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The impact of gain change on perceiving one's own actions

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Abstract

Tool use often challenges the human motor system, especially when these tools require sensorimotor transformations. We report an experiment using a digitizer tablet, in which different gains are introduced between the hand movement (proximal effect) and the intended action effect presented on a display (distal effect). The question is how one's own movements are perceived in this situation. With regard to an action-effect account movements are represented and controlled by anticipating the movement effects. As a consequence, participants should be less aware of their own hand movements. The reason for this is that what counts for a successful tool use is the representation of the distal effect, not the proximal effect. Our results supported this view. Potential application of this research includes the optimization of the HCI with the imperceptible gain method. It benefits from the human flexibility to compensate for and adapt to smaller biases without any costs.

1 Introduction

The human motor system is often challenged by the use of tools in modern work – especially when these tools introduce unfamiliar transformations between manual movements and intended effects. An instructive example is laparoscopic surgery. Here the surgeon operates through a tiny, artificial aperture in the patient's torso with an endoscopic tool. This operation technique has many advantages from a medical point of view, but it creates problems for the surgeon as well. For example, there is only indirect and distorted sight on the field of operation provided by a small camera inserted in the patient's body. Consequently the surgeon has to learn the relations by which his hand movements are transformed into movements of the tip of the tool inside the patient's body (cf. Kunde et al. 2007).

In the present paper an experiment with a digitizer tablet is reported, in which different sensorimotor transformations are introduced between the hand movement (proximal effect) and the intended action effect presented on a display (distal effect). We focus on the question of how one's own movements are perceived in this situation. With regard to our theoretical framework, the theory of event coding (Hommel et al. 2001), movements are represented and controlled by anticipating the movement effects. As a consequence, participants should be less aware of their own hand movements. The reason for this is that what counts for a successful tool use is the representation of the distal effect, not the proximal effect. This was – for instance – demonstrated in a study by Rieger and colleagues (2005). They introduced different transformations between hand movements on a digitizer tablet and intended action effects presented on a display. They found a rather fast and accurate movement execution if the target amplitude visualized on the display corresponded to the hand amplitude on the tablet (high correspondence between distal and proximal effect). But, if the proximal effect (hand amplitude) did not correspond with the distal effect – experimentally realized by extension of the display amplitude while the hand amplitude remained constant – movement times varied correspondingly to the display amplitude, although the required motor activity was the same.

The predominance of action effects was further supported by research in human-computer interaction based on Fitts' law (Fitts, 1954) as well as on gain changes. First, movement times followed the perceived index of difficulty on the display when using graphical input devices (e.g. Armbrüster et al. 2007; Ballagas & Borchers 2006; Card et al. 1978; MacKenzie 1992; Sutter 2007). It was shown that rather the distal effects (e.g. the anticipated action effect of the cursor on the display) determined the movement execution than the proximal effect (tactile sensations from the moving hand). Second, performance improved when the gain was relatively close to a 1:1 transformation (e.g. Arnaut & Greenstein 1986; Tränkle & Deutschmann 1991). With higher gains, when no correspondence between hand and cursor movement was given, performance decreased. This was also found for non-linear gains (Graham 1996). However, some studies have shown that dynamically adaptive gains can increase pointing performance (e.g. Blanch et al. 2004). Performance improved by either increasing the gain while approaching the target, or by decreasing the gain while inside the target.

All these findings hint at a critical point in designing human-computer interfaces. Although most studies did not measure the awareness of participants towards gain changes, most authors interpreted their findings in the way of the user facing a problem or feeling disturbed. The mismatch between hand movement and cursor movement caused interferences in the user's control of actions. Based on research results we assume a cognitive dominance of distal action effects over proximal action effects. For example, in recent studies participants quickly compensated for and adapted to changes in transformation introduced by visual feedback (e.g. Knoblich & Kircher 2004; Rieger et al. 2005). Most importantly, this seemed to occur completely unaware to the human and the likelihood of change detection systematically rose as a function of the extent of change (Knoblich & Kircher 2004). These findings could be due to the fact that the motor system is highly adaptive, but that the sensory feedback is noisy and proprioceptive feedback is not very accurate in predicting hand position (Ghilardi et al. 1995). This makes contexts with larger sensory differences easier to distinguish than those with similar sensory feedback (Vetter & Wolpert 2000).

In the present paper we focus on effects of sensorimotor transformation when using graphical input devices. In particular, we examine whether and how changes in gain affect user perception. The experiment consisted of several trials with different gains. By carefully adjusting the display amplitude, we managed to keep the required user action on the digitizer tablet constant. In essence this means that the participants had to execute the very same movement with the input device, but got a different representation of the task on the display, depending on the current gain. A cover screened the users' hands, thus the only visual feedback the participants perceived of their movement was provided by the computer display (beside the users' haptic and proprioceptive feedback). We hypothesized that the different visual feedback of the very same motor action results in variations of user perception.

2 Research Method

The experiment was based on a one-factorial design with repeated measures. Overall, 9 graduate students (6 male) from the RWTH Aachen University were under survey. Figure 1 depicts the experimental setup. The task was presented on a 17'' CRT display (EIZO F563-T) with a 1024 x 768 resolution. In front of the display was a graphic tablet (Wacom Intuos2 A3), which was operated with a stylus (Wacom Intuos2 Grip Pen). A cover screened the users' hands. Visual feedback was exclusively provided by the cursor on the display. The experimental task consisted of two horizontally arranged target boxes and involved moving the cursor back and forth between the target boxes. Each trial lasted until 25 error-free movements occurred.

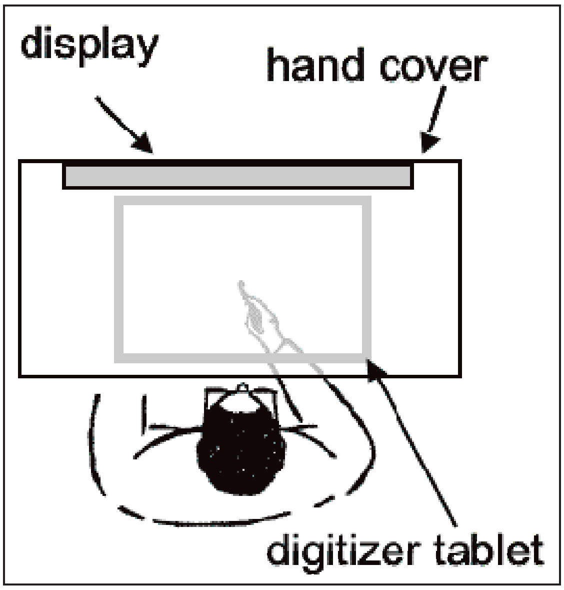

Figure 1: Experimental setup with digitizer tablet, hand cover and display

The experiment consisted of 3 blocks with 3 experimental conditions each. The movement distance of the hand was the same within a block (2, 4 or 6 cm). Within each block movement distance of the cursor varied as a result of gain variation: For the tablet amplitude of 2 cm low (2 x 1.22), middle (2 x 2.44) and high gain (2 x 4.88) resulted in display amplitudes of 2.4, 4.8 and 9.7 cm. For the tablet amplitude of 4 cm display amplitudes were 4.8, 9.7 and 19.5 cm, and for the tablet amplitudes of 6 cm the display amplitude were 7.3, 14.6 and 29.3 cm.

Participants were instructed to continuously move the cursor back and forth between the two target boxes and to move as fast and turn as accurately as possible. As soon as they reached one target box movement direction was reversed without pausing inside the target box. Participants worked throughout three blocks of tablet amplitudes. The block order was counterbalanced between participants. Within a block gain was randomly varied. Each block consisted of 11 to 12 trials with 25 repetitions and additional 3 x 25 training trials in advance of the experiment.

The dependent variables were time of movement execution (time for each target-to-target movement), error rate (number of trials where the reversal point of movement was outside of the target box) and rating of the hand amplitude. At the end of each block participants rated the hand amplitude for the low, middle and high gain condition. The rating task is depicted in Figure 2. The distance between the target boxes indicated the gain conditions that had to be estimated: short distance (low gain), middle (middle gain) and long distance (high gain). Below the boxes an adjustable bar was displayed. Participants were able to adjust the bar by moving the stylus on the tablet. They were instructed to adjust the bar to the distance they thought to have covered with the stylus on the tablet. It was stressed that they estimate the tablet distance independently from the visual feedback of the transformed movement of the display.

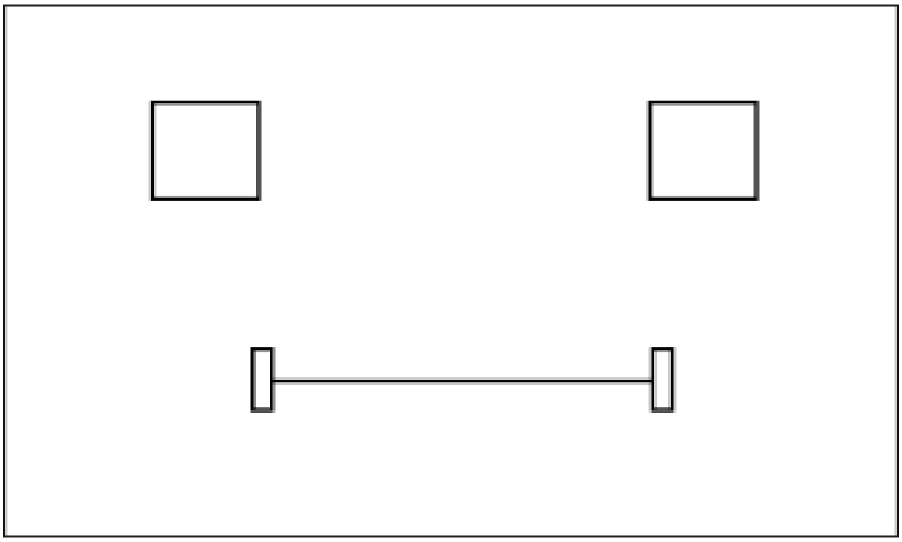

Figure 2: Screenshot of a rating task with tapping task (top) and adjustable bar (bottom)

3 Results

Perception of transformation: Although the tablet amplitude was held constant within a block, we assumed a perceived increase of hand amplitude if the cursor movement on the display increased as well. Blocks of tablet amplitude (2, 4 and 6 cm) were analyzed with separate analyses of variances (ANOVAs) with the within-factor gain (short, middle, long distance). The analyses confirmed that judgments of hand amplitude increased significantly in accordance with the transformed movement displayed on the screen (each p<0.01).

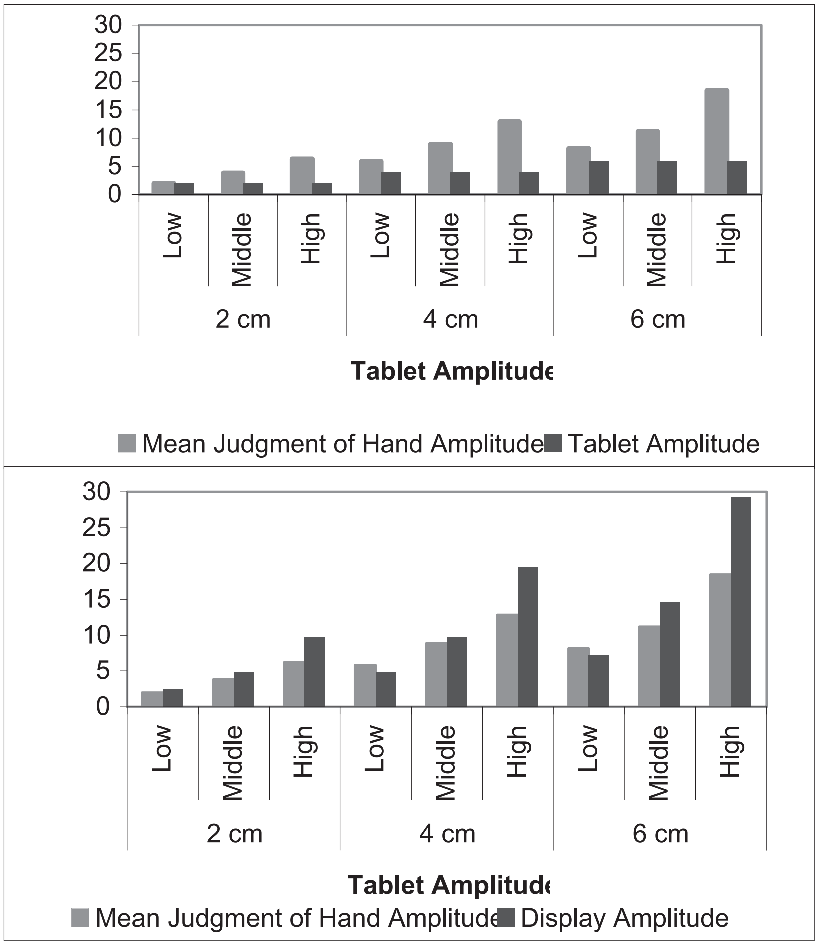

Figure 3: Mean estimation of hand amplitude compared to tablet amplitude (top) and display amplitude (bottom)

Additionally, blocks were analyzed with separate t-tests comparing tablet amplitude with the judgment of hand amplitude (Figure 3, top, comparison of black bar vs. grey bar) for each gain condition. For all blocks a comparable pattern was found in the data. For the short distance (1.22:1 gain) subjective hand amplitude and tablet amplitude were rated as similar in each block (each t-test was not significant). For the middle (2.44:1 gain) and the long distance (4.88:1 gain) participants clearly overestimated the hand amplitude compared to the tablet amplitude (each t-test was significant). In the 2 cm-block participants estimated that they had covered 3.8 cm (middle) and 6.26 cm (long distance) with their hand. In the 4 cm-block they rated about 8.83 cm (middle) and 12.86 cm (long distance). In the 6 cm-block their ratings were about 11.19 cm (middle) and 18.45 cm (long distance). Findings showed that the distance of hand movements was overestimated for higher gains. Compared to the tablet amplitude of 2, 4 or 6 cm the hand movement was rated by 2-3 times farther than actually executed.

Blocks were further analyzed with t-tests comparing display amplitude to the judgments of hand amplitude (Figure 3, bottom, comparison of black bar vs. grey bar for each condition). For all blocks a comparable pattern of results was found. For the short (1.22:1 gain) and the middle distance (2.44:1) subjective hand amplitude and display amplitude were rated as similar in each block (each t-test was not significant). For the long distance (4.88:1) participants underestimated the hand amplitude compared to the display amplitude (each $p<0.05$). The subjective hand amplitude was about 6.26 cm (vs. 9.7 cm in the 2 cm-block), 12.86 (vs. 19.5 cm in the 4 cm-block) and 18.45 (vs. 29.3 cm in the 6 cm-block).

The results hint at a strong interference of the visual feedback with the proprioceptive perception of the hand movement. Participants did not discover that they performed the very same motor task. In contrast, with increasing display amplitude hand amplitudes were overestimated although participants were able to rate distances very precisely as long as the tablet and display amplitude were nearly the same (1.22:1 gain).

Perception and motor performance: We hypothesized a decrease in motor performance as a function of display amplitude. Blocks were analyzed with separate ANOVAs with the within-subject factor gain (low, middle vs. high). For all blocks a comparable pattern was found in the data (Figure 4). Movement time and error rates increased with the high gain compared to the low and middle gain (each $p<0.05$). In the 2 cm-block movement time increased about 176 ms (error rate about 15%), in the 4 cm-block about 240 ms (error rate about 18%) and in the 6 cm-block about 308 ms (error rate about 16%). Correlations between ratings of hand amplitude and performance measures revealed strong coherences. The judgments correlated highly with movement time (r between 0.54 and 0.78; each $p<0.01$) and error rate (r between 0.47 and 0.59; each $p<0.05$).

We can conclude that in accordance with our assumption and the findings for the ratings it is indeed the display amplitude that strongly affected performance and perception likewise. Most amazingly was the observation that participants were mostly unaware of their tablet amplitude.

Carry-over effects resulting from gain changes: We assumed a fast compensation for and adaptation to gain changes. Blocks were analyzed with separate ANOVAs with the within-subject factors gain (low, middle vs. high) and time on task (25 trials). For all blocks a comparable pattern of results was found. The ANOVAs showed significant main effects of gain (each p<0.01) and time on task (each p<0.01). The interactions were never significant. Movement time was highest in the first trials, dropped most in the first five trials and leveled off in the following 20 trials. In the 2 cm-block movement time dropped about 197 ms from the first to the 15th trial, in the 4 cm-block about 244 ms and in the 6 cm-block about 281 ms.

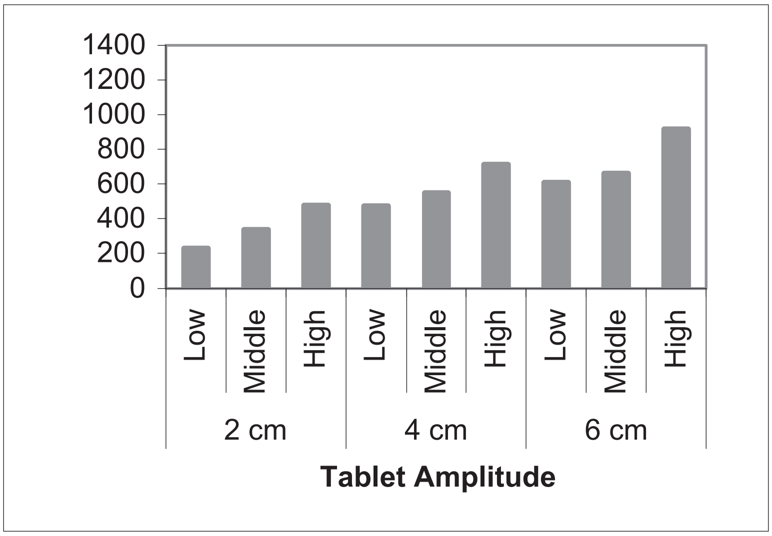

Figure 4: Mean movement time per condition

4 Discussion

In the present paper different gains were introduced between the hand movement (proximal effect) and the intended action effect presented on a display (distal effect). The question was how one's own movements were perceived in this situation. In the experiment users executed the very same movement with the stylus on a digitizer tablet, but got a different representation of the task on the display, depending on the current gain. A blind covered the users' hands and visual feedback was given exclusively via the display. The results showed that participants were able to judge their hand amplitude very precisely as long as tablet and display amplitude were similar, as it was given in the low gain condition (1.22:1 gain). However, for the higher gains amplitudes of hand movements were distinctly overestimated. This seems to confirm the position of Ghilardi et al. (1995), who found the proprioceptive feedback to be not very accurate in predicting hand position. One explanation for our findings could be in fact that sensory feedback is very noisy. However, results further showed that the judgments seemed more corresponding to the visual feedback of the display amplitude than to the hand movement executed on the tablet. For low and middle gain participants exactly rated the display amplitude instead of the actual covered tablet amplitude. But, the precision of judgment decreased with greater discrepancy between hand and display amplitude. For example, with the high gain display amplitude was underestimated, as if participants felt uncertain of having covered such a long distance. We can conclude that in accordance with our assumptions the action effect (display amplitude) mostly determined the perception of hand movement. It overlapped the proprioceptive feedback of the moving hand and determined also the movement execution. Movement times as well as the judgments followed the extent of amplitude displayed on the screen. Movement time increased together with the display amplitude, although participants performed the same movement amplitude with their hand within each block of the experiment. In other words, as tablet amplitude was held constant the action-effect movements on the display determined user behavior. These findings are in accordance with Rieger et al. (2005), who also found that the visualized action effect sufficed to reduce or extend movement times correspondingly, although the same motor task was carried out. An amazing observation in our study was that participants were mostly unaware of their motor behavior. Comments of participants gathered during and after the experiment revealed that they had not noticed that hand amplitude remained constant while display amplitude varied by gain changes.

A second finding was that the impact of the action effect on perception and motor performance did not express the similar linear coherence as provided by the variation of gain. Judgments were most inaccurate for the long display distances and motor performance was worse for the high gain, too. For the low and middle gain condition perception was in accordance with the display amplitude, and motor performance was comparably good for the low and middle gain. Arnaut and Greenstein (1986) found the best performance when the gain was close to a 1:1 transformation. This represents the best match between manual and cursor movement. In our experiment motor actions with gains up to 2.44:1 were executed very efficiently and motor performance was the same compared to the 1.22:1 gain. However, with greater discrepancies between manual and cursor action – as realized with the 4.88:1 gain – movement time increased by 50% and judgments of hand amplitude were most imprecise, either when compared to the tablet amplitude and the display amplitude. We can conclude that users were able to compensate for and adapt to smaller gain changes relatively fast. This happens automatically and without affecting motor performance.

Our third finding deepens the compensation for and adaptation to gain changes and considers carry-over effects. In Rieger and colleagues' study (2005) participants compensated for a gain change directly in the first trial after a new gain was introduced. The following adaptation to the new gain continued until the fifth trial. A similar pattern of results was found in our experiment. Indeed, a new gain had an effect on motor behavior, although participants performed the very same motor task. Again, the change of the visual feedback (= change of gain) alone produced a carry–over effect in motor performance.

At least, one critical aspect in this experiment is addressed. In the progress of data gathering it became obvious that some participants were slightly confused about the judgment task at the end of each block. The rating task was presented on the display (Figure 2). Participants were instructed to adjust a visualized bar on the display to the distance they had actually covered with their hand. Some expressed their uncertainty whether they should rate the display amplitude or the hand amplitude. In a recent study in our lab we introduced a verbal rating task after each trial, where we instructed participants to repeat the hand movement on the tablet once more (without visual feedback on the display) and then to judge the distance with regard to a tape-measure. Participants were able to respond easily and results support the reported findings.

We can conclude that sensorimotor transformations affect movement perception and performance to a great deal, which is in accordance with the action-effect account (Hommel et al. 2001). Human-computer interaction containing sensorimotor transformations is highly determined by the perceived distal action effect (moving cursor), while the proximal action effects (moving hand) is to a great amount imperceptible to the user. This dissociation in perceiving proximal and distal effects is important, as it is a precondition for using computers successfully. The present study introduced research on perceptibility of gain changes and its impact on performance, and results help to optimize human-computer interactions. Most studies so far found distinct performance losses for higher gains (e.g. Arnaut & Greenstein 1986; Graham 1996; Tränkle & Deutschmann 1991) and research is still looking for solutions to improve human-computer interaction when big displays and large distances demand for higher gains (e.g. Grossmann & Balakrishnan 2005). The present results demonstrated the highly flexible and adaptive nature of the human motor system, since lower gains (≤ 2.44:1) were compensated for and adapted to very quickly, and without any performance loss at all. As a consequence the optimized interaction should rely on gains that are within that range of undetected compensation and adaptation, being therefore without effect to human perception and performance. We will introduce this as the imperceptible gain. In other words, action effects are adapted to this human bias. The imperceptible gain method can be further combined with the optimization of the cursor expressiveness with the selexel method (Ballagas & Borchers 2006). It describes an approach to improve the match between the selection resolution of the user interface to the expressiveness of the input device. The screen is divided into atomic selectable elements, or selexels, with a resolution that is independent of the pixel resolution of the screen. Especially the use of low precision pointing devices will be improved. Another example to improve the pointing performance in combination with the imperceptible gain is to increase the size of the cursor (e.g. bubble cursor by Grossmann & Balakrishnan 2005). This cursor dynamically resizes the active cursor region to always encompass exactly one selectable object that is nearest to the center position of the cursor. The imperceptible gain benefits to a great deal of other approaches in HCI and improves the use of graphical input devices.

References

Armbrüster, C., Sutter, C., & Ziefle, M. (2007). Notebook input devices put to the age test: The usability of trackpoint and touchpad for middle-aged adults. *Ergonomics, 50*, 426-445.

Arnaut, L. Y. & Greenstein, J. S. (1986). Optimizing the Touch Tablet: The Effects of Control-Display Gain and Method of Cursor Control. *Human Factors, 28*(6), 717-726.

Ballagas, R. & Borchers, J. (2006). Selexels: A conceptual framework for pointing devices with low expressiveness. Technical Report RWTH Aachen University. Aachen, http://aib.informatik.rwth-aachen.de.

Blanch, R., Guiard, Y., & Beaudouin-Lafon, M. (2004). Semantic pointing: improving target acquisition with control-display adaptation. In *Proc. CHI '04*, ACM Press, 519-526.

Card, S.K., English, W.K., & Burr, B.J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys and text keys for selection tasks on a CRT. In R. Baecker & W. Buxton (Eds.): *Readings in Human-Computer Interaction*, pp. 386-392. San Mateo, CA: Morgan Kaufmann.

Fitts, P.M. (1954). The information capacitiy of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381-391.

Ghilardi, M.F., Gordon, J., & Ghez, C. (1995). Learning a visuomotor transformation in a local area of work space produces directional biases in other areas. *Journal of Neurophysiology, 73*, 2535-2539.

Graham, E.D. (1996). Virtual pointing on a computer display: Non-linear control-display mappings. *Graphics Interface*, 39-46.

Grossmann, T. & Balakrishnan, R. (2005). The bubble cursor: enhancing target acquisition by dynamic resizing of the cursor's activation area. In *Proc. CHI '05*, ACM Press, 281-290.

Hommel, B., Müsseler, J. Aschersleben, G., & Prinz, W. (2001). The theory of event coding (tec): a framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5) 849-937.

Knoblich, G. & Kircher, T.T.J. (2004). Deceiving oneself about being in control: Conscious detection of changes in visuomotor coupling. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 657-666.

Kunde, W., Müsseler, J., & Heuer, H. (2007). Spatial compatibility effects with tool use. *Human Factors, 49*(4), 661-670.

MacKenzie, I.S. (1992). Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human-Computer Interaction, 7*, 91-139.

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*, 12, 1999-2016.

Tränkle, U. & Deutschmann, D. (1991). Factors influencing speed and precision of cursor positioning using a mouse. *Ergonomics, 34*(2), 161-174.

Vetter, P. & Wolpert, D.M. (2000). Context estimation for sensorimotor control. *Journal of Neurophysiology, 84*, 1026-1034.

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