Original Article

On the Persistence of Tool-Based Compatibility Effects

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Abstract. Using tools, such as simple levers, makes specific demands on the motor system. Two related performance decrements have been reported: The costs that arise when required tool movements and movements of the operating hand are spatially incompatible (hand-tool compatibility), and the costs that arise when relevant stimuli and tool movements are spatially incompatible (stimulus-tool compatibility). We performed two experiments to test the boundary conditions of both effects. Experiment 1 revealed a strong hand-tool compatibility effect despite visual occlusion of the hand and instructions to ignore hand movements. Experiment 2 revealed influences of stimulus-tool compatibility despite instructions to ignore the tool and to pay attention to the operating hand alone. These results suggest that lever movements of the type studied here become automatically represented and constrain motor performance.

Keywords: hand-tool compatibility, stimulus-tool compatibility, automatic representation, motor performance, movement

Using a tool often implies a transformation of one's own hand and arm movements in a way that body-related proximal effects and tool-related distal effects of an action may or may not be compatible to each other (hand-tool compatibility). Incompatible relations of hand and tool movements are prevalent among different types of tools, for example, in a simple first-class lever with one pivotal point as it is used in laparoscopic surgery. Since this movement inversion involves performance costs (e.g., Kunde, Müsseler, & Heuer, 2007; Massen & Sattler, 2010; Müsseler, Kunde, Gausepohl, & Heuer, 2008), it is important to know whether and how it might be possible to reduce these costs. In the following sections, we briefly review recent studies on this issue, followed by an introduction to the theoretical framework for understanding (hand-tool) compatibility effects. Finally, we introduce the present experiments that aimed at reducing the detrimental effects of hand-tool (in)compatibility.

Tool Transformation

The ability to create and aptly use tools has played a major role in human phylogenetic development. Not only was the way cleared for previously inaccessible achievements and products, but nowadays, tool use has replaced mere muscle power in many instances. Most tools impose a transformation of the (proximal) hand movement and the (distal) tool movement. Using pliers to grasp an object, for example, requires distinguishing the hand target location from the tip of the pliers' target location. Often, however, tools introduce specific and more unfamiliar transformations, and this is true even for a simple first-class lever with one pivot transforming the hand movement into the opposite direction. Such tools are widely used in many working environments: In laparoscopic surgery, for example, the patient's abdomen serves as the pivot which reverses the hand movement (the "fulcrum effect"; see also Heuer & Sülzenbrück, 2009; Sülzenbrück & Heuer, 2009). The advantages and potential disadvantages of this method have prompted extensive research and led to recommendations to provide reinverted visual feedback (e.g., Crothers, Gallagher, McClure, James, & McGuian, 1999), while others argued that the inversion might not be a problem calling for a technical solution at all (Heemskerk, Zandbergen, Maessen, Greve, & Bouvy, 2006).

However, to thoroughly investigate and understand the additional demands imposed by transformed movements (as compared to natural movements) is important for both theoretical and practical reasons. Understanding how tool movements are planned and executed plays an important role for general theories of action planning. In turn, such theories provide recommendations, for example, on how to construct working environments in order to minimize detrimental effects of movement transformations. A step toward these goals was recently made by Kunde and colleagues (2007). In this study, the movement direction of the participants' hand and that of the tip of a first-class lever were compatible in one condition and were inverted (thus incompatible) in a second condition (see Figure 1 for an illustration). Two results were notable: First, the inversion caused overall longer response times. Secondly, movements were initiated faster when the location of the imperative stimulus and the direction of the lever movement corresponded, regardless of the direction of the operating hand (cf. Riggio, Gawryzewski, & Umiltà, 1986). These results demonstrate cognitive costs of a simple transformation, but do not indicate how to overcome these detrimental effects. The experiments we report here were designed to identify boundary conditions for both compatibility effects.

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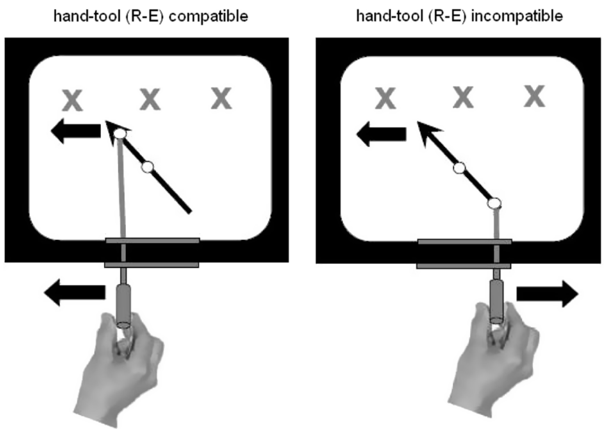

Figure 1. Illustration of the hand-tool (or response-effect, R-E) compatibility conditions: In the left panel the controller was (virtually) connected to the lever in a way that a hand movement resulted in lever movement of the same direction (compatible hand-tool relation). In contrast, in the right panel, a hand movement resulted in a lever movement of the opposite direction (incompatible hand-tool relation).

Tool Use as an Instance of Stimulus-Effect and Response-Effect Compatibility

Compatibility effects between stimuli, responses, and response-contingent effects have thoroughly been investigated for natural movements, mostly (but not exclusively) in relation to a shared spatial dimension. One instance concerns the compatibility of stimuli and responses (hereinafter S-R compatibility): Responses are faster and more accurate when stimuli and responses are located on the same side (S-R compatible) as compared to different sides (S-R incompatible; e.g., Fitts & Seeger, 1953), even when the stimulus' spatial location is task-irrelevant (i.e., the Simon effect; Simon, 1969; for an overview see Proctor & Vu, 2006).

However, what happens if the responses reliably produce distal effects? Hommel (1993) introduced visual effects into a Simon-like task, where participants responded to low/high pitch tones presented to the left or right ear. In one condition, participants produced visual action effects on the same side as their key press and a typical Simon effect resulted. However, in a second condition, the participant's key presses triggered visual action effects on the opposite side than their manual response. Here, the Simon effect was inverted with faster reactions if the spatial locations of stimuli and effects were compatible (i.e., stimuli and manual responses were on opposite sides). Hence, crucial for the Simon effect was not the spatial location of the response, but the location of the to-be-produced effect – an instance of stimulus-effect (S-E) compatibility. In addition, responding was generally faster when responses and visual effects were on the same rather than on opposite sides, independent of stimulus location.

The (spatial) compatibility of responses and their effects was studied in more detail later (R-E compatibility; Kunde, 2001; Pfister, Kiesel, & Melcher, 2010). Similar effects have been demonstrated for other overlapping dimensions, such as response force and effect intensity (Kunde, 2001), response and effect duration (Kunde, 2003), and the semantic content of responses and effects (Koch & Kunde, 2002). Even bimanual actions are performed better when both lead to similar rather than distinct visual or tactile effects (Janczyk, Skirde, Weigelt, & Kunde, 2009). Such results can be reconciled with ideomotor theories of action control (e.g., Herbart, 1825; see Hommel, Müsseler, Aschersleben, & Prinz, 2001; Shin, Proctor, & Capaldi, 2010), which assume that all actions are cognitively represented by and are accessed via the anticipation of their associated sensory effects.

Which factors might determine whether spatially incompatible tool transformations produce performance costs or not? Conceivably, to obtain costs from mutually incompatible movements of hands and tools, aspects of both must be cognitively represented somehow, and there is evidence that (visuospatial) attention can be allocated to both aspects (Collins, Schicke, & Röder, 2008). Now, if one of these representations is suppressed, for example, by actively directing attention away from either of the two movements, mutual interference might be reduced or even removed. Perhaps, this is the reason why tool users in general have only very limited conscious access to movements of their hand when using a tool: "the unawareness of one's own actions appears to be a precondition for using tools successfully: especially in tool use, proximal and distal action effects are often in conflict which would result in interference, if they would be equally ranked within the system" (Müsseler & Sutter, 2009, p. 364; see also Liu, Crump, & Logan, 2010). Thus, removing the cognitive codes of hand movements might reduce performance costs of spatially incompatible transformations. This was investigated in Experiment 1 by withdrawing visual feedback from the proximal aspect of the action, that is, the operating hand. Experiment 2 complemented this approach by altering the representation of the distal aspects of a tool action, namely the tool movement. This was done by manipulating the task relevance of the tool. Although perhaps of limited interest for the practitioner, because the tool movement is normally the intended action in applied settings, it is still of theoretical importance to know if the resulting tool movements are encoded into action plans, even though they are task-irrelevant.

Experiment 1

The R-E (hand-tool) compatibility effect in the experiments by Kunde and colleagues (2007) suggests that both the tool and the hand were mentally represented. Otherwise, an influence of compatibility between these two features of the same action can hardly be explained. Consequently removing the mental representation of one of these action features may help to remove the problems arising from hand-tool incompatibility. Possibly, the hand representation is mainly driven by available visual feedback of hand movements. If this was so, a simple and in most cases easily applicable method to reduce costs of hand-tool incompatibility would be to eliminate visual feedback of the hand movement. Indeed it has been shown that bimanual movements that are otherwise difficult to perform simultaneously become feasible when (1) no visual feedback of the hands is available and (2) these movements produce similar visible effects (Mechsner, Kerzel, Knoblich, & Prinz, 2001). Thus, occluding vision of the hand movement should further lower the awareness of the actual hand movement resulting in smaller conflict with incompatible hand-tool relations.

Unfortunately the available evidence is equivocal in this respect. For instance, Flach, Press, Badets, and Heyes (2010) found that hand-shaking responses with the left or right hand were facilitated when these actions produced the presentation of a hand on the same side on a computer screen. However, this effect was removed when the participants viewed their own hand simultaneously. Possibly, the encoding of the own hand and that of another person on the screen created some form of perceptual confusion. In any case, the role of feedback in constraining action-effect compatibility phenomena requires empirical clarification.

In the present Experiment 1, participants moved the tip of a lever to the left or the right according to the color of visual imperative stimuli. The lever moved either in the same direction as the hand, or its direction was inverted. Crucially, participants had no visual feedback of their hand movements because their hands rested in an opaque box. If this manipulation is sufficient to diminish the problems associated with the R-E compatibility effect, we would expect similar RTs for both, compatible and incompatible R-E relations.

Method

Participants

Sixteen undergraduate students from Martin Luther University Halle-Wittenberg participated for course credit. All participants were naïve regarding the hypotheses underlying this experiment.

Apparatus and Stimuli

The apparatus we used here was the same as in the study by Kunde et al. (2007). In short, participants sat in front of a custom-made controller placed directly in front of a 17″ computer monitor. Participants grasped the controller which was horizontally movable by 10 cm. The monitor displayed a lever (9 cm) that rotated around one pivotal point in its middle. Moving the controller to either side affected the movement of the lever in one of the following ways: In one condition, the controller was virtually connected with the upper part of the lever (see Figure 1, left panel). In this case, moving the hand to the left (or right) caused the lever to make a left (or right) movement. In a second condition, the controller was virtually connected to the lower part of the lever (see Figure 1, right panel). Hence, a hand movement resulted in a lever movement to the opposite direction. We will subsequently refer to these conditions as "hand-tool compatible" and "hand-tool incompatible," respectively. Additionally, three white "X" were displayed centrally and 12 cm to the left and right of the pivot point, 4 cm above the upper end of the pointer. Imperative stimuli were changes of one of these X into red or green. Importantly, in this experiment the participants' hands rested in a box, so that the participants had no visual feedback about their hand movement.

Procedure

Each participant took part in one single session of about 45 min. A trial started with a warning click (2,000 Hz, 100 ms) that occurred 500 ms after the participants moved the controller to its middle position. Another 500 ms later one X turned red or green. The participants' task was to move the lever 3 cm to the left or the right according to the stimulus color while the color-direction mapping was counterbalanced across participants. Reaction time (RT) was measured when the controller had moved more than 1 cm. Movement times (MT) were recorded from this point on until the lever first crossed the target area. An error was detected if the controller was moved for more than 1 cm into the wrong direction. Visual feedback was provided after erroneous responses by presenting the German word "Fehler" ("Error") for 1,000 ms.

All participants completed 10 blocks of 12 trials each with compatible hand-tool movements and the same amount with incompatible hand-tool movements. The order of conditions was counterbalanced across participants.

Data Treatment and Analyses

We excluded trials with RTs < 100 ms or > 1,500 ms, and with MTs < 10 ms or > 100 ms (8.1% of the data). RT analyses are based on correct trials only. Analyses were mainly done by means of a 2 × 3 repeated-measures analysis of variance (ANOVA). The first factor was "hand-tool compatibility" (compatible vs. incompatible). The second factor was "stimulus-tool compatibility" (compatible vs. neutral vs. incompatible), that is, whether the movement of the upper part of the pointer was compatible with the spatial location of the stimulus (neutral means that the central X changed its color). If necessary, Greenhouse-Geisser corrections were applied.

Results

Figure 2 (upper-left panel) shows the mean RTs of Experiment 1. Responses were faster when hand and tool movements were compatible than when they were not, $F(1, 15) = 38.96$, $p < .01$, $\eta_p^2 = .72$. In addition, responses were faster when stimulus location and the direction of the pointer movement were compatible than when they were not,

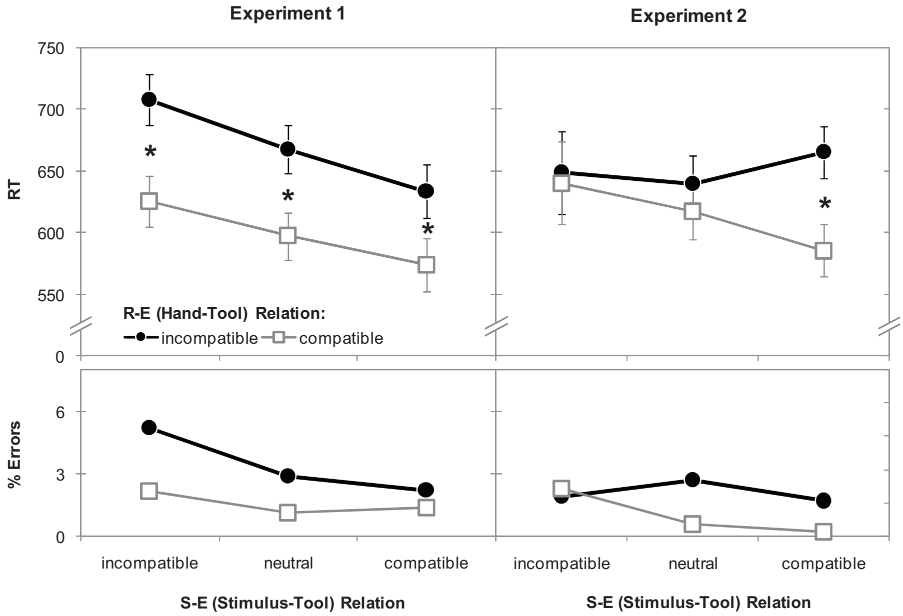

Figure 2. Mean correct reaction times (RT; upper panels) and percentages of errors (% Errors; lower panels) from Experiments 1 and 2 as a function of the response-effect (R-E) relation and the stimulus-effect (S-E) relation. RT results are supported by 95% within-subject confidence intervals calculated separately for each level of S-E compatibility.

$F(2, 30) = 25.68, p < .01, \eta_p^2 = .63$. Subsequent contrast analyses revealed significant costs (incompatible vs. neutral), $F(1, 15) = 17.08, p < .01, \eta_p^2 = .53$, and significant benefits (neutral vs. compatible), $F(1, 15) = 11.11, p < .01, \eta_p^2 = .43$. The interaction of stimulus-tool and hand-tool compatibility was not significant, $F(2, 30) = 1.50, p = .24, \eta_p^2 = .09$.

Mean error percentages varied from 1.1 to 5.3 (see Figure 2, bottom-left panel). Both, the main effect of stimulus-tool compatibility, $F(2, 30) = 2.77, p = .10, \eta_p^2 = .16$, and the main effect of hand-tool compatibility, $F(1, 15) = 3.26, p = .09, \eta_p^2 = .18$, were not significant. The interaction was not significant as well, $F(2, 30) = 0.80, p = .42, \eta_p^2 = .05$.

Discussion

Experiment 1 aimed at testing whether the R-E compatibility effect in previous studies on tool use (Kunde et al., 2007) can be eliminated by occluding visual feedback of the hand movement. While this manipulation was reported to be successful in allowing otherwise incompatible bimanual movements (Mechsner et al., 2001), the results from our experiment were negative: Even without visual feedback, the R-E compatibility effect persisted and responses were slower when the hand movement was inverted by the lever (as in Figure 1, right panel). Apparently, kinesthetic feedback – or possibly the imagination of the hand movement – was sufficient to pose problems in movement initiation. In fact, when compared with conditions of unconstrained view on the hand (Kunde et al., 2007, Experiment 2), the influence of R-E compatibility was numerically very similar. In addition, a clear S-E compatibility effect emerged such that, irrespective of the hand-tool (R-E) relationship, responses were faster when the direction of the resulting tool movement was toward the (irrelevant) stimulus location. This effect is under further investigation in Experiment 2.

Experiment 2

Experiment 1 showed that drawing attention away from the proximal aspect of a tool-based action (i.e., the hand movement) does not reduce problems that arise when tool and hand move in incompatible directions. Experiment 2 explored the effects of drawing attention away from the distal aspects of a tool-based action (i.e., the tool movement). We now instructed participants to move their hands in a certain direction and to ignore the ensuing movements of the lever. The question is thus, whether the tool movement is automatically integrated into a representation of the motor action. Hommel (1993) suggested that "the cognitive representation of the action would mainly refer to the intended action effect, but would also include other features (perceived effects) of the action, just as object representations may include both relevant and irrelevant features of an object" (p. 278). In accordance with this proposal, it has been reported that even task-irrelevant effects shape performance. These observations suggest that action effects become part of the action concept, irrespective of the goal relevance of the effect, at least when they are contingent on action (e.g., Koch & Kunde, 2002; Kunde, Hoffmann, & Zellmann, 2002).

However, the work by Hommel (1993) suggests that the intention to produce an effect is important for such an effect to become part of an action concept. In that study participants flashed a light to their left with a right button press and a light to their right with a left button press. When participants were instructed to flash these lights, the spatial compatibility between stimuli and lights determined performance; when instructed to ignore the lights, however, the spatial compatibility between stimuli and manual responses was crucial. In a similar vein, Ansorge (2002) observed that R-E compatibility seems to be confined to conditions where action effects are rendered task-relevant through the instructions.

It is quite uncertain, however, whether this result will transfer to tool effects of the type studied here, which were continuous rather than simple onsets. First, the effects in our experiment became visible already during the response proper, while they appear only after the response with simple key presses. Furthermore, simple and discrete key presses and more enriched forms of responses have yielded different results concerning other compatibility effects. S-R compatibility effects, for instance, are eliminated in mixed (compared to blocked) conditions only for key presses, but not for more enriched responses, such as turning a yoke to the left or right (Yamaguchi & Proctor, 2006). Finally, a tool moving jointly with the hand might be a more intuitive action effect that is harder to exclude from the mental representation of that action than the onset of a short-lived light flash is. In Experiment 2 we instructed participants to move their hands (in contrast to the lever) in specified directions according to the color of the stimuli, and to ignore the resulting lever movement. Note that, even though several experiments showed that (visuospatial) attention is directed to hand and tool location in parallel (e.g., Collins et al., 2008), such an instruction was successful with wheel rotations in a study by Wang, Proctor, and Pick (2003). If the present tool can efficiently be suppressed, this should (1) reduce or even eliminate the R-E compatibility effect and (2) yield a reversed S-E compatibility effect for the incompatible R-E condition.

Method

Twelve new undergraduate students from Martin Luther University Halle-Wittenberg participated for course credit. The design of Experiment 2 was similar to that of Experiment 1, with the following differences. First, visual feedback of the hand movement was no longer occluded. Secondly, participants were instructed to focus on their hands and to ignore the (compatible or incompatible) movement of the tool. Data were excluded from RT analyses for the same criteria as in Experiment 1 (5.9%).

Results

Mean RTs are illustrated in Figure 2 (upper-right panel). In general, responses were slower with incompatible than with compatible hand-tool movements, $F(1, 11) = 6.53$, $p < .05$, $\eta_p^2 = .37$. As the interaction of stimulus-tool and hand-tool compatibility was significant, $F(2, 22) = 11.53$, $p < .01$, $\eta_p^2 = .51$, two separate ANOVAs were performed for compatible and incompatible hand-tool conditions. The pattern for compatible hand-tool movements closely resembled the respective condition of Experiment 1. Accordingly, a main effect of stimulus-tool compatibility, $F(2, 22) = 17.80$, $p < .01$, $\eta_p^2 = .62$, was driven by significant costs, $F(1, 11) = 7.98$, $p < .05$, $\eta_p^2 = .42$, and significant benefits, $F(1, 11) = 12.80$, $p < .01$, $\eta_p^2 = .54$. In contrast, with incompatible hand-tool movements, the main effect of stimulus-tool compatibility only approached significance, $F(2, 22) = 2.85$, $p = .08$, $\eta_p^2 = .21$. While there were now significant costs for compatible stimulus and tool movements locations, $F(1, 11) = 6.89$, $p < .05$, $\eta_p^2 = .39$, there were no benefits when stimulus and tool movement were incompatible, $F(1, 11) = 0.62$, $p = .45$, $\eta_p^2 = .05$.

Mean error percentages were low in general and varied from 0.2 to 2.7 (see Figure 2, bottom-right panel). The interaction of stimulus-tool and hand-tool compatibility was significant, $F(2, 22) = 3.94$, $p < .05$, $\eta_p^2 = .26$, thus we calculated two separate ANOVAs for compatible and incompatible hand-tool movements. With compatible hand-tool movements there was a significant main effect of stimulus-tool compatibility, $F(2, 22) = 5.50$, $p < .05$, $\eta_p^2 = .33$. Repeated contrasts revealed significant costs, $F(1, 11) = 6.77$, $p < .05$, $\eta_p^2 = .38$, but no benefits, $F(1, 11) = 1.00$, $p = .38$, $\eta_p^2 = .08$. With incompatible hand-tool movements the main effect of stimulus-tool compatibility was not significant, $F(1, 11) = 1.00$, $p = .38$, $\eta_p^2 = .08$.

Discussion

In Experiment 2 we investigated whether a tool is represented automatically, or can be suppressed by intention. In particular, participants were now instructed to move their hands into specified directions and to ignore the resulting tool movement. Altogether the results suggest that the consideration of the tool movement was suppressed to some extent, but not entirely. With compatible hand-tool movements, the compatibility of stimulus and hand coincides with compatibility of stimuli and tool tip. We expected a positive stimulus-tool compatibility effect to ensue, irrespective of whether the tool movement is registered or not, and it did so. With incompatible hand-tool movement directions, the stimulus-tool compatibility effect should reverse, when the action is coded in terms of the hand movement, because stimuli incompatible to the tool tip are now compatible to the hand movement direction. And in fact this reversal occurred. However, the reversal was much smaller than the effects of stimulus-tool/hand compatibility with compatible movement directions of hand and tool. This aspect of the data suggests that the tool movement was not entirely removed from the representation of the action. In accordance with this, responses were overall still slightly longer with the incompatible R-E relation, an effect that likely can only emerge if both the hand and the tool were represented.

General Discussion

The present experiments aimed at determining whether compatibility costs for hand and tool movements and the respective stimuli (Kunde et al., 2007) can be eliminated. Such knowledge is practically important since the mere existence of these costs may have detrimental practical effects, for example, in laparoscopic surgery (Crothers et al., 1999; Heemskerk et al., 2006). Considering results from previous studies with discrete key press responses (Hommel, 1993) or bimanual movements (Mechsner et al., 2001), we examined two potential methods for eliminating the compatibility costs. In Experiment 1 we occluded visual feedback of the hand movements, and in Experiment 2 we instructed participants to focus on their hand movements (instead of the tool movements).

A first consistent result concerns the relation between the hand and tool movement directions, in more technical terms: the R-E compatibility. In both experiments, responses were slower in the incompatible condition (when hand and tool moved in opposite directions; see Figure 1, right panel) than in the compatible condition (see Figure 1, left panel; cf. Kunde et al., 2007). Hence, it was not possible to diminish the problems imposed by such lever transformations with either of the two investigated methods. This finding has theoretical implications, since Mechsner et al. (2001) showed that normally incompatible bimanual movements become feasible in the absence of visual feedback of the hand, given that they produce similar effects. Our results are thus at odds with these findings and suggest that in our experiment kinesthetic feedback was sufficient to create a hand representation interfering with the effect representation. One difference, however, between our study and the Mechsner et al. (2001) study is the kind of movements. While the latter authors investigated the feasibility of bimanual movements, our participants responded only with one hand. In addition, these authors investigated continuous and repetitive movements, while this was not true for our responses.

The second result concerns the relationship of tool or hand movements and the spatial location of the stimuli. In Experiment 1 we observed the same pattern as did Kunde et al. (2007): Tool movements toward the (irrelevant) location of the stimuli were faster than those directed into the opposite direction. With the compatible R-E relationship in Experiment 2, we observed the same; however, this effect was diminished (but not completely reversed) in the incompatible R-E condition. When participants were instructed to move their hands and to ignore the tool movements, they were apparently able to suppress the tool to some degree, but not completely (see also Wang et al., 2003). In fact, this aspect of the data closely mirrors findings from research with discrete responses and effects where significant costs, but only a numerical but nonsignificant facilitation were reported (e.g., Hommel, 1993).

In sum, the results suggest that the motor system is rather sensitive to encode the effects that a continuously moving tool produces. In fact, even when the tool is entirely task-irrelevant it affects the cognitive processes of generating a corresponding manual action. So a perhaps important message of the present study is: Even action effects that are momentarily irrelevant to the actors can interfere with action planning when they are incompatible with the required manual action. In other words, it appears that performance decrements due to R-E incompatibility between hand and tool movements cannot easily be overcome. This conclusion, however, also points at an astonishing ability of the human cognitive system: The ability to integrate multiple and diverse sources of action effects in behavioral control. It seems that predicting and monitoring proximal and distal action effects simultaneously occurs automatically and effortless – and that this ability is wired deep enough to be resilient to external influences.

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