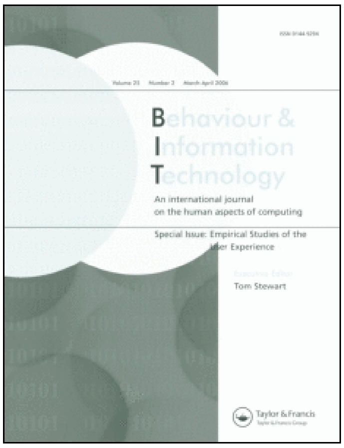

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Effects of sensorimotor transformations with graphical input devices

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The impact of sensorimotor transformations with graphical input devices is surveyed with regard to action control. Recent evidence lets us assume that the distal action effect (the moving cursor) rather than the proximal action effect (the moving hand) determines the efficiency of tool use. In Experiment 1, different gains were explored with a touchpad and a mini-joystick. In correspondence with our assumptions the results revealed evidence that Fitts' law holds for distal action–effect movements, but less for proximal action–effect movements. Most importantly, this was not only true for the touchpad but also for the mini-joystick. We further found a more efficient use of the touchpad in comparison to the mini-joystick when a high gain was used. In Experiment 2, the dominance of the action effect on motor control was confirmed in an experiment with a digitiser tablet. The tablet amplitude was held constant, but again, movement times followed the perceived index of difficulty on the display. It is concluded that Fitts' law did not rely on the movements of the motor system, but on the distal action effects on the display (changes in visual space). Distal action–effect control plays an important role in understanding the constraints of the acquisition and application of tool transformations.

Keywords: action effect; visual feedback; gain; Fitts' law; sensorimotor transformation

1. Introduction

Tool use in modern work often challenges the human motor system, especially when the execution and observation of motor skills are spatially separated, and when transformations are in effect. The use of computer input devices is only one example in this respect. More elaborate tools are used for instance in laparoscopic surgery, virtual reality (VR) or teleoperation. Recent studies (Kunde *et al.* 2007, Müsseler *et al.* 2008) give evidence that distal action effects (the moving cursor on the display) play the more essential role in controlling tools than proximal action effects (the moving hand). We aim to further the understanding of cognitive processes that mediate the usability of input devices. In two experiments we evaluate user behaviour towards changes in motor space and/or visual space. We will question, what is more important for controlling input devices successfully, to supervise one's own hand or the cursor movement on the display? As a consequence changes in either motor space or visual space should have a predominant influence on performance. The findings will help to understand the constraints of the acquisition and application of tool transformations.

Sensorimotor transformations with input–output devices differ in two aspects. Firstly, the input device manipulation (proximal effect) can or cannot correspond to the cursor action (distal effect). For example, most input devices (e.g. mouse, digitiser tablet, touchpad, displacement joystick or flystick) transform hand movements into cursor movements. The transformation is kept rather simple, i.e. the relationship between the moving hand and the cursor movement is obvious to the user. A considerable amount of studies (for an overview see Douglas and Mithal (1997)) reported a very efficient usage of motion-transforming input devices. Other input devices are rotary (e.g. trackball) or force-sensitive (e.g. isometric joystick or spacemouse). The transformation between applied rotation or force is less obviously connected to the cursor movement. Consequently, the user has more difficulties to anticipate the movement path, to control it and to terminate it successfully (e.g. Armbrüster *et al.* (2007), Card *et al.* (1978), Douglas and Mithal (1997), Epps (1986), Sutter (2007), Sutter and Müsseler (2007)).

Secondly, when operating a device the user has to account for a considerable display-control gain. Generally, performance is best when the hand movements nearly match the cursor movements (gains between 1:0.8 and 1:2). The missing concordance between one's own action and the intended action's effect (i.e. the cursor movement) accounts for interferences, and leads to increased movement times and/or errors for very low and high gains (for digitiser tablet see Accot and

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Zhai (2001), Arnaut and Greenstein (1986, 1990); for trackball see Arnaut and Greenstein (1986, 1990); for mouse see Casiez *et al.* (2008), MacKenzie and Riddersma (1994), Lin *et al.* (1992), Tränkle and Deutschmann (1991)). The findings of previous studies suggest that it is the concordance (discordance) between hand action and cursor movement that facilitates (hampers) performance. However, none of these studies conceptualised the usability of input devices with regard to action–effect control. Here, we provide a first step towards such a cognitive account in human–computer interaction. The theoretical basis will provide a better understanding of the cognitive strategies mediating the interaction in technical environments.

Of course, pointing with a cursor to a certain position on a display requires always a corresponding hand movement (except for isometric devices), thus hand movement and cursor movement are usually confounded. But this does not necessarily imply that hand movement and cursor movement are equally represented and used in the same way for controlling movements. On the contrary, recent evidence lets us assume that the action effect is essential regarding these kinds of tool use. For example, Kunde *et al.* (2007) (see also Müsseler *et al.* (2008)) introduced a lever to reach at a stimulus with the lever's effect point. Using different pivot points for the lever allowed dissociating effects between proximal hand-movement direction and distal tool-movement direction. For example, when the effect point of the lever was in front of the pivot point and thus on the side of the hand, hand movement and effect movement corresponded. If it was beyond the pivot point, hand movement and effect movement were contrary. The finding was that reactions were performed more efficiently when the tip of the tool was moved towards the stimulus, irrespective of the hand movement. This was clear evidence for the assumption that the intended action effect determines the response.

What does this finding mean for tool use in modern workplaces? Take for example the laparoscopic surgery. Here, the surgeon inserts a tool through a tiny, artificial aperture in the patient's torso. Although this operation technique has many advantages from a medical point of view, it creates severe problems for the surgeon as well. The aperture functions as a pivot and inverts the surgeon's hand movement and tool movement direction, i.e. if the surgeon moves the hand to the right the tool tip inside the body moves to the left and vice versa. The results from Kunde *et al.* (2007) suggest that what counts most in this situation is the representation of the distal action effect (i.e. tool tip moves towards stimulus), not the proximal effect (i.e. surgeon's hand moves towards the stimulus). This finding is consistent with predictions proposed by the ideo-motor principle (Greenwald 1970, James 1890; for recent overviews of empirical evidence see e.g. Hommel *et al.* (2001), Nattkemper and Ziessler (2004)). Any intentional act requires a goal, that is, some anticipatory representation of the intended action effect. The anticipation of these action effects may fulfil a generative function in motor control: actors select, initiate and execute a movement by activating the anticipatory codes of the movement's effects. These may be representations of body-related effects, like tactile feedback from the moving hand operating a tool (proximal effects). However, the intended action effects when using a tool are the movements of the tool tip displayed on the screen (distal effects). As a consequence, they should play the more essential role in controlling a tool successfully.

The present article aims to explore if these conclusions will also hold for controlling input devices, especially when these tools are force-controlled and require no hand movement at all. In Experiment 1, we evaluated a touchpad and a mini-joystick. The touchpad is motion-controlled and the mini-joystick is force-controlled. They represent the class of small input devices, integrated for example in mobile devices (camera, mobile phone, laptop computer) or in medical equipment (ultrasound system). Motor control is much more difficult when using small input devices due to restricted motor space (Accot and Zhai 2001) and less inertia (Douglas and Mithal 1997). So, effects from previous studies might be underestimated for these tools. We introduced changes in motor space and/or visual space by varying gain, target amplitude and size. We explored whether Fitts' law (Fitts 1954) would hold for cursor movements produced by touchpad and isometric mini-joystick in a comparable way. Of special interest in the present context was that the handling of the mini-joystick required no hand movement at all and that the cursor movements resulted only from the hand-force transformation. Nevertheless, the action–effect account claims that Fitts' law holds for action–effect movements (i.e. the cursor movements), irrespective of the input device and gain used. The reason for this is given by the very robust nature of the psychomotor law, which holds not only for all kinds of manual movements (e.g. finger, wrist, arm: Langolf *et al.* (1976)) but also for movement imagination (e.g. Grosjean *et al.* (2007)) and transformed movements (e.g. mouse: Casiez *et al.* (2008); touchpad, mini-joystick: Sutter (2007)), as long as the reference to the ballistic nature of rapid aimed movements is apparent. Experiment 2 tested the generalisation of the findings with a digitiser tablet. In motion-controlled input devices, hand movement and cursor movement are usually confounded, and hence we introduced changes in visual space only. Although in this experiment the proximal hand movements were kept constant, Fitts' law should again hold for the action–effect movements (i.e. the cursor movements) produced by different gains.

2. Experiment 1

Sensorimotor transformations of touchpad and mini-joystick are basically different and represent different classes of input devices. The touchpad is an *isotonic* device. Its gain is a function of finger motion to cursor motion. The mini-joystick represents an *isometric* device, i.e. the gain is a function of finger force to cursor speed. To compare device performance in a precisely and methodologically objective manner, a number of input and output factors have to be considered, e.g. differences in receptor-effector processes, sensitivity of device and cursor speed. In accordance with the action–effect account we expect the more corresponding input–output transformation of the touchpad to be used more efficiently than the less corresponding transformation of the mini-joystick. Also in accordance with the action–effect account we predict Fitts' law to hold for cursor movements produced by the mini-joystick as well, although this input device does not require a translational movement of the hand.

2.1. Method

2.1.1. Pretest

The experimental comparison of input devices with different input–output parameters reveals methodological problems. Note that the two input devices differ in several features too, apart from transforming finger motion (isotonic) and finger force (isometric) into cursor movements. These features are inherent properties of the devices and are not aimed at in the present study. However, to minimise the differences and to allow an experimental comparison of performance we measured the output parameters of each device and adjusted cursor speed on a similar level (for the methodology of the pretest in more detail see Sutter (2007)).

Cursor velocity was measured when the maximum speed of finger movement (touchpad) or the maximum force of finger press (mini-joystick) was applied to the input device. The pretest was conducted for the touchpad and mini-joystick of a Dell Inspiron 8100 laptop computer. For the duration of 2 min, the cursor was moved as fast as possible horizontally on the display ($N = 3$ participants). This procedure was repeated for all 11 gain settings provided by the system (low to high). For each gain setting, cursor speed was calculated by the ratio of cursor movement to time.

On the 11-point presetting scale, the 'low' gain settings (settings 1–3) resulted in a cursor speed below 1000 p/s, the 'medium' (settings 4–6) between 1000 and 3500 p/s and the 'high' setting (settings 7–11) in a cursor speed higher than 3500 p/s. In the present experiment we will focus on the 'low' (3) and 'high' (7) gain settings. Setting 3 resulted in a rather slow cursor movement on the screen, comparable to a cursor speed below the average mouse speed. A fast cursor speed was given with setting 7, which was above the average mouse speed found in desktop computers. For touchpad and mini-joystick, respectively, low gain (setting 3) resulted in a cursor speed at about 563 p/s and 970 p/s. Cursor speed was high (setting 7) at about 4565 p/s and 3760 p/s. Apparently, gain specifications as preset by the device drivers do provide an approximation of cursor speed between touchpad and mini-joystick.

2.1.2. Participants

Twenty students from the RWTH Aachen University (five males) volunteered for the study. They were all highly experienced laptop users: 10 students used the touchpad (3 males) and 10 students used the mini-joystick (2 males) as their regular graphical input device. Their expertise in operating the input device was determined by the daily contact hours with the laptop and the particular input device. All of them had been full-time laptop users for more than 2 years, with an average use of 2.7 h/day ($SD = 2.2$). Expert groups did not differ according to their laptop habits (*t*-tests n.s.). It was controlled that experts with one input device were having no (or less) experience with the other input device.

2.1.3. Apparatus and stimuli

Participants sat in front of a laptop computer (Dell Inspiron 8100) that was connected to an external 15″ TFT flat screen (Iiyama TXA 3841J) with a 1024×768 resolution. The input devices integrated in the laptop were a touchpad, a flat 60 mm × 44 mm touch sensitive panel and a mini-joystick, a small force-sensitive joystick placed between the 'G', 'H' and 'B' keys on the keyboard. Two mouse buttons were arranged horizontally in the wrist rest.

On the display a cross-hair cursor and a target box were presented in black colour on white background. The point-click task included to move the cursor inside the target box, and to press the left mouse button. Target boxes appeared in two sizes (2.5 mm and 5.0 mm) and in two distances (25 mm and 50 mm).

Indices of difficulty (IDs) according to Fitts' law (ISO 9241-9 2000, MacKenzie 1992) were 2.6, 3.5 and 4.4 bits. The target box was always located centrally. The starting position of the cursor was placed in eight different directions (45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°) relative to the target excluding confounds with movement direction.

2.1.4. Procedure

Participants were assigned to two experimental conditions according to their expertise with touchpad or mini-joystick. In the *motion* transformation condition all participants were exclusively experts with the touchpad and operated the touchpad throughout the experiment. In the *force* transformation condition participants were mini-joystick experts and solved the experimental point-click tasks by operating the mini-joystick. Each trial started with a self-paced press of the space bar. The task was to move the cursor inside the target box and confirm the correct positioning by pressing the left mouse button. Participants were instructed to move the cursor as fast and accurate as possible, and to operate the input device with their dominant hand, the left mouse button with their non-dominant hand.

The *movement time* was defined as the interval from onset of cursor movement to final button press. *Error percentages* were calculated on the basis of trials where the left mouse button was pressed when the cursor was not inside the target box. The participants worked throughout a block with *low gain* of the cursor (gain 3) and a block with *high gain* (gain 7). The order of the gain conditions was counterbalanced across participants. Each block consisted of four ID *conditions* (with 16 repetitions) and additional 10 training trials in advance of each block. In total, the experiment lasted 30 min.

2.2. Results

The data were analysed with a 2 × 2 × 3 analysis of variance (ANOVA) with the between-subject factor 'sensorimotor transformation' (movement vs. force transformation) and with the within-subject factors 'cursor gain' (low vs. high) and 'ID' (2.6, 3.5 and 4.4 bits). For movement times, the ANOVA revealed a significant main effect of the group factor 'sensorimotor transformation' ($F(1, 18) = 10.49$; $p < 0.01$). Movements times were generally 225 ms shorter with the touchpad than with the mini-joystick, but this advantage based on the high-gain condition (Δ 377 ms; $p < 0.01$) and less on the low-gain condition (n.s.), resulting in a significant interaction between sensorimotor transformation and cursor gain ($F(1, 18) = 22.35$; $p < 0.01$). Movement times significantly decreased with the touchpad from the low gain to the high gain condition (1399 vs. 1162 ms; $p < 0.01$), while they remained nearly unaffected by gain change with the mini-joystick (1473 vs. 1539 ms; n.s.).

Additionally, the main effects of the factors 'cursor gain' ($F(1, 18) = 7.14$; $p < 0.05$) and 'ID' ($F(2, 17) = 353.13$; $p < 0.01$) were significant. Movement times increased from the easiest (2.6 bits) to the most difficult task (4.4 bits). However, this increase of movement times was more pronounced in the low-gain condition with an increase of 874 ms than in the high-gain condition (increase of 633 ms) yielding a significant interaction between both factors with $F(2, 17) = 20.18$; $p < 0.01$. The analysis of the error percentages revealed no significant effects. Participants responded quite accurately with a mean error percentage below 5%.

The data were further analysed with regard to effects of ID according to Fitts' law (Fitts 1954). For each of the four gains by transformation conditions a separate regression analysis with the 4 ID conditions ($=\log_2 (A/W + 1)$, modified formula by MacKenzie (1992)), was calculated for movement time (Figure 1). In the low-gain conditions slopes were different from zero (all with $p \leq 0.05$) and they were comparable between touchpad and mini-joystick (482 ms/bits and 488 ms/bits). Intercepts did not differ significantly from zero. Overall, regression lines fit the data very well and ID accounted for most variance in movement time in the low- (all R^2 above 0.95) and high-gain conditions (all R^2 above 0.68).

2.3. Discussion

There were three main findings of Experiment 1. Firstly, the touchpad was used more efficiently than the mini-joystick when a high gain was used. At first glance – and in accordance with our hypotheses – the more demanding force transformation of the mini-joystick seems to be inferior when compared with the motion transformation of the touchpad, especially when a higher gain was introduced. At second glance, however, results showed an impact of gain change on touchpad performance only. As observed for other motion transforming input devices (e.g. Accot and Zhai (2001), Casiez *et al.* (2008), Jellinek and Card (1990)) the gain change of the touchpad followed a half-parabola with an optimum for the higher gain condition. Remember, in the present experiment visual target sizes and distances were held constant. As a consequence low gain resulted in longer hand amplitudes on the pad and longer movement times than compared with those of high gain. More surprisingly, using a mini-joystick was totally unaffected by gain

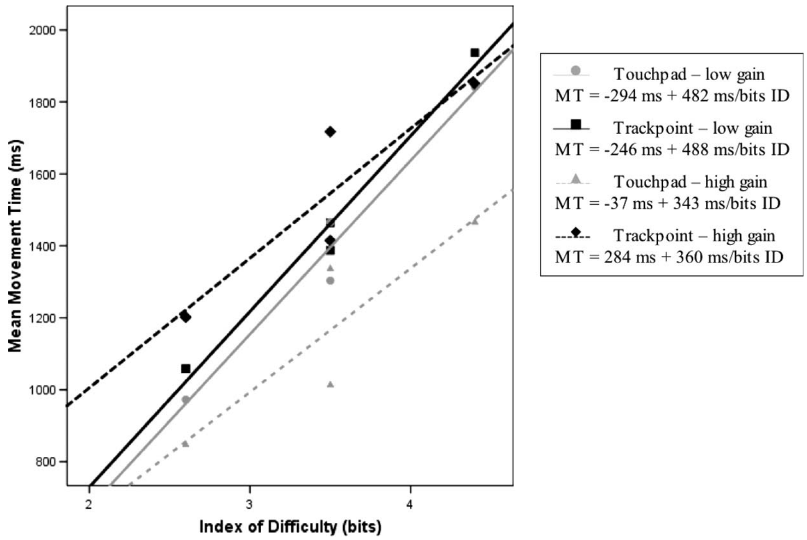

Figure 1. Mean movement times (ms) as a function of ID (bits) and gain for the touchpad and mini-joystick (Experiment 1).

and performance remained stable for low- and high-gain settings. For now we can summarise that changes in motor space have an impact on motion transforming input devices, but not necessarily on force transforming devices.

Secondly, the regression analysis of movement time and ID revealed that Fitts' law holds for visually perceived action–effect movements, that is, for cursor movements on the display. Most importantly, this is not only true for the touchpad but also for the mini-joystick, in which force is the input. Thus, Fitts' law does not necessarily need movements of the motor system, but it holds for action–effect perception. In accordance with this finding, Grosjean *et al.* (2007) found when observers judged others' movements, they also tend to rate them with regard to Fitts' law. This is additional evidence in favour of the action–effect account. However, one might argue that each regression line in Figure 1 is based only on three IDs, which do not provide a sufficient database. Therefore, Experiment 2 aimed to extend and generalise the findings.

Thirdly, the observed difference in movement times for similar IDs but different amplitude/width combinations is also in accordance with previous work (Sheridan 1979, Sutter and Ziefle 2004). Contrary to Fitts' law, target size accounts for more variance in movement time than amplitude and – as a result – movements towards closer but smaller targets were executed slower than towards farther but larger targets.

3. Experiment 2

One result of the previous experiment was that Fitts' law held for touchpad and mini-joystick. Since the use of the mini-joystick did not need a translational hand movement, but force, our findings strongly supported the view that the display movements were controlled and executed by the anticipated action–effect movements (see also Sutter and Ziefle (2004, 2006)). The question of what the user controls is not answered that clearly, since hand movement and cursor movement were confounded in Experiment 1. Therefore, to replicate and extend the finding of visual action–effect control, a digitiser tablet was used in the present experiment with a Fitts' task. Within a block of the experiment, participants always executed the same proximal movement on the digitiser tablet (no change in motor space), but the gains and/or the target sizes varied (changes in visual space only). Movement times should be constant within a block if the proximal hand movement on the digitiser tablet actuates motor control. On the contrary, we expect them to vary with regard to Fitts' law, if it is the distal action effect on the display (i.e. the cursor movement) that determines movement times.

3.1. *Method*

3.1.1. *Participants*

Nine students from the RWTH Aachen University (six males) participated in this experiment.

3.1.2. *Apparatus, task and stimuli*

Participants sat in front of a digitiser tablet (WACOM Intuos2 A3) that was operated with a pen (WACOM Intuos2 Grip Pen). Experimental tasks were presented on a 17″ CRT display (EIZO F563-T) with a 1024 × 768 resolution. A cover screened the hands from view.

Participants were only able to see the display of the cursor movement, not the movements of their hand on the digitiser tablet. The task involved moving the cursor back and forth between two target boxes that were horizontally displayed on the screen. Each trial lasted until 25 error-free movements occurred.

The movement distance of the hand (tablet amplitude) was the same for all trials within a block (20, 40 or 60 mm). Within each block movement distance of the cursor (display amplitude) varied as a result of gain factor (1.22 (low gain), 1.44 (middle gain) and 4.88 (high gain)). The display amplitude was 24 (low gain), 48 (middle gain) and 97 mm (high gain) within the 20-mm block, 48, 97 and 195 mm within the 40-mm block, and 73, 146 and 292 mm within the 60-mm block. Additionally, within each block the target sizes varied randomly with 5, 10, 20 and 40 mm. The combination of 24-mm display amplitude and 40-mm target size in the 20-mm block was skipped from the procedure, as overlapping target boxes resulted. For display amplitude and display target size the index of difficulty was calculated using Fitts' law (ID modification by MacKenzie (1992)). Display ID varied from 1.2 to 4.4 bits (11 different A/W ratios) for the 20-mm block, from 1.2 to 5.4 bits (12 different A/W ratios) for the 40-mm block and from 1.5 to 5.9 bits (12 different A/W ratios) for the 60-mm block.

3.1.3. *Procedure and design*

Participants were instructed to continuously move the cursor back and forth between the two target boxes. As soon as they reached one target box the movement direction should be reversed without pausing in the target box. The instruction stressed the need to move continuously, and to move as fast and turn as accurately as possible.

The *movement time* was defined as the time for each target-to-target movement. *Error percentages* were calculated on the number of trials, where the reversal point of movement was outside the target box. The participants worked throughout the three blocks of tablet amplitudes. The order of blocks was counterbalanced across participants. Within a block, gain and target size were randomly varied. Each block consisted of 11 or 12 A/W combinations with 25 repetitions and additional 3 × 25 training trials in advance of the experimental trials. In total, the experiment lasted about 45 min.

3.2. *Results*

Blocks of tablet amplitudes were analysed with separate ANOVAs with the within-subject factors 'gain' (low, middle and high) and 'target size' (5, 10, 20 and 40 mm). For all tablet amplitudes a comparable pattern of results was found (Figure 2a–c). Movement times and error percentages were increased with the high gain compared to the low and middle gain. In all gain conditions, movement times and error percentages were lowest for the largest target and increased as a function of target size. Movement times increased from 301 to 519 ms with the 20-mm tablet amplitude (Figure 2a), from 404 to 797 ms with the 40-mm tablet amplitude (Figure 2b) and from 514 to 976 ms with the 60-mm tablet amplitude (Figure 2c). Corresponding effects were observed in the errors: error percentages increased from 1 to 19% with the 20-mm tablet condition, from 3 to 22% with the 40-mm tablet condition and from 3 to 25% with the 60-mm tablet condition.

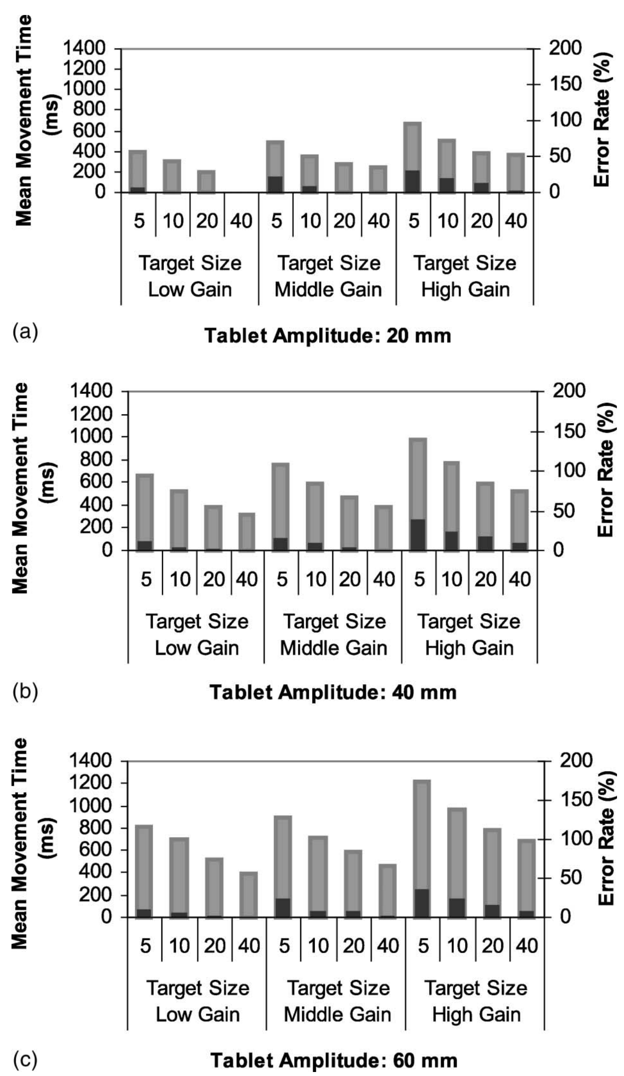

Figure 2. Mean movement times (grey) and percentage of errors (black) as a function of target size (mm) and gain for the tablet amplitudes (a) 20, (b) 40 and (c) 60 mm (Experiment 2).

The ANOVA of movement times revealed consistently significant main effects of the factors 'gain' (20 mm: $F(2, 7) = 57.66$; $p < 0.01$; 40 mm: $F(2, 7) = 43.80$; $p < 0.01$ and 60 mm: $F(2, 7) = 33.99$; $p < 0.01$) and 'target size' (20 mm: $F(3, 6) = 48.40$; $p < 0.01$; 40 mm: $F(3, 6) = 32.10$; $p < 0.01$; 60 mm: $F(3, 6) = 53.93$; $p < 0.01$). The interactions were always not significant.

Corresponding effects were observed in the ANOVA of error percentages for gain (20 mm: $F(2, 7) = 18.22$; $p < 0.01$; 40 mm: $F(2, 7) = 24.05$; $p < 0.01$; 60 mm: $F(2, 7) = 21.05$; $p < 0.01$) and target size (20 mm: $F(3, 6) = 7.90$; $p < 0.05$; 40 mm: $F(3, 6) = 20.44$; $p < 0.01$; 60 mm: $F(3, 6) = 20.52$; $p < 0.01$). For the tablet amplitude of 60 mm the interaction of gain and target size was also significant ($F(6, 3) = 9.01$; $p < 0.05$).

The data were further analysed with regression analyses. For each tablet amplitude separate regression lines were calculated between movement time and ID (with 11 and 12 different A/W ratios; Figure 3). Slopes were different from zero (all with $p \leq 0.001$) and increased with tablet amplitude (from 129 to 153 and 174 ms/bits for the tablet amplitudes of 20, 40 and 60 mm, respectively). The intercept differed significantly from zero in the conditions with the 20-mm ($p < 0.05$) and 40-mm tablet amplitude ($p < 0.01$). Over all, regression lines fit the data very well (all R^2 above 0.94). The regression analysis with tablet amplitude, target size and gain accounted for most variance of movement time ($R^2 = 0.88$) with MT = 151 ms + 94 ms/cm A_{tablet} − 99 ms/cm $W_{display}$ + 72 ms/unit gain. Intercept and slopes differed significantly from zero ($p < 0.01$). Within a given ID movement times were lowest if the gain was 1:2.44 and increased if gain was below (1:1.22) or above (1:4.88) that optimum.

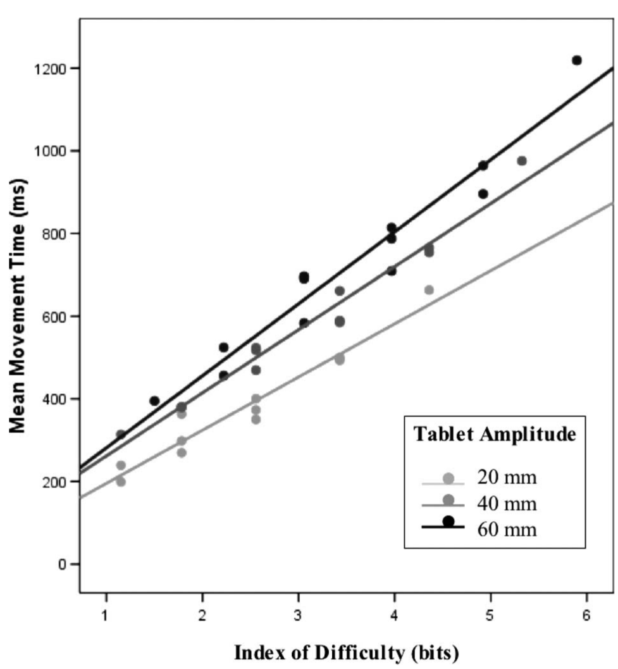

Figure 3. Mean movement times (ms) as a function of ID (bits) for the tablet amplitudes 20, 40 and 60 mm (Experiment 2).

Separate regression lines were also calculated between error percentage and ID. Slopes differed from zero (all with $p < 0.01$) and decreased with tablet amplitude (from 10 (20 mm) to 8%/bits (40 mm and 60 mm)). The intercept differed significantly from zero (all with $p < 0.01$) and decreased with tablet amplitude (from −14 (20 mm and 40 mm) to −16%/bits (60 mm)). Overall, regression lines fit the data very well (all R^2 above 0.82). The regression analysis with tablet amplitude, target size and gain accounted for most variance of errors ($R^2 = 0.80$) with MT = 2% + 1%/cm A_{tablet} − 5%/cm $W_{display}$ + 5%/unit gain. Slopes differed significantly from zero ($p < 0.05$). Within a given ID error percentages were lowest if the gain was between 1.22 and 2.44 and increased if the gain was above that optimum (4.88).

3.3. Discussion

We can conclude in accordance with our assumptions and the findings of Experiment 1 that it was the target distance and the target size on the display that determined movement times. In other words, as tablet amplitudes were held constant in each panel of Figure 2a–c, Fitts' law holds again for the action–effect movements on the display (i.e. the cursor movements). Performance was best if the gain was 2.44 and dropped with lower or higher gains. Once more, this result confirms the optimum gain setting for motion transforming input devices (cf. Arnaut and Greenstein (1986, 1990), Lin *et al.* (1992), Tränkle and Deutschmann (1991)).

A further observation of the present experiment was that participants were mostly unaware of their tablet amplitude. Informal reports gathered after the experiment revealed that participants did not notice that the hand amplitude remained constant within a block and only display amplitude was varied by a change in the gain. In other words, the proprioceptive feedback of the hand movement did not countervail against the visual action effect (cf. Müsseler and Sutter (2009)).

Two aspects are critical to note. First, the cursor movements on the display did not only determine movement times, but they also depended strongly on the tablet amplitude. Comparing the panels of Figure 2a–c, larger tablet amplitudes seemed to lead to an increase in movement times. One might argue that for the smaller tablet amplitudes movements involve distal joints (e.g. finger, wrist), which produce shorter movement times. Contrary, for larger tablet amplitudes movements involve proximal joints (e.g. arm) yielding longer movement times (Langolf *et al.* 1976, Bohan *et al.* 2003). However, in our experiment participants were able to cover all distances with wrist movements, even the longest distance of 60 mm. This lets us conclude that the increase of hand amplitude intensified the impact of changes in visual space. And furthermore, if distal joints were involved even stronger effects on movement time can be expected.

Second, the increase in movement times is not just described by an additive component, as the different slopes of regression lines in Figure 3 suggest. When additionally error percentages were taken into account, we found an increase of errors with the larger tablet amplitudes. This further increased movement time. In other words, if participants had worked more accurately then the increase in movement times would have been stronger as observed in the present data. Thus, one could even assume that the differences in slopes are rather underestimated than overestimated.

4. General discussion

The present article aimed to examine the question of what the user controls when using an input device: the hand movement or the cursor movement. With regard to the action–effect account (Hommel *et al.* 2001) the intended action effects are achieved by the cursor movements on the display (distal effect). Consequently, we assumed that the cursor movements could play the more essential role in controlling an input device. The main finding of Experiment 1 was that Fitts' law holds for visually perceived action–effect movements, that is, for the cursor movements on the display. Most importantly, this was also true when the mini-joystick was used which required no translational movement of the hand. Obviously, Fitts' law did not need the movements of the hand, but the action–effect movements on the display. This finding was elaborated in Experiment 2. Participants performed a Fitts' task on a digitiser tablet with a pen without seeing their hand. Within each block of the experiment, participants always performed the same movement amplitude with their hand, while the amplitude on the display was changed by various gains. Results demonstrated that movement times varied with the amplitude and the target size on the display. Again, it was Fitts' ID calculated from display values that determined movement times.

When movements are represented and controlled by anticipating the distal movement effects, participants need to be less aware of their own hand movements (cf. the informal reports of the participants in Experiment 2; see also Müsseler and Sutter (2009)). The present findings revealed further evidence for the dominance of the distal action effects (i.e. the cursor movement on the display) over the proximal action effects (i.e. the hand movement on touchpad and digitiser tablet, or hand force applied to the mini-joystick). This view makes sense, as it is a precondition for using tools successfully. If distal and proximal effects were equally important in information processing, any deviation between them would be a steady source of interference. To avoid this interference, actions should be represented by the action effects and thus by the laws which establish them.

As outlined in Section 1, the understanding of cognitive processes underlying tool use becomes increasingly important. Modern technologies progressively create workplaces in which movement execution and observation are spatially separated. Computer input devices are only an example in this respect. More challenging workplaces in which users act by technical equipment in a distant space are – for instance – laparoscopic surgery, VR (for training or product development) or teleoperation. Recent studies more and more revealed that what counts most for controlling movements successfully are the action effects in distant space (e.g. Kunde *et al.* (2007), Lukas *et al.* (2010), Massen and Prinz (2008), Müsseler *et al.* (2008)).

A second finding of Experiment 1 was that the impact of gain change was only apparent when using the motion transforming device (touchpad), but not when using the force transforming one (mini-joystick). Importantly, both input devices were handled by highly experienced users, which excludes that the discrepancies between devices are a matter of exercise. Instead, Fitts' law has to be taken into account, which is determined by the physical hand movement on the touchpad, but not by the finger press on the mini-joystick. It becomes obvious that the motion-transforming input device is additionally affected by changes in motor space, but the force-transforming device is not. Thus, if proximal target distance and size becomes shorter and larger, respectively, faster responses occur with the touchpad. Blanch *et al.* (2004) also found effects of ID in motor space and in visual space when performing movements on a digitiser tablet. With reference to our results we conclude that the concordance between proximal action effects (proprioceptive, tactile feedback from the moving hand) and distal action effects (moving tool) facilitate performance. However, we – more or less automatically – compensate for and adapt to smaller discordances (e.g. Rieger *et al.* (2005)). Larger discrepancies, as perceived with extreme gain changes (very low, very high) or unfamiliar transformations (force into speed or left into right transformations) produce interferences (e.g. gain transformations: Accot and Zhai (2001), Jellinek and Card (1990); transformation with changes in movement direction: e.g. Kunde *et al*. (2007), Müsseler *et al*. (2008); force transformations: Lukas *et al*. (2010), Sutter (2007)).

In sum, the present experiments allow theoretical and practical conclusions for a better understanding of controlling input devices or tools with sensorimotor transformations in technical environments. Based on the cognitive account of action–effect control (Hommel *et al*. 2001), our results revealed evidence that distal action effects are predominant in action control. In other words, supervising the cursor movement on the display plays a more essential role in controlling an input device than supervising one's own hand. However, the concordance or discordance between distal and proximal action effects is still able to facilitate or hamper performance.

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