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Does a tool eliminate spatial compatibility effects?

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Responding to a stimulus is faster and more accurate when stimulus location and response location spatially correspond than when they do not correspond (stimulus–response compatibility). In five experiments this standard compatibility effect is examined when using a T-shaped lever as a tool. Handling the lever allowed distinguishing body-related action effects (e.g., the tactile feedback from the moving finger) from external action effects (e.g., reaching at the stimulus with the lever's end-point). Results showed that the spatial relationship between stimulus and the direction of the hand movement (S-R compatibility) as well as the relationship between the stimulus and the functional end-points of the tool (S-E compatibility) determine performance. More precisely, responses were fast and less error prone when both kinds of compatibility did correspond than when they did not correspond.

Intentional actions require a goal, that is, some anticipatory representation of the expected action effects. Moreover, it has been assumed that the anticipations of these action effects may fulfil a generative function in motor control, formulated in the so-called ideomotor principle (Greenwald, 1970;

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James, 1890; for recent overviews of empirical evidence see, e.g., Hommel, Müsseler, Aschersleben & Prinz, 2001; Nattkemper & Ziessler, 2004). The ideomotor principle holds that actors select, initiate, and execute a movement by activating the anticipatory codes of the movement's sensory effects. These may be representations of body-related effects, like tactile sensations from the moving finger, and/or representations of more external effects, like the cursor on a display controlled by the user's mouse movements.

In the present context we focus on the external effects when handling a tool. Specifically, we examine whether and how tool use is able to reduce or to eliminate the phenomenon of spatial stimulus–response compatibility (S-R compatibility). Usually, responding to a stimulus is faster and more accurate when 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 & Deininger, 1954; Fitts & Seeger, 1953). However, also in S-R compatibility tasks external action effects are crucial as already demonstrated by Hommel (1993) and others. In Hommel's experiments pressing a left key switched on a right lamp and a right key switched on a left lamp (i.e., the action effect). Hommel instructed one group of participants to ignore the lamp and to press a left/right key in response to the pitch of a tone that appeared on the (task-irrelevant) left or right side. In this condition he observed faster and more accurate responses when keypress location and tone location corresponded than when they did not correspond. For the other group of participants the to-be-lit lamps were stressed by instruction. Participants were required to respond to the tone by switching on the right or left lamp. In this case, when a left keypress switched on the lamp on the right side, pressing this key was faster with a tone on the right rather than on the left side. What counts in this case seems to be the correspondence between tone location and the location of the intended action effect (switching on the lamp) rather than the correspondence between tone location and keypress location.

In Hommel's (1993) experiment the relation between response and action effect is endowed by instruction. Handling a tool allows for much more direct control of action effects. For example, in a study by Riggio, Gawryszewski, and Umiltà (1986), participants used sticks to press the response keys and the sticks were crossed or uncrossed. This allowed the spatial correspondence to vary orthogonally between the imperative stimulus, the location of the hand, and the location of the intended action effect (the tip of the stick). They found that what mattered was the spatial correspondence between the stimulus and the intended action effect.

In another example, Proctor and colleagues (Proctor, Wang, & Pick, 2004; Wang, Proctor, & Pick, 2003) studied steering-wheel responses, which resulted in right (with clockwise wheel rotations) or left (with counterclockwise wheel rotations) movements of a cursor on a display. The result was that wheel rotations were initiated faster when the stimulus location corresponded to the direction of the to-be-produced cursor movement (see also Kerr, 1976). This was observed, even when the wheel was grasped at its bottom, so that hand and cursor moved in opposite directions (see also Guiard, 1983; Michaels & Stins, 1997). Thus, it seems again that correspondence between stimulus location and effect movement (cursor) rather than between stimulus location and hand movement is crucial.

Grasping from the upper to the bottom part of a steering wheel introduces an inversion of movement direction. Such tool-related transformation always occurs when a so-called first-class lever movement is afforded (see also Kunde, Müsseler, & Heuer, in press; Massen & Prinz, in press). Consider the T-shaped lever illustrated in Figure 1. It resembles the roulette tool that croupiers use for collecting the chips. The tool consists of a vertical rod with a grip at the bottom part of the figure and a centrally placed horizontal rod in the upper part. The pivot point is in the mid of the horizontal rod and the tool's effect points are at the left and right ends of the horizontal rod. Consequently, when participants' task is to "reach" with the lever at the bottom right stimulus (Figure 1c), the lever's grip has to be shifted contrarily, that is to the left side (incompatible S-R relationship).

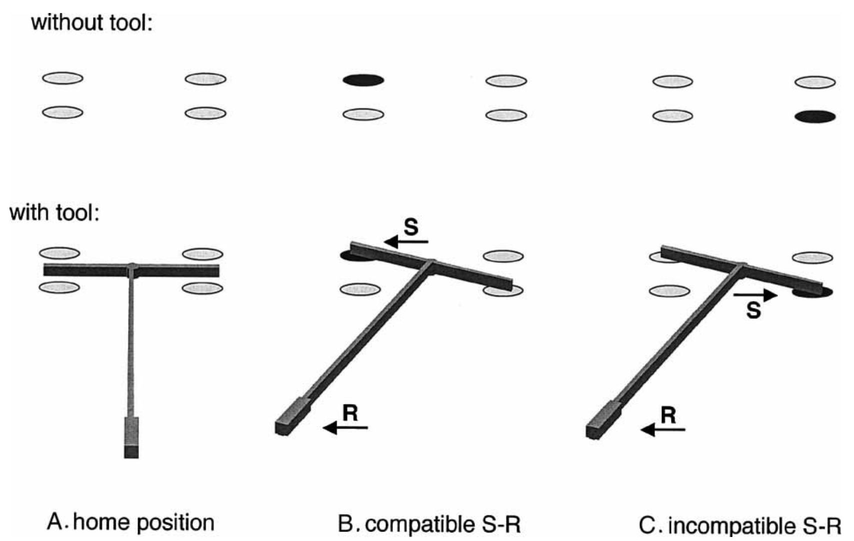

Figure 1. Stimulus configurations without (top) and with (bottom) tool in Experiments 1a and 1b. (A) shows the home position of stimuli and lever. (B) When the upper *left* stimulus is lit, a *left* response is required (compatible S-R relationship). With the response the lever is moved to the left. (C) When the lower *right* stimulus is lit, a *left* response is required (incompatible S-R relationship). In correspondence with the response the lever moves to the left.

However, when the stimulus at the upper left is lit, the grip has to be shifted to the side of the stimulus (compatible S-R relationship, Figure 1b).[1]

What to expect when comparing conditions with and without tool use? What the with-tool condition adds is the external action effect: A correct response shifts the effect point of the T-lever always towards the stimulus independently of the S-R relationship. The action-effect account claims that the relationship between stimulus and external action effect (S-E relationship) rather than the relationship between stimulus and hand movement (S-R relationship) is crucial. Consequently, all conditions are S-E compatible, and should thus be more or less equivalent according to the action-effect account. In other words, if all that matters is the S-E relationship, the S-R compatibility effect should be removed. In contrast, in the without-tool condition the external action effect is missing. Maybe, the body-related action effect (e.g., the tactile sensation from the moving hand) becomes prominent, but its spatial relationship corresponds to the S-R relationship anyway. Thus, in the without-tool condition responding to a stimulus should be faster and more accurate when stimulus and response spatially correspond than when they do not correspond.

To conclude, the action-effect account predicts a compatibility effect in the without-tool condition and a reduced or even eliminated compatibility effect in the with-tool condition. This prediction was examined with a computer-animated and a real T-lever in Experiment 1. In Experiments 2 and 3, a further condition was introduced in which the participants were to move the effect point of the T-lever away from the stimulus. Thereby the relationship between stimulus and external action effect was varied. Finally, Experiment 4 examined whether the temporal contiguity between response and its effect is crucial when using a tool.

EXPERIMENTS 1A AND 1B

Experiments 1a and 1b examined the prediction of the action-effect account that a tool is able to reduce or even to eliminate the spatial S-R compatibility effect. Therefore, a without-tool condition was compared with a T-lever

[1] Compatible and incompatible S-R relationship is confounded here with the vertical positions of the stimuli. When an upper stimulus is lit, a compatible response is always required, while when a bottom stimulus is lit, an incompatible response is demanded. Several findings indicate that responding to an upper stimulus is somewhat faster and more accurate with a right response than when with a left response and vice versa (orthogonal compatibility effects, see, e.g., Cho & Proctor, 2003; Lippa, 1996). So, in the present paradigm one could expect slightly different results for upper and bottom stimuli depending on their side of presentation (left vs. right), but these effects cancel each other out.

condition (cf. Figure 1), in which—after a correct response—the effect point of the tool is moved onto the corresponding stimulus.

In Experiment 1a a computer-animated version of the T-lever is realised, in Experiment 1b a real lever. In the computer-animated version, participants moved the lever virtually on a computer screen with a left or right keypress. In this case, the tool is beyond reaching distance in extrapersonal space. Further, keypresses and action effects are discrete events and do not represent continuous spatial movements. In the real-lever condition, participants moved the grip of a T-lever as a tool, which "elongates" the movement of the hand towards the effect points of the lever. In this case the tool elongates the reaching distance of peripersonal space (cf. Farné & Làdavas, 2000). Further, the real lever transforms continuously the hand movement into a tool movement. A comparison of Experiments 1a and 1b allows evaluating these differences between both conditions with regard to the action-effect account.

Method

Apparatus and stimuli. The experiments were carried out in a dimly lit and soundproof room and were controlled by an Apple Macintosh computer with Matlab software using the OS-9 Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997).

In Experiment 1a, the stimuli were presented on a 22-inch colour CRT monitor (100 Hz refresh rate, 1024 × 768 pixels). Stimuli were ellipses placed at the angles of a rectangle of 65 × 16 mm. The ellipses were 14 × 4 mm and grey coloured at first. When one of the ellipses turned into black, participants were required to press a right or left key according the instruction (see below). The T-shaped lever covered a visual field of 63 × 69 mm and was three-dimensionally animated with the pivot point in the mid of the horizontal axis and a virtual grip at the lower end of the vertical axis (Figure 1). In the home position the effect points at the ends of the horizontal axis of the lever were between the ellipses. After a left or right keypress the lever turned with the next vertical retrace of the monitor immediately to the left or right end position. Thus, the lever was presented only in two positions, the home position and the end position of the lever. Observers perceived a movement of the lever between these positions through the phi phenomenon. The lever turned back to the home position after the release of the key. The participant's head was placed on a chinrest 500 mm in front of the monitor. Two microswitches in front of the participants served as response keys, which were pressed with the index fingers of the right and left hand.

In Experiment 1b participants handled a real T-lever. It was mounted on a black wooden board, 500 × 450 mm in size. Green light-emitting diodes

(10 × 10 mm) were embedded in the board forming a virtual rectangle of 320 × 70 mm. The lever was 360 × 500 mm in size with the pivot point in the mid of the horizontal stick. Participants were informed about the exact home position of the lever by a mechanical snap point. Movement onsets (deviations of 13 mm from the home position of the T-lever) were collected by reed contacts and the corresponding reaction times were registered via a digital input–output device (ActiveWire, Inc., USB board). The end positions of the lever were also collected and used to determine a correct response. As a correct response counted a T-lever position if the corresponding effect point of the lever was within an area of 13 mm from the imperative stimulus (i.e. the light-emitting diodes).

The input–output device also allowed switching the light-emitting diodes on and off. The upper horizontal stick of the T-lever was removed in the without-tool condition so that there were no effect points of the lever in this condition. Participants sat before a table with the handle of the lever in front of them. They moved the lever with their preferred hand and the observing distance was about 650 mm.

Design. Both experiments had a 2 × 2 mixed design with condition (without vs. with tool use) as between-subject factor and S-R correspondence (compatible vs. incompatible) as within-subject factor. In each condition, participants worked through 400 trials presented in 20 blocks. The first two blocks were considered as practice trials and were not analysed. Dependent measures were median reaction times and the percentage of incorrect responses.

Procedure. Experiment 1a started with the presentation of the grey ellipses, which remained visible until the end of the experiment. In Experiment 1b stimulus configuration was visible from the beginning. When one of the stimuli (ellipses in Experiment 1a, light-emitting diodes in Experiment 1b) was lit, participants were required to press a right/left key (Experiment 1a) or to move the lever to the left/right end position (Experiment 1b). The next trial started 1.5 s after the key was released or the lever was returned to the home position.

Participants were instructed in written form prior of the experiment. In the with-tool condition of Experiment 1a, participants were informed in one sentence at the beginning of the instruction that a left or right keypress produced a left or right turn of the lever as if participants would handle the virtual grip of the lever. This first sentence was omitted in the without-tool condition. In Experiment 1b, participants were informed to handle the lever at the grip correspondingly. Otherwise, the instruction was identical: If the upper left stimulus or the lower right stimulus was lit, participants should perform a left response; if the lower left stimulus or the upper right stimulus was lit, participants should perform a right response. Thus, in the tool condition this mapping is equivalent to moving the tip of the tool on the side of the stimulus towards the stimulus. The instruction stressed the importance of responding as fast as possible to the stimuli.

An error feedback (a tone of 800 Hz with a duration of 150 ms) was given, if participants had made the wrong response or if reaction times exceeded 1000 ms. A wrong response in Experiment 1b was defined as an incorrect deviation of 13 mm from the T-levers' home position, independently of whether the direction of the movement was corrected or not. Each experiment lasted about 30 min.

Participants. Fifteen adults participated in Experiment 1a (five female; all between 18 and 30 years of age, mean age 22.5 years). Eight participants were assigned by chance to the without-tool condition and seven to the with-tool condition.

Sixteen participants participated in Experiment 1b (six female; all between 18 and 40 years of age, mean age 30.9 years). Half of them were assigned to the without-tool condition and the with-tool condition.

Results

Median reaction times and percentage of errors of each experiment were entered into separate 2 (condition: without-tool vs. with-tool use) × 2 (S-R compatible vs. incompatible) analyses of variance (ANOVAs). Results are shown in Figure 2.

With the computer-animated lever in Experiment 1a, an effect of S-R compatibility was observed with $F(1, 13) = 24.02$, $MSE = 452.10$, $p < .001$ in the reaction-time analyses and with $F(1, 13) = 7.00$, $MSE = 7.60$, $p = .020$ in the analysis with percentage of errors. Compatible responses were performed about 37 ms faster and with 2.5% less errors than incompatible responses. An interaction with condition was not observed. Contrary to our predictions, there was even a more pronounced S-R compatibility effect in the with-tool condition than in the without-tool condition.

In Experiment 1b, participants responded 124 ms faster and with 6.4% less errors in the with-tool condition than in the without-tool condition, $F(1, 14) = 40.45$, $MSE = 3069.52$, $p < .001$ and $F(1, 14) = 9.22$, $MSE = 35.02$, $p = .009$, respectively. Additionally, compatible responses were again performed faster (23 ms) than incompatible responses, $F(1, 14) = 5.95$, $MSE = 737.50$, $p = .029$. Further effects in reaction times and errors were not observed (all $F < 1$).

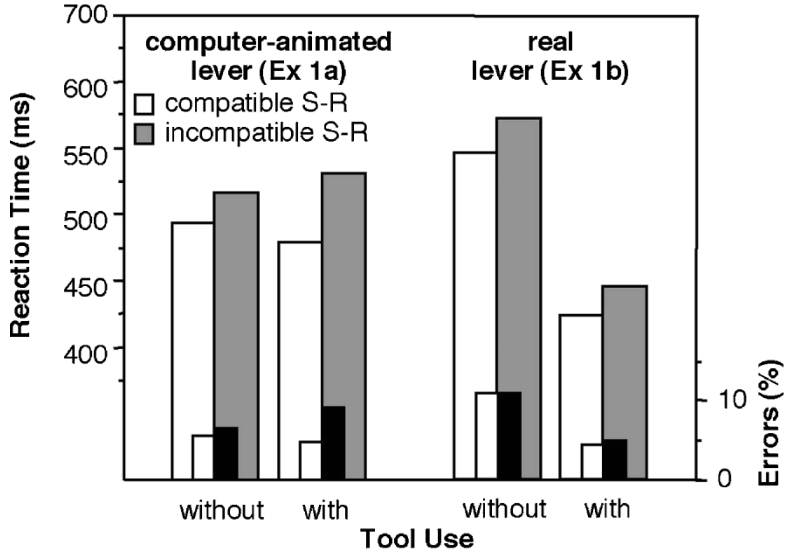

Figure 2. Mean reaction times and percentage errors with a computer-animated lever (Experiment 1a) and a real lever (Experiment 1b). For each experiment the without-tool and with-tool condition is shown. Light bars represent compatible S-R relationships, dark bars incompatible S-R relationships.

Discussion

There were three main findings of the experiments. First, in both experiments compatible responses were performed faster than incompatible responses independently of whether a tool is involved or not. In Experiment 1a there was even a tendency for a more pronounced compatibility effect in the condition with-tool use than in the condition without-tool use. Thus, contrary to the predictions of the action-effect account, we must conclude that tool use as such did not reduce or even eliminate the spatial compatibility effect. In the subsequent experiments the role of action effects to compatibility phenomena is further examined by introducing different action effects.

Second, the compatibility effect was observed with the computer-animated movements of Experiment 1a and with the real-lever movements of Experiment 1b. From this we must conclude that compatibility did not depend on the discrete movements in extrapersonal space or on the continuous movements in peripersonal space (but see Yamaguchi & Proctor, 2006). Third, however, tool use was not completely inefficient. In the condition with the real T-lever of Experiment 1b, reaction times and errors were reduced when compared with the without-tool condition. Obviously, the real tool generally facilitated responding. The main difference compared to the computer-animated version is that the real lever allowed for continuous movements of the lever, whereas the animated version allowed only for discrete movements. Another difference is that in the real-lever condition the grip of the lever was beyond the visual field of the observers while it was within the visual field in the computer-animated version. Maybe, the nonvisibility of the grip in the real-tool condition let participants concentrate more on the action-effect points and thereby facilitated responding. Anyway, this effect did not interact with compatibility and is only marginal in the present context.

EXPERIMENT 2

In Experiments 1, a correct response moved the effect point of the T-lever to the corresponding stimulus. In other words, stimulus and effect point of the tool always spatially corresponded after the response. It is also possible that the response moves the effect point of the T-lever *away* from the stimulus. In this case, stimulus and effect points of the tool do not correspond (lower part of Figure 3). We define the first correspondence as compatible S-E relationship and the second correspondence as incompatible S-E relationship. Note that this definition is not spatially with regard to the left-right dimension, but it reflects the spatial correspondence and noncorrespondence of effect point and stimulus after the response.

In the present experiment we examine whether the missing effect of tool use in the previous experiment originated from the fact that in Experiments 1 only compatible S-E relationships were realised. Therefore, we introduced a further condition in the present experiment, in which the effect points of the tool were also moved away from the stimulus (incompatible S-E relationship). We did that by introducing two different imperative stimuli: A "+" sign indicated to move the effect point of the lever towards the stimulus. An "×" sign indicated to move the lever away from the stimulus. All four conditions allow S-R and S-E relationships to vary independently (Figure 3).

Method

Stimuli, procedure, and design. These were the same as in Experiment 1a, except for the following changes. The experiment was run in four blocks with the sequence of blocks randomised between participants. As in Experiment 1, in each block the task afforded the execution of two responses (left/right) to four different stimuli (stimuli "+"/"×" at two positions). Two blocks were performed in the without-tool condition. In one of these blocks, stimuli were presented only in the upper row and observers were informed to press the key on the ipsilateral side of the stimulus when a "+" sign was presented. When an "×" sign appears, observers were to press the key on

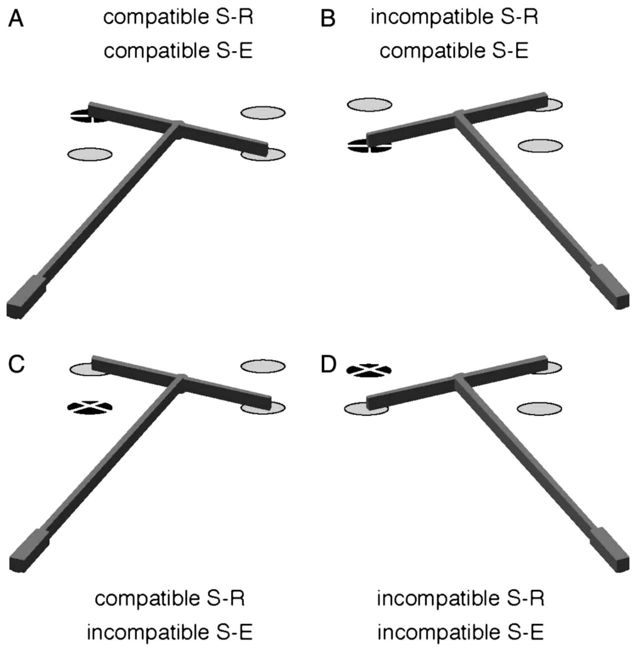

Figure 3. Stimulus configurations in Experiment 2. In A and C, left stimuli appeared which required a left response (compatible S-R relationship). In B and C, left stimuli appeared which required a right response (incompatible S-R relationship). In A and B, stimuli and effect points of the tool corresponded (compatible S-E relationship). In C and D, stimuli and effect points of the tool did not correspond (incompatible S-E relationship).

the contralateral side of the stimulus. In the other block, only stimuli in the bottom row were presented and the instruction was inverted. In the two remaining blocks, stimuli appeared again either in the upper or lower row, but now stimuli were presented together with the tool. The instruction now stressed to move the effect points of the lever to the location of the " + " sign and to move them away from the " × " sign. Participants went through 800 trials with 40 practice trials at the beginning of each block, which were not analysed. The experiment lasted about 90 min.

Participants. Ten observers (one male) between 19 and 26 years of age participated in the experiment.

Results

Median reaction times and percentage of errors were entered as dependent variables into separate 2 (condition: without-tool vs. with-tool use) × 2

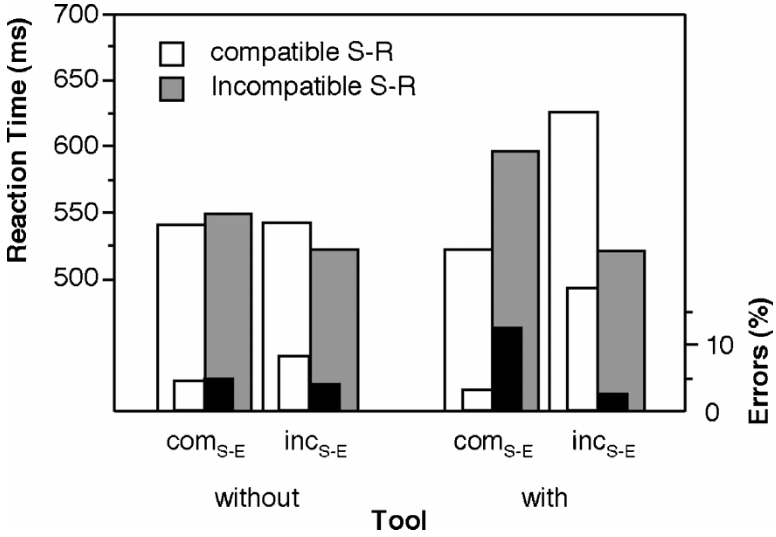

Figure 4. Mean reaction times and percentage errors with S-E compatible (com$_{S-E}$) and incompatible (inc$_{S-E}$) relationship and S-R compatible (light bars) and incompatible (dark bars) relationships (Experiment 2).

(compatible vs. incompatible S-R) $\times$ 2 (compatible vs. incompatible S-E) ANOVAs with repeated measurements. Results are shown in Figure 4.

Only marginal compatibility effects were observed in the without-tool condition. S-R compatible responses were performed only 8 ms faster than S-R incompatible responses in the S-E compatible condition. An even inverted effect of 19 ms was observed in the S-E incompatible condition. In the with-tool condition, in contrast, pronounced compatibility effects appeared: An S-R compatibility effect of 75 ms was observed with S-E compatible trials, in which the effect points of the lever were moved towards the stimulus. In the S-E incompatible trials, in which the effect points of the lever were moved away from the stimulus, the S-R incompatible responses were performed 106 ms faster than S-R compatible responses. This effect in reaction times corresponded to the findings in the errors. Consequently, the three-way interaction was significant in reaction times with $F(1, 9) = 16.14$, $MSE = 1829.77$, $p = .003$ and in the errors with $F(1, 9) = 16.60$, $MSE = 32.81$, $p = .003$. Further, the two-way interaction between S-R and S-E compatibility was significant with both dependent variables: reactions times, $F(1, 9) = 10.76$, $MSE = 5058.47$, $p = .01$; errors, $F(1, 9) = 17.54$, $MSE = 64.69$, $p = .002$.

There were other effects only significant in one dependent measure. The ANOVA with errors yielded more errors in the with-tool trials than in the without-tool trials; main effect of condition with $F(1, 9) = 11.69$,

$MSE = 26.10$, $p = .008$. Further, more errors were observed with S-E incompatible trials than with S-E compatible trials, main effect of S-E compatibility with $F(1, 9) = 5.19$, $MSE = 17.90$, $p = .049$, but less errors with S-R incompatible trials than with S-R compatible trials, main effect of S-R compatibility with $F(1, 9) = 8.11$, $MSE = 16.58$, $p = .019$. In the ANOVA with reaction times, the interaction of condition (without-tool vs. with-tool use) and S-E compatibility was also significant with $F(1, 9) = 12.77$, $MSE = 297.53$, $p = .006$.

Discussion

The experiment has two main findings. First, the pattern of compatibility effects in the without-tool condition was qualitatively comparable to the pattern in the with-tool condition, but effects were negligible in size. Small or even eliminated compatibility effects sometimes occur with mixed mappings conditions of compatibility, as was applied here (cf. Shaffer, 1965; Vu & Proctor, 2004; Yamaguchi & Proctor, 2006). The comparability in the pattern of results might originate from marginal transfer effects when participants shifted from a with-tool block to a without-tool block.

Second, compatibility effects were much more pronounced in the with-tool condition. With the tool, the findings of Experiment 1 were successfully replicated with S-E compatible trials, in which the effect points of the lever were moved on the stimulus. In this case, S-R compatible responses were performed faster than incompatible responses. However, in S-E incompatible trials, in which the effect points of the lever were moved away from the stimulus, the result was inverted. In other words, responses were faster and less erroneous when S-R and S-E compatibility matched than when they did not: When a left stimulus required a left response (compatible S-R relationship; Figure 3A and 3C), the response was faster (and less error-prone) than a right response only when the effect point of the tool was moved towards the stimulus (compatible S-E relationship; Figure 3A). When a left stimulus required a right response (incompatible S-R relationship; Figure 3B and 3D), the response was faster (and less error-prone) than a left response only when the effect point of the tool was also moved away from the stimulus (incompatible S-E relationship; Figure 3D). This is clear evidence that—when the T-lever is used—S-R *and* S-E relationships contribute to response times and errors.

EXPERIMENT 3

Conditions in the previous experiment did not only differ with regard to whether a tool was employed or not, but both conditions also differed with regard to the instruction. In particular, in the with-tool condition the instruction stressed to move the effect points of the lever to or away from the stimulus location, while in the without-tool condition the instruction stressed to press the ipsilateral or contralateral response key. Therefore one might argue that the dissimilar findings of the experiment originated from the differences in the instruction. To examine this objection with the present experiment, the neutral response-key instruction was also applied in the with-tool condition.

Method

Stimuli, procedure, and design. These were the same as in Experiment 2, except for the following changes. Only the with-tool condition was used and the instruction was now neutral with regard to the tool. The experiment was run in two blocks. In one block, stimuli were presented only in the upper row and observers were informed to press the key on the ipsilateral side of the stimulus when a "+" sign was presented. When an "×" sign appeared, observers were to press the key on the contralateral side of the stimulus. In the other block, only stimuli in the bottom row were presented and the instruction was inverted. Participants went again through 400 trials with 40 practice trials at the beginning of each block, which were not analysed.

Participants. Fifteen observers (10 female) between 19 and 26 years of age participated in the experiment. Eight participants performed first the block, in which stimuli were presented only in the upper row. Seven participants performed first the block, in which stimuli were presented only in the bottom row.

Results and discussion

Median reaction times and percentage of errors were entered into separate 2 (compatible vs. incompatible S-R) × 2 (compatible vs. incompatible S-E) ANOVAs. The findings of the with-tool condition were similar to the previous experiment (Figure 5). When considering the S-E compatible trials, S-R compatible responses were performed 68 ms faster than incompatible responses. However, when considering the S-E incompatible trials, S-R incompatible responses were performed 56 ms faster than S-R compatible responses. Consequently, the interaction of both factors was again significant with $F(1, 14) = 9.60$, $MSE = 6011.22$, $p = .008$. The error analysis revealed a corresponding interaction effect with $F(1, 14) = 5.45$, $MSE = 83.27$, $p = .035$. We can conclude that the instruction given by the experimenter was not essential for the interaction of S-E and S-R compatibility to appear. But it remains possible that participants quickly

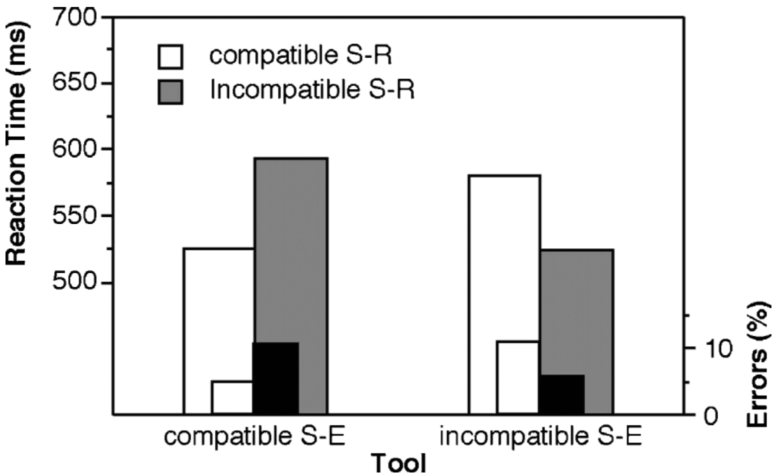

Figure 5. Mean reaction times and percentage errors with compatible and incompatible S-E relationship. Light bars represent compatible S-R relationships, dark bars incompatible S-R relationships (Experiment 3).

recoded the complicated instruction of the present experiment into the simpler rule referring to the tool.

EXPERIMENT 4

Experiment 4 aimed to replicate and to extend the findings of the previous experiments. If actions are initiated by the anticipation of their desired effects (here the left or right turn of the lever), temporal contiguity between the action and its effects could be critical. For example, Proctor et al. (2004) observed that the compatibility of a stimulus and a cursor manipulated by a steering wheel, affected performance only when the cursor moved as an immediate consequence of wheel rotation, but not when it moved only after completion of an initial 8° wheel rotation. Also, Elsner and Hommel (2004) have shown that action-effect associations are established only if the effect of the action is delayed for no more than 1 s. This let us expect that the interaction observed in Experiment 2 and 3 degraded with an increase of delay between response and effect.

Method

Stimuli, procedure, and design. These were the same as in Experiment 3, except for the following changes. The left or right turn of the lever was presented with three different delays after the left or right keypress. The response-effect asynchronies (REA) were 50, 500, and 2000 ms.

REAs were presented blockwise with the sequence of blocks counterbalanced between participants according to a Latin square. Counterbalancing allows us to include the factor "sequence of blocks" in the design. This factor serves as dummy variable to extract the variance owing to the error associated with sequence of blocks (see Pollatsek & Well, 1995). Sequence of blocks was a nonrepeated measures factor in the ANOVAs, whereas REA, S-R, and S-E compatibility were within-participants factors.

Within each block, all combinations of S-R and S-E compatibility were presented in a randomised order. Therefore, in contrast to the four alternative forced-choice task (4-AFC task) in the previous experiments the task was now an 8-AFC task in each block (2 stimuli "+"/"×" at 4 positions). As an 8-AFC task let expect a general increase of reaction times, an error feedback was given not until reaction times exceeded 2000 ms (in Experiments 1 and 2: 1000 ms).

Participants went through 1080 trials (360 trials each block) with 40 practice trials at the beginning of each block, which were not analysed. The experiment lasted about 75 min, with short breaks between the blocks.

Participants. Twelve observers (nine female) between 19 and 56 years of age participated in the experiment.

Results and discussion

Figure 6 shows that reaction times and percentage of errors were generally increased—probably in consequence of the 8-AFC task of the present experiment compared to the 4-AFC task of the previous experiments. The figure further shows that in the first block (upper part of Figure 6) the pattern of results within each REA is similar to the pattern of results obtained in the previous experiment (see also Figures 4 and 5). In S-E compatible trials, S-R compatible responses were performed faster than incompatible responses. In S-E incompatible trials, this result is inverted; S-R incompatible responses were performed faster than compatible responses. When looking at the second and third blocks, the S-R compatibility effect proved robust in the S-E compatible trials. However, the reversion of the effect disappeared in the S-E incompatible trials.

When reaction times and errors entered into separate 3 (sequence of blocks) × 3 (REA: 50, 500, 2000 ms) × 2 (S-R compatible vs. incompatible) × 2 (S-E compatible vs. incompatible) ANOVAs,[2] a significant four-way interaction was observed in reaction times, $F(4,\ 18) = 5.29$, $MSE = 1054.19$, $p = .005$, and errors, $F(4,\ 18) = 3.48$, $MSE = 6.78$, $p =$ .028. The two-way interactions of S-R and S-E compatibility were also

[2] If necessary, F probabilities of the ANOVAs were Greenhouse-Geisser corrected.

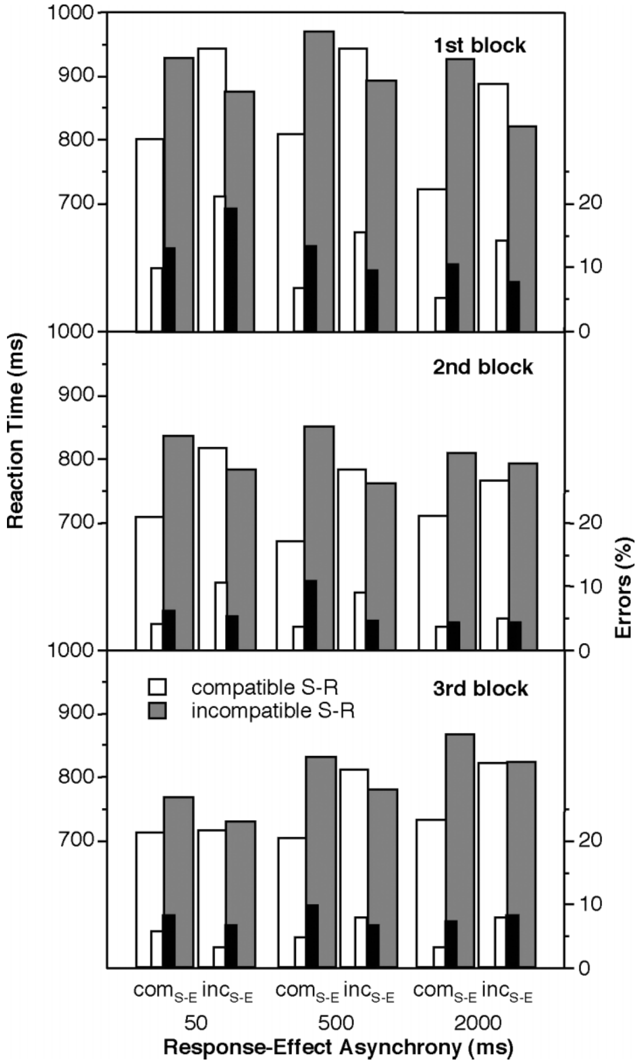

Figure 6. Mean reaction times and percentage errors with S-E compatible ($com_{S\text{-}E}$) and incompatible ($inc_{S\text{-}E}$) relationship, S-R compatible (light bars), and incompatible (dark bars) relationships and the response-effect asynchronies (50, 500, and 2000 ms). Panels show three different phases of the experiment (first to third block; Experiment 4).

significant in both dependent variables: reaction times, $F(1, 9) = 22.13$, $MSE = 4934.18$, $p < .001$; errors, $F(1, 9) = 12.80$, $MSE = 29.96$, $p = .006$. Both interactions originated from the first block, in which an S-R compatibility effect and its reversion were observed in the S-E compatible trials and in the S-E incompatible trials, respectively. But also the pattern of results in the second and third blocks, in which the S-R compatibility effect disappeared in the S-E incompatible trials, contributed to the interaction. A last effect, significant in both reaction times and errors, was the two-way interaction of sequence of blocks and REA: reaction times, $F(4, 18) = 5.63$, $MSE = 18{,}702.23$, $p = .004$; errors, $F(4, 18) = 9.01$, $MSE = 34.19$, $p < .001$. Obviously, in the first block, reaction times and errors tend to decrease with an increase of the REA, while in the third block this tendency is inverted.

There were other effects only significant in one dependent measure. In the ANOVA with reaction times, S-R compatible trials were performed generally faster than incompatible trials, main effect of S-R compatibility with $F(1, 9) = 22.13$, $MSE = 4934.18$, $p < .001$. In the ANOVA with errors, S-E compatible trials proved to be less error-prone than S-E incompatible trials, main effect of S-E compatibility with $F(1, 9) = 5.12$, $MSE = 28.51$, $p = .05$. Additionally, in this analysis the three-way interaction of sequence of blocks, S-E compatibility and REA, $F(4, 18) = 5.47$, $MSE = 9.22$, $p = .005$, was significant and the three-way interaction of REA, S-E, and S-R compatibility, $F(2, 18) = 4.59$, $MSE = 6.78$, $p = .024$.

In sum, there are three main findings in the present experiment. First, the previous reversion of the S-R compatibility effect in S-E incompatible trials was successfully replicated in the first block of the experiment. Second, the observed effects of S-R and S-E compatibility were not (or less) modified by the temporal delay with which the left/right turn of the lever followed the left/right keypress (REA). Thus, it seems that a strong contiguity of response and its effect is not needed when a tool is used. Third, the reversion of the S-R compatibility effect in S-E incompatible trials was not observed in the second and third blocks. In other words, the effects of S-R compatibility were robust only in S-E compatible trials, while they disappeared in S-E incompatible trials.

The second finding contradicted our hypothesis. With regard to the studies of Elsner and Hommel (2004) and Proctor et al. (2004), our assumption was that action-effect associations work only if the effect of the action is delayed for no more than a brief period of time. This let us expect that the interaction observed in Experiment 2 and 3 degraded with an increase of delay between response and effect—but that was not the case. On the other hand, the associations of action and effects in the study of Elsner and Hommel (and of related studies) were quite arbitrary associations of responses and tones which make less sense in other contexts. On the contrary, the T-lever and its handling determines the possible action effects from the beginning. It is easy to mentally rotate the tool in order to achieve the intended end position. Moreover, the keypresses and tool movements might have a higher plausibility, or "belongingness", as Thorndike and Lorge (1935) termed it, than keypresses and tones (Elsner & Hommel, 2004) or wheel rotations and cursor movements (Proctor et al., 2004). The ease of imagination of the present effects and their belongingness to the manual actions might have rendered a prompt confirmation of the action effect relation dispensable.

GENERAL DISCUSSION

The present study aimed to examine whether and how tool use is able to reduce or to eliminate the S-R compatibility effect. In five experiments participants responded to the appearance of a left/right stimulus with a T-shaped lever. Different hypotheses emerged from considering the direction of the hand movement and the direction at which the external effect point of the tool was aiming at. Thus, tool use allowed evaluating compatibility effects with different body-related and external action effects.

In Experiment 1a the with-tool condition was compared with a without-tool condition. In both conditions participants responded to left/right stimuli with left/right keypresses (i.e., with discrete movements), but only in the with-tool condition the lever was presented and turned to the left/right immediately after the keypress. Results revealed the common S-R compatibility effect that is responses were faster and more accurate when stimulus and hand location corresponded than when they do not correspond. More important, results showed no difference between the without-tool and with-tool condition—a finding that proved to be robust also in the real-lever condition (i.e., with continuous movements; Experiment 1b). Obviously, the external action effects produced by tool use did not modify the S-R compatibility effect.

Contrary to the findings of Experiment 1, the significance of the external action effects were demonstrated in the subsequent experiments. Taking into account the S-E relationship when using a tool, results showed that the common S-R compatibility effect occurred only in S-E compatible trials (i.e., when the effect points of the lever were moved on the stimulus). In S-E incompatible trials, in which the effect points of the lever were moved away from the stimulus, the finding was inverted: S-R incompatible responses were performed faster and with fewer errors than S-R compatible responses (Experiment 2). This inverted effect also occurred with an instruction, which was neutral with regard to the tool use (Experiment 3). Both experiments demonstrated convincingly that S-R *and* S-E relationships contribute to response times and errors when a T-lever is used.

In the first block of Experiment 4 the observed effect of S-R compatibility in S-E compatible trials and its reversion in S-E incompatible trials proved to be robust with different REAs. Thus, it seems that a strong contiguity of response and its effect is not needed when a tool is used. Contrary to other studies, which emphasised the necessity of action-effect contiguity (e.g., Elsner & Hommel, 2004), the handling of the T-lever determined the possible action effects from the beginning. In this case it does not seem to need the enduring confirmation of the action effects.

To explain the present pattern of results consider the main finding of the study: When the tool is used, responses were fast and less error prone when S-R and S-E compatibility did correspond than when they did not correspond. This finding can be easily explained when suggesting that participants first translated the stimuli into one of the two S-E rules (move the effect points towards or away from the stimulus) and then translated the effect code into the response-key location. Applying this idea, observers use the same rule (towards or away) for both translations when S-E and S-R relationships are both corresponding or are both noncorresponding. By contrast, observers have to use different rules when the S-E relationship is corresponding and the S-R relationship is noncorresponding and vice versa. One further has to assume that using the same rule for both translations reveals better performance than using different rules. This assumption makes sense because when using the same rule twice, participants have not to switch the rule and they do not have to worry about the order of rule application.

A related explanation originates from linking the present inversion of the compatibility effect in S-E incompatible trials to an inverted compatibility effect observed by Hedge and Marsh (1975). These authors presented coloured stimuli to the left or to the right of fixation and they introduced response keys, which were labelled by the stimulus colours. Participants performed with a compatible mapping of stimulus colour to response colour (red/green stimulus → red/green keypress) or with an incompatible mapping (red/green stimulus → green/red keypress). The compatible mapping yielded the standard compatibility effect (Simon effect), that is, faster responses when stimulus and response locations corresponded than when they did not. However, the incompatible mapping (e.g., red stimulus → green keypress) yielded an inverted Simon effect, that is, faster responses when stimulus and response locations did not correspond than when they did.

Hedge and Marsh (1975) attributed the inverted Simon effect to logical recoding: misapplication of a reversal rule (respond with the opposite of the stimulus value) to the irrelevant spatial stimulus dimension. For example, a "respond-opposite" rule yields "left" when the stimulus occurred in the right location, facilitating responding if the correct response was left and interfering if it was right. A similar mechanism might be at play in Experiments 2 and 3. In order to explain the effects of S-E compatibility on S-R correspondence, one has to further assume that the rules used for determining the S-E relationship are (involuntarily) applied to the S-R relationships.

What remains to be explained is the finding that the reversion of the S-R compatibility effect in the S-E incompatible trials disappeared in the second and third block of Experiment 4. In other words, there was no compatibility difference anymore between conditions C and D illustrated in Figure 3. Possibly, the end positions of the levers were recoded in such a way that action-effect points were not moved any further away from the imperative stimulus, but instead towards the two empty diagonal stimuli, which covered both action-effect points. Then there is no difference between conditions C and D. If this is correct, one could even expect the reappearance of the standard S-R compatibility effect with further extensive practice, but it is beyond the scope of the present paper to elaborate on this idea. At least, more empirical data are needed to clarify this finding completely.

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