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The Locus of Tool-Transformation Costs

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Transformations of hand movements by tools such as levers or electronic input devices can invoke performance costs compared to untransformed movements. This study investigated by means of the Psychological Refractory Period (PRP) paradigm at which stage of information processing such tool-transformation costs arise. We used an inversion transformation, that is, the movement of the operating hand was transformed into a spatially incompatible movement of a lever. As a basic tool-transformation effect, the initiation of inverted tool movements was delayed compared to noninverted movements. Experiment 1 suggested a central (or postcentral) locus of this tool-transformation effect and ruled out a (precentral) perceptual locus. Experiments 2 and 3 confirmed the central locus and ruled out a later, motor-related stage of processing. The results show that spatially incompatible tool movements delay a capacity-limited stage of information processing, often referred to as response selection.

keywords: tool use, action control, dual task, PRP, action effects

Tool use is quite common in the animal kingdom, and it is particularly prevalent in human behavior. In any case, tool use implies that movements of the hands are transformed in regard to certain aspects such as gain, location, or force. Such tool transformations can be mechanical, as with sticks or levers, or they can be virtual, as with computer mice (Heuer & Hegele, 2010). In this article, we investigate which stages of information processing are involved in specifying such tool movements. Specifically, we hypothesized that programming such tool actions draws on a capacity-limited process. We therefore start with considerations on tool use and capacity limitations. Then we describe the Psychological Refractory Period (PRP) paradigm and a set of "tried and tested" experimental methods to isolate the locus of certain experimental manipulations. Finally, we report three PRP experiments that systematically combined a tool task with another capacity-limited task. On the basis of these experiments we conclude that transformed tool movements bear on a capacity-limited stage of processing, whereas other stages (most likely perceptual and motor-related processes) are less influenced by the tool-transformation.

Tool Use and Capacity Limitations

At first glance, there is good reason to assume that tool use does not bear heavily on limited cognitive resources. After all, capuchin monkeys use tools (de Moura & Lee, 2004) and even ants do (Fellers & Fellers, 1976), even though at least the latter species is not suspected to possess particularly high amounts of cognitive capacity as compared to humans. Also, the frequency and ease of human tool use suggest that this activity cannot be particularly challenging. Often tool users do not even become aware of the transformation of their hand movements (Müsseler & Sutter, 2009; Knoblich & Kircher, 2004) and in many cognitive aspects, using a tool resembles natural hand movements as well (Janczyk, Franz, & Kunde, 2010). In fact, neuroscientific studies have suggested that tools become part of the body schema even with very little practice (Iriki, Tanaka, & Iwamura, 1996). Thus, programming a tool movement should not be much more effortful than programming a natural body movement without tools.

On the other hand, tool actions may yield cognitive demands, depending on their specific type of transformation. A severe transformation is, for instance, the inversion of movement directions in a way that, when the hand moves to the left, the tool moves to the right and vice versa. This transformation occurs already with one of the simplest mechanical tools: a lever with one pivot. Such levers are used frequently, and they pose problems in practical situations such as in laparoscopic surgery (Savader, Lillemoe, & Prescott, 1997). It has been shown several times that this inversion—compared to an untransformed tool movement—creates performance costs in terms of response speed and accuracy (Janczyk, Pfister, & Kunde, in press; Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008; Müsseler & Skottke, 2011). Because these performance costs are hard to overcome by practically feasible methods (Janczyk et al., in press), it is important to arrive at a clearer understanding of the underlying processes. To this end, we aimed at determining where these performance costs arise in the processing stream from perception to the resulting (tool) movement.

The Locus of the Tool-Transformation Effect

When we refer to the "locus" or "origin" of tool-transformation effects, we assume a classical information-

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processing model. This model assumes three stages of processing: perceptual processes, central processes, and motor execution processes (e.g., McClelland, 1979; Sanders, 1980; Smith, 1968; Sternberg, 1969). Perceptual processes encode stimuli, central processes are assumed to be responsible for response selection among other things (Koch, 2008). Finally, motor execution processes are responsible for the initiation and execution of the observable motor action. Tool-transformation costs might arise at any of these stages independently of each other. We do not want to discuss here whether or not such a model is an appropriate description of all types of motor tasks—most likely it is not (cf. Hommel, 1998). However, this rather simple model has been remarkably successful in describing many different behavioral effects (e.g., Janczyk & Kunde, 2010; Krüger, Klapötke, & Mattler, 2011; Kunde, Landgraf, Paelecke, & Kiesel, 2007; Miller & Reynolds, 2003; Ruthruff, Johnston, & Remington, 2009; Ruthruff, Miller, & Lachmann, 1995), and we believe that it consistently captures the tool-transformation effect as well.

On the basis of available evidence it is hard to judge at which processing stage(s) such tool-transformation costs may arise. For example, during the preparation of a tool movement, visual attention is directed toward the tip of the tool as well as to the operating hand (Collins, Schicke, & Roeder, 2008). When hand and tool move into opposite directions, visual attention has to be spread over a broader spatial range than when hand and tool move into the same direction, which conceivably leaves less visual attention available for stimulus processing. This would suggest a perceptual locus of the effect of spatially incompatible hand-tool transformations.

That the central capacity-limited stage of processing is affected by tool transformations appears possible when previous research on the phenomenon of response-effect compatibility is considered. Response-effect compatibility refers to the finding that responding is normally faster and more accurate, when actions predictably produce reafferences (i.e., action effects) that are compatible to the response in certain respects. For example, pressing a left button is easier when this button press foreseeable switches on a light bulb on the left rather than the right side of the observer's visual field (Kunde, 2001; Pfister, Kiesel, & Melcher, 2010). Previous research has shown that response-effect compatibility effects arise at a central stage of processing (Paelecke & Kunde, 2007). In principle, spatially incompatible tool movements can be construed as incompatible action effects, suggesting a central locus of tool-transformation costs. Note, however, that tool movements differ in several respects from the action effects studied in previous research. First, tool movements are continuous consequences of hand movements, whereas the effects in previous research were all discrete events such as flashing lights or certain sounds (e.g., Keller, Dalla Bella, & Koch, 2010; Keller & Koch, 2006; Kunde, Koch, & Hoffmann, 2004). Second, tool movements can be predicted from the perceptible mechanical properties of the tool, whereas most other action effects have to be learned. Finally, action effects in previous studies were a salient but otherwise dispensable consequence of the responses; that is, they were task irrelevant. The movement of a tool, however, is mostly the goal of the action and thus by definition task relevant (Heuer & Hegele, 2010; Sülzenbrück & Heuer, 2009). Given these differences it is unknown whether the effects of tool movements have a similar locus as action effects in previous research.

Finally, a "late" locus, related to the initiation or completion of the response, cannot be excluded either. Specifically, it has been shown that action effects can have an impact on the initiation of responses that have been selected in advance. For example, in a study by Kunde et al. (2004) responses with incompatible as compared to compatible response effects were initiated slower even when the responses were already cued before a go signal a considerable amount of time before (cf. also Kunde, 2003; Kunde & Weigelt, 2005). These observations suggest that even the initiation of already selected actions suffers from incompatible action effects, rendering a contribution of such a late locus also plausible.

In sum, the present literature does not allow definite conclusions about which processing stages are influenced by tool transformations. Identifying these stages, however, is important for both, basic and applied research. Regarding basic research, this conceptual advance will help to merge two relatively separate lines of research, namely research on tool use (e.g., Iriki, 2006; Müsseler & Skottke, 2011) and effect-based motor control (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kunde, 2001; for historical comments, see Pfister & Janczyk, in press). Finding similar constraints in producing continuous, mechanical tool movements and discrete learned action effects would support the assumption of common cognitive processes (Massen & Prinz, 2009).

In regard to applied purposes, this research informs about consequences of tool use in practical situations. Consider a surgeon in laparoscopic surgery, for example. Here, the use of a laparoscopic tool is combined with many other simultaneous cognitive tasks, such as encoding visual information (e.g., from a control monitor), recollection of information from memory (e.g., facts about the patient's medical status), and carrying out motor actions with the other hand (e.g., grasping an object passed by another member of the surgery team). Several of these potential tasks will invoke capacity-limited processes. If the production of transformed movements bears on a stage before a capacity-limited stage of processing (mostly referred to as perceptual processes) or a later stage (mostly referred to as motor processes) there would be no reason to expect the performance cost of producing transformed movements to transfer to other concurrent tasks. If, however, transformed movements bear on a capacity-limited stage, the performance costs of such movements will transfer to other capacity-limited tasks. Obviously it is important to know that producing transformed movements does not only produce costs compared to untransformed movements but also whether other concurrent tasks might suffer from such transformations as well.

This eminent gap in our understanding of the processes that underlie human tool use can be overcome by suitable experimental paradigms that we describe in the following section.

Locus-of-Slack and Effect-Propagation Logic

To determine the impact of experimental manipulations on different stages of processing, the Psychological Refractory Period (PRP) paradigm has become a standard procedure (e.g., McCann & Johnston, 1992; Miller & Reynolds, 2003; Pashler, 1984, 1994; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachmann, 1995; Van Selst & Jolicoeur, 1994). In the PRP paradigm, participants perform two tasks in close succession. For example, they might have to respond to an auditory stimulus (Task 1) and then to a visual stimulus (Task 2). Crucially, the two imperative stimuli occur with varying stimulus onset asynchronies (SOAs). Responding in Task 1 is typically unaffected by the SOA manipulation whereas responding in Task 2 is delayed when the SOA is shortened—the PRP effect. The crucial assumption to explain the PRP effect is the existence of a capacity-limited stage of processing located in between perception and motor processes. This central stage can only be occupied by one task at any given point in time. In other words, when the SOA is short, there occurs an idle time after perceptual processing in Task 2 (the cognitive slack; see Figure 1).

There are two ways to make use of the PRP paradigm to localize experimental effects, the *locus-of-slack logic* and the *effect-propagation logic*. The crucial prediction of the locus-of-slack logic is illustrated in Figure 1. An experimental factor implemented in Task 2 that lengthens the perceptual stage will not have an effect on RT2 at a short SOA. In this case, the lengthened perceptual stage occurs while Task 2 has to wait anyway and thus simply stretches into the cognitive slack. With a long SOA, however, response selection does not have to wait in Task 2, so that a lengthening of the perceptual stage will also directly increase RT2. By contrast, experimental factors in Task 2 that affect processing at the response selection stage or later will have identical effects at all SOA levels because lengthened processing is insurmountable after the presumed slack. In a nutshell, if a to-be-localized experimental factor, which is manipulated in Task 2, affects the perceptual stage, this will show up at long but not at short SOAs, thereby producing an underadditive interaction with SOA. To the contrary, a factor affecting a postperceptual stage will increase RTs in Task 2 at all SOAs to the same extent.[1]

The effect-propagation logic is illustrated in Figure 2. The factor including the crucial manipulation is now implemented in Task 1 (typically by reversing the order of Task 1 and Task 2). The crucial prediction is that influences of factors located at or before the bottleneck in Task 1 should fully propagate to Task 2, given sufficient task overlap (i.e., at short SOAs). Influences on processes after the bottleneck in Task 1 will, however, not appear in Task 2 because the second task can proceed despite ongoing motor processes in Task 1.

It is obvious that a particularly powerful inferential tool is the combination of these two methods. A given factor can be attributed unambiguously to the central capacity-limited stage (while excluding other stages) if it (a) produces an additive effect when manipulated in Task 2 (locus-of-slack logic) and (b) fully propagates to Task 2 when manipulated in Task 1 (effect-propagation logic).

Experiment 1

This experiment used the locus-of-slack logic. Task 1 was a binary tone discrimination task with key presses of the left hand. Task 2 was a tool action with the right hand (see Figure 3). Participants had to move the tip of a digital lever to the left or right, according to the color of a visual stimulus. In different blocks, the lever was either manipulated directly at the relevant tip, so that hand and tip always moved in corresponding directions, or the lever was manipulated at the other end, so that hand and the relevant tip of the lever always moved in opposite directions. Following the locus-of-slack method, the main question of Experiment 1 was whether the expected effect of incompatible tool movements would be underadditive to the effect of SOA (indicating a perceptual locus) or additive (indicating a postperceptual locus).

An additional manipulation concerned the spatial congruency of the imperative visual stimulus and the required movement direction of the tool. In a previous study we observed faster responses when the location of the stimulus and the direction of the required tool movement were spatially congruent (e.g., a stimulus on the left required a movement of the tool to the left), than when they were incongruent (e.g., a stimulus on the left required a tool movement to the right; cf. Kunde, Müsseler, et al., 2007, Experiment 2). To test the generalizability of this tool-based Simon effect to dual-task conditions, it was included in Experiment 1 as well.

Method

Participants. Sixteen right-handed psychology students from the Technical University of Dortmund, Germany, participated for course credit. All participants reported normal or corrected-to-normal vision and had no knowledge of the expected outcome of this experiment. Each participant gave informed consent, and this experiment (as well as the following experiments) was carried out according to the Declaration of Helsinki.

Apparatus and stimuli. Stimuli were presented on a 17″ monitor against a black background. In Task 1, participants responded to the pitch of a tone (250 Hz or 900 Hz, 100 ms duration) with the index or middle finger of the left hand on a custom-made response box. The apparatus for Task 2 was the same as in the study by Kunde, Müsseler, et al. (2007). Participants manipulated a custom-made (physical) controller placed in front of the monitor. Participants operated this controller, which was horizontally movable by 10 cm, with their right hand. Moving the controller to either side affected the movement of a digital lever, which was displayed on the computer screen in one of the following ways (see Figure 3): In one condition, the controller was virtually connected to the upper part of the lever. In this case, moving the hand to the left (or right) resulted in a left (or right) lever movement. In a second condition, the controller was virtually connected to the lower part of the lever. 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 Xs were displayed centrally and 12 cm to the left and right of the lever's pivot point, 4 cm above the upper end of the pointer. Imperative stimuli were changes of one of these Xs to red or green. Although the stimulus location was task irrelevant, it was either congruent or incongruent to the required movement direction of the tool. Stimulus-tool

[1] Although it is common to describe precentral processes as perceptual processes and postcentral processes as motor processes, this labeling is a simplification. There are certain perceptual tasks, such as letter identification and box width judgment that seem to take place after the bottleneck of processing (Johnston & McCann, 2005), whereas certain postperceptual processes, such as memory retrieval seem to occur before the bottleneck (Green, Johnston, & Ruthruff, 2007). Strictly speaking, the locus-of-slack logic thus distinguishes precentral from later processes, but these need not necessarily be perceptual and postperceptual.

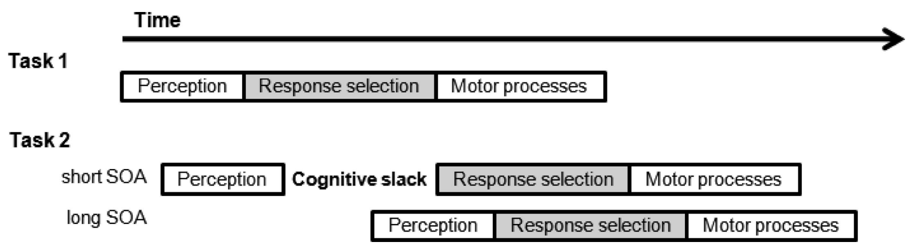

Figure 1. Illustration of the locus-of-slack logic. According to a central (or response-selection) bottleneck model, only a single capacity-limited stage (shaded gray) can be performed at any given time. Thus, with short stimulus onset asynchronies (SOAs) perceptual processing in Task 2 can be finished before the central bottleneck has been released from Task 1 processing. Accordingly, further Task 2 processing must wait. The resulting idle time is called the "cognitive slack" and produces longer RTs in Task 2 with short SOAs in a PRP experiment. If a manipulation is implemented in Task 2 and affects the perceptual stage, at short SOAs the required additional processing simply stretches into the slack. Thus, RTs in Task 2 do not increase with short SOAs but only at sufficiently long SOAs (yielding an underadditive interaction of SOA and the manipulation). In contrast, manipulations affecting postperceptual stages of Task 2 affect RTs in Task 2 to the same extent across all SOA levels.

congruency[2] was "neutral" when the color of the X in the middle position was changed.

Design and procedure. Each participant completed one single session of about 45 min. At the beginning of each trial, participants moved the digital lever into a central start position. When the central position was reached, a warning click (2000 Hz, 50 ms) signaled the upcoming tone stimulus for Task 1 which appeared after 500 ms. After an SOA of either 100 ms or 1,000 ms one of the Xs changed its color to red or green and kept this color until completion of the tool response in Task 2. The participants' task was to move the controller 3 cm to the left or right according to the stimulus color. Reaction times (RT) were measured when the controller had moved more than 1 cm in either direction. Movement times (MT) were recorded from this point on until the controller first crossed the target area. Participants were instructed to respond as quickly and as accurately as possible, first to the tone and then to the color. Visual feedback followed erroneous responses. All participants completed 10 blocks of 24 trials with compatible hand-tool movements and 10 blocks with incompatible hand-tool movements. The S-R mappings in Task 1 and Task 2, and the order of hand-tool compatibility conditions in Task 2 were counterbalanced across participants.

Results

All RT analyses focused on trials where both responses were correct. Trials in which the MT of the tool was below 10 ms or above 1,000 ms were removed (0.5% of all trials).[3] Also, RTs below 300 ms and RTs more than 2.5 standard deviations above the mean RT of each participant and experimental condition were excluded as outliers[4] (3.7% and 2.6% of the data for Task 1 and Task 2, respectively). Mean RTs and error percentages were submitted to analyses of variance (ANOVAs) with the factors of SOA (100 ms vs. 1,000 ms), hand-tool compatibility (compatible vs. incompatible), and stimulus-tool congruency (congruent vs. neutral vs. incongruent) as repeated measures. Mean RTs are shown in Figure 4 and Table 1 and error percentages are listed in Table 1.

Task 1. RTs in Task 1 were higher with a 100 ms SOA than with a 1,000 ms SOA, $F(1, 15) = 17.17$, $p < .001$, $\eta_p^2 = .54$. This decrease of RT1 with an increasing SOA was slightly more pronounced with incongruent than with congruent tool movements, $F(2, 30) = 3.99$, $p = .029$, $\eta_p^2 = .21$. No other effect reached significance (all *p*s $> .070$). There were no significant effects in the analysis of errors (all *p*s $> .110$).

Task 2.

Response times. The theoretically important results according to the locus-of-slack logic are those in Task 2. RTs were higher with a 100 ms SOA than with a 1,000 ms SOA, hence a PRP effect, $F(1, 15) = 119.36$, $p < .001$, $\eta_p^2 = .89$. Also, RTs were higher when movement directions of hand and tool were incompatible than when they were compatible, $F(1, 15) = 9.61$, $p = .007$, $\eta_p^2 = .39$. Finally, responding was faster when the stimulus location corresponded to the movement direction of the tool, than when it was neutral or incongruent, $F(2, 30) = 12.19$, $p < .001$, $\eta_p^2 = .49$. No other effect approached significance (all *F*s < 1). Specifically, the effect of SOA was additive to both, the effects of hand-tool compatibility, $F(1, 15) = 0.01$, $p = .922$, $\eta_p^2 = .01$, and of stimulus-tool congruency, $F(2, 30) = 0.21$, $p = .812$, $\eta_p^2 = .01$ (see Figure 4).

[2] For the sake of clarity, we use the term *congruency* when referring to the relationship of stimulus location and tool movement and the term *compatibility* when referring to the relationship of hand and tool movement.

[3] Extreme MTs mostly indicated some malfunction of the apparatus. We refrained from reporting MTs in detail here, because preliminary analyses revealed that they were generally unaffected by experimental factors. This observation suggests, however, that responses were programmed before movement onset and that these programming processes are captured by RTs.

[4] Three hundred milliseconds appeared as a reasonable lower limit in regard to the overall level of RTs for the present apparatus (cf. Janczyk et al., in press; Kunde, Müsseler et al., 2007). We confirmed, however, that other criteria such as removal of RTs smaller than 2.5 *SD*s below mean RTs of each participant and condition yielded the same data pattern.

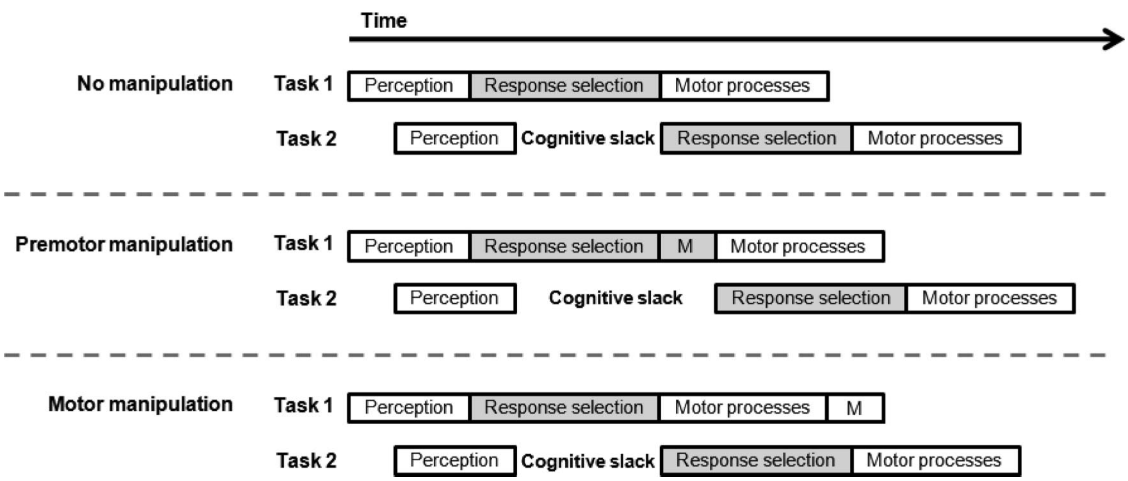

Figure 2. Illustration of the effect-propagation logic. This illustration shows processing according to a bottleneck model that assumes that only one single capacity-limited stage (shaded gray) can be performed at any given time (here only depicted for short SOAs). The manipulation of interest M is implemented in Task 1. If it affects a premotor stage of processing, this results in a lengthened cognitive slack, and as a consequence, RTs in Task 2 are lengthened to the same degree. In contrast, if the manipulation affects the motor stage of Task 1 (which can be processed in parallel with other stages) only RTs in Task 1 but not in Task 2 are affected.

Error percentages. Error percentages increased when the stimulus–tool relationship was incongruent rather than neutral or congruent, $F(2, 30) = 11.71$, $p < .001$, $\eta_p^2 = .44$ (see Table 1). Finally, with a short SOA, responding was 0.7% more accurate with compatible than with incompatible hand-tool relations, whereas with a long SOA, responding was 0.9% less accurate with compatible than with incompatible hand-tool movement directions, $F(1, 15) = 6.71$, $p = .020$, $\eta_p^2 = .31$, for the interaction of SOA and hand-tool compatibility. In other words, the hand-tool compatibility effect was larger with short than with long SOA (where it was in fact negative). This overadditive interaction precludes that a speed–accuracy trade-off might have masked an underadditive interaction in RTs. Yet, to further rule out this possibility we additionally analyzed inverse efficiency scores[5] (IES; Townsend & Ashby, 1983; see Table 1). IES combine RTs and PEs into a single measure by dividing mean correct RTs by the proportion of correct trials for each participant and condition. An analysis of IES thus complements the analysis of RTs by compensating for potential differences in PEs. This analysis confirmed the additive effects of SOA and hand-tool compatibility from the RT analysis, $F(1, 15) = 0.23$, $p = .638$, $\eta_p^2 = .02$ (cf. Table 1).

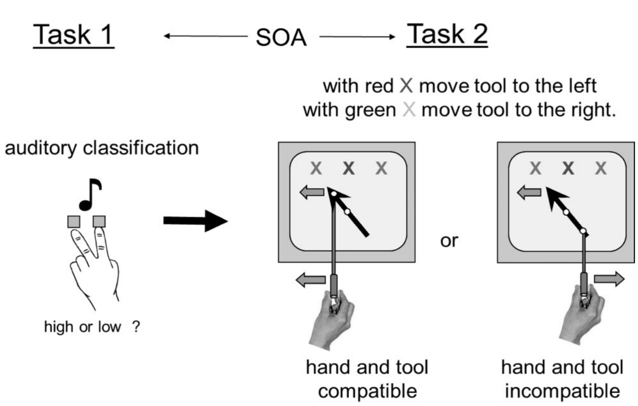

Figure 3. Procedure of Experiment 1. For Task 1, participants responded to the pitch of a tone with a button press of their left hand. For Task 2, participants moved the tip of a lever to the left or right according to the color of an X. In one block of trials the tip of the pointer was manipulated by a controller connected directly to the tip of the pointer (i.e., hand and tool movements were spatially compatible). In another block of trials the tip of the pointer was manipulated by a controller connected to the other end of the pointer (i.e., hand and tool movements were spatially incompatible). SOA = stimulus onset asynchrony.

Discussion

Experiment 1 investigated whether the effect of an inversion transformation of hand movements into tool movements would be additive or underadditive to the effect of SOA. The results revealed an effect additive to the SOA effect. According to the locus-of-slack logic this observation precludes a precentral locus of the tool-transformation effect and suggests a central or motor locus.

Additionally, we replicated an effect of stimulus-tool congruency under dual-task conditions. Initiating the tool movement was faster when the tool had to be moved to the location of the imperative stimulus, rather than to the other direction, independent of whether the hand moved toward the stimulus or not. Hence, what counted was the congruency of stimulus location and required tool movement, not the congruency of stimulus location and direction of hand movement (cf. Hommel, 1993; Janczyk et al., in press; Kunde, Müsseler, et al., 2007). It is interesting to note that this tool-based Simon effect was additive to the SOA, which suggests that it may also invoke a capacity-limited stage of processing. We consider this an interesting question for future research that, however, goes beyond the scope of our study.

[5] We thank an anonymous reviewer for this suggestion.

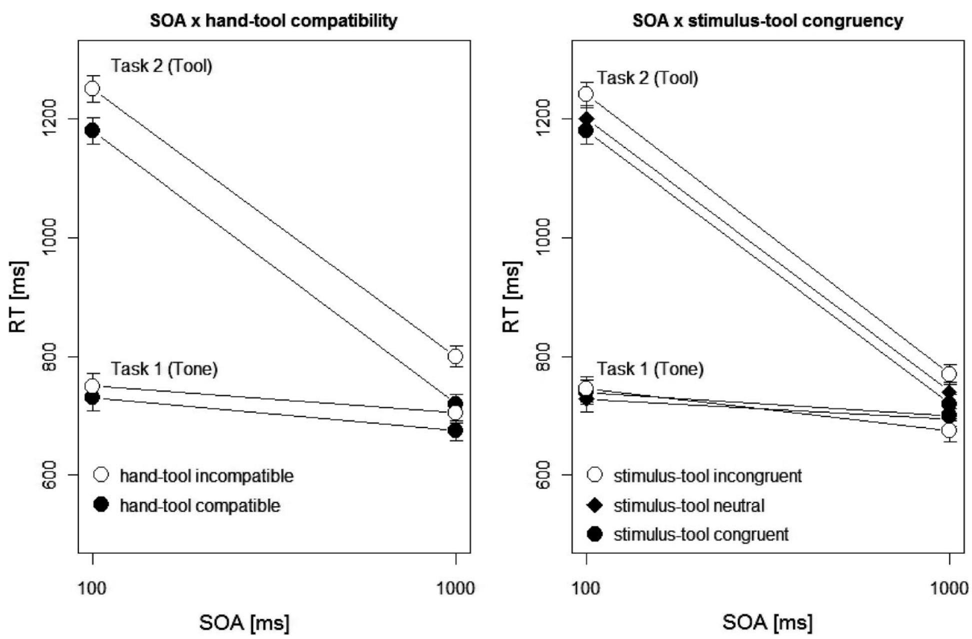

Figure 4. Experiment 1. Left panel: Response times (RTs) in Tasks 1 and 2 as a function of stimulus onset asynchrony (SOA) and hand-tool compatibility. Right panel: RTs in Tasks 1 and 2 as a function of SOA and stimulus-tool congruency. Error bars indicate within-subjects standard errors (Loftus & Masson, 1994), calculated separately for each task and SOA. ms = milliseconds.

It is interesting to note that there was a small but significant increase of RT1 with a decreasing SOA, which complies better with a model of graded capacity sharing between tasks rather than an all-or-none occupation of capacity-limited processes (Tombu & Jolicoeur, 2002). Note, however, that the "predictions for the Central Bottleneck and Central Capacity Sharing models are the same for Task 2" (Tombu & Jolicoeur, 2002, p. 275). Therefore, even if capacity sharing between tasks took place, the additive effect of hand-tool compatibility to SOA effectively precludes a precentral locus of this effect.

Experiment 2

Experiment 1 used two manual tasks. This may invoke output interference, hence interference at a late, motor-related stage of processing (De Jong, 1993). Possibly, it is hard to initiate a tool action with the right hand, while there is still an outgoing motor command for the left hand (Heuer, 1993). In agreement with this proposal, PRP effects are typically larger when two manual rather than a manual and a vocal task are combined (McLeod, 1977; Pashler & Christian, 1994). Such considerations suffice to conjecture that the PRP effect found in Experiment 1, and the additive effect of tool-transformation compatibility, may simply be a result of combining two manual responses. To test this conjecture, and to make a first step to rule out a motor-related origin of the tool-transformation effect, the possibility for output-related interference was minimized in Experiment 2 (see Figure 5). Task 1 was now a memory-encoding task, which is known to invoke capacity-limited processes without response-related demands (Jolicoeur &

Table 1
Mean Response Times (RTs), Error Percentages (EPs), and Inverse Efficiency Scores (IESs) in Experiment 1

		Task 1 (tone task)				Task 2 (tool task)			
		SOA 100 ms		SOA 1,000 ms		SOA 100 ms		SOA 1,000 ms	
	Stimulus-tool	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible
RTs	Congruent	731	761	675	723	1152	1226	683	761
	Neutral	715	741	690	695	1170	1240	718	776
	Incongruent	753	745	655	690	1202	1275	729	818
EPs	Congruent	2.8	2.2	2.0	1.1	3.9	3.9	2.0	3.1
	Neutral	1.9	1.7	1.4	0.9	3.3	3.8	3.6	2.7
	Incongruent	2.3	1.4	2.7	1.4	5.6	7.3	9.7	6.1
IESs	Congruent	760	780	696	732	1204	1274	698	788
	Neutral	734	755	703	701	1211	1288	748	798
	Incongruent	775	758	680	700	1276	1374	810	877

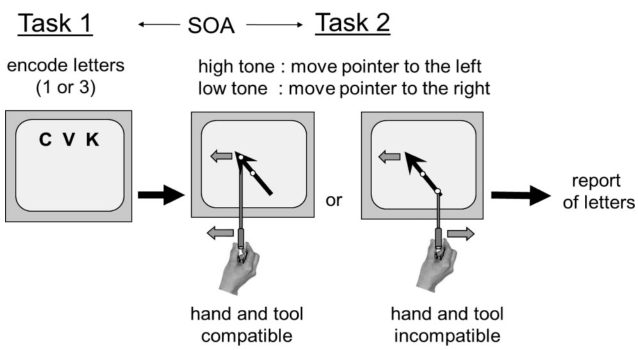

Figure 5. Procedure of Experiment 2. Participants were first shown either one or three letters for later report. Following a stimulus onset asynchrony (SOA) of either 100 ms or 1,000 ms a high or low tone was presented and required a movement of the pointer on the screen to the left or to the right. In one block of trials the tip of the pointer was manipulated by a controller connected directly to the tip of the pointer (i.e., hand and tool movements were spatially compatible). In another block of trials the tip of the pointer was manipulated by a controller connected to the other end of the pointer (i.e., hand and tool movements were spatially incompatible).

Dell'Acqua, 1998). As Task 1, participants were first presented with either one or three letters for later report at the end of the trial. Then, the stimulus for the tool task was presented. Because the stimuli in the memory task were visual, we now used tones as Task 2 stimuli, which always occurred in a spatially neutral position so that stimulus-tool congruency was now held constant.

The choice of the primary memory task was to some extent inspired by dual-task requirements of tool use in practical situations such as in laparoscopic surgery. Here, the surgeon often has to use tools while concurrently encoding information from measuring instruments or from communication with members of the surgery team. It is important to know to which extent such nonmotor tasks interfere with programming tool transformations as well. We expected to find a PRP effect and an effect of hand-tool compatibility, which should again combine additively.

Method

Participants were 16 students from the same pool as in Experiment 1. Apparatus and design were the same as in Experiment 1—Task 1, however, was now a memory task. To start a trial, participants moved the lever into a central start position and an auditory warning click (2,000 Hz, 100 ms) appeared when this start position was reached. After 500 ms, either one or three consonants that were randomly drawn from the alphabet were presented at the top of the computer screen for 100 ms (one letter was approximately 0.8 cm wide and 1.5 cm high with an interletter distance of 0.8 cm). After an SOA of either 100 ms or 1,000 ms, a low or high tone (400 Hz or 800 Hz, 100 ms duration) prompted a speeded movement of the tip of the tool to the left or right, according to tone pitch. After the tool response was completed, a question mark appeared and asked the participants to type in at leisure the letters that they memorized from the initial display. The report was counted as incorrect, if one or more of the actually presented letters were incorrect or missing. After completion of this report, the tool had to be moved back to the central position to start the next trial. Participants performed in 8 blocks of 24 trials each with hand and tool moving in corresponding directions and the same amount with hand and tool moving in opposite directions. The order of these hand-tool compatibility conditions and the S-R mapping were counterbalanced across participants.

Results

For RT analyses, only trials were considered where both responses were correct. Trials in which the MT of the tool was below 10 ms or above 1,000 ms were removed (0.05%). The same outlier criteria as in Experiment 1 were applied, which removed 2.7% of all trials. Mean RT2s and error percentages were submitted to repeated-measures ANOVAs with the factors SOA (100 ms vs. 1,000 ms), set size in Task 1 (1 vs. 3 letters), and hand-tool compatibility in Task 2 (compatible vs. incompatible). Mean RTs from Task 2 are shown in Figure 6 and Table 2, and error percentages for both tasks are shown in Table 2.

Task 1. Participants made more errors when three letters rather than one letter had to be remembered, $F(1, 15) = 44.43$, $p < .001$, $\eta_p^2 = .75$ (see Table 2). No other effect was significant (all $ps > .300$).

Task 2. RTs decreased with an increasing SOA, hence a PRP effect, $F(1, 15) = 140.85$, $p < .001$, $\eta_p^2 = .90$. Additionally, RTs were increased when hand and tool movements were spatially incompatible rather than compatible, $F(1, 15) = 6.14$, $p = .026$, $\eta_p^2 = .29$. These two effects were additive, $F(1, 15) = 0.21$, $p = .653$, $\eta_p^2 = .01$, for the interaction. RTs were higher when set size in Task 1 was three rather than one, $F(1, 15) = 83.84$, $p < .001$, $\eta_p^2 = .85$, and this effect was stronger when the SOA was short than when it was long, $F(1, 15) = 17.72$, $p < .001$, $\eta_p^2 = .54$, for the interaction of SOA and set size.

Error percentages were higher with a short than with a long SOA, $F(1, 15) = 4.74$, $p = .046$, $\eta_p^2 = .24$. The only other significant effect was an interaction of SOA and hand-tool compatibility, $F(1, 15) = 5.53$, $p = .033$, $\eta_p^2 = .27$, reflecting a stronger influence of SOA when movement directions of hand and tool were compatible than when they were incompatible. No other effect was significant (all $ps > .400$). As in Experiment 1, we conducted an analysis of inversed efficiency scores, which revealed an additive effect of SOA and hand-tool compatibility and thus confirmed the corresponding data pattern we observed for RTs, $F(1, 15) = 0.03$, $p = .865$, $\eta_p^2 = .01$ (cf. Table 2).

Discussion

Experiment 2 replicated the main findings of Experiment 1. Initiating a lever movement in Task 2 was delayed when this movement had to be brought about by a hand movement into the opposite direction. This effect was additive to the SOA effect, suggesting that it occurs at or after the capacity-limited stage. It is important to note that this data pattern ensued despite the use of a memory task as Task 1, which did not involve an obvious motor component and therefore argues against explanations of the additive effects of tool transformation and SOA in terms of peripheral output interference.

The results for the memory task fully replicate previous research (Jolicoeur & Dell'Acqua, 1998). It is not surprising that participants made more errors when three instead of only one letter had to be memorized. Moreover, participants responded slower in Task

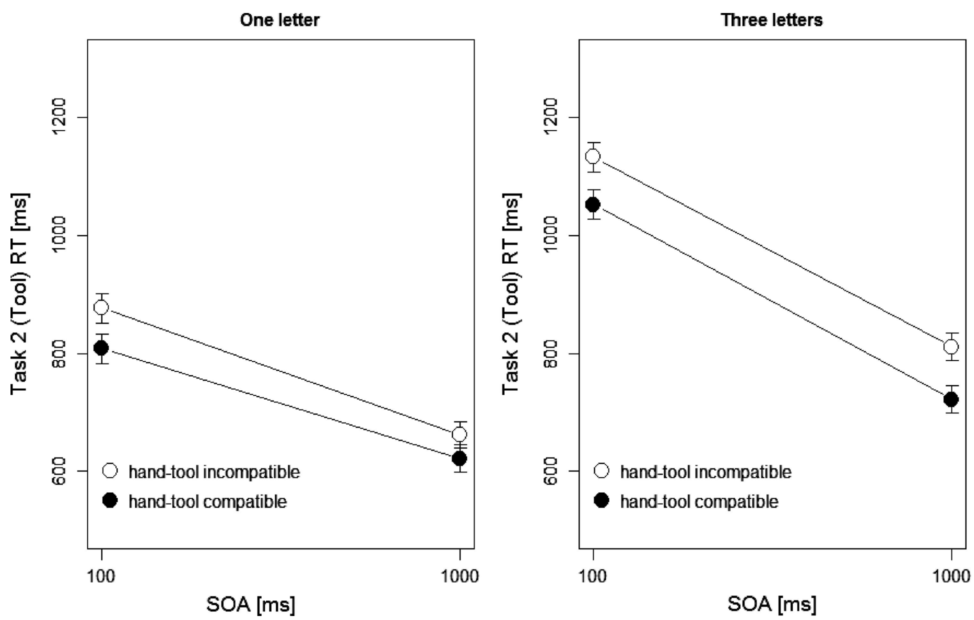

Figure 6. Experiment 2. Response times (RTs) in Task 2 (tool-task) as a function of stimulus onset asynchrony (SOA), hand-tool compatibility, and number of letters in Task 1. Error bars indicate within-subjects standard errors, calculated separately for each task and SOA. ms = milliseconds.

2 with three instead of one letter to be encoded in Task 1, significantly more so, when the SOA was short. This confirms that letter encoding invokes a capacity-limited stage of processing and that this stage is involved for a longer period of time with three letters instead of one letter, and more so right after presentation of the letters (short SOA) than when some time has elapsed (long SOA). Task 1 was essentially unaffected by SOA, which suggests that no capacity sharing occurred here.

The most relevant observation of Experiment 2 according to the locus-of-slack logic is the additive effect of hand-tool compatibility and SOA. It is generally a problem to infer from the lack of an interaction in standard null-hypothesis tests the additivity of factors, here as well as in Experiment 1. There are, however, considerations that support the additivity hypothesis beyond absence of a significant interaction. First, the absence of an interaction is unlikely due to a general insensitivity of the experimental design, because with the same design another previously reported interaction (that between memory set size in Task 1 and SOA) was clearly replicated (cf. Jolicoeur & Dell'Acqua, 1998). Second, the additive pattern of SOA and hand-tool compatibility was not an accidental observation, but the predicted pattern based on the results of Experiment 1. Third, as outlined by Sternberg (1969), "Experimental artifacts are more likely to obscure true additivity of factor effects than true interactions" (p. 287). Consider that there was a real underadditive interaction of hand-tool compatibility and SOA, hence a smaller compatibility effect at short than at a long SOA. It is unlikely that experimental artifacts increase the effect at short SOAs, decrease it at long SOAs, or both, to exactly the amount that creates the almost perfect additive pattern we observed here. Conversely, it seems more likely that a real additive pattern is distorted by artifacts that affect combinations of factors randomly. Fourth, whereas standard significance testing precludes proofing

Table 2
Mean Response Times (RTs), Error Percentages (EPs), and Inverse Efficiency Scores (IESs) in Experiment 2

		Task 1 (memory task)				Task 2 (tool task)			
		SOA 100 ms		SOA 1,000 ms		SOA 100 ms		SOA 1,000 ms	
	Number of letters	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible
RTs	One					808	877	622	662
	Three					1052	1133	722	811
EPs	One	0.9	0.7	0.9	1.3	5.2	3.9	4.3	3.1
	Three	7.2	8.5	6.5	8.1	5.3	5.3	3.1	4.7
IESs	One					872	919	658	694
	Three					1126	1213	751	865

Note. Task 1 was unspeeded so that no RTs are available.

the null hypothesis, recent developments in Bayesian statistics allow to express at least preferences for the null hypothesis over the alternative (cf. Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayesian *t* tests for differences of the hand-tool compatibility effect in RTs between SOA levels revealed JZS Bayes factors of 4.79 for Experiment 2 and 5.27 for Experiment 1. Bayes factor values larger than 1 favor the null hypothesis, whereas values smaller than 1 favor the alternative. According to the conventions of Jeffreys (1961), the present range of values can be considered as "substantial" support for the additivity hypothesis. Altogether there is thus some reason to trust in the additive pattern observed here.

In sum, the results of Experiment 2 can already be seen as preliminary evidence for a central origin of the tool-transformation effect and against a postcentral, motor-related origin. However, as explained in the introduction, the most straightforward technique to test for a postcentral influence of an experimental factor is the effect-propagation logic, which we used in Experiment 3.

Experiment 3

Experiment 3 used the effect-propagation logic. To this end, we used the same tasks as in Experiment 1 but reversed the task order and implemented the tool movement task as Task 1. If the tool-transformation effect is located entirely in processes at or before the central stage, it should fully propagate to Task 2 (i.e., to the tone discrimination task) when the SOA is short. However, to the extent that the effect arises in postcentral processes, it should be smaller in RT2 than in RT1 (or even absent), because the Task 1 motor stage is assumed to work in parallel with other stages, and the response in Task 2 would thus not be delayed (see Figure 2).

Method

Sixteen students from the University of Würzburg participated for monetary compensation. Apparatus and design were the same as in Experiment 1 but with a changed task order. Accordingly, the stimulus for the tool task appeared first, and the instruction emphasized the priority of this task. Additionally, the imperative stimulus was now always presented in the middle position. After an SOA of 100 ms or 1,000 ms the stimulus for the tone discrimination task was presented. Participants were allowed to respond to the tone stimulus while still carrying out the tool movement in Task 1. This was demonstrated by the experimenter prior to the experiment proper. All other aspects were identical to Experiment 1.

Results

For RT analyses, only trials were considered where both responses were correct. Trials in which the MT of the tool was shorter than 10 ms or longer than 1,000 ms were removed (18.6% of all trials[6]). The same outlier criteria as in Experiment 1 were used which removed 2.0% and 2.7% of the trials for Task 1 and 2, respectively. Mean RTs and error percentages were submitted to repeated-measures ANOVAs with the factors SOA (100 ms vs. 1,000 ms) and hand-tool compatibility (compatible vs. incompatible). Mean RTs are shown in Figure 7 and Table 3. Mean error percentages are summarized in Table 3.

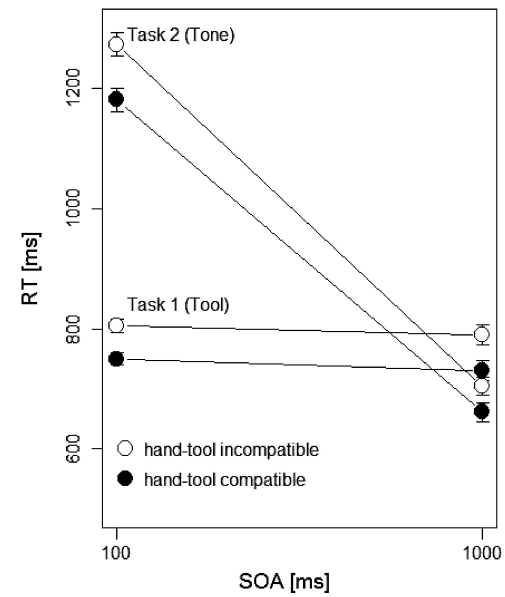

Figure 7. Experiment 3. Response times (RTs) in Tasks 1 and 2 as a function of stimulus onset asynchrony (SOA) and hand-tool compatibility. Error bars indicate within-subjects standard errors, calculated separately for each task and SOA. ms = milliseconds.

Task 1. Mean RTs were 58 ms higher with an incompatible than with a compatible hand-tool transformation, $F(1, 15) = 10.61$, $p = .005$, $\eta_p^2 = .41$. No other effect was significant (all *p*s > .220). There were no significant effects in the analysis of errors (all *p*s > .060). The analysis of inverse efficiency scores revealed higher scores with an incompatible than a compatible hand-tool transformation, $F(1, 15) = 7.89$, $p = .013$, $\eta_p^2 = .34$ (cf. Table 3).

Task 2. Mean RTs decreased when the SOA increased, $F(1, 15) = 253.85$, $p < .001$, $\eta_p^2 = .94$—the PRP effect. Crucially, however, RTs were 67 ms higher with an incompatible than a compatible hand-tool transformation, $F(1, 15) = 8.75$, $p = .010$, $\eta_p^2 = .37$. This effect of hand-tool compatibility was larger at the short SOA (92 ms) than at the long SOA (43 ms), $F(1, 15) = 7.50$, $p = .015$, $\eta_p^2 = .33$, for the interaction. Clearly, the effect of hand-tool compatibility in Task 1 fully propagated to Task 2, particularly at the short SOA. There were no significant effects for error percentages (all *p*s > .117). The main effect of SOA in RTs was also present in the analysis of inverse efficiency scores, $F(1, 15) = 341.79$, $p < .001$, $\eta_p^2 = .96$, and so was the effect of hand-tool compatibility, $F(1, 15) = 5.60$, $p = .032$, $\eta_p^2 = .27$ (cf. Table 3).

Discussion

The important observation of Experiment 3 is that the effect of hand-tool compatibility is—at the short SOA—at least as large for a subsequent tone discrimination task as for the tool task itself. In

[6] The proportion of MT outliers was relatively high in Experiment 3. We checked, however, that applying more liberal outlier criteria did not substantially change the data pattern. For the sake of consistency we eventually used the same outlier criteria as in the other experiments.

Table 3
Mean Response Times (RTs), Error Percentages (EPs), and Inverse Efficiency Scores (IES) in Experiment 3

	Task 1 (tool task)				Task 2 (tone task)			
	SOA 100 ms		SOA 1,000 ms		SOA 100 ms		SOA 1,000 ms	
	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible	Hand-tool compatible	Hand-tool incompatible
RTs	749	804	728	789	1181	1273	661	704
EPs	5.0	4.1	3.5	4.2	7.1	6.6	6.0	5.2
IESs	792	840	757	826	1285	1366	704	750

other words, the hand-tool compatibility effect propagates fully to Task 2. According to the effect-propagation logic we conclude that the entire effect of this tool transformation is located at (or before) the capacity-limited bottleneck process, and no later.

General Discussion

This study aimed at determining which stages of information processing are delayed when a spatially incompatible compared to a spatially compatible tool movement is prepared. By means of the locus-of-slack logic, Experiment 1 ruled out a perceptual locus. This result was replicated in Experiment 2, in which output-related interference was reduced by using a nonmotor memory task as Task 1. By means of the effect-propagation logic, Experiment 3 ruled out a motor-related locus as well. Taken together, the results force the conclusion that spatially incompatible tool-transformations delay a capacity-limited stage of processing.

This conclusion fits rather well with the influences of discrete and nominally task-irrelevant action effects, which have been attributed to a capacity-limited stage as well by using the same logic (Paelecke & Kunde, 2007). These convergent findings support the idea that incompatible tool movements can be construed as incompatible action effects, or conversely, that incompatible action effects can be construed as incompatible tool-transformations. Hence, in terms of information processing, whenever an action contingently produces a certain effect (be it a flashing light, tone, or whatever else), this action might be conceived as a tool action.

Influences of response-effect compatibility have been attributed to the impact of anticipated or imagined action effects, because these effects are a result of the executed response and can thus affect the response time only when anticipated in advance (Kunde, 2001; Paelecke & Kunde, 2007; Pfister et al., 2010). Essentially the same argument applies to the present tool effects. The start displays were always the same in the conditions with compatible and incompatible tool movements (always a pointer pointing upward). Only after the hand had moved, and thus response time was measured, did the predictable movement of the tool become noticeable. Hence, tool effects on response time can only be brought about when participants somehow anticipated the forthcoming movement of the tool.

What is the nature of the capacity-limited stage of processing involved in programming tool-transformed movements? Traditionally, this stage is interpreted as "response selection" (Pashler, 1984). However, it has been shown several times that other processes without a requirement for response selection invoke this stage as well (Jolicoeur & Dell'Acqua, 1998; Koch & Rumiati, 2006; Pashler, 1994). The observation of interference between a letter encoding task and a tool movement task in the present Experiment 2 is in agreement with the assumption of a more general cognitive capacity.

This observation has also practical implications. It shows that the programing of manual tool movements does not only interfere with other manual tasks but also presumably with any task that invokes this capacity-limited stage, just like driving a car is affected not only by manipulating a mobile phone but also to a similar extent by communicating via head set (Horrey & Wickens, 2006). When driving a car, effects that are incompatible with the hand movement occur when the steering wheel is grasped at its bottom rather than at its top (moving the hand to the right causes the car to move to the left). Doing so will not only affect driving performance as such but also concurrent cognitively demanding tasks, such as navigation in an unknown environment. Cognitively demanding tasks are common in other practical situations, such as in laparoscopic surgery. Here the surgeon operates while concurrently encoding information from other sources such as the members of the surgery team. Tool users should be aware that incompatible tool transformations not only delay the preparation of the tool action itself (compared to compatible transformations), but other concurrently performed tasks as well—as is apparent in the present Experiment 3. What we do not yet know, however, is whether this applies only to the inversion transformation used here, or to other more moderate transformations as well, such as changes in gain or rotations of directions (Hegele & Heuer, 2010; Heuer & Hegele, 2008). This is certainly a point for future research.

To conclude, tool movements that transform hand movements in a spatially incompatible manner delay responding. The present experiments consistently show that this delay is due to a lengthening of a central, capacity-limited stage of information processing. We hope that these findings help to guide research on tool use toward its underlying processes to arrive at a clear, functional understanding of this ubiquitous phenomenon.

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