A kinematic analysis of directional effects on mouse control

Byungjoo Lee & Hyunwoo Bang

School of Mechanical and Aerospace Engineering, Seoul National University, Daehak-dong, Gwanak-gu, Seoul, 151-742, Republic of Korea

Published online: 16 Sep 2013.

To cite this article: Byungjoo Lee & Hyunwoo Bang, Ergonomics (2013): A kinematic analysis of directional effects on mouse control, Ergonomics, DOI: 10.1080/00140139.2013.835074

To link to this article: http://dx.doi.org/10.1080/00140139.2013.835074
A kinematic analysis of directional effects on mouse control

Byungjoo Lee and Hyunwoo Bang*

School of Mechanical and Aerospace Engineering, Seoul National University, Daehak-dong Gwanak-gu, Seoul 151-742, Republic of Korea

(Received 16 January 2013; accepted 7 August 2013)

The directional effects associated with cursor movement controlled by a computer mouse have long been studied to improve mouse performance during precise tasks. However, those studies have rarely considered the kinematic variables associated with directional effects and have only analysed the projection of trajectories along the main axes of movement, eventually reducing the original dimensions of the data. In addition, as the angle of approach has a limited number of levels, it has been difficult to observe singular behaviour in the horizontal directions. In this study, we investigated the directional effects on kinematic variables when using a mouse to select circular targets. In this experiment, the measured trajectory of 16 different angles of approach was measured after separating the $x$ and $y$ components. The results revealed interesting biomechanical and cognitive features of mouse control and led to the suggestion of two improvements to be made upon the typical mouse design.

Practitioner Summary: The angle of approach was varied to determine its effect on the kinematic variables of a cursor trajectory. We analysed both the $x$ and $y$ coordinates separately without reducing the original dimensions of the data. Therefore, we succeeded in identifying previously unknown characteristics of mouse control.

Keywords: mouse; kinematic analysis; directional effect; ISO 9241-9

1. Introduction

A mouse is a pointing device that detects two-dimensional (2D) motion with respect to its supporting surface. Among the currently available types of non-keyboard input devices, the mouse is the most common device used with desktop computers (97%) for a wide range of applications, from word processing to computer-aided design (Hastings et al. 2000).

Several factors have been revealed to affect mouse performance, with most research on this subject having been carried out based on the framework of Fitts’ law (Fitts 1954). Fitts’ law is a model of rapid aimed human movement that predicts that the time required to reach a target area is a function of the distance to the target and the width of the target. Within the framework, the performance of any pointing input device is represented by a variable called the throughput that is measured independently of speed-accuracy trade-offs. From early research based on Fitts’ law, we can derive a general conclusion that the mouse is a fairly efficient pointing device (MacKenzie 1992; MacKenzie, Sellen, and Buxton 1991). Moreover, the throughput of the mouse has even been found to be nearly the maximum achievable compared with the level of other eye–hand pointing tasks (Card, English, and Burr 1978).

However, recent studies (Bohan, Thompson, and Samuelson 2003; Hwang et al. 2005; Phillips and Triggs 2000; Phillips, Triggs, and Meehan 2001; Po, Fisher, and Booth 2005) have argued that control of the mouse is far from being optimised and in fact falls short in various situations. Intensive mouse use has also been associated with increased risk of upper extremity musculoskeletal disorders, including carpal tunnel syndrome (Keir, Bach, and Rempel 1999).

Such problems can be fully understood and resolved when we investigate the effect of factors not considered by Fitts’ law (Bohan, Thompson, and Samuelson 2003; MacKenzie, Kauppinen, and Silfverberg 2001; Phillips and Triggs 2000, 2001; Phillips, Triggs, and Meehan 2005). Among other factors, the angle of approach to the target has long been studied because it is able to fully capture the spatial information related to the 2D movement of an input device on the surface. The angle of approach has been reported to have a significant effect on the performance of a pointing device. However, it is not clear how this factor influences cursor movement on the computer screen (Dillen, Phillips, and Meehan 2005). Instead, different interpretations of the hidden principles of operation related to this directional effect have been proposed. Generally, these interpretations were associated with the concept of compatibility (Phillips, Triggs, and Meehan 2005), biomechanical factors of the upper extremities (Dillen, Phillips, and Meehan 2005; Hertzum and Hornbæk 2010; Meng, Chen, Chu, Wu, et al., 2007; Smyrnis et al. 2000), efforts stemming from coordinate transformation (Phillips and Triggs 2000; Phillips, Triggs, and Meehan 2001), the reading screen direction (Donker and Reitsma, 2007b) and functional cerebral asymmetries (Phillips and Triggs 2001).

*Corresponding author. Email: savoy@snu.ac.kr

© 2013 Taylor & Francis
Early studies (Phillips and Triggs 2000; Whisenand and Emurian 1996, 1999) investigated the directional effects with the classic measures originating from the framework of Fitts’ law. But as completion time and error rate are classic measures and do not reveal any time-varying characteristics of the cursor trajectory, interpretations of the results of early studies are limited. However, the time-varying characteristics of the cursor trajectory can be revealed by analysing the kinematic variables of the trajectory. The results of such study may provide an understanding of the factors limiting cursor placement (Phillips, Meehan, and Triggs 2003) and indicate what role planning cursor movements, creating terminal guidance, resolving mismatches between display and control coordinate systems, moving cursors across the screen or gauging screen distances (Dillen, Phillips, and Meehan 2005) might play in the problem.

A few recent studies (Dillen, Phillips, and Meehan 2005; Donker and Reitsma 2007a; Hertzum and Hornbæk 2010; Meng, Chen, Chu, Wu, et al., 2007; Phillips, Triggs, and Meehan 2001, 2005) have analysed the directional effects on cursor movement in terms of kinematics. The mouse is a real-time input device used to move a cursor in various directions on a 2D surface. As such, an analysis of the directional effects by investigating kinematic variables may be the most effective way to capture both the spatial and time-dependent characteristics of mouse control and could give us clues as to how to improve such functioning. Despite the application of new kinematic techniques in recent studies, though, there were several factors that limited the analysis, leaving the exact nature of how the angle of approach influences the movement of a cursor on a screen unclear. These problems significantly reduced the power of the analysis and limited efforts to search for means by which to improve mouse performance.

First, the kinematic features of the directional effects were only determined along the main axis of movement (Dillen, Phillips, and Meehan 2005; Donker and Reitsma 2007a; Hertzum and Hornbæk 2010). This dimensional reduction may be valid when the angle of approach is not considered as an individual factor. However, when we want to investigate the directional effects, all dimensions of data are fully correlated with these effects, and the reduction causes a loss of the half of the information contained in the original data, which was not the case with 1D measures of the movement time. Second, past studies did not effectively determine the reference frame of the trajectory coordinates, instead making the horizontal axis of the reference frame coincide with the line connecting the start position and the target position (Dillen, Phillips, and Meehan 2005; Donker and Reitsma 2007a; Hertzum and Hornbæk 2010; Hwang et al. 2005; MacKenzie, Kauppinen, and Silfverberg 2001; Phillips, Meehan, and Triggs 2003; Phillips, Triggs, and Meehan 2001, 2005). However, as suggested by Teulings, Thomassen, and Maarse (1989), there were two orthogonal main axes that were useful at the descriptive level of handwriting movement, one corresponding to wrist-joint movements and the other corresponding to finger-joint movements. For a mouse, the wrist-joint movement is naturally transferred to the cursor as horizontal movement and the finger-joint movement is transferred to the cursor as vertical movement in the display reference frame. Consequently, the fixed reference frame in the display space would be much more useful for describing the kinematic features of cursor movement.

Lastly, one feature associated with the horizontal movement of a cursor guided by a mouse has been neglected (Dillen, Phillips, and Meehan 2005; Donker and Reitsma 2007a; Hertzum and Hornbæk 2010; Meng, Chen, Chu, Wu, et al., 2007; Phillips, Triggs, and Meehan 2001, 2005). For a handwriting system, the wrist-joint movements in adults will not produce a perfectly straight trajectory but rather a circular trajectory with a radius of about 150 mm (Teulings, Thomassen, and Maarse 1989). However, in the case of cursor movement using a mouse, the wrist-joint movements will produce an almost perfectly straight line because the sensor is fixed on the body of the mouse and only measures the tangential components of the trajectory on the surface reference frame. As wrist-joint movements consist of short stroke durations and have very little spatial error as compared with finger-joint movements (Teulings, Thomassen, and Maarse 1989), the advantage of the horizontal motion originating from wrist-joint movement is amplified in the case of a mouse. However, only a limited number of levels for the angle of approach have been used in past research to demonstrate this effect.

The main objectives of this study were to analyse the effect of the angle of approach on several kinematic variables considering all the suggestions discussed above. The experiment consisted of a standard pointing task done from 16 different angles of approach in order to reveal the singular feature of cursor movement along the horizontal direction. The kinematic analysis of the cursor coordinates was done along two separate axes of the display reference frame in order to fully capture the information related to the directional effects. The results of the experiment pointed to two potential future improvements in mouse design, one to reduce the larger overshoot in the downward direction and another to eliminate the coordinate disturbance that originates from the detachable coordinate system of a mouse.

2. Method

2.1. Participants

Nineteen healthy university students (10 males, 9 females) with a mean age of 23.8 years (SD = 2.78 years) and a median age of 27 years were recruited for this study. All the participants were right-handed, and they were compensated at a rate of $10 per hour for their participation. All were users of computers, reporting 4–50 h of usage per week (M = 19.77 h,
SD = 14.83 h). They all had previous experience using a mouse and had no previous experience using a pointing acceleration function.

2.2. Apparatus
The task was performed on a 2.2 GHz desktop computer (HP TouchSmart 600) with a 23-inch LCD monitor and a two-button wireless optical mouse (Microsoft Arc Touch) with a resolution of 1000 CPI. The resolution of the LCD monitor was 1920 x 1080 pixels. The cursor was a standard arrowhead pointing to the upper left measuring 15 x 15 pixels and representative of cursors used in typical graphical user interfaces. The control-display gain for the mouse was maintained at a 1:1 ratio in all conditions. The cursor location was sampled as the x and y coordinates at 125 Hz (i.e. every 8 ms).

2.3. Task
The multidirectional pointing task was used in order to comply with the ISO 9241-9 standard. Participants were asked to use a mouse to move a cursor between two circles, one red and one blue, simultaneously displayed on a black background. The target was made visible before launching each trial in order to minimise the initial downward anticipatory movement reported in previous research (Whisenand and Emurian 1999). The task screen is depicted in Figure 1. The participants were asked to move the cursor into the red starting circle and then to left click to begin a trial. The red circle would then disappear and the participants were required to move the cursor into the blue target circle and left click to end the current trial, thus using the left-button-down event to begin and end each trial. Any movement made before clicking on the red circle was not recorded in order to present an exact angle of approach to the participants. The two circles were located symmetrically in relation to the centre of the computer screen. The task was systematically varied with regard to three aspects that were expected to influence performance (see Figure 1):

(a) Distance to target (two levels). The distance between the centres of the two circles was 400 or 800 pixels.
(b) Target size (three levels). The diameter of the circles was set at 10, 20 or 30 pixels. The range of the index of difficulty calculated for the chosen sets of target distances and sizes (3.84–6.34 bits) was those commonly used in earlier studies regarding Fitts’ law (Soukoreff and MacKenzie 2004).
(c) Angle of approach (16 variations). The angle of approach was varied according to increments of 22.5° (clockwise 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180°, 202.5°, 225°, 247.5°, 270°, 292.5°, 315° and 337.5°) in order to reveal the singular characteristics of cursor movement along a particular direction.

2.4. Design
The experiment was a 2 x 3 x 16 within-subjects design with repeated measures ANOVA. An α level of 0.05 was used for all statistical tests. The experiment consisted of 10 blocks of trials, with a block consisting of 96 trials. For each block, the

![Figure 1. Description of the task and independent variables: (a) distance to target, (b) target size and (c) angle of approach.](image-url)
angle of approach was given in a clockwise order, and the widths and distances of the task were randomly presented to the participants.

- 10 blocks ×
- 2 distances to target ×
- 3 target sizes ×
- 16 angles of approach ×
= 960 trials per participant

### 2.5. Procedure

The participants were seated such that they were aligned with the midline of the computer screen and were free to utilise the entire workspace to accommodate various mouse control strategies. Before the experiment, they completed a pre-test questionnaire about their age, gender, computer usage and previous experience with pointing acceleration functions. After finishing the questionnaire, they were instructed as to how to perform the task, and the experimenter briefly demonstrated the task and the software. The participants were asked to move the cursor from the red circle into the blue circle as quickly and as accurately as possible. An error was counted if a participant failed to click inside the blue circle after having clicked inside the red circle, and the corresponding trial was then presented again. If a participant failed to start the trial by clicking inside the red circle, this was not counted as an error. Before the experimenter began taking measurements, the participants finished one practice block, which took about 5 min. The participants were given a 3-min break between each block, and the total time required by each participant was about 45 min.

### 2.6. Dependent measures

A total of 18,833 trials, including errors, were conducted to collect data for seven dependent measures. We measured the trial completion time and the reaction time (which was not required to be analysed) in separate $x$ and $y$ components of movement in display coordinates. We also measured the same kinematic variables as had been measured in past studies, including the number of submovements (Dillen, Phillips, and Meehan 2005; Hertzum and Hornbæk 2010; Phillips and Triggs 2000, 2001; Phillips, Triggs, and Meehan 2005), the force inefficiency (Meng, Chen, Chu, Wu, et al., 2007; Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2000, 2001; Phillips, Triggs, and Meehan 2001, 2005) and the proportion of trial completion time spent in acceleration (Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2000, 2001) for each of the separate $x$ and $y$ components of movement in the display coordinates. We measured two more variables along the movement direction: movement variability and overshoot. All variables were calculated for each trial and then averaged for each condition. The measured cursor coordinates were low-pass filtered using a recursive dual-pass second-order Butterworth filter with a 10 Hz cut-off frequency. There was no phase lag after using the dual-pass digital filter. The coordinates of the filtered displacement function were differentiated twice using a central finite difference algorithm to obtain the velocity and acceleration functions.

The measured trial completion time started with the selection of the red starting circle and ended with the next left-click. The reaction time was determined by measuring the time between the selection of the red circle and the emergence of the first local minimum absolute velocity along the movement direction. This algorithm did not allow meaningless clicking movements to be measured in a very short reaction time.

The kinematic variables were determined along each of the two axes of the reference frame fixed on the display. The number of submovements and the force inefficiency were determined by counting the number of zero crossings in each of the velocity and acceleration functions. The proportion of the trial completion time spent in acceleration was determined using the point at which the global maximum speed occurred (the period of time from the end of the reaction phase to the maximum speed was divided by the trial completion time).

The standard deviation of the perpendicular coordinates along the main axis of movement (i.e. in the direction of the target), termed movement variability (MacKenzie, Kauppinen, and Silfverberg 2001), was calculated in order to determine whether the measured trajectory was close to being a straight line. The amount of overshoot was measured along the main axis of movement about the centre of the target circle.

### 3. Results

#### 3.1. Learning effects

There was no main effect of the block on the trial completion time ($F(1, 18) = 1.59, p = 0.22$). The subsequent statistics were averaged for all blocks.
3.2. Trial completion time
The angle of approach was found to have a significant effect on the trial completion times \( F(1, 18) = 17.24, p < 0.001 \) (see Figure 2). The fastest movement was to the left \( (90^\circ, M = 936.93 \text{ ms}) \) and the slowest was upwards \( (180^\circ, M = 1092.42 \text{ ms}) \). The movement to the right was also very fast and resulted in a local minimum \( (270^\circ, M = 954.56 \text{ ms}) \). The movement towards the bottom resulted in a local maximum \( (0^\circ, M = 1042.67 \text{ ms}) \). The pairwise comparisons between these directions were all significant \( (p < 0.02) \) except for \( 0^\circ \) versus \( 180^\circ \) and \( 90^\circ \) versus \( 270^\circ \). In summary, the differences between the movements to the left versus right and upwards versus downwards were not significant, but the horizontal movement was significantly faster than the vertical movement. The movement times along the diagonal direction fell between those of the vertical and horizontal measurements.

3.3. Reaction time
It was found that the participants’ reaction time was significantly altered by the angle of approach \( F(1, 18) = 7.54, p = 0.013 \) (see Figure 3). The overall mean and standard deviation of the reaction times were 53.60 and 5.34 ms, respectively. Despite the small amount of variation, movement along the horizontal and vertical directions resulted in a local minimum. Pairwise comparisons showed a significant difference for \( 90^\circ \) versus \( 67.5^\circ \) and \( 112.5^\circ \) \( (p = 0.015 \) and 0.002, respectively) and \( 180^\circ \) versus \( 157.5^\circ \) \( (p = 0.006) \). However, the difference between the vertical and horizontal directions was not significant.

3.4. Movement variability
The angle of approach had a significant effect on movement variability \( F(1, 18) = 13.70, p = 0.002 \) (see Figure 4). The movement along horizontal directions showed less variability \( (M = 14.47 \text{ pixels}) \) than did the movement along vertical directions \( (M = 27.5 \text{ pixels}) \). The pairwise comparison also showed a significant difference between \( 0^\circ \) and \( 180^\circ \) versus \( 90^\circ \) and \( 270^\circ \) \( (p < 0.002) \); however, the pairwise comparison of \( 0^\circ \) versus \( 180^\circ \) and \( 90^\circ \) versus \( 270^\circ \) showed no significant difference. Specifically, the down peaks in the horizontal directions were much sharper than the up peaks in the vertical directions. This effect was reflected in the pairwise comparison, showing a significant difference for \( 90^\circ \) versus \( 22.5^\circ \), \( 45^\circ \), \( 67.5^\circ \), \( 112.5^\circ \), \( 135^\circ \) and \( 157.5^\circ \) \( (p < 0.016) \) and \( 270^\circ \) versus \( 202.5^\circ \), \( 225^\circ \), \( 247.5^\circ \), \( 315^\circ \) and \( 337.5^\circ \) \( (p < 0.039) \), but no significant difference with their neighbours for \( 0^\circ \) and \( 180^\circ \).

3.5. Overshoot
The angle of approach had a significant effect on overshoot \( F(1, 18) = 7.54, p = 0.013 \) (see Figure 4). The downward movement involved more overshoot \( (0^\circ, M = 19.20 \text{ pixels}) \) than did the upward movement \( (180^\circ, M = 7.68 \text{ pixels}) \).
difference was also found to be significant in the pairwise comparison \((p = 0.011)\). For the other angles of approach, the overshoot became shorter when there was generally less upward movement involved.

### 3.6. Number of submovements

The angle of approach was found to have a significant effect on the number of submovements in the \(x\) component of movement \((F(1, 18) = 37.90, p < 0.001)\) (see Figure 5). There were two sharp peaks at 0° and 180°, which were significantly larger than those of any other direction \((p < 0.001)\). In addition, there was a significant difference between 22.5°, 45° and 67.5° versus 270°, 292.5°, 315° and 337.5° \((p < 0.03)\).

The angle of approach was found to have a significant effect on the number of submovements in the \(y\) component of movement \((F(1, 18) = 20.77, p < 0.001)\) (see Figure 5). There were two sharp peaks at 90° and 270°, and these two directions were significantly larger than any other directions \((p < 0.049)\) except 0° \((p = 0.074\) and 0.955, respectively). The differences between 0° versus 22.5°, 45° and 67.5° were significant \((p < 0.013)\).
3.7. Force inefficiency

The angle of approach had a significant effect on the force inefficiency in the \( x \) component of movement (\( F(1, 18) = 34.74, p < 0.001 \)) (see Figure 6). The two peaks at \( 0^\circ \) and \( 180^\circ \) (vertical directions) were significantly larger than at any other angle \( (p < 0.001) \), and \( 45^\circ \) showed a significant difference from \( 270^\circ \) and \( 337.5^\circ \) \( (p = 0.017 \) and \( 0.016 \), respectively).

We also found that the angle of approach had a significant effect on the force inefficiency in the \( y \) components of movement (\( F(1, 18) = 61.26, p < 0.001 \)) (see Figure 6). The two peaks at \( 90^\circ \) and \( 270^\circ \) (horizontal directions) were significantly larger than any other angle \( (p < 0.001) \), and \( 180^\circ \) showed a significant difference from \( 0^\circ \) and \( 22.5^\circ \) \( (p < 0.008 \) and \( 0.021 \), respectively).

3.8. Proportion of trial completion time spent in acceleration

We found that the angle of approach had a significant effect on the proportion of acceleration in the \( x \) components of movement (\( F(1, 18) = 16.01, p < 0.001 \)) (see Figure 7). The measurement for \( 0^\circ \) was significantly larger \( (p < 0.022) \) than...
for any other angle except 180°, and the measurement for 180° was significantly larger ($p < 0.022$) than for any other angle except 0° and 337.5°.

We also found that the angle of approach had a significant effect on the proportion of acceleration in the $y$ components of movement ($F(1, 18) = 14.65$, $p < 0.001$) (see Figure 7). The measurement for 90° was significantly larger ($p < 0.008$) than for any other angle except 270°, and the measurement for 270° was significantly larger than for 22.5°, 135°, 292.5°, 315° and 337.5° ($p < 0.038$).

4. Discussion

4.1. Trial completion time

The shorter times obtained in the horizontal movement coincided with those of previous studies which used the same target presentation paradigm (Donker and Reitsma 2007b; Meng, Chen, Chu, Yeh, et al., 2007; Meng, Chen, Chu, Wu, et al., 2007; Phillips, Triggs, and Meehan 2001; Whisenand and Emurian, 1999). Despite these studies all having reported shorter completion times in the horizontal direction, statements about this effect were not included in those papers, because the completion time data alone was limited in terms of its ability to provide much information about the biomechanical factors of the upper extremities. However, the other kinematic variables for which we have gathered data allow us to further speculate on the issue of faster horizontal movement.

Another study (Thompson et al. 2007) reported shorter times in the horizontal direction using a different target presentation paradigm. The authors attributed the effect to the inertial anisotropy of the upper extremities, in which the lower inertia of the arm during horizontal movement was responsible for the shorter completion time of the pointing task in the horizontal direction. However, this anisotropy was not verified for other kinematic variables such as overshoot, the number of submovements and force inefficiency. If inertial anisotropy were the main reason for the directional effect, the corresponding trend of efficiency would also have been reflected in the other kinematic variables.

4.2. Reaction time

The mean reaction times reported in several previous studies (Dillen, Phillips, and Meehan 2005; Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2000, 2001; Phillips, Triggs, and Meehan 2001, 2005) were approximately 200–300 ms; however, the mean reaction time found in this study (about 50 ms) was much shorter. The reason for this large difference may originate in the differences between the target presentation paradigms employed. As discussed in one earlier study (Prablanc et al. 1979), the response latency of the eye and hand consists of the shared time consumed during the detection and localisation of the target and the separate times for a decision and the computation of the movement for both the eye and the hand motor systems. In addition, the target was not visible before each trial in those previous studies (Dillen, Phillips,
and Meehan 2005; Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2000, 2001; Phillips, Triggs, and Meehan 2001, 2005), and the reaction time measured in their experiments included the time required for the detection and localisation of the target. In our study, though, the location of the target was visible before each trial; the measurement of the reaction time did not include the time required for the detection and localisation of the target.

We found that the measured reaction time was shorter for both the horizontal and vertical directions of movement. As noted above (Prablanc et al. 1979), our measurement of the reaction time included the decision and computation of both the eye and hand systems. A shorter reaction time means that the participants felt that it was easier to choose or compute the noted above (Prablanc et al. 1979), our measurement of the reaction time included the decision and computation of both the x and y components as opposed to dealing only with the 1D movement of an x or y component (Phillips and Triggs 2000). The continuous rotation of the detachable coordinate system during the diagonal movement may also have imposed more of a cognitive load when computing the movement. However, as the remaining movement was not independent of the movement preparation step but was carried out based on preparation, this effect would be reflected in the other kinematic variables.

4.3. Overshoot

Two other studies (Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2001) reported directional effects on the overshoot when using a mouse. The latter study reported a larger overshoot towards the left than it did towards the right or upward. However, as each trial in the study was ended immediately after the cursor entered the target area, the overshoot while passing through the target was not included in their measurements. The other study (Phillips, Meehan, and Triggs 2003) reported a larger overshoot for movement to the right than it did for movement to the left, but they only reported an averaged case of two different cursor shapes that could not be generalised to a situation involving normal mouse usage.

In our results, the overshoot became larger as the portion of downward movement increased. As greater overshoot is generally thought to result in inefficient pointing performance, it is interesting to note that the pattern of the anisotropy of overshoot measured in our experiment was completely different from that of the trial completion time. As the inertial anisotropy of the upper extremities (Thompson et al. 2007) does not discriminate between the upward and the downward movement, it does not provide an explanation of the current overshoot measurements. However, in our opinion, this overshoot pattern was obtained because the participants used their fingertips and wrists rather than the whole arm to control the mouse. This assumption is reasonable because the resolution of our mouse was 1000 Counts per inch (CPI), which is quite high considering that only one inch of movement on the desktop was sufficient to move the cursor about 1000 pixels. When people hold the mouse using their fingertips, it is difficult to stop the downward movement because there is no support at the back of the mouse. However, for the upward movement, the frontal face of the mouse is naturally supported by the fingertips, and an appropriate braking force is thus applied. This braking force is not supposed to be actively applied to the mouse but is supposed to passively dampen the initial fast and large submovement in the upward movement. Furthermore, this effect was also found in other subsequent kinematic variables, thus solidifying our opinion.

4.4. Movement variability

The horizontal movement was very stable compared with the movement in other directions, and the down peaks during the measurement of movement variability were so steep that even the difference between the nearest directions was still significant. However, this effect was not unexpected given the fact that very stable wrist rotation (Teulings, Thomassen, and Maarse 1989) is naturally converted into a straight-line movement of the cursor using a mouse with a detachable coordinate system. Due to its detachable coordinate system, the optical sensor of the mouse only captures the tangential movement along a circular path and converts it into the straight-line movement of the cursor. We considered that the short trial completion time of the horizontal movement most likely led to this effect when the mouse was used with the appropriate control-display gain.

This fact also reveals that people using a mouse treat the control space as a Cartesian coordinate system rather than as a polar coordinate system. Due to the detachable coordinate system of a mouse, mouse rotation affects the current orientation of the coordinate system, which leads to unpredictable disturbance to the user. While performance of the pointing task used in this study did not depend very much on the detailed shape of the cursor trajectory, this effect could become a serious problem for mouse control if a precise cursor trajectory were required. In fact, several previous studies (Zabranski 2011; Zabranski and Stuerzlzinger 2012) have addressed just this issue of reduced mouse performance in the execution of precise tasks.

4.5. Number of submovements

Compared to previous studies (Phillips and Triggs 2000, 2001) (M = 2.20), relatively more mean submovements were measured in our experiment (M = 2.925) for both the x and y components of velocity. This result is feasible because the
probability of crossing zero increases when we count both the $x$ and $y$ components of velocity separately. Furthermore, few studies have reported the effect of the direction of movement on the number of submovements.

By separating the $x$ and $y$ components of movement, clear trends could be observed. The most noteworthy feature was one additional submovement found just in the horizontal or vertical direction of movement, the peaks of which were only observed in the components orthogonal to their movement direction. This effect can be explained in the same context as the reaction time results, in which the participants felt that it was easier to begin the movement in the horizontal and vertical directions. When engaging in horizontal or vertical directions of movement, the participants appeared less concerned about the orthogonal components of movement. This may have resulted in the abrupt increase of one more unit of correction in those directions. However, those increases in the number of submovements did not result in longer trial completion times in the horizontal direction because the movement variability was still lowest in this movement.

In addition, for the $y$ components of velocity, more submovements were noted at $0^\circ$ than at $22.5^\circ$, $45^\circ$ and $67.5^\circ$. This effect likely stemmed from participants trying to correct the greater overshoot in the downward movement.

### 4.6. Force inefficiency

Although few studies have reported on the effects of direction on force inefficiency, we found a pattern of such effects similar to that of the number of submovements. With regard to horizontal and vertical movement, we found sharp peaks in the force inefficiency for acceleration components orthogonal to the movement direction. This effect is likely related to the increased number of submovements at this point. Generally, it is believed that movement requiring more corrections results in higher force inefficiency.

However, one interesting feature that was not observed in the measurements of the number of submovements is worth noting. In the $y$ components of acceleration, the force inefficiency was higher at a $180^\circ$ angle of approach than it was at $0^\circ$ and $22.5^\circ$. Here, $180^\circ$ represents vertical upward movement, which showed less overshoot than the other movement directions. Based on these collective measurements, we postulate that the fingertips passively damped the overshoot during the upward movement and that this damping effect altered the acceleration of the $y$ components to yield a large force inefficiency. However, as this effect did not seem to have been consciously applied by the participants, we consider that this increased force inefficiency was not an actual inefficiency felt by the participants.

### 4.7. Proportion of trial completion time spent in acceleration

The proportion of the trial completion time spent in acceleration was around 15–16% in both the $x$ and $y$ components of acceleration. This measurement shows the very inefficient nature of interaction when using a mouse considering that 50% of the time in optimised pointing movement generally consists of acceleration (Nelson 1983). The small portion of acceleration time means that correcting and decelerating the movement after a large primary submovement consumed most of the movement time. This inefficiency has been reported in several previous studies (Phillips, Meehan, and Triggs 2003; Phillips and Triggs 2000, 2001). Hence, we again recognise an opportunity to enhance the performance of the mouse.

However, no research has reported on the directional effects on the acceleration portion of the total trial completion time.

We found that the proportion of trial completion time spent in acceleration increases by about 5% only in the horizontal or vertical direction of movement and that those peaks can only be observed in the acceleration components orthogonal to their movement direction. The increase in the acceleration portion means that the correction began late for the acceleration components. Moreover, as we have already seen in the measurement of reaction time, the number of submovements and force inefficiency, the participants appeared less concerned about the manipulation of the orthogonal component during the horizontal or vertical direction of movement, resulting in a late beginning when correcting them.

### 5. Conclusions

In this study, the angle of approach was varied to determine the changes in several kinematic variables of a cursor trajectory. Because the mouse is a real-time input device for moving a cursor in various directions on a 2D surface, an analysis of the directional effects by investigating the kinematic variables may be the most effective way to capture both the spatial and time-dependent characteristics of mouse control. In our study, we analysed these kinematic variables for both the $x$ and $y$ coordinates separately without reducing the original dimension of the data over 16 different angles of approach to make it possible to capture singular behaviour in specific directions.

The most interesting feature of the mouse found in this study was the very low movement variability observed in the horizontal movement. While there have been many studies on the efficiency of horizontal movement, the main cause of this efficiency had been a subject of controversy. In this study, we found evidence supporting our claim that the rotation of the wrist joint (as reported to be more effective than finger-joint movement) was naturally transformed into a straight line in the...
display space, boosting the pointing performance of the mouse in the horizontal direction. Furthermore, this fact tells us that the users generally act as if they are controlling the mouse in Cartesian space rather than on a polar coordinate system originating from the rotation of the mouse coordinate system. This induces an unexpected disturbance to the trajectory and possibly reduces the performance in steering or drawing tasks. To resolve this problem, we suggest implementing a mouse capable of measuring its rotation and compensating for the coordinate rotation during a stroke. Several previous studies (MacKenzie, Soukoreff, and Pal 1997; Tresanchez et al. 2009) have already demonstrated that such rotation measurement is not difficult to conduct. However, those studies only used the rotational measurements to add extra degrees of freedom for graphical input; as such, future research into the use of such information to correct for unintended coordinate rotation is called for.

We observed reduced overshoot for the upward movement, which appeared to have originated from the passive braking force given by the fingertips. The sensitivity of today’s mouse is sufficiently high as to allow users to generally control the cursor all over a high-resolution display using only the finger and wrist joints. Hence, a mouse could be designed according to the suggested form (see Figure 8) which provides a passive braking force during the downward movement.

The reaction time results showed that people felt it was easier to prepare for a horizontal or vertical movement; this effect was also reflected in the number of submovements, the force inefficiency and the proportion of trial completion time spent in acceleration. However, this cognitive advantage did not directly transfer to a shorter trial completion time because several other biomechanical factors influenced the trial completion time throughout all phases of motion and not just during the preparation phase. On the other hand, this effect can be used to design a graphical user interface (GUI) in which very sudden input is required from the computer mouse by locating the target at a certain location with a lower reaction time.

As shown in this study, a kinematic analysis of an input device can reveal many biomechanical and cognitive features that cannot be examined within the framework of Fitts’ law. Those effects that were not explainable by means of a single variable can be revealed by analysing several variables together. For example, the pattern of overshoot was reflected in the acceleration pattern but not in the number of submovements, thus solidifying our hypothesis.

Despite the fact that much research is presently being done into creating new types of input devices, such as a tangible user interface and natural interfaces, the classic mouse and keyboard are the primary input devices by which the vast majority of users interface with a computer. Therefore, studies on the development of new input devices should continue in parallel with those that seek to understand the hidden characteristics of classic input devices in a continuing effort to enhance a long history of studying input devices effectively.

References


