Spatial Compatibility Effects With Tool Use

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Objective: We explored constraints in responding to spatially variable stimuli when hand movements are transformed into inverse movements of a tool. **Background:** Generally, the spatial compatibility between stimuli and responses is a powerful determinant of performance. However, many tasks require the use of simple tools such as first-class levers that transform hand movements into inverted movements of a tool. What types of compatibility effects arise with such tools? **Method:** Participants moved the tip of a pointer to the left or right according to the color of a stimulus. The pointer was manipulated either directly, so that a hand movement caused a pointer movement in the corresponding direction, or indirectly, so that the hand moved the pointer in the opposite direction. **Results:** Responding was faster when the location of stimulus and the movement direction of the tool corresponded than when they did not correspond, independent of the movement direction of the hand. This occurred when stimulus location was task relevant (Experiment 1) as well as when it was task irrelevant (Experiment 2). Furthermore, responding was delayed when the hand and the relevant end of the tool moved in noncorresponding rather than corresponding directions. **Conclusion:** These results point to two distinct compatibility effects in tool use: one that relates to the transformation of stimuli into goals and one that relates to the transformation of goals into movements. **Application:** Potential applications of this research include the prediction and possibly manipulation of unwanted "fulcrum effects" in laparoscopic surgery and other first-class lever movements.

INTRODUCTION

Fortunately, in the modern world of work, the requirements for mere muscle power have decreased because of the extensive use of tools. For example, lifting a heavy weight with a crane or machining a workpiece with a computer-controlled milling cutter requires no more effort than a few button presses or lever movements on the input device of a corresponding machine.

However, the use of tools introduces novel challenges for the motor control system. Often tools produce unfamiliar transformations between manual actions and intended effects. This is the case even with very simple tools, such as so-called first-class levers with a pivot. A representative task that includes such a tool, which to some extent prompted the present work, is laparoscopic surgery. Here the surgeon operates through a tiny aperture in the patient's abdomen with an endoscopic tool (see Figure 1).

This operation technique has many advantages from a medical point of view, but it creates problems for the surgeon as well. The aperture at the abdominal wall serves as a pivot that inverts hand and tool movement directions: If the surgeon moves the hand upward, the relevant end of the tool, which is typically displayed on a control monitor, moves downward, and vice versa. This inversion of movement direction is known as the "fulcrum effect," and it is likely to contribute to the increased rate of operative injuries as compared with open surgery (Savader, Lillemoe, & Prescott, 1997). Thus it is desirable from a theoretical and from a practical point of view to understand the constraints of the acquisition and application of such tool transformations.

The present study focused on two such

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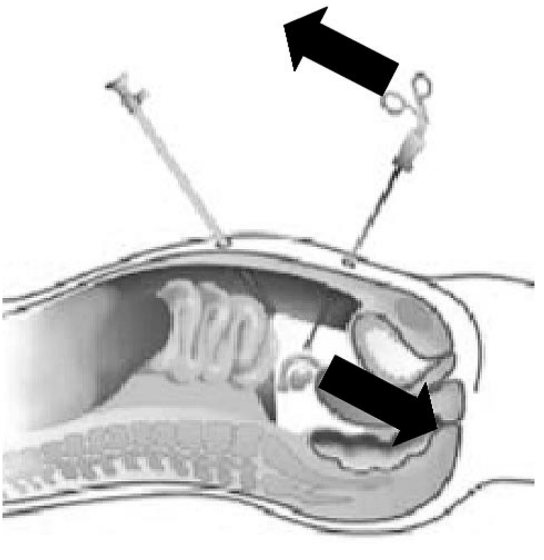

Figure 1. Illustration of an endoscopic tool in laparoscopic surgery. The pivot of the tool transforms the surgeon's hand movements into inverted movements of the tip of the tool.

constraints. The first one is spatial stimulus-response (S-R) compatibility. Normally, responding to a stimulus is faster and more accurate when the stimulus location and response location spatially correspond (e.g., responding to a left stimulus with a left response) than when they do not correspond (e.g., responding to a left stimulus with a right response; Fitts & Seeger, 1953; see Proctor & Vu, 2006, for a recent review). This is a strikingly robust phenomenon that occurs even when stimulus location is task irrelevant – for example, when responding to the color of a left or right stimulus with a left or right response (Simon, 1969).

Does this phenomenon apply to transformed movements as well? The available evidence suggests that this might be so. Hommel (1993) showed that pressing a key in response to a stimulus is faster when a salient effect of the key press corresponds to the stimulus location, independent of the location of the key itself. Specifically, when a left key press switched on a lamp on the right side, pressing this key was faster with a stimulus on the right rather than on the left. What counts seems to be the correspondence between stimulus and intended effect (lamp) rather than the correspondence between stimulus and response (key press). However, with only two discrete responses and response effects, there was no continuous spatial transformation of hand movements into tool movements. It is thus unclear if this finding holds for continuous movement-effect inversions as well.

More telling in this respect are recent experiments by Proctor, Wang, and Pick (2004; see also Wang, Proctor, & Pick, 2003). Based on work by Guiard (1983), these authors studied wheel-rotation responses to tones presented to the left or right. The most relevant conditions in the present context used wheel rotations that resulted in the movement of a cursor on a display. Clockwise wheel rotations moved the cursor to the right, whereas counterclockwise rotations moved it to the left. Wheel rotations were initiated faster when the stimulus location corresponded to the direction of the to-be-produced cursor movement, even when the wheel was grasped at its bottom, so that hand and cursor moved in opposite directions (Proctor et al., 2004, Experiment 3). Thus, it seems that correspondence between stimulus location and effect movement (cursor) rather than between stimulus locations and hand movement is crucial.

However, this was the case only under specific conditions. When the cursor movement occurred after completion of the 8° wheel rotation, no effect of stimulus-cursor correspondence was found. Interestingly, in a set of experiments from our group (Müsseler, Kunde, Gausepohl, & Heuer, in press), the spatial correspondence between stimulus and tool effect did impact responding even with temporal delays up to 2,000 ms between hand and effect. It is thus fair to say that the necessary conditions for coding responses in terms of response effects are not yet settled. Consequently, it is questionable whether the spatial correspondence between stimuli and hand movements or stimuli and tool movements is crucial when tools such as laparoscopic instruments are used.

The second question addressed was whether the inversion of hand and tool movement would cause costs as such, independent of the spatial correspondence to the stimulus. One must keep in mind that when hand and tool move in opposite directions, these movements are spatially incompatible with each other. Provided that both aspects of a tool-mediated action (i.e, the proximal movement of the hand and the distal movement of the tool) are cognitively represented, this incompatibility might cause some interference. Regarding such tool-induced costs, the available evidence is ambivalent. Mechsner, Kerzel, Knoblich, & Prinz (2001) found that the normally observed inferiority of asymmetrical over symmetrical cyclic movements of the hands disappears when asymmetric hand movements are transformed into symmetric tool movements. Hence in this situation, the tool transformation was beneficial rather than harmful.

In the wheel-rotation study by Proctor et al. (2004, Experiment 2), when participants rotated the wheel by grasping it at the bottom while attempting to move a tape at the wheel's top in the opposite direction, responding was slightly, but not systematically, delayed as compared with a condition in which participants had only to move the hand, without having to move the tape. However, there are also observations suggesting that actions are harder to generate when they predictably produce incompatible sensory effects. For example, when participants manipulated a cursor on a screen with a handle, it took longer to initiate a movement when the handle and cursor moved in noncorresponding rather than corresponding directions (Kerr, 1976).

Likewise, pressing a key forcefully is harder when this key press produces a quiet rather than a loud tone (Kunde, 2001; Kunde, Koch, & Hoffmann, 2004), and uttering a word is harder when the vocal response triggers the presentation of an incompatible rather than a compatible word on a visual display (Koch & Kunde, 2002). Hence, there are reasons to speculate that mutually incompatible proximal and distal aspects of an action, under certain conditions, cause notable interference. From the perspective of applied research, it would be important to know whether such conditions are met when hand movements are transformed into spatially incompatible lever movements.

EXPERIMENT 1

In Experiment 1 we implemented the basic paradigm (see Figure 2). The participants were to move the distal tip of a simulated tool presented on a computer screen either toward a stimulus or away from it, depending on the stimulus's color (comparable to a surgeon moving a laparoscopic tool toward a tissue to treat it or moving away from it to avoid damage). Hence, stimulus location was a relevant feature as it determined, in conjunction with stimulus color, the required movement direction.

Moving the tool was achieved by moving a handle, which was mounted in front of the screen, to the left or right. There were two conditions. In the *indirect* control condition (Figure 2, top panels) the lever was connected to the lower end of the tool and affected the tip of the tool by means of a pivotal point. In this condition the hand and tool tip moved in opposite directions. This experimental condition mirrors to some extent the conditions employed by Megaw (1972), who studied the impact of movement direction and extent on movement programming. Our focus, however, was on the impact of the spatial correspondence between movement of the hand and the relevant part of the lever, rather than on movement direction or extent. Therefore, we compared the indirect control condition with a *direct* control condition, in which the handle was directly connected to the tip of the tool (Figure 2, bottom panels). Consequently, in this condition the hand and tip of the tool always moved in corresponding directions.

Note that in both conditions the pointer rotated around its midpoint, so the hand movements required to rotate the pointer around a certain angle were identical in the direct and indirect control conditions. Therefore, performance differences between these conditions must arise from the cognitive representation of the virtual tool on the computer screen, not from differences in programming muscle commands. Also, in both conditions the initial displays in a trial were identical (i.e., an up-pointing pointer was shown). The display changed only as a consequence of the response – that is, after reaction time (RT) was measured. Thus, RT differences between direct and indirect control conditions cannot result from differences in afforded hand movements or perceptual differences of the display. Such differences must result from anticipated tool effects when the responses are prepared during the RT interval.

We expected that moving the tip of the tool toward the stimulus would generally be faster than moving it away from the stimulus, irrespective of the direction of the hand (i.e., stimulus-tool correspondence). Second, responding might be delayed overall in the indirect control condition as compared with the direct control condition because of the incompatibility of hand movement and tool movement (i.e., hand-tool correspondence).

Method

Participants. Twelve students from the University of Halle-Wittenberg (4 men, 8 women) participated and were paid €6.

Apparatus and stimuli. The participants sat in

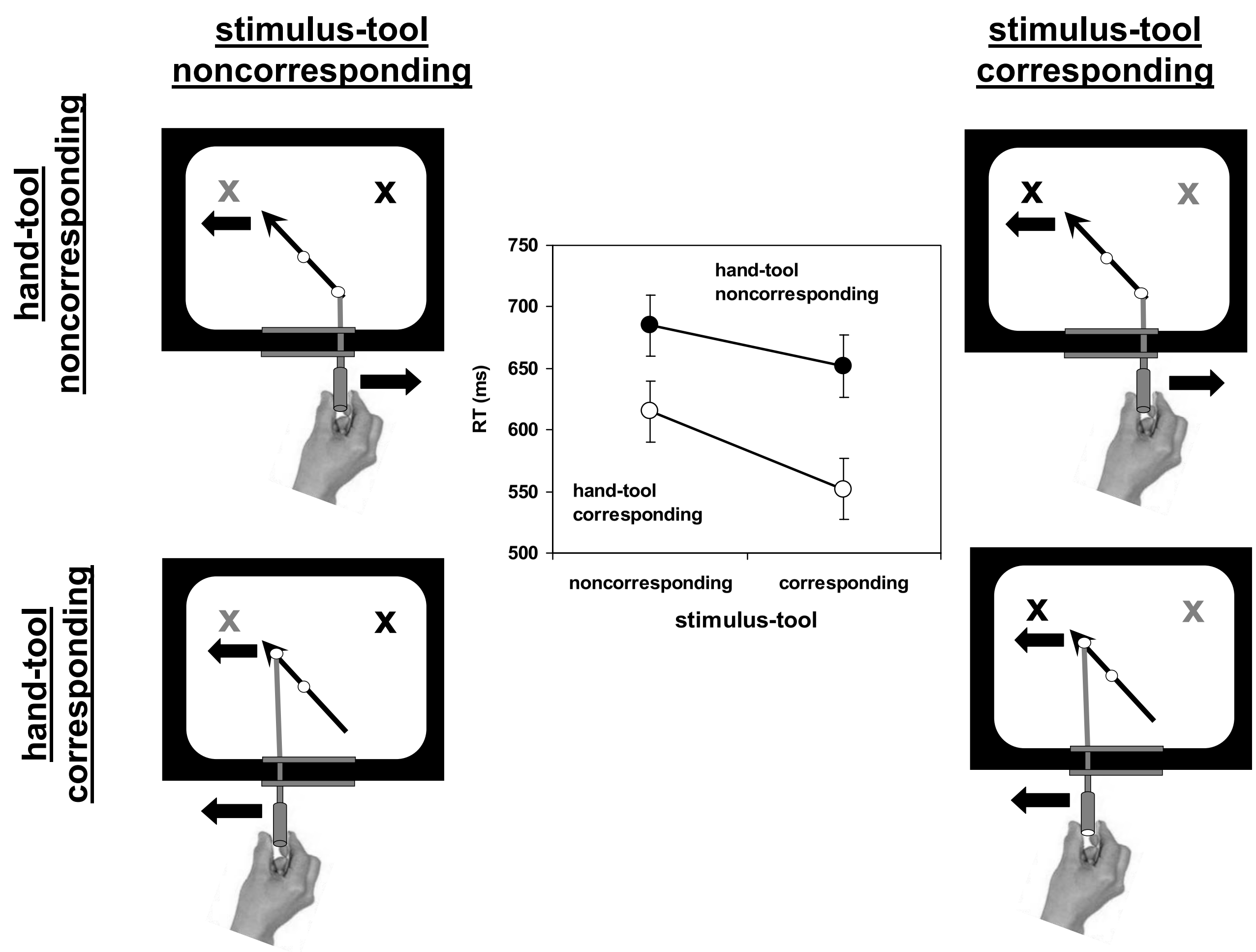

Figure 2. Conditions and results in Experiment 1. Assume that the stimulus is the black X (in the Experiment this X was red or green). Stimulus side and side direction of tool movement were either noncorresponding (left panels) or corresponding (right panels). Hand and tool movement directions were either corresponding (bottom panels) or noncorresponding (top panels). Middle: RTs as a function of stimulus-tool correspondence and hand-tool correspondence. Error bars represent standard errors of the means.

front of a custom-made lever that was mounted directly in front of a 17-inch (~42-cm) video graphics array display. The lever was movable 10 cm in the horizontal direction, and the position of the lever was recorded with a sample rate of 100 Hz and an accuracy of 0.1 mm. On the display a pointer (length 9 cm) was displayed throughout the experiment in white on a black background. The pointer rotated around a pivotal point in its middle. The top of the physical lever that the participants manipulated ended at the bottom of the screen (see Figure 2). In the direct control condition there was a virtual prolongation of the physical lever presented on the screen (in dark gray), which ended at a rotary connection at the tip of the pointer. In the indirect control condition the virtual prolongation ended at a rotary connection at the bottom of the pointer.

Movements of the lever were continuously transformed into movements of the virtual lever prolongation and the pointer. The impression resulting from this arrangement was that the lever via its virtual connection manipulated either the top end or the bottom end of the pointer on the screen. All participants readily agreed on this impression. The hands moved in a straight line on the horizontal dimension, whereas the pointer rotated around its midpoint and, thus, moved slightly in the vertical direction as well. Consequently the virtual connection between the lever and the rotating pointer had to in length as well (see Figure 2). Therefore, it was explained to the participants that the lower end of the connection would be movable in the shaft of the lever, like the plunger of a bicycle pump. Additionally there were two white Xs (3 × 3 mm) presented 40 mm to the left and right of the screen, 40 mm above the top end of the pointer. The critical stimulus was the change of one of these Xs into red or green.

Procedure. To equalize the start displays under direct and indirect control conditions, a trial started when the participants had moved the lever to the middle position, so that the pointer on the screen was vertically oriented. A brief tone (2000 Hz, 100 ms) was presented 500 ms after the pointer had reached its starting position; 500 ms later, one of the two Xs became red or green. The task was to move the tip of the pointer about 3 cm either toward the colored stimulus or away from it. Half the participants moved the pointer toward a red stimulus and away from a green stimulus, whereas this mapping was reversed for the other half. The RT was the interval between stimulus presentation and movement of the lever more than 10 mm away from the middle position. In case of an error, a brief visual feedback was provided.

Participants worked through a block with direct control of the tip of the pointer and a block with indirect control of the tip of the pointer separated by a brief break of about 5 min. The order of these conditions was counterbalanced across participants. Each participant performed 120 trials in the direct control condition and 120 trials in the indirect control condition. In half of the trials of each control condition a movement toward the stimulus was required, whereas in the other half a movement away from the stimulus was required. The order of trials within these conditions was random.

Results

Trials with RTs below 100 ms and above 1500 ms were discarded as outliers (4.1% of the data). The data were submitted to a 2 × 2 ANOVA, with the stimulus-tool correspondence (whether or not the side at which the stimulus was presented corresponded to the afforded pointer movement) and hand-tool correspondence (whether the hand and tool moved in corresponding or noncorresponding directions) factors as repeated measures.

The mean RTs from the factorial combinations of these factors are shown in Figure 2 (middle). RTs were lower when the tool tip moved to the side of the stimulus rather than away from it, $F(1, 11) = 9.40$, $MSE = 2166.15$, $p < .01$, and when hand and tool movement corresponded than when they did not, $F(1, 11) = 41.55$, $MSE = 1758.2$, $p < .01$. The interaction of these factors was not significant ($F < 1$), which implies that the influence of stimulus-tool correspondence was independent of whether the hand moved toward or away from the stimulus. Mean error rate was 2.1%. Responding was more accurate when hand movement and tool movement corresponded (1.9%) than when they did not (3.3 %), $F(1, 11) = 8.01$, $MSE = 3.32$, $p < .05$. No other effect was significant.

Discussion

Experiment 1 aimed at answering two questions. First, what is important when a tool is used for responding to a stimulus: the spatial correspondence of the stimulus to the intended effect or its correspondence to the hand movement? The results are clear cut: The spatial correspondence between stimulus and intended effect is crucial. Responding was faster when the relevant tip of the tool moved toward the stimulus rather than away from it, independent of the movement direction of the hand. If the relation between stimulus and hand was of any importance, the effect of stimulus-tool correspondence should reverse (or at least differ) when the hand and tool moved in opposite directions (see Figure 2, top panels). Obviously, this was not the case.

The influence of spatial correspondence between stimulus and tool movement is noteworthy because spatially corresponding trials (moving the tool toward the stimulus) were mixed with spatially noncorresponding trials (moving the tool away from the stimulus). Mixing compatible and incompatible trials often removes spatial compatibility effects (e.g., Vu & Proctor, 2004). Recent observations suggest that the removal of compatibility effects with mixed compatibility conditions depends on the type of responses. It occurs with discrete key press responses but not with continuous responses, such as rotations of a flight yoke (Yamaguchi & Proctor, in press). The presence of S-R compatibility effects with continuous lever movements in Experiment 1 fits into this picture. Still, the reasons for these apparent response type effects remain to be scrutinized by future research.

Second, are there any costs when a hand movement is translated into a spatially inverted movement of a tool? Again, the answer is clear cut: Yes, there are costs. Responding was overall slower (and less accurate) when the movement direction of the intended effect did not correspond to that of the hand, as compared with when it did correspond. Thus, spatial noncorrespondence between proximal hand movement and distal tool movement seems to produce substantial interference (e.g., Kunde, 2001). Before we discuss these results in more detail, we present a second experiment in which we wished to replicate these results under slightly different conditions.

EXPERIMENT 2

Experiment 2 was designed to further the results of Experiment 1 in two respects. First, in Experiment 1 stimulus location was relevant, as the afforded tool directions (toward the stimulus or away from it) were defined relative to the location of the stimulus itself. Is the spatial correspondence effect between stimulus location and tool direction strong enough to affect performance even when stimulus location is task irrelevant? To test this we turned the task into a standard Simon task.

Participants were asked to move the tool leftward when the stimulus was red and rightward when it was green (or vice versa). Stimulus location is thus task irrelevant. Normally, the spatial stimulus code decays over time when it is task irrelevant, which is reflected in a decreasing correspondence effect when RT increases (e.g., Hommel, 1994). To explore whether this applies to the present stimulus-related correspondence effect as well, we additionally conducted distribution analyses of RTs (see the Results section for further details).

Second, do costs of incongruent hand and tool movements ensue when there is no spatial correspondence between stimulus and hand or stimulus and tool? To clarify this seems important because of a potential confound in Experiment 1.

Note that the four conditions shown in Figure 2 differed with respect to the spatial correspondence of stimulus and hand as well. Although this stimulus-hand correspondence does not seem to have any effect, strictly speaking a comparison between the conditions in the graph in Figure 2 is confounded with variations of stimulus-hand correspondence. Specifically, responding in the top right condition might be slower than in the bottom right condition not only because of noncorrespondence between hand and tool but also because stimulus and hand were spatially noncorresponding as well. We therefore felt that it would be best to replicate the impact of hand-tool correspondence while keeping constant the relations between stimulus and hand and stimulus and tool. This was done by presenting the stimulus in a neutral middle position.

Method

Participants. There were 16 participants (5 men, 11 women) in this experiment.

Apparatus, stimuli, and procedure. We will note only the differences from Experiment 1 here. In Experiment 2 there was an additional X presented in the middle between the two lateral Xs that were shown in Experiment 1. In each third of the trials, the stimulus was presented in the left, middle, or right position. The instruction was to move the pointer to the left or right according to the stimulus color. There were 120 trials in the direct and indirect control condition, consisting of 40 trials that afforded a movement of the pointer that was spatially corresponding, neutral, or noncorresponding to the stimulus position.

Results

Reactions with RTs below 100 ms and above 1500 ms were discarded (2.1% of the data). The RTs were submitted to an ANOVA with the factors stimulus-tool correspondence (corresponding, neutral, noncorresponding) and hand-tool correspondence (corresponding or noncorresponding).

Responding was faster when stimulus location and direction of the tool tip corresponded than when they did not, $F(2, 30) = 47.34$, $MSE = 490.94$, $p < .01$ (see Figure 3). Compared with the neutral condition, the 25-ms costs with noncorrespondence, as well as the 29-ms benefits with correspondence, were significant (both *p*s < .01). Responding was faster when hand and tool moved in the same direction rather than in opposite directions $F(1, 15) = 11.67$, $MSE = 3{,}201.04$, $p < .01$. This difference was significant at all levels of stimulus-tool correspondence (all *p*s < .01). Stimulus-tool correspondence and hand-tool correspondence did not interact ($F = 1.01$, $p > .35$). The mean error rate was 2.9%. There were no effects in the analysis of error rates.

To gain insight into the temporal dynamics of the stimulus-tool correspondence effect, we performed distribution analyses of the RT data. For each participant and stimulus-tool correspondence level, RTs were rank ordered and divided into five proportional bins. Then the mean RTs within these bins were subjected to ANOVAs with the factors bin and stimulus-tool correspondence. These data are shown in Figure 4 (right panel). The effect of stimulus-tool correspondence decreased with increasing RTs, $F(8, 120) = 4.54$, $MSE = 493.26$, $p < .01$. The same analysis performed on the data of Experiment 1, in which stimulus location was relevant, revealed no significant changes of the stimulus-tool correspondence effects across RT levels (see Figure 4, left panel).

Discussion

Experiment 2 replicated the results of Experiment 1. First, responding was faster when the tool moved toward the stimulus rather than away from it. This was the case even though stimulus location was irrelevant. This stimulus-tool correspondence effect decreased with increasing RT, which suggests that the irrelevant spatial stimulus code decays (Hommel, 1994). By contrast, there were no signs of decay in Experiment 1, in which stimulus location was relevant. Thus, in this respect

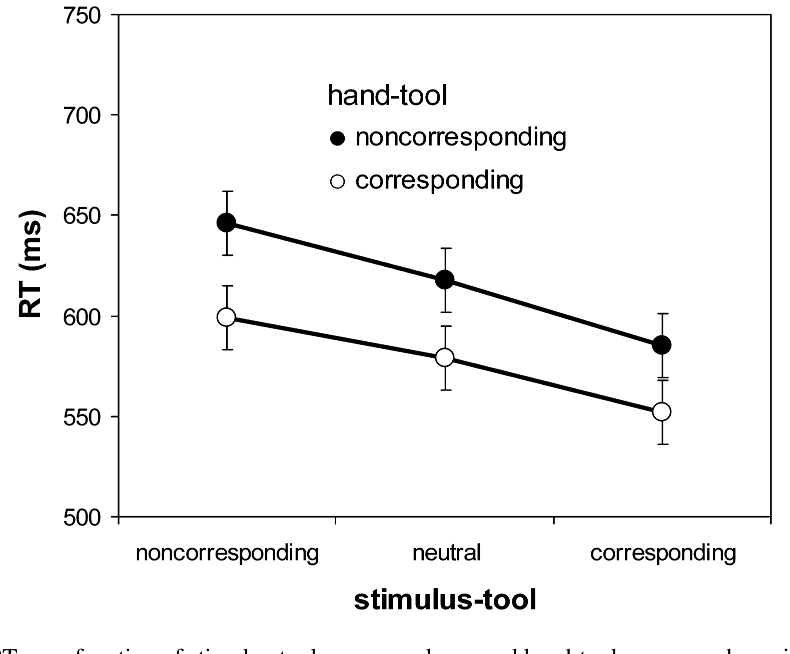

Figure 3. RTs as a function of stimulus-tool correspondence and hand-tool correspondence in Experiment 2. Error bars represent standard errors of the means.

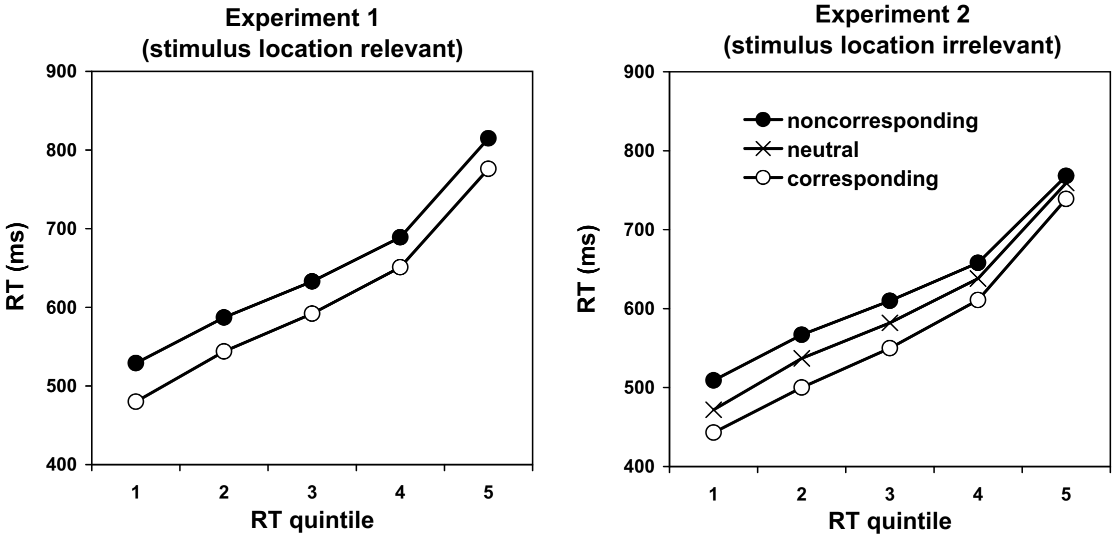

Figure 4. Reaction times as a function of RT quintile and stimulus-tool correspondence in Experiment 1 (left panel) and Experiment 2 (right panel).

the present tool-mediated compatibility effects resemble spatial S-R compatibility effects without transformation between response and effect, in which task-irrelevant spatial stimulus codes decay whereas task-relevant spatial codes do not (Roswarski & Proctor, 1996).

Second, we also replicated the overall performance benefit of actions when hand and tool move in the same direction rather than in opposite directions. This was the case even when stimulus location was neutral to both direction of the hand and direction of the tool. Thus, we can be confident that at least under the present conditions, there is a cost when an intended tool effect has to be brought about by a hand movement that is spatially incompatible to the tool movement.

GENERAL DISCUSSION

The present paper sought to specify the constraints that arise when responses to a stimulus are required with a quasi-mechanical tool that creates spatially incompatible movements of hand and tool. Learning about these constraints is of interest from a theoretical as well as an applied perspective. Basically, the situation in our experiments is determined by three events: the stimulus, the intended tool movement, and the hand movement.

These three events varied on a common spatial dimension. Thus, in principle, there might be spatial compatibility effects between all these events – that is, between stimulus and hand, stimulus and tool, and hand and tool. As it turned out, only two of these potential effects had an impact on behavior. Performance was superior when the stimulus location corresponded to the intended tool movement and when the intended tool movement corresponded to the necessary hand movement. By contrast, the spatial correspondence between stimulus location and hand movement had no impact on performance under the present conditions.

Regarding the compatibility effect between stimuli and intended effects (tool movements), our results are in accord with those of a previous study by Hommel (1993), which used discrete key press responses and discrete visual effects. However, there are noteworthy differences as well.

First, the spatial correspondence effect between responding hand and intended effect was significant in the present two experiments, whereas it was numerically smaller and not significant in all conditions of the studies by Hommel (1993) and Proctor et al. (2004). This might relate to a stronger overlap of the continuous movements of the hand and the tool in the present study, as compared with the discrete key presses and visual key press effects (Hommel, 1993) or the wheel turns and cursor movements in previous studies (Proctor et al., 2004).

Second, Hommel (1993) observed small effects of correspondence between stimulus and response hand, but such “traditional” S-R correspondence effects were not apparent in the present study. If they were there, the impact of a stimulus-effect correspondence (i.e., the variable depicted on the x axis in Figures 2 and 3) should differ between conditions in which the hand and tool moved in identical directions and those in which they moved in opposite directions. Such differences were not apparent.

How can one account for these results? We find it simplest to describe the present results in terms of the transformations involved. Stimulus-oriented lever movements presumably involve two such transformations: one that converts the stimulus into an afforded movement of the tip of the tool and a second one that converts the afforded movement of the tool tip into a necessary movement of the tool handle. Obviously, response times depend only on the relationship of neighboring elements of this processing chain, as there is no direct correspondence effect between stimulus location and hand (or handle) movement. Thus, these two transformations remain separate under the conditions investigated here.

The reasons for this apparent separation are not trivial and remain to be scrutinized. They might have to do with the involvement of visual attention in stimulus-tool and tool-hand transformations. It seems plausible that in the present task visual attention, covertly or overtly, has to visit three locations in serial order: the stimulus location, the target location of the tool, and the target location of the hand. Moving attention first from the stimulus to the tool's target location would be easier when both coincide, to some degree, than when they diverge.

In fact, orienting attention in a direction opposite to a previous attention shift is especially time costly (the so-called meridian effect; Umiltà, Riggio, Dascola, & Rizzolatti, 1991). Only after the tool's target direction is specified is attention oriented to the hand to determine or control its movement direction. This shift from the tip of the tool to the hand is likely to proceed faster when tool and hand move in the same direction rather than in opposite directions (i.e., attention would have to travel a shorter distance or cover a smaller area). A straightforward prediction from this model is that factors that affect reorienting of attention (e.g., spatial distance) should affect the present compatibility effects as well.

Recommendations

Although the explanations of the observed effects are admittedly speculative and afford further specification, there are practical implications of the present results. First, users of tools similar to the one simulated here should be aware that there is a cost of moving hand and tool in opposite directions, as compared with a more natural corresponding movement of hand and tool. As noted, these costs appear quite substantial in terms of RTs and presumably correspond to the problem of inverting the movements of handles and working ends of surgical instruments in laparoscopic surgery, known as the fulcrum effect.

Our results prompt the recommendation to avoid such inversions when possible – for example, by providing reinverted visual feedback of the tool end on a control monitor. In line with such a recommendation, it has been reported that providing visual feedback that corresponds to the direction of hand movements enables novices, with a very limited amount of practice, to reach the performance levels of experienced surgeons (Crothers, Gallagher, McClure, James, & McGuian, 1999).

Second, the correspondence between stimulus and response location (i.e., location of the hand), which is normally a strong determinant of performance, loses its importance when a tool is used that spatially transforms this movement. In other words, the spatial relation between stimulus and intended effect, rather than that between stimulus and necessary hand movement, seems to be crucial. When the use of tools is inevitable, one should take care to make stimuli (e.g., warning signals or other information about the status of the patient or operation system) and intended effect compatible, rather than stimuli and proximal arm movements. Of course, these recommendations need to be evaluated in simulated conditions.

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