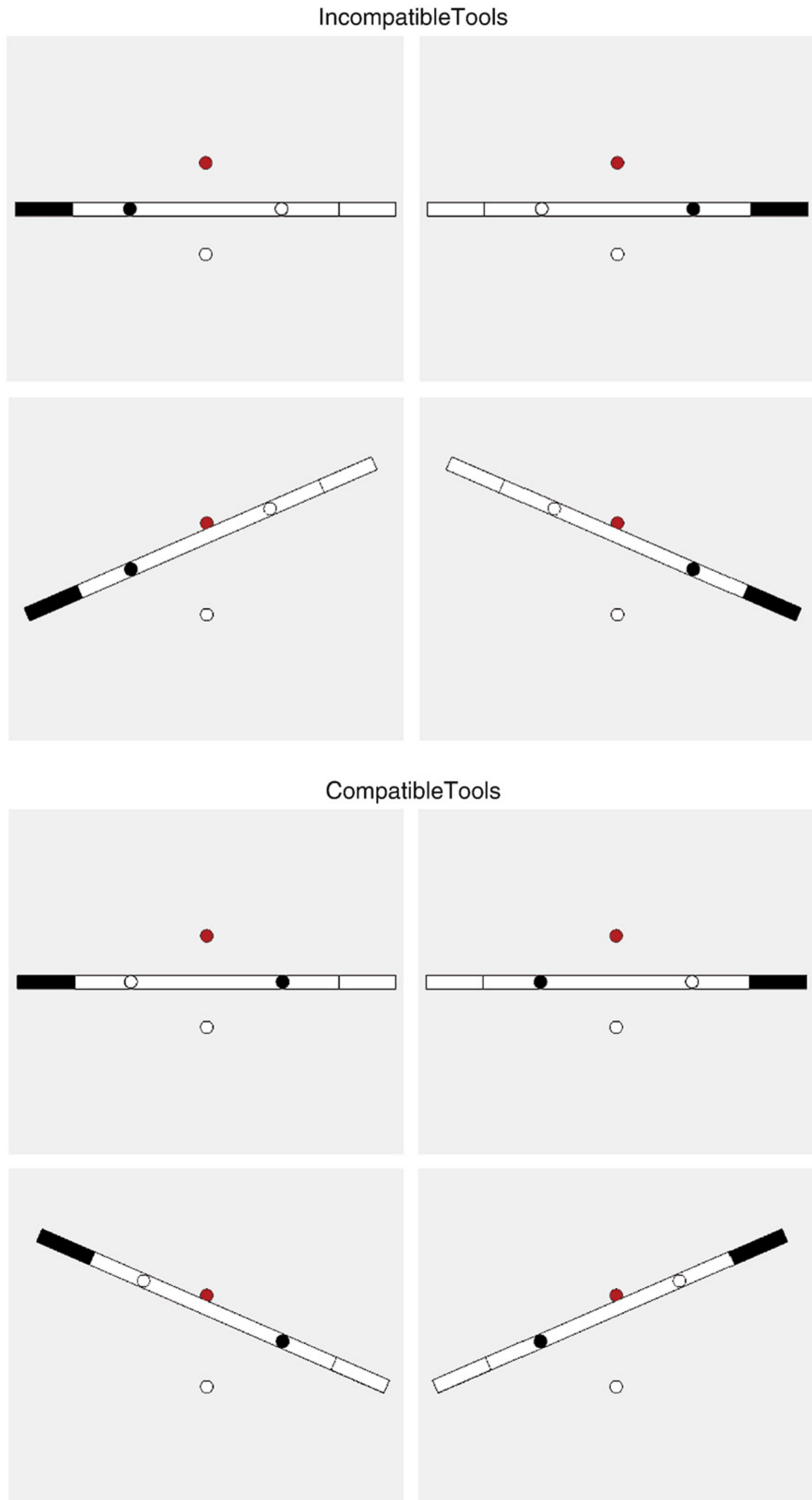

Fig. 1. Illustration of the levers used in experiment 1. In the first and second rows, the pivotal points of the levers (shown as black circles on the lever) are situated near the handles (shown as black rectangles) and the target-to-movement transformation is incompatible. The first row shows the starting position of the levers, in the second row, the end positions of the levers are shown for the case, where the upper targets have to be touched. The third and fourth rows show the case where the pivotal points are situated at the distal end of the lever and the target-to-movement transformation is compatible.

computer received signals about the position of each lever by means of an incremental shaft encoder (resolution 5000 counts per revolution). Movement initiation in one or the other direction was defined as a lever rotation of 0.072° in a clockwise or counterclockwise direction.

1.1.3. Design and procedure

The experiment took place in a dimly illuminated room. Each trial started with a preparation interval of 2000 ms. Then two target diodes (one for each lever) were turned on. Simultaneously with the appearance of the lights, the levers were unlocked and the subject had to react. Participants were instructed to initiate the movements of the two levers simultaneously. Reaction time for each hand was defined as the time from the lighting of the diode to the levers' leaving of the resting position. As soon as the subject reacted and the lever left the resting position, the respective diode was turned off until the target point was reached by the lever, which caused the light diode on the target point to again light up. Movement time for each hand was measured from the point in time when the lever left its resting position until the target point was touched. After two target points had been touched (one with each lever), the participant received auditory feedback whether both reactions were correct. As soon as the levers moved away from the targets, the lights were turned off. If participants had not reacted simultaneously with both levers in the respective trial (i.e., the difference between both hands was larger than 200 ms), they received an additional feedback (stressing the importance of reacting simultaneously) after the levers had reached the resting position. Then the next trial started.

Participants went through two experimental blocks of 96 trials, one with the compatible and one with the incompatible relationship between targets and bodily movements. Block type order was counterbalanced between participants. Prior to each block, participants were given the opportunity to get acquainted with the respective tool functioning. Then, they performed 16 practice trials with each type of lever. Within each experimental block, there were four different possible target combinations for both hands (left and right far target, left and right near target, left far target/right near target, left near target/right far target). Each target combination appeared equally often, in a randomized order for each participant, and no more than three times in a row.

The whole experiment took approximately 40 min.

1.2. Results

Dependent variables were error rates and reaction and movement times for correct responses. Errors were all reactions in which at least one of the movements was initiated in the wrong movement direction (irrespective of whether it was corrected or not). We excluded all trials with a *RT* of one of the movements less than 100 ms (anticipations, 0.8% of the data), larger than 5000 ms (misses, 0.2% of the data), or with a lag between both hands larger than 200 ms (5.8% of the data). *RT*s (and *MT*s) were averaged across hands. An alpha level of .05 was used for all statistical tests.

In an initial analysis of reaction times with tool type (compatible vs. incompatible), target congruence (same target direction vs. different target direction) and target position for left hand (near target vs. far target) as factors, target position did not have any significant impact on the results. We therefore collapsed data for near and far target positions and analyzed reaction times with a repeated-measures ANOVA with tool type (compatible vs. incompatible) and target congruence (same target direction vs. different target direction) as factors (cf. Fig. 2). The ANOVA revealed a main effect of target

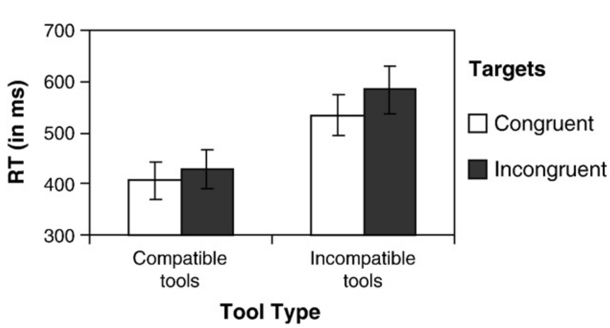

Fig. 2. Mean *RT* (in ms) as a function of tool type and target congruence in experiment 1. Error bars indicate standard deviations.

Table 1
Error rates (in %, standard deviations in brackets) as a function of tool type and target condition in experiments 1 and 2.

Tool type		Target condition: Congruent targets	Incongruent targets
Exp 1	Compatible	6.3 (5.3)	7.4 (5.0)
	Incompatible	1.7 (2.6)	6.2 (4.8)
Exp 2	Compatible	7.6 (6.4)	7.1 (5.8)
	Incompatible	2.5 (4.1)	17.3 (12.7)

congruence ($F(1, 23) = 59.4$; $p < .01$; $MSE = 540.1$), that was due to shorter reaction times when both movements were executed to targets in the same direction (470 ms) as compared to targets in different directions (507 ms). The effect of target congruence was significantly larger for incompatible tools (50 ms) than for compatible ones (23 ms), giving rise to a significant interaction of target congruence and tool type ($F(1, 23) = 8.0$; $p < .01$; $MSE = 546.7$). A main effect of tool type ($F(1, 23) = 228.6$; $p < .01$; $MSE = 2098.6$) reflected shorter *RT*s with compatible (418 ms) as compared to incompatible tools (559 ms).

For error rates (cf. Table 1), there was a main effect of target congruence ($F(1, 23) = 9.8$; $p < .01$; $MSE = 19.7$), reflecting more errors to targets in different directions. The interaction of target congruence and tool type was also significant ($F(1, 23) = 5.7$; $p < .05$; $MSE = 12.3$). Like for *RT*s, this interaction was due to a larger effect of target congruence for incompatible tools. Error rates were low overall, but more errors occurred for the compatible tools ($F(1,23) = 10.8$; $p < .01$; $MSE = 19.0$). This might reflect a more liberal response criterion with compatible tools (i.e. participants tend to respond faster and more error-prone when using compatible tools).

The ANOVA on movement times (cf. Table 2) revealed neither significant effect of target congruence ($F(1, 23) = 2.7$; $MSE = 524.8$), nor of the interaction of target congruence and tool type ($F(1, 23) = 1.6$; $MSE = 260.9$). The only significant effect was a main effect of tool type ($F(1, 23) = 49.9$; $p < .01$; $MSE = 5167.9$), that was due to shorter movement times with incompatible tools. This effect is due to the shorter distance the lever handles have to travel in the incompatible condition until the distal part of the tool reaches the target.

1.3. Discussion

The results of experiment 1 show that spatial congruency effects occur with direct cuing of target locations in bimanual tool use. Furthermore, these spatial congruency effects are significantly larger if an incompatible relationship exists between the direction of target locations and the direction to which bodily movements have to be executed.

The results obtained provide further evidence for the notion that bimanual interference in *RT* occurs (at least in part) at the level of stimulus–response translation and that the difficulty of this translation process determines the amount of bimanual interference. This is because bimanual interference effects in our study were modulated by spatial compatibility, and spatial compatibility effects have been shown to occur at the stage of stimulus–response translation, also

Table 2
Movement times (in ms, standard deviations in brackets) as a function of tool type and target condition in experiments 1 and 2.

Tool type		Target condition: Congruent targets	Incongruent targets
Exp 1	Compatible	325 (152)	322 (150)
	Incompatible	226 (99)	214 (87)
Exp 2	Compatible	295 (93)	324 (99)
	Incompatible	341 (120)	331 (115)

called response selection stage (e.g., Hasbroucq et al., 1989, 1995; Adam, 2000). In contrast to previous studies, however, the increased demands of response selection are not due to artificial, symbolic cuing conditions, but are manipulated under rather natural, direct cuing conditions.

However, a potential problem associated with these conclusions is, that bodily movements in the conditions with incompatible and compatible tool transformations are not fully comparable. Although they are equivalent with respect to the directions of movements, they slightly differ in other respects like force and movement amplitude, because of the different locations of the levers' pivotal points. We therefore ran a second experiment, in which we kept bodily movement aspects constant between conditions with compatible and incompatible tool transformations.

2. Experiment 2

In experiment 2, we used levers with only one pivotal point in the centre. The compatibility of the relationship between target directions and bodily movement directions was manipulated by presenting the targets in different distances to the lever handles (cf. Fig. 3). If targets are located far from the handle, in the region between the tool's end and the pivotal point, the relationship between target direction and bodily movement direction is incompatible (cf. Fig. 3, first and second rows). If targets are located near the handle, in the region between handle and pivotal point, the relationship between target direction and bodily movement direction is compatible (cf. Fig. 3, third and last rows). Because the pivotal point of the lever is constant in both conditions, bodily movements in the same direction have identical movement characteristics, regardless of whether the lever action is directed towards a target near the handle (compatible tool transformation) or towards a target at the other end of the lever (incompatible tool transformation).

2.1. Method

2.1.1. Participants

24 right-handed participants from the subject pool of the Max-Planck-Institute in Leipzig served as participants (12 female, mean age = 23.6 years). They were paid 7 Euro for their participation.

2.1.2. Apparatus

The apparatus consisted of a pair of metal, horizontal levers, that were shorter and finer (42 cm × 1 cm) than those used in experiment 1. They were mounted on two plastic plates (each 25.5 cm × 22 cm in size) and had a pivotal point in the centre each. They had to be grasped and operated at the lateral ends, which were in a distance of 86 cm from one another. For each lever, there were two target points (illuminable by light diodes situated under the plastic surface) to the left of the pivotal point, and two target points to the right. The horizontal distance to the pivotal points was 4.75 cm, the vertical distance was 3.25 cm. In the blocks with a compatible relationship between target and movement direction, only the target points that were between handle and pivotal point of each lever were used. In the blocks with an incompatible relationship between target and movement direction, only the target points that were on the side opposite to the handle were used (cf. Fig. 3).

The apparatus was controlled by a standard IBM-compatible computer and connected to it via the parallel port. The light diodes could be turned on and off by signals from the computer. Furthermore, it was possible to lock and unlock each lever with the experimental software by activating magnets attached beneath it. The computer received signals about the position of each lever by means of an incremental shaft encoder (resolution 6000 counts per revolution). Movement initiation in one or the other direction was defined as a lever rotation of 0.06° in a clockwise or counterclockwise direction.

2.1.3. Design and procedure

Design and procedure were the same as in experiment 1. Participants went through two experimental blocks of 96 trials, one with each type of tool (i.e. relationship between target direction and movement direction). Block type order was counterbalanced between participants. Prior to each block, participants were given the opportunity to get acquainted with the respective tool functioning. Then, they performed 16 practice trials with each tool. Within each experimental block, there were four different possible target combinations for both hands (left and right far target, left and right near target, left far target/right near target, left near target/right far target). Each target combination appeared equally often, in a randomized order for each participant, and no more than three times in a row.

The whole experiment took approximately 40 min.

2.2. Results

Trials with a *RT* of one of the movements less than 100 ms (anticipations, 0.6% of the data), larger than 5000 ms (misses, 0.0% of the data), or with a lag between both hands larger than 200 ms (3.6% of the data) were excluded from analysis. A repeated-measures ANOVA on reaction times (see Fig. 4) with tool type (compatible vs. incompatible) and target congruence (same target direction vs. different target direction) as factors yielded a main effect of target congruence ($F(1, 23) = 32.2$; $p < .01$; $MSE = 16388.2$), that was due to shorter reaction times when both movements were executed to targets of the same direction (500 ms) as compared to targets in different directions (648 ms). The effect of target congruence was significantly larger for incompatible tools (248 ms) than for compatible ones (48 ms), resulting in a significant interaction of target congruence and tool type ($F(1, 23) = 13.6$; $p < .01$; $MSE = 17638.7$). There was also a main effect of tool type ($F(1, 23) = 5.8$; $p < .05$; $MSE = 45690.0$), that was due to shorter *RT*s for compatible tools (522 ms) than for incompatible ones (627 ms).

For error rates (cf. Table 1), there was a main effect of target congruence, reflecting higher error rates in the conditions with incongruent target directions ($F(1, 23) = 24.8$; $p < .01$; $MSE = 49.3$). However, this effect of target congruence was only significant for incompatible tools, giving rise to a significant interaction of tool type and target congruence ($F(1,23) = 33.4$; $p < .01$; $MSE = 41.9$). The main effect of tool type was also significant ($F(1, 23) = 5.4$; $p < .05$; $MSE = 30.0$) and reflected higher error rates for incompatible tools.

The ANOVA on movement times (cf. Table 2) yielded no significant main effect, but a significant interaction of tool type and target congruence ($F(1, 23) = 10.7$; $p < .01$; $MSE = 815.2$). For compatible tools, movement times were shorter to congruent (295 ms) as compared to incongruent targets (324 ms), whereas for incompatible tools, movement times did not differ as a function of target congruence.

2.3. Discussion

The results of experiment 2 replicate those of experiment 1 in two important respects. First, they show that reaction times are longer and error rates higher when participants move two tools to targets that differ in direction for the two hands. Second, the amount of interference is significantly larger when the relationship between target directions and bodily movement directions is incompatible, as compared to when it is compatible. Importantly, this was found under conditions where bodily movement characteristics for incompatible and compatible tools are comparable. The only exception to this general result was the small advantage for congruent targets in

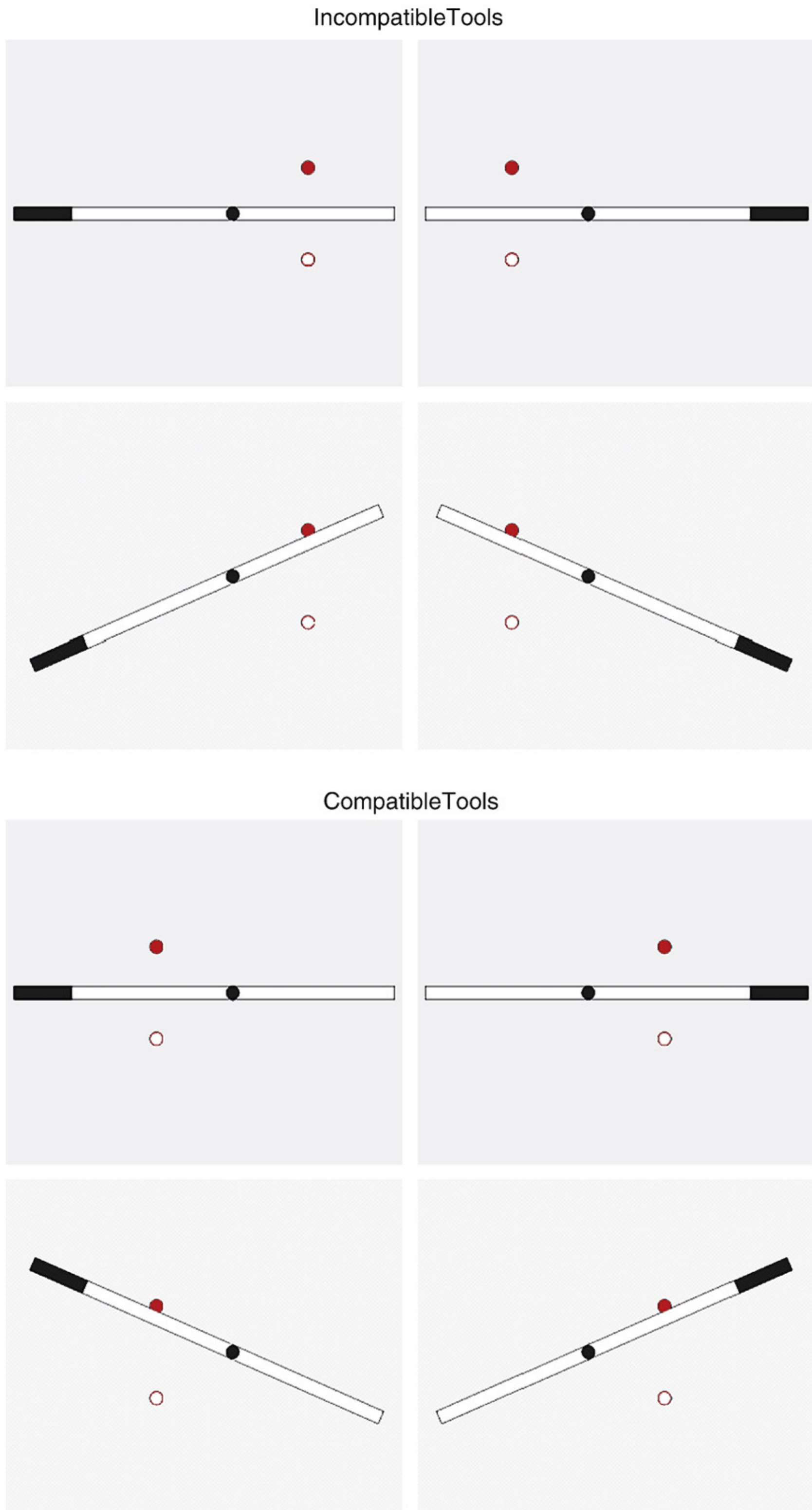

Fig. 3. Illustration of the levers used in experiment 2. Each lever has only one pivotal point, which is located in the middle. The first and second rows of the figure show start and end positions for the case where the upper targets have to be touched and the target-to-movement transformation is incompatible. The third and fourth rows show the case where the target-to-movement transformation is compatible.

movement times, that occurred only with the compatible, but not with the incompatible tools. This effect was rather small in comparison to the large interference effects found in reaction times and error rates for the incompatible tools. An explanation for it might be, that the use of only one pivotal point for the levers in experiment 2 required different positions of the targets in the conditions with compatible and incompatible tool transformations. In the condition with compatible tool transformations, the distance between the two targets for the hands was larger than in the conditions with incompatible tool transformations. This might render it more difficult

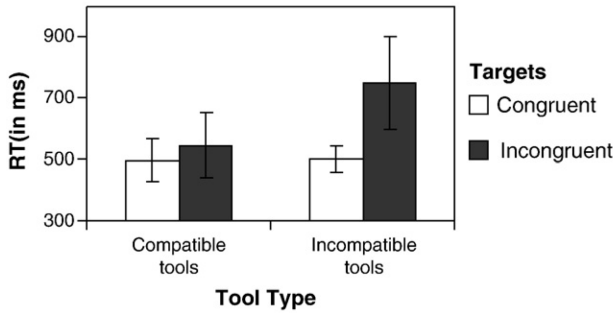

Fig. 4. Mean *RT* (in ms) as a function of tool type and target congruence in experiment 2. Error bars indicate standard deviations.

to simultaneously move the tools to the targets in this condition, especially when target directions are incongruent. However, it should be emphasized that this hypothesis cannot explain the increased interference found in *RTs* and error rates for the incompatible tools. If any, one would expect larger interference effects for compatible tools as compared to incompatible tools according to this hypothesis.

3. General discussion

The goal of the present study was to investigate the degree of bimanual interference that results when people have to concurrently move two tools to targets in different directions. In particular, we asked whether bimanual interference is influenced by the tool transformation involved, i.e. the compatibility of the relationship between target and bodily movement direction. Based on previous studies, in which larger interference effects with more indirect links between visual cues and bodily movements have been shown, we predicted larger interference effects for an incompatible relationship between distal target direction and bodily movement direction. The results of the two experiments conducted confirm this prediction in showing that bimanual interference in *RT* and error rate is significantly increased when participants have to coordinate incompatible as compared to compatible tool transformations. These results extend previous research in showing, that the translation of a direct target cue into a spatially incompatible body movement increases bimanual interference in a similar way as does the translation of a symbolic cue into a required body movement. In the study by Heuer and Klein (2006) translating a spatial cue presented on a monitor into a movement to be performed on the table did not increase bimanual interference relative to directly cuing movement targets on the table. However, in their study the relationship between target directions and amplitudes on the monitor and the corresponding movement directions and amplitudes on the table was always compatible (i.e. a finger movement on the table generated a cursor movement with the same amplitude and direction on the monitor). Presumably, response selection is easy under these circumstances, whereas it is more difficult with either symbolic cues or spatially incompatible cues. In the former case the difficulty of response selection is due to the selection of a response on the basis of a (rather arbitrary) mapping between symbolic cues and associated movements kept in memory, whereas in the latter case it is most likely due to code interference during the translation of spatial target features into movement features and/or to an automatic activation of the compatible, but incorrect movement (cf. Kornblum, Hasbroucq, & Osman, 1990; Wascher, Schatz, Kuder, & Verleger, 2001). The results thus suggest that increased response selection demands, whether they are caused by memory-based selection processes or by interfering codes, increase bimanual interference.

Compared with other studies on bimanual coordination, in which either no *RT* interference effects (e.g., Diedrichsen et al., 2001) or only small effects in the order of 10 ms (e.g., Heuer & Klein, 2006) were found with direct spatial cues, the magnitude of the interference effects found in our study was quite substantial, even in the condition with compatible tool transformations (e.g., 48 ms in experiment 2). This finding suggests that moving tools towards directly cued spatial targets engages different processing mechanisms than moving one's hands towards these targets. Using tools seems to increase *RT* interference in a similar way as does the selection of movements on the basis of symbolic cues. This finding converges with studies demonstrating that the neural mechanisms involved in translating symbolic cues into associated movements substantially overlap with those responsible for tool use. For instance, in an fMRI study by Diedrichsen, Grafton, Albert, Hazeltine, and Ivry (2006), relative to spatially cued movements, symbolically cued movements were associated with an increase in activation of a left-lateralized network including the intraparietal sulcus, the inferior parietal cortex, the premotor cortex, and the inferior frontal cortex. This network seems to be part of a distributed left-hemisphere network that has been associated with skilled movements and complex tool use in general (e.g., Johnson-Frey, 2004; Johnson-Frey, Newman-Norlund, & Grafton, 2005).

3.1. Practical implications

The results reported also have practical implications. For instance, quite some research has been conducted on applied aspects of minimally invasive surgery techniques. While earlier studies compared performance in endoscopic surgery to that in open surgery (Berguer, Smith, & Chung, 2001) or focused on factors influencing the complex visuo-motor transformations involved in endoscopic surgery (e.g., Hanna, Shimi, & Cuschieri, 1997, 1998; Zheng, Janmohamed, & MacKenzie, 2003; Tendick, Jennings, Tharp, & Stark, 1993), more recent studies have acknowledged the problems that arise from the bimanual character of many laparoscopic tasks. It has been shown that these tasks are often better performed by dyad teams than by a single operator using two hands (Zheng, Swanström, & MacKenzie, 2007; Zheng, Verjee, Lomax, & MacKenzie, 2005). With regard to this applied research, our results show that whenever tools with an incompatible tool transformation like an endoscopic instrument inserted into a patient's body are used, two factors produce a substantial performance cost relative to the use of compatible tools. First, there is a cost of moving the hand in the opposite direction as the intended tool movement. This has already been shown by Kunde et al. (2007), who found longer reaction times and higher error rates for incompatible as compared to compatible tools. In their study on unimanual tool use, participants moved the handle of a lever to the left or right in order to generate a tool movement to the left or right. In our study, in which participants concurrently moved two handles towards or away from the body in order to generate respective tool movements, results were similar with longer overall reaction times for incompatible tools in experiment 1 and longer reaction times as well as higher error rates in experiment 2.

In the case, where two tools are used concurrently, the problems that incompatible tool transformations already bring about in unimanual tool use are aggravated. Here, substantial bimanual interference may arise, when the tools have to be moved to targets in different directions. One possibility to overcome these problems, at least in the case of laparoscopic surgery, might be to provide reinverted visual feedback of the tools' movements on a control monitor, such that the visual feedback of the tools' movements on the monitor is again compatible with the surgeon' s hand movements. Such a possibility has already been investigated by Crothers et al. (1999) and has proven successful in improving performance. In any case, if it is not possible to avoid incompatible tool transformations, one should be aware of the potential costs of using such tools, especially with asymmetrical movements in bimanual tool use.

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