Original Article

Crosstalk Between Proximal and Distal Action Effects During Tool Use

Stefan Ladwig, Christine Sutter, and Jochen Müsseler

Department of Work and Cognitive Psychology, RWTH Aachen University, Aachen, Germany

Abstract. When using a tool, proximal action effects (e.g., the hand movement on a digitizer tablet) and distal action effects (e.g., the cursor movement on a display) often do not correspond to or are even in conflict with each other. In the experiments reported here, we examined the role of proximal and distal action effects in a closed loop task of sensorimotor control. Different gain factors perturbed the relation between hand movements on the digitizer tablet and cursor movements on a display. In the experiments, the covert hand movement was held constant, while the cursor amplitude on the display was shorter, equal, or longer, and vice versa in the other condition. When participants were asked to replicate the hand movement without visual feedback, hand amplitudes varied in accordance with the displayed amplitudes. Adding a second transformation (Experiment 1: 90°-rotation of visual feedback, Experiment 2: 180°-rotation of visual feedback) reduced these aftereffects only when the discrepancy between hand movement and displayed movement was obvious. In conclusion, distal action effects assimilated proximal action effects when the proprioceptive/tactile feedback showed a feature overlap with the visual feedback on the display.

Keywords: tool use, sensorimotor transformation, feature overlap, multimodal processing, gain, rotation

In modern tool use, for instance when operating computer input devices, human beings are often confronted with two, not necessarily concordant effects of their actions: On the one hand they are confronted with bodily related action effects, like the kinesthetic/proprioceptive feedback from a limb's spatial orientation when manipulating the device. On the other hand there are distal action effects, like movements of a joystick-controlled avatar in a computer game. Processing discordant feedback from the moving hand (proximal effect) and the moving effective part of the tool (distal effect) challenges the human information processing system, as this offers two (competing) reference frames for action control (for proximal action control see ideo-motor principle by Greenwald, 1970; James, 1890). Recent studies on tool use (e.g., Kunde, Müsseler, & Heuer, 2007; Massen & Prinz, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008; Rieger, Knoblich, & Prinz, 2005; Sutter, 2007), however, showed that anticipated visual effects in external space (from the effective part of the tool) may fulfill a generative function and play a prominent role in the selection, initiation, and actual execution of movements, while the anticipated proximal effects (from the moving hand) were attenuated or ignored. Nevertheless, proximal action effects have an impact on action control. Prinz (1997) introduced a common representational domain of perception (afferent part) and intended action (efferent part), wherein each code comprises individual feature codes. The common coding approach proposes that when perceptual stimuli share some features with planned actions, these stimuli can either induce those actions or interfere with them depending on their degree of similarity in terms of an overlap of feature codes.

With reference to tool use feature overlap between perception and intended action is often low when sensorimotor transformations are in effect, especially when proximal hand movements and intended distal effects do no longer correspond. It can be observed that human movements become slow, inaccurate, and strenuous (e.g., Müsseler & Skottke, 2011; Proctor, Wang, & Pick, 2004; Sutter, Müsseler, & Bardos, 2011). At the same time, agents are little aware of what their hands are doing, as demonstrated by Müsseler and Sutter (2009): Participants produced circular movements on a display while their covered hand movements were perturbed either to a vertically or a horizontally orientated ellipse. When asked to evaluate their hand movement participants were unable to perceive the discrepancy between proximal hand movements and distal action effects for a wide range of the sensorimotor perturbation magnitudes (threshold 1:1.86). Furthermore, Rieger and colleagues (2005) found short-term aftereffects of the previous gain following sudden gain changes. Participants performed continuous up and down movements on a display while their covered hand movements were perturbed to shorter, equal, or longer amplitudes compared to the cursor amplitude (= proximal perturbation), and vice versa in another condition (perturbed cursor amplitudes and constant hand amplitude = distal perturbation). In six drawing movements the gain factor was 1:1 and participants performed a default amplitude. For another six drawing movements, in some conditions a gain change was introduced and hand (cursor) amplitudes appeared shorter or longer. This sequence of unperturbed and perturbed trials was repeated several times. For perturbed trials gain intensity varied randomly. The main finding was that participants compensated for shorter (longer) cursor amplitudes with shorter (longer) hand amplitudes as a consequence of the gain changes. That means, in subsequent movements the visual cursor motion assimilated hand movements.

DOI: 10.1027/2151-2604/a000085

This aftereffect was observed within the first five trials, after that, participants were nearly adapted to the gain change. It was further observed that the compensation onset was faster with distal than with proximal perturbation.

The purpose of the present study was to further this line of investigation by exploring the crosstalk between proximal and distal action effects under conditions of high and low feature overlap between vision and proprioception. To do so, we used a rather simple drawing task in which participants performed a constant (perturbed) movement with their covered hand on a digitizer tablet while they received a perturbed (constant) visual feedback presented on a display. Subsequently, subjects reproduced the former hand amplitude without any visual feedback. Feature overlap between proximal and distal action effects was either high, when hand and cursor movement direction corresponded, or reduced, when cursor amplitude was rotated. With regard to the common coding principle (Prinz, 1997), we hypothesized aftereffects from the visually controlled movement with high feature overlap (condition of unrotated visual feedback), and a reduction in aftereffects (compared to the unrotated visual feedback) when feature overlap is low (condition of rotated visual feedback). That means, that replicated hand amplitudes are expected to be more precise when participants become aware of the mismatch between vision and proprioception. In this case motor control should more depend on the kinesthetic/proprioceptive than on visual feedback.

Furthermore, Rieger and colleagues (2005) found a faster compensation onset for distally perturbed movements than for proximally perturbed movements. They argued that information to detect distal perturbations was immediately available (because visual cursor amplitude changed), whereas information to detect proximal perturbations had to be accumulated by comparing internally predicted and observed visual effects. Compared to this, we investigated if these mechanisms also influence the extent of aftereffects.

Experiment 1

In order to assess the impact of visual feedback on motor performance we varied the feature overlap between vision and proprioception. While participants performed a perturbed movement on a digitizer tablet, visual feedback on a display was either unrotated or rotated by 90°. We expected reduced aftereffects when feature overlap between vision and proprioception was low (visual feedback rotated by 90°) compared to high feature overlap (unrotated visual feedback). Furthermore, we investigated if the extent of aftereffects differs between proximally and distally perturbed movements (cf. Rieger et al., 2005).

Method

Apparatus, Task, and Stimuli

The experiment was carried out in a dimly lit room and controlled by an Apple Macintosh computer with Matlab software using the Psychophysics Toolbox extension (Kleiner, Brainard, & Pelli, 2007). Figure 1 depicts the experimental setup. Participants sat in front of a DIN-A3 digitizer tablet (WACOM Intuos2, 100 Hz sampling rate). A fiberboard with a cut-out groove was mounted onto the digitizer tablet (width and length of the groove: 0.4 and 50 cm). To perform horizontal strokes on the tablet participants positioned the tip of the pen (WACOM Intuos2 Grip Pen) into the groove. An occluder and a curtain prevented direct vision of the digitizer tablet and the participant's hand. The experimental tasks and visual feedback of the hand movements were presented on a 22 inch color CRT display, with a distance of approximately 60 cm between participant and display (Figure 1, Display A: Iiyama HM204DT, Vision Master Pr514, 100 Hz refresh rate, 1,024 × 768 pixels). The experimenter sat next to participants and monitored their movement trajectories on a separate display (Figure 1, Display B).

Two black bars (rectangles of 0.2 × 0.8 cm each) and a gray circular cursor (diameter 0.4 cm) appeared on the white screen (Figure 2). The cursor was positioned onto the start bar. The task involved moving the cursor from the start bar to the target bar by performing a horizontal movement with the pen. When the cursor had reached the target bar, movement direction had to be reversed. Participants were asked to replicate the initially performed hand movement as accurately as possible when they moved in the opposite

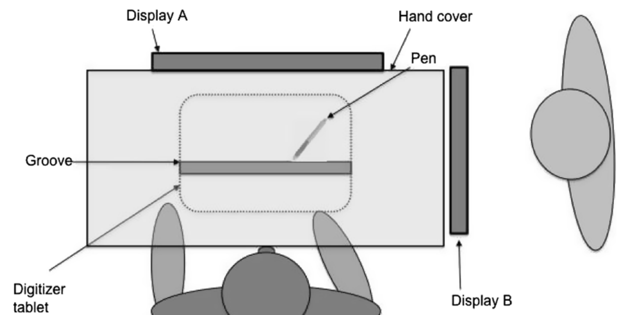

Figure 1. Sketch of the experimental setup.

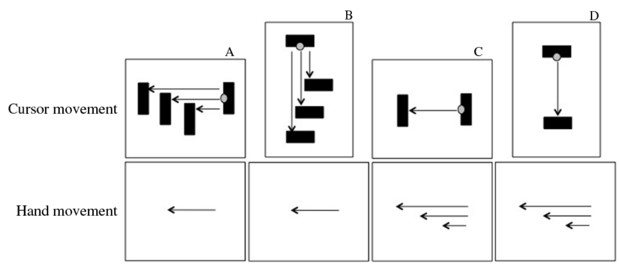

Figure 2. Task, cursor movement (top row), and hand movement (bottom row) with distal perturbation (A and B) and proximal perturbation (C and D). Visual feedback was unrotated (A and C) or 90°-rotated (B and D).

direction after the reversal. They did not receive any visual feedback during this movement.

For the visually guided movements three different gain factors perturbed amplitudes (= translational transformation with gain factors 1:0.5, 1:1.0, 1:1.5). That means, in the condition of distal perturbation (Figure 2, A and B) cursor amplitudes were 6, 12, or 18 cm, while hand amplitudes remained at 12 cm. In the condition of proximal perturbation (Figure 2, C and D) cursor amplitudes remained at 12 cm, while hand amplitudes were 6, 12, or 18 cm. Furthermore, visual feedback was provided either unrotated (Figure 2, A and C) or rotated by 90° (Figure 2, B and D).

Design and Procedure

Participants were randomly assigned to the perturbation conditions: eight participants worked with the distal perturbation throughout the experiment, another eight participants worked with the proximal perturbation. For each group the experiment consisted of four blocks: two blocks with unrotated visual feedback and two blocks with 90°-rotated visual feedback. The order of blocks was counterbalanced across participants. Each block consisted of 30 trials (three gain factors with 10 repetitions each, randomly presented) and another nine trials presented in advance of each block in order to familiarize subjects with the task (the same three gain factors as used in the experimental trials with three repetitions each, randomly presented). We controlled the initial movement direction (from right to left, from left to right) across participants: Within each group half of the participants moved leftwards and vice versa for the other half of participants. The experiment lasted about 45 min.

At the beginning of a trial, the start bar with the cursor and the target bar were presented. Participants were instructed to bring the cursor from the start bar to the target bar by moving the pen on the tablet. A first click of the pen's button unlocked the cursor, and participants moved the cursor to the opposite target bar while receiving continuous visual feedback. When the cursor was positioned within the target area participants pressed the button of the pen again. Then the bars and the cursor disappeared. Participants had to replicate their initial hand amplitude as accurately as possible without any visual feedback by moving the pen in the opposite direction after the reversal. When they thought to have reached their initial starting point they pressed the button of the pen a third time to terminate the trial. Subsequently a new trial was presented. The instruction stressed to produce a continuous and smooth forward-backward movement as accurately as possible, and to monitor the hand movement carefully. The nondominant hand rested relaxed on the participant's lap.

We used a 2 × 2 × 3 mixed design with the between-subject factor location of perturbation (distal vs. proximal), and the within-subject factors translational transformation (cursor movement shorter vs. equal vs. longer compared to initial hand movement) and rotational transformation (unrotated vs. 90°-rotated visual feedback). We analyzed the deviation between the predetermined initial hand amplitude (6, 12, or 18 cm) and the replicated hand amplitude. Trials were omitted from analysis when the initial movement trajectory was noncontinuous (with $v = 0$ within the initial hand movement) and/or its direction changed, when the initial movement overshot the target area, and when the second button click occurred while the cursor was outside the target area.

Participants

A total of 16 students (14 female) of the RWTH Aachen University, aged from 18 to 36 years ($M = 23$; $SD = 4.6$), participated in the experiment for credit in a psychology course or for €8. All participants had normal or corrected-to-normal vision, were naïve to the purpose of the experiment, and took part voluntarily.

Results and Discussion

The mean deviation (cm) between the predetermined initial hand amplitude and replicated hand amplitude was calculated for error-free trajectories (error rate at 5.7%). The deviation was analyzed using a 2 (location of perturbation: distal vs. proximal) × 2 (rotational transformation: unrotated vs. 90°-rotated visual feedback) × 3 (translational transformation: cursor movement shorter vs. equal vs. longer compared to initial hand movement) mixed analysis of variance (ANOVA). Separate *t*-tests (between observed deviation and zero) were conducted for gain factor 1:1. We did not find any bias (aftereffects) for untransformed movements, except for unrotated proximally perturbed movements, $t(7) = 3.07$; $p < .05$.

Results are depicted in Figure 3. The analysis revealed significant main effects for the factors translational transformation, $F(2, 28) = 52.03$; $p < .01$ and location of perturbation, $F(1, 14) = 5.05$; $p < .05$. For distally perturbed movements replicated hand amplitudes were shorter than required when the displayed cursor movement was shorter than the initial hand movement, it was very precise when cursor and initial hand movement corresponded, and it was longer than required when the cursor movement was longer than the initial hand movement (−0.5, 0, 0.6 cm; Figure 3 squares).

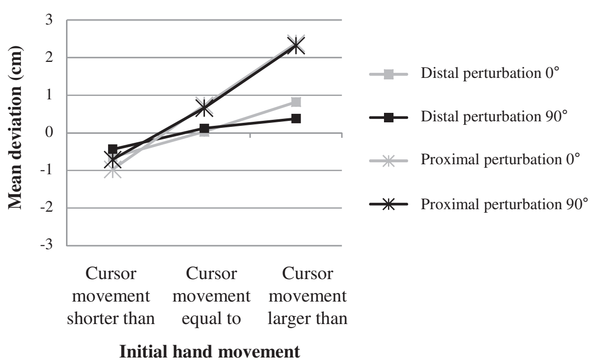

Figure 3. Mean deviation (cm) between predetermined initial hand amplitude and replicated hand amplitude for distally perturbed movements (squares) and proximally perturbed movements (asterisks). Visual feedback was unrotated (gray lines) or 90°-rotated (black lines).

This pattern was more pronounced for proximally perturbed movements (−0.8, 0.7, 2.4 cm; Figure 3 asterisks) than for distally perturbed movements, yielding a significant interaction, $F(2, 28) = 11.71$; $p < .01$. Furthermore, for transformed initial movements (cursor amplitude shorter or longer than initial hand amplitude) replicated hand amplitudes deviated to a greater extent from the predetermined hand amplitudes when visual feedback was unrotated than when it was 90°-rotated (unrotated −0.8 to 1.6; 90°-rotated −0.6 to 1.4; interaction: $F(2, 28) = 3.18$; $p = .05$). Other effects or interactions did not reach significance (p's > .39).

Results showed the assumed aftereffects from visually controlled movements. Subsequent hand amplitudes were shorter (longer) after having perceived a shorter (longer) cursor amplitude, although either the initial hand amplitude or cursor amplitude remained constant. However, the impact of visual feedback on subsequent movements was asymmetric and more pronounced for proximal perturbations than for distal perturbations. Even for proximally unperturbed hand movement a bias was observed. It could be argued, that the high variability in hand amplitudes led to an increased susceptibility to visual effects. This would be in line with the slower compensation onset after gain changes found by Rieger and colleagues (2005). When reducing the feature overlap between proprioception and vision (90° rotation of visual feedback) aftereffects decreased. This means, participants were able to replicate their initial hand amplitude more precisely when feature overlap was low than when it was high.

Experiment 2

The aim of the present experiment was to further reduce the feature overlap between vision and proprioception through rotating the visual feedback by 180° in one condition. This meant that leftward movements with the hand resulted in rightward movements of the cursor. We expected aftereffects to disappear in this condition. Concerning the location of perturbation we expected greater aftereffects for proximally perturbed movements than for distally perturbed movements.

Method

Stimuli, Procedure, and Design

Again, we compared conditions with unrotated and rotated visual feedback. While procedure and design remained the same as in Experiment 1, the visual feedback in the rotated condition was presented horizontally inverted (180°-rotation) with rightward (leftward) movements on the tablet resulting in leftward (rightward) movements of the cursor.

Participants

Another 16 students (12 female) from 19 to 31 years (M = 22; SD = 3.1) voluntarily took part in the experiment for credit in a psychology course or for €8.

Results and Discussion

The mean deviation (cm) between predetermined initial hand amplitude and replicated hand amplitude was calculated for error-free trajectories (error rate at 5.9%). As in Experiment 1 deviation was analyzed using a 2 (location of perturbation: distal vs. proximal) × 2 (rotational transformation: unrotated vs. 180°-rotated visual feedback) × 3 (translational transformation: cursor movement shorter vs. equal vs. longer compared to initial hand movement) mixed ANOVA. Separate t-tests (observed deviation vs. zero) were conducted for gain factor 1:1. They did not reveal any aftereffects.

Results are depicted in Figure 4. The analysis revealed a significant main effect for the factor translational transformation, $F(2, 28) = 67.50$; $p < .01$. For distally perturbed movements replicated hand amplitudes were shorter than required when the cursor movement was shorter than the initial hand movement. It was very precise when cursor and initial hand movement were equal and longer than required when the cursor movement was longer than the initial hand movement (−0.6, 0.2, 0.7 cm; Figure 4 squares). Again, this pattern of results was more pronounced for proximally perturbed movements (−1.6, 0.1, 2.1 cm; Figure 4 asterisks) than for distally perturbed movements, yielding a significant interaction, $F(2, 28) = 17.42$; $p < .01$. The factor rotational transformation was marginally significant, $F(2, 28) = 3.79$; $p = .07$, indicating a trend that aftereffects disappeared with visual feedback rotated by 180° (unrotated: 0.3 cm; 180°-rotated: 0 cm). Other effects or interactions did not reach significance (p's > .40).

We replicated a similar pattern of results as observed in Experiment 1: Visual cursor motions assimilated subsequent hand amplitudes, and aftereffects were more pronounced for proximal perturbations than for distal perturbations. However, by further reducing the feature overlap between proprioception and vision (180°-rotation of visual feedback) aftereffects did not disappear (we only observed a trend). This is against our expectations. One explanation might be that we did not, after all, reduce the feature overlap in this condition. Effectively, with additional 180°-rotation of the

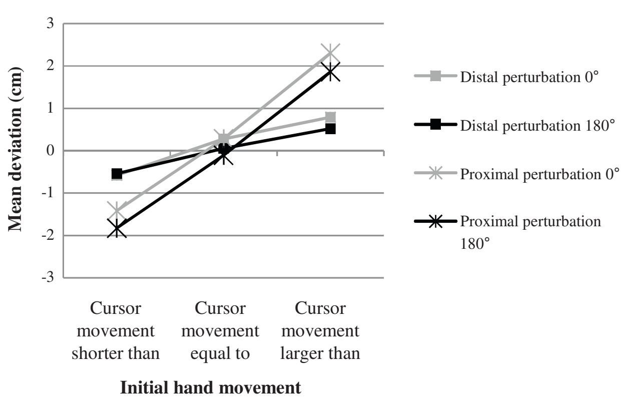

Figure 4. Mean deviation (cm) between predetermined initial hand amplitude and replicated hand amplitude for distally perturbed movements (squares) and proximally perturbed movements (asterisks). Visual feedback was unrotated (gray lines) or 180°-rotated (black lines).

visual feedback the direction of the cursor movement exactly matched the direction of the hand when replicating the initial movement. Thus, some participants might have created a mental image of the initially seen distance supporting its recall. Hence, this matching can be interpreted as consistent feature overlap in the sense of the common coding principle (Prinz, 1997). Others might have perceived an ambiguity resulting in highly variable responses.

General Discussion

The main purpose of the present study was to investigate the crosstalk between proximal and distal action effects when using tools. As outlined in the Introduction, proximal action effects (e.g., manipulating a joystick) and distal action effects (e.g., movements of an avatar in a computer game) do often not correspond or are even in conflict. These discrepancies between the kinesthetic/proprioceptive feedback and distal visual feedback challenge the human information processing system. However, the human information processor solves this problem by favoring distal action effects while neglecting body-related effects. Theoretical and empirical evidence for this has already been provided (e.g., Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Massen & Prinz, 2007; Rieger et al., 2005).

To this end, we asked whether perturbed visual feedback influences motor control and to what extent aftereffects in subsequent hand amplitudes are induced. Furthermore and based on the common coding principle (Prinz, 1997), we investigated whether this is still true for tasks with reduced feature overlap between vision and proprioception. In this case we expected reduced aftereffects. That means, subsequent hand amplitudes should become more precise since motor control should depend on the kinesthetic/proprioceptive feedback instead of the visual feedback. In total we have three main findings to be discussed.

First, in both experiments we demonstrated that seeing perturbed movements on a display led to aftereffects in subsequent hand movements. This finding is new since previous studies reporting similar effects used continuous visual feedback (genuine closed loop task) with regard to covered hand movements (i.e., Müsseler & Sutter, 2009; Rieger et al., 2005). However, our study additionally involved an open loop component since hand amplitudes ought to be replicated without any visual feedback. Furthermore, in contrast to our investigations, Rieger et al. (2005) focused on compensation for and adaptation to gain changes, and Müsseler and Sutter (2009) exclusively aimed at body perception with distorted feedback. Thus, our findings can be interpreted as proof of crosstalk between proximal and distal action effects, since visual cursor motions assimilated hand movements.

Beyond this and second, this crosstalk was asymmetric. Aftereffects were more pronounced when hand amplitudes varied (while distal effects were constant) than when the cursor amplitude varied (while proximal effects were constant). We assume that proximal perturbations induced substantial variance in motor behavior so that replications became very susceptible to distal action effects. Thus, the competing information loops have to be investigated separately in future experiments. This could, for instance, be done by replicating the initial hand amplitude by producing a keystroke-controlled line on the display instead of a manual movement on the tablet.

Third, when reducing the feature overlap between vision and proprioception (90°-rotated visual feedback) we found a decrease of aftereffects. This is in line with our hypothesis. We assume that motor control depends more on kinesthetic/proprioceptive feedback than on visual feedback when sensorimotor transformations are obvious. However, when we rotated the visual feedback by 180° aftereffects were still present and statistically indifferent from those observed with unrotated visual feedback. A reason for this might be that in both conditions of Experiment 2 some kind of feature overlap existed: For unrotated visual feedback movement directions of initial hand and cursor motion were similar, whereas for 180°-rotated visual feedback movement directions of subsequent hand motion and initial cursor motion were the same. Results indicate that participants did not perceive a reduction in feature overlap at all. For this reason and in line with the feature overlap hypothesis, subsequent experiments should induce visual rotations by 45° or 135° to decrease feature overlap.

Acknowledgments

We thank Florian Bade, Laura Makowski, Kathrin Wendler, and Nora Zekorn for carrying out the experiments. Furthermore, we thank Cristina Massen, Matthias Hegele, and an anonymous reviewer for their instructive and helpful comments on the manuscript. This research was supported by a grant from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) to Christine Sutter and Jochen Müsseler (DFG Su 494/4).

References

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*, 73–99.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action. *Behavioral and Brain Sciences, 24*, 869–937.

James, W. (1890). *The principles of psychology*. New York, NY: Dover.

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception, 36*(Suppl.), 14.

Kunde, W., Müsseler, J., & Heuer, H. (2007). Spatial compatibility effects with tool use. *Human Factors, 49*, 661–670.

Massen, C., & Prinz, W. (2007). Programming tool-use actions. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 692–704.

Müsseler, J., Kunde, W., Gausepohl, D., & Heuer, H. (2008). Does a tool eliminate spatial compatibility effects? *European Journal of Cognitive Psychology, 20*, 211–231.

Müsseler, J., & Skottke, E. M. (2011). Compatibility relationships with simple lever tools. *Human Factors, 53*, 383–390.

Müsseler, J., & Sutter, C. (2009). Perceiving one's own movements when using a tool. *Consciousness and Cognition, 18*, 359–365.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*, 129–154.
Proctor, R. W., Wang, D.-Y., & Pick, D. F. (2004). Stimulus-response compatibility with wheel-rotation responses: Will an incompatible response coding be used when a compatible coding is possible? *Psychonomic Bulletin & Review, 5*, 124–129.
Rieger, M., Knoblich, G., & Prinz, W. (2005). Compensation for and adaptation to changes in the environment. *Experimental Brain Research, 163*, 487–502.
Sutter, C. (2007). Sensumotor transformation of input devices and the impact on practice and task difficulty. *Ergonomics, 50*, 1999–2016.
Sutter, C., Müsseler, J., & Bardos, L. (2011). Effects of sensorimotor transformations with graphical input devices. *Behaviour & Information Technology, 30*, 415–424.

Stefan Ladwig

Department of Work and Cognitive Psychology
RWTH Aachen University
Jägerstraße 17–19
52056 Aachen
Germany
Tel. +49 241 80-93999
Fax +49 241 80-92140
E-mail stefan.ladwig@psych.rwth-aachen.de

