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Compatibility Relationships With Simple Lever Tools

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Objective: The study focuses on potential compatibility relationships when simple lever tools are used.

Background: Spatial compatibility between stimuli and responses determines performance. However, many tasks require the use of simple tools, such as levers that transform hand movements into tool movements. We explore with such a tool whether and how the correspondence or noncorrespondence between stimulus-side and hand movement (stimulus-response compatibility), between stimulus-side and tool-effect movement (stimulus-effect compatibility), and/or between hand movement and tool-effect movement (response-effect compatibility) affects performance.

Method: *U*-shaped and inverted-*U*-shaped levers were used as tools, allowing us to examine the contribution of each compatibility relationship to response times and errors without any confounds and omissions.

Results: Responding was delayed and error prone when the hand movement and the movement of the effect point of the tool did not correspond. Effects of stimulus-response compatibility and stimulus-effect compatibility were observed only when the hand movement direction remained untransformed in the tool-effect movement.

Conclusion: The results point out that the inversion or noninversion of tool-effect movements plays an underlying role when handling a tool.

Application: Potential applications of this research include the prediction and possibly manipulation of unwanted behavioral tendencies in laparoscopic surgery and other lever movements.

Keywords: SR compatibility, reaction times, tool use, sensorimotor transformation, laparoscopic surgery, teleoperation

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INTRODUCTION

It is well known that 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 [SR] compatibility; Fitts & Deininger, 1954; for an overview, see Proctor & Vu, 2006). The spatial relation between stimulus and response still affects performance when stimulus location is irrelevant for the task (Simon effect; see Simon, Hinrichs, & Craft, 1970). Especially this latter finding has inspired models of SR compatibility according to which the presentation of a stimulus activates automatically an ipsilateral response. This activation is advantageous in spatially corresponding conditions but results in a response conflict in spatially noncorresponding conditions. The solution of the response conflict increases the time needed to select the response and the probability of selecting a wrong response (Proctor & Vu, 2006).

Recent studies with simple lever tools further showed that response times and errors are determined not only by the relationship between stimulus location and response location but also by the spatial effect points of a lever (Beisert, Massen, & Prinz, 2010; Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2007; Massen & Sattler, 2010; Müsseler, Kunde, Gausepohl, & Heuer, 2008). The theoretical background of these studies is that actors select, initiate, and execute a movement by activating the anticipatory codes of the movement's sensory effects (ideomotor principle, cf. Greenwald, 1970; James, 1890; for a more recent views, see Hommel, Müsseler, Aschersleben, & Prinz, 2001; Shin, Proctor, & Capaldi, 2010). These may be representations of body-related effects, such as tactile sensations from the moving finger, and/or representations of more external effects, such as the moving effect points of a lever, as used in these studies.

For instance, when a surgeon operates through a tiny hole in a patient's abdomen with an inflexible

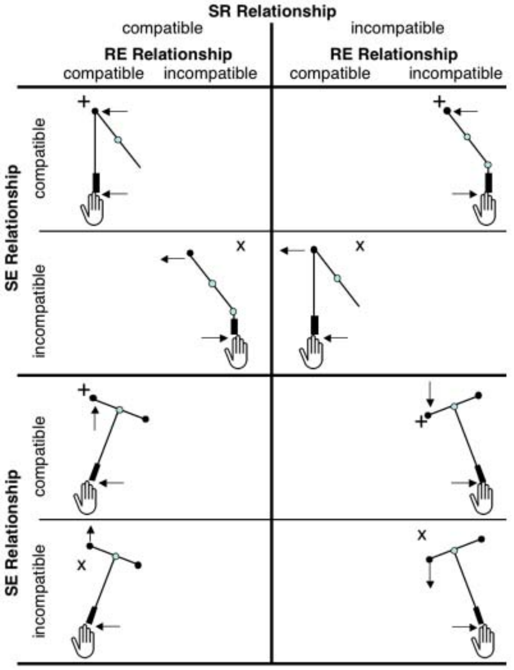

Figure 1. Stimulus-response (SR), stimulus-effect (SE) and response-effect (RE) relationships with the *I*-shaped lever (first and second rows) and the *T*-shaped lever (third and fourth rows). Imperative stimuli were indicated by "+" and "×," indicating to move the lever's effect point toward or away from the stimulus, respectively. Circles represent pivot points, dots the effect points of the lever.

endoscope, she or he has to move her or his hand to the left if she or he wants to move the effect point of the endoscope to the right and vice versa. Kunde and colleagues (2007) conducted experiments simulating this kind of lever movement. They used an *I*-shaped lever and participants were to move the effect point of the lever toward a stimulus or away from it, depending on the stimulus's color (comparable to a surgeon moving a laparoscopic tool toward a tissue to treat it or moving away from it to avoid damage). In an indirect control condition (Figure 1, first row right and second row left), the hand moved the lower end of the lever and affected the tip of the tool by means of a pivot point. In this case, hand and effect point of the lever moved in opposite directions. In a direct control condition, the hand was directly connected to the tip of the tool (Figure 1, first row left and second row right). Consequently, in this condition, the hand and tip of the tool always moved in corresponding directions.

One objection against the tool used by Kunde et al. (2007) was that when performing the task in the direct control condition, the pivot point of the lever is not necessary at all. Thus, this condition mimics more a simple pointing task with a stick (cf. Riggio, Gawryszewski, & Umiltà, 1986) and is therefore not comparable at all with a lever task. The *T*-shaped lever used by Müsseler and colleagues (2008) handles this objection. The tool resembles the roulette tool that croupiers use for collecting chips. It consists of a vertical rod with a grip at the bottom part of the figure and a centrally placed horizontal crossbar in the upper part. The pivot point is in the middle of the crossbar, and the tool's effect points are at the left and right ends. Consequently, when a stimulus at the upper (lower) left is presented, the grip has to be shifted to the side of the stimulus to reach or to avoid it (Figure 1, third and fourth row left).

However, when the imperative stimuli were exchanged, and participants' task was to reach with the lever at the lower left stimulus position, the lever's grip has to be shifted contrarily, that is, to the right side (Figure 1, third row right). This requirement is also the case when participants' task was to avoid, with the lever at the upper left stimulus (Figure 1, fourth row right).

Conditions with the *I*-shaped lever and the *T*-shaped lever were different in three aspects, at least: First, the *I* lever has only one effect point, and the *T* lever has two effect points. Second, stimulus locations were varied only on the horizontal dimension with the *I* lever but on the horizontal *and* vertical dimensions with the *T* lever. And third, lever-effect movements were to the right or left with the *I* lever but upward or downward with the *T* lever. Nevertheless, mean response times with both levers were amazingly consistent.

Figure 2 shows the response times when conditions of the *I* lever and *T* lever were analyzed with regard to the SR relationship and the stimulus-effect (SE) relationship. The SR relationship is the correspondence (or noncorrespondence)

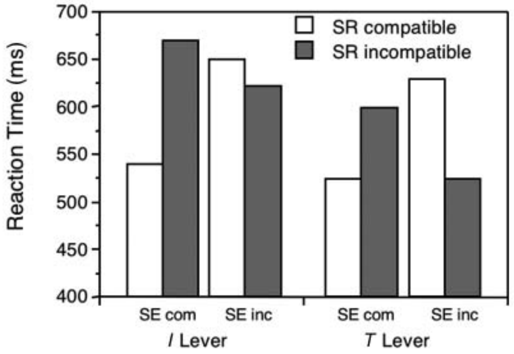

Figure 2. Mean reaction times of stimulus-response (SR) and stimulus-effect (SE) conditions with the *I*-shaped lever (left bars; Kunde, Müsseler, & Heuer, 2007, Experiment 1) and the *T*-shaped lever (right bars; Müsseler, Kunde, Gausepohl, & Heuer, 2008, Experiment 2). Light bars represent compatible SR relationships; dark bars represent incompatible SR relationships. Com = compatible; inc = incompatible.

between stimulus location and hand-response direction. The SE relationship is the correspondence (or noncorrespondence) between stimulus location and the direction of the lever's effect point. A compatible SE relationship represents the situation in which the lever's effect points have to reach at the stimulus; an incompatible SE relationship represents the situation in which the effect points have to be shifted away from the stimulus. The results demonstrated the advantage of SR compatible conditions with both levers but only when the SE relationship was compatible. When the SE relationship was incompatible, the SR compatibility effect was inverted. In other words, responses were faster when SR and SE compatibility matched than when they did not.[1]

However, Figure 1 also indicates that when the spatial effect points of the lever are taken into account, in principle, three compatibility relationships are relevant. Besides the just-mentioned SR and SE relationship, the response-effect (RE) relationship reflects the correspondence (or noncorrespondence) between hand-response direction and the direction of the spatial effect point of the lever. In other words, the RE relationship represents the compatibility between hand movement and its tool effect transformation (see also Yamaguchi & Proctor, in press).

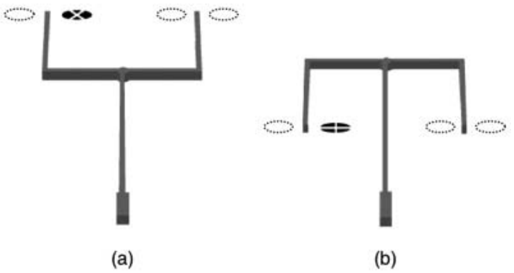

Figure 3. The *U* lever (a) and the inverted-*U* lever (b) in the experiment. Imperative stimuli were "+" and "×," indicating either to move the lever's effect point toward the stimulus or to move the lever's effect point away from the stimulus, respectively. After a left or right key press, the lever turned with the next vertical retrace of the monitor immediately to the left or right end position (see Figure 4). Dotted ellipses indicated other presentation positions. The example in Figure 3a represents a trial with incompatible SR, RE, and SE. The example in Figure 3b represents a trial with incompatible SR and compatible RE and SE.

The problem with the *I* lever and the *T* lever is that they did not allow unequivocal evaluation of the contribution of SR, RE, or SE relationship to response times and errors. The reason is that Figure 1 contains empty cells and therefore confounds. For instance, with the *T* lever, SR and RE relationship were completely confounded. With the *I* lever, the RE relationships matched with the SE relationships in compatible SR conditions but mismatched in incompatible SR conditions.

The aim of the present study is to examine a tool that allows varying orthogonally SR, SE, or RE relationships. Such a tool is the *U*-shaped lever and the inverted-*U*-shaped lever, as depicted in Figure 3. Like the *T* lever, it consists of a vertical rod with a grip at the bottom part of the figure and a centrally placed crossbar in the upper part. The pivot point is in the midpoint of the horizontal rod, but the tool's effect points are at the ends of additional upward- or downward-oriented rods attached at the crossbar. This configuration allows presentation of the stimuli at four positions, each reachable by the effect points of the lever.

Figure 4 shows that the *U*-shaped lever and the inverted-*U*-shaped lever fill the complete

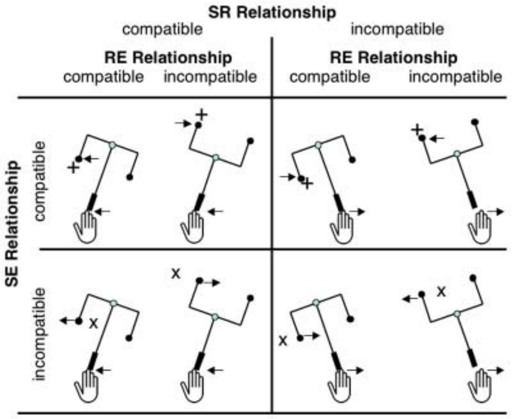

Figure 4. Stimulus-response (SR), response-effect (RE), and stimulus-effect (SE) relationships with the *U* lever and the inverted-*U* lever. In the figure, the imperative stimulus "+" indicated to move the lever's effect point toward the stimulus, and the imperative stimulus "×" indicated to move the lever's effect point away from the stimulus. Circles represent pivot points; dots represent the effect points of the lever.

matrix of SR, RE, and SE relationships. Thus, this tool allows for the examination of the contribution of each relationship to response times and errors without any confounds and omissions.

In the subsequent experiment, a computer-animated version of the lever is presented in which the lever "moves" virtually to the left or right in response to a left or right key press. There are mainly two reasons that led to this decision: First, a computer-animated lever is much easier to realize than a real lever. Second, simple lever movements can be assumed to reflect ballistic movements, especially when they are performed in response to a stimulus. As a demonstration, consider Figure 2, which shows amazingly consistent response times even though the study of Kunde and colleagues (2007, Experiment 1) was based on real lever movements and the study of Müsseler and colleagues (2008, Experiment 2) used key presses with a computer-animated lever (for a direct comparison of both types of levers, see Müsseler et al., 2008, Experiments 1a and 1b).

METHOD

Apparatus and Stimuli

The experiment was carried out in a dimly lit and soundproof chamber and was controlled by an Apple Macintosh computer with Matlab software and the Psychophysics Toolbox (Kleiner, Brainard, & Pelli, 2007). Stimuli were presented on a 22-in. color CRT monitor (100 Hz refresh rate; 1,024 × 768 pixels). The *U*-shaped lever and the inverted-*U*-shaped lever were 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. Levers covered a visual field of 67 × 85 mm (*U*-shaped lever) and 67 × 67 mm (inverted-*U*-shaped lever). Imperative stimuli were "+" and "×" presented in ellipses (14 × 4 mm) at the left or right effect points of the lever (Figure 3). Two microswitches in front of the participants served as response keys, which were pressed with the index fingers of the right and left hand. The participant's head was placed on a chin rest 500 mm in front of the monitor.

Design

The experiment had a 2 (SR relationship: compatible vs. incompatible) × 2 (RE relationship: compatible vs. incompatible) × 2 (SE relationship: compatible vs. incompatible) repeated-measures design. The *U*-shaped lever and inverted-*U*-shaped lever were presented blockwise with the sequence of blocks balanced between participants. Participants worked through 12 blocks of 40 trials, for a total of 480 trials. The first blocks with the *U*-shaped lever and the inverted-*U*-shaped lever were considered as practice trials and were not analyzed. Dependent measures were median reaction times and the percentage of incorrect responses of each participant.

Procedure

Participants were instructed in written form prior of the experiment. Participants were informed that a left or right key press produced a left or right turn of the lever as if participants were handling the virtual grip of the lever.

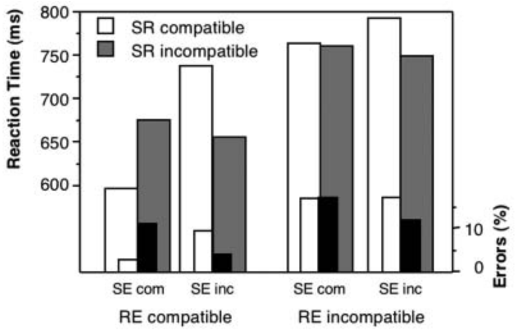

Figure 5. Mean reaction times and percentage errors of the stimulus-response (SR), response-effect (RE), and stimulus-effect (SE) relationships. Com = compatible; inc = incompatible. Light bars represent compatible SR relationships; dark bars represent incompatible SR relationships.

The experiment started with the presentation of the lever, which remained visible until the end of the experiment. At the beginning of each trial, the lever was in the middle position. When the imperative stimulus appeared, participants were required to press a right or left key as fast and accurately as possible according the instruction: The "+" indicated to move the lever's effect point toward the stimulus, and the "×" indicated to move the lever's effect point to the opposite side of the stimulus.

After a left or right key press, the lever turned with the next vertical retrace of the monitor immediately to the left or right end position. Thus, levers were presented only in two positions, the home position and the end position of the levers. Through the phi phenomenon, observers perceived a movement of the lever between these positions. The phi phenomenon is an optical illusion (cf. Wertheimer, 1912) in which constant movement is perceived instead of a sequence of images. The lever turned back to the home position after the release of the key. The next trial started after 1.5 s.

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 were shorter than 100 ms or exceeded 2,000 ms. The experiment lasted approximately 45 min, including short breaks between blocks.

Participants

In this experiment, 10 adults (8 female, between 20 and 26 years of age, mean age 22.9 years) from RWTH Aachen University participated for pay or course credit.

RESULTS

Median reaction times and percentage of errors of each participant were entered into 2 (SR relationship: compatible vs. incompatible) × 2 (RE relationship: compatible vs. incompatible) × 2 (SE relationship: compatible vs. incompatible) ANOVAs with repeated measurements. Results are shown in Figure 5. An effect of RE relationship was observed in the reaction time analyses, $F(1, 9) = 7.57$, $p = .022$, $\eta_p^2 = .457$, and in the analysis of percentage of errors, $F(1, 9) = 13.15$, $p = .006$, $\eta_p^2 = .594$. Compatible RE responses were performed 107 ms faster and with 8.9% fewer errors than were incompatible RE responses (655 vs. 762 ms and 7.0% vs. 15.9%). In other words, handling a lever tool with incompatible movement-effect transformations yields increased response times and errors compared with tools with compatible movement-effect transformations.

Additionally, compatible SE responses were performed faster (694 ms) than were incompatible SE responses (724 ms), yielding a significant main effect in the reaction time analyses, $F(1, 9) = 14.99$, $p = .004$, $\eta_p^2 = .625$. However, this finding is qualified by the two-way interaction between SE and RE relationships, which was significant in the reaction time analyses, $F(1, 9) = 15.18$, $p = .004$, $\eta_p^2 = .628$, and in the analysis of percentage of errors, $F(1, 9) = 7.70$, $p = .022$, $\eta_p^2 = .461$. Averaged across the SR relationship, these findings indicate that the differences in the left part of Figure 5 with RE compatible responses are more pronounced than the differences in the right part with RE incompatible responses.

Finally, the three-way interaction was significant in the reaction time analyses, $F(1, 9) = 6.53$, $p = .031$, $\eta_p^2 = .420$. This interaction reflects the finding that in the left part of Figure 5, SR compatible responses are advantageous when the SE relationship is compatible but that this compatibility effect is inverted when the SE relationship is incompatible. Only minor differences between conditions are observed in the right part of Figure 5. When compared with the left part of the figure, this yields to the significant three-way interaction. All other effects were not significant, $p > .10$.

GENERAL DISCUSSION

For the first time, to the best of our knowledge, all compatibility relationships that result from handling a simple lever tool and that comprehend the SR, SE, and RE relationships were tested in one experiment. The advantage of using the *U*-shaped and inverted-*U*-shaped levers is that it allowed us to examine the contribution of each relationship to response times and errors without any confounds.

Three main results were observed. First, reaction times and errors were drastically increased with incompatible RE relationships compared with compatible RE relationships. Incompatible RE relationships comprise conditions with the *U* lever; compatible relationships, with the inverted-*U* lever. The main difference between these conditions is that with the *U* lever, the hand movement is transformed to an inverted tool-effect movement, whereas with the inverted-*U* lever, the hand movement direction remains untransformed in the tool-effect movement. It is already known that the inversion of the tool-effect movement has important consequences for the time needed to initiate a movement (e.g., Kunde et al., 2007; Massen & Sattler, 2010; Müsseler et al., 2008), but what the present study adds is that this effect overrules all other relationships.

Second, compatible SE responses were performed faster than incompatible SE responses. Obviously, it is easier to reach with the levers' effect points at the stimulus than to shift the effect points to the contrary side. Similar findings have been observed with tools (e.g., Kunde et al., 2007) and without tools, for instance, when approach behavior is contrasted with avoidance behavior (Rinck & Becker, 2007). However, the present finding has to be discussed with regard to the significant interaction between SE and RE and the significant three-way interaction. These interactions came about by the substantial differences within compatible RE conditions (left bars of Figure 5), whereas only minor differences were observed within incompatible RE conditions (right bars in Figure 5).

Obviously, when the transformation between hand movement and tool effect is incompatible, and thus hand movement direction is inverted by the tool (i.e., fulcrum effect; Gallagher, McClure, McGuigan, Ritchie, & Sheehy, 1998), SR and SE relationships are overruled, but come to the fore when hand movement and tool-effect movement match.

Third, when handling a tool, an advantage of the compatible SR relationship was observed only when the SE and RE relationships were also compatible. In all other combinations with the SE and RE relationships, either the SR relationship proved to be irrelevant or the incompatible relationship was even better than the compatible SR relationship. This finding indicates that the spatial SR mapping is by far not that dominant, as traditional compatibility research suggests—at least not when a lever is used.

The sequence stimulus → response → effect is not an invention of tool use. For instance, the extension of the stimulus → response sequence has already been formulated in the ideomotor principle, which holds that anticipations of action effects fulfill a generative function in motor control (see Introduction). The critical point in the present context is that whenever a tool is used, actors' intentions are usually directed to the tool's effect points. As a consequence, actors are less aware of their performed hand movements—at least when the tool works with moderate transformations (e.g., Müsseler & Sutter, 2009; Rieger, Knoblich, & Prinz, 2005; Sülzenbrück & Heuer, 2009). In this vein, computer users often do not realize the transformations between mouse and cursor movement on the display (Sutter, Müsseler, & Bardos, 2010). With moderate transformations and thus compatible RE relationships, the information processor seems to work in an automated manner, which allows for additional automated SR and SE effects.

However, when inverse transformations between hand and tool movement and thus incompatible

RE relationships are introduced, tool demands require much more attention to control hand movements (e.g., McLaughlin, Rogers, & Fisk, 2009; Rogers, Fisk, McLaughlin, & Pak, 2005; Sutter & Müsseler, 2010). It is likely, then, that the automated processes of motor control are overruled by the intentional processes, which are slow and nevertheless error prone.

CONCLUSION

With regard to the applied implications of the present results, users of lever tools with inverse transformations between hand and tool movements should be aware of the substantial costs in reaction times and errors, which are most relevant in security-relevant situations. For instance, grasping a steering wheel at its bottom is probably hazardous, as in these situations, hand and car move in opposite directions. Evidence for this possibility was reported by Proctor, Wang, and Pick (2004) but only when the responses were coded relative to the hand-referenced frame and not when responses were coded relative to the distal action effects (i.e., when the wheel controlled a visual cursor). The present results show, moreover, that problems with laparoscopic tools originate presumably from the inverse transformation necessary to control the handles and the effects points of the surgical instrument. A still-open question is whether such costs could be abolished by reinverted visual feedback of the tool-effect movements (e.g., on a control monitor).

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NOTE

1. In the study by Kunde, Müsseler, and Heuer (2007), data were originally analyzed with regard to stimulus-effect relationship and response-effect relationship. To compare both studies, the present analyses contrasts stimulus-response relationship with stimulus-effect relationship.

KEY POINTS

- All compatibility relationships that result from handling a simple lever tool and that comprehend the spatial relationships between stimulus and hand response, between stimulus and the tool's effect point, and between hand response and the tool's effect point were tested in one experiment.
- Performance was worst when the hand response was transformed to an inverted tool-effect movement.
- When handling a lever, an advantage of the compatible stimulus-response relationship was observed only when the stimulus-effect and response-effect relationships were also compatible.
- In all other combinations, either the stimulus-response relationship proved to be irrelevant or the incompatible relationship were even better than the compatible stimulus-response relationship.

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