PAPER

A Comparison of Pressure and Tilt Input Techniques for Cursor Control

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SUMMARY Three experiments were conducted in this study to investigate the human ability to control pen pressure and pen tilt input, by coupling this control with cursor position, angle and scale. Comparisons between pen pressure input and pen tilt input have been made in the three experiments. Experimental results show that decreasing pressure input resulted in very poor performance and was not a good input technique for any of the three experiments. In "Experiment 1-Coupling to Cursor Position", the tilt input technique performed relatively better than the increasing pressure input technique in terms of time, even though the tilt technique had a slightly higher error rate. In "Experiment 2-Coupling to Cursor Angle", the tilt input performed a little better than the increasing pressure input in terms of time, but the gap between them is not so apparent as Experiment 1. In "Experiment 3-Coupling to Cursor Scale", tilt input performed a little better than increasing pressure input in terms of adjustment time. Based on the results of our experiments, we have inferred several design implications and guidelines.

key words: *pressure input, tilt input, target selection tasks, pen-based interfaces*

1. Introduction

With advances in hardware technology, pen computing in the forms of handheld devices and tablets has made pen-based interfaces increasingly relevant to mainstream applications. Consequently, research into pen-based interaction has intensified in recent years [5], [8], [9], [13], [19], [24], etc.

Pen input offers not only pen tip's position, but also extended continuous degrees-of-freedom controlled by the amount of pressure or tilt applied to the pen relevant to the display surface. These potential input modalities are natural aspects of pen usage which can be used to affect a wide variety of interaction techniques with minimal user movement. They could serve to increase the human-computer interaction bandwidth.

To date, pen pressure has attracted users of practical software applications (such as in Adobe Photoshop for controlling drawing width or opacity) and also HCI researchers [10], [14]–[18], [20], [23]. Studies on tilt techniques have focused mainly on the tilt of the display or input device (regardless of the angle of the pen) [12], [22], while few studies have paid attention to the tilt of the pen in relation to the screen. Three exceptional studies on pen tilt are [6], [11], [21].

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In Ramos et al.'s study [17], they indicated that the pressure input channel can be coupled to: *position* if variation in the channel translates to changes in x-y coordinates, e.g., cursor position in the List Menu; *angle* if it translates to changes in angle or orientation of the cursor, e.g., cursor angle in the Pie Menu; and *scale* if it translates to changes in size or scale of the cursor, e.g., cursor scale in Bullseye. Similarly, we think the tilt input channel can also be coupled to the three visual attributes. But so far, no evaluations or comparisons between pen pressure input and pen tilt input with regard to these three couplings have been presented. We should ask, for example, is pressure input better than tilt input for performing zooming tasks? Or when we select a target, is tilt input easier to use than pressure input?

In this paper, the relevant studies are reviewed first, and then three experiments are conducted to investigate human performance with pressure-controlled input and tilt-controlled input for the three visual attributes of the cursor, i.e., position, angle and scale. In light of the experimental results, we discuss implications for the UI design of pen pressure and tilt input techniques.

2. Related Work

An early study on the use of pressure in user interfaces was presented by Herot and Weinzapfel [4], who investigated how pressure and torque can be applied to object manipulation on a computer screen. Another early study by Buxton, Hill, and Rowley [1] analyzed the characteristics of touch-sensitive tablets and presented application examples such as using continuous pressure sensing to control the width of a drawing tool.

Recent research on the use of pen pressure in user interfaces has primarily focused on novel interaction technique design. For example, Ramos and Balakrishnan investigated a video editing application that allows users to annotate video segments using pressure-sensitive techniques [14]. The same researchers later designed *Zlider* [15], which allows users to apply pressure to zoom in while performing x-y cursor movement for scrolling or sliding. They also introduced and investigated pressure marks [16] - pen strokes where variations in pressure make it possible to indicate both a selection and an action simultaneously, which can potentially improve selection-action interactions. In 2007, Ren et al. [20] proposed the Adaptive Hybrid Cursor to facilitate the target selection tasks by automatically adapting the size of the cursor based on pen pressure input. This technique improved particularly effective for small-target and high-density environment. In the same year, Yin and Ren [23] proposed a zoom-based techniques to improve pixel-target selection, in which the pressure is used as a mode switch. Meanwhile, a Pressure Scroll technique was also presented to advance the scroll performance where the pen presure was considered as an additional control factor to adjust the range of scrolling velocity.

A systematic investigation on pressure sensitive pens was presented by Ramos et al. [17]. This study evaluated the human ability to use pen pressure when performing discrete target selection tasks. Letting participants push the pen tip to drive a vertical one-dimensional cursor, the researchers were able to establish that pressure control can follow Fitts' law [2]. In their experiment, pen pressure controlled the cursor's position. In other words, the pressure channel was coupled to the cursor's position. However, the couplings of other visual attributes, such as cursor angle or scale were not evaluated. Moreover, there is no comparison between pressure input and pen-tilt input techniques, which is the main purpose of this study.

So far, the studies on tilt techniques mainly focus on the tilt of the display or input device (regardless of the angle of the pen). For example, Wigdor and Balakrishnan [22] propose a new technique, *TiltText*, for entering text into a mobile phone, in which the phone is tilted in one of four directions to choose which character on a particular key to enter. Similar work has been done by Partridge et al. [12]. Compared to the tilt of the display or input device, little literature has reported pen-tilt input potential. An early study about a pen-tilt technique was presented by Kuroki and Kawai [6]. They proposed the use of pen-tilt information for pen interfaces. They observed that users are used to holding three physical tools (pencil, knife, and syringe) differently, and thus they implemented drawing software in which the user can do three operations (copy, paste, and cut) by changing between three pen tilt angles using a tablet. Oshita [11] developed a pen-based intuitive interface to control a virtual human figure interactively. In this system the tilt of the pen is used to affect the figure's motion. Recently, Tian et al. [21] used the tilt and azimuth information of a pen to present a tilt cursor and evaluated the tilt cursor's performance in circular menu selection and specific marking menu selection tasks. However, there is no systematic investigation about the human ability to control the angle of tilt-sensitive pens.

Various interaction techniques appear in current pen-based user interfaces, and comparisons and evaluations have been made among some of these techniques. But these comparisons are limit in range to the same input channel [10] or pressure input vs. x-y position input [18]. Little literature has reported any comparison between pressure-controlled input and tilt-controlled input.

In summary, our review indicates that little study has been done on the human ability to effectively control pen pressure and pen tilt, and no studies have been presented that compare pressure-controlled and tilt-controlled input techniques. This study fills a void in these areas.

3. Method

3.1 Apparatus

We used a Wacom Cintiq21UX interactive LCD graphics display tablet with a wireless pen which has a pressure sensitive and tilt sensitive isometric tip. The pen provides 1024 levels of pressure and 120 levels of angle† (dividing the azimuth into two range intervals: 0~180 degrees and 180~360 degrees, see Fig. 1). Hereafter, Pressure-left denotes decreasing pressure input technique, Pressure-right denotes increasing pressure input techniques, Tilt-left denotes the tilt changes from 150 to 30 degrees, and Tilt-right denotes the tilt changes from 30 to 150 degrees. The Wacom display was placed horizontally. It had a resolution of 1280 by 1024 pixels. The experiment was done in full-screen mode, with a white background. The experimental software, developed using Java, ran on a 2.13 GHz 2 core CPU with the Windows XP OS.

3.2 Pressure and Tilt Space

During this study, 1024 pressure values or 120 tilt values were uniformly divided into 4, 6, 8, 10 and 12 levels, much like the way Marking Menus retain a uniform size regardless of the number of menu items [7]. Keeping the pressure or tilt to spatial movement mapping constant will likely facilitate the user's ability to develop haptic or visual memory of various pressure or tilt levels [17].

3.3 Measurement

The user performance measurements included: *TT* (*Total Time*, defined as the time elapsed from the confirmative click of the "0" key on the numeric key area of keyboard to the next "0" key click), *MT* (*Movement Time*, defined as the time elapsed from the current key click to the first entry of

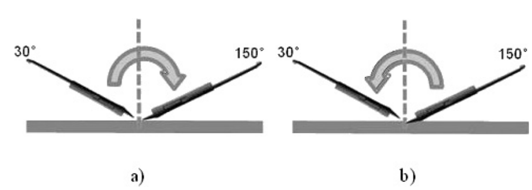

Fig. 1 Skecth map of pen tilt. a) Increase tilt (Tilt-right) b) Decrease tilt (Tilt-left).

†The pen tilt angle from 0 to 30 degrees is not supported by the experimental apparatus, azimuth is considered in the experiment, in which the azimuth is divided into two range intervals: 0~180 degrees and 180~360 degrees in clockwise. The 0 degree direction of the azimuth is the angle that pen tip points just the writer's side. In the experiment, we assume that 30~90 degrees tilt angle is supported by the 180~360 degrees azimuth, and 90~150 degrees tilt angle is supported by the 0~180 degrees azimuth.

the cursor onto the next target), AT (*Adjustment Time*, defined as the time elapsed from the first entry of the cursor into the blue target to the "0" key click). TT, MT, and AT describe how fast subjects performed these target selection tasks, but from slightly different perspectives. MT describes the speed of user controlling pen pressure or pen tilt to get to the target (only arrival not acquisition); AT describes the stability of user controlling pen pressure or pen tilt at certain interval (from arrival to acquisition); TT describes the total target selection time, and is the sum of MT and AT. ER (*Error Rate*, defined as the percentage of trials where the confirming "0" key click resulted in erroneous selections), and NC (*Number of Crossings*, defined as the number of times the cursor enters or leaves a target for a particular trial, minus 1). An example of the "*Number of Crossings*", NC=2, means the user overshot the target once and then reacquired it.

4. Experiment 1-Coupling to Cursor Position

4.1 Subjects

Ten male subjects (aged from 20 to 36, with an average age of 24.4) participated in the experiment. The participants performed the test using their preferred hand (all right handed) and had little to no prior experience using the pressure or tilt sensitive pens.

4.2 Cursor Position Mapping

The cursor used in the first experiment was a one-dimensional, red arrow-like live cursor which has two pointing directions, i.e., towards the right or towards the left. The direction in which the arrow was pointed was changed by changing the pen pressure or tilt values, depending on the input modality being tested. When the current pen pressure or tilt values increased, the arrow direction of the cursor was toward the right; when the pressure or angle was reduced, the direction of the arrow was toward the left.

4.3 Task

A series of target acquisition and selection tasks were used. Pen pressure or pen tilt was used to control the movement of the small red arrow cursor along a horizontal line. The HotPoint of the red cursor was at the tine. 1024 pressure values or 120 tilt values were mapped uniformly to a spatial distance of 1024 pixels. A set of consecutive rectangles was drawn along the line's length, but only two target rectangles were visible on the Wacom display. The size of the rectangles had been experimentally predetermined. During each experimental trial, one of the visible targets was highlighted in blue, and the other one was highlighted in gray. The user's task was to apply the appropriate amount of pen pressure or pen tilt to move the red arrow cursor into the blue target. Once the cursor was in the blue target, there was a mechanism for the user to confirm selection. This

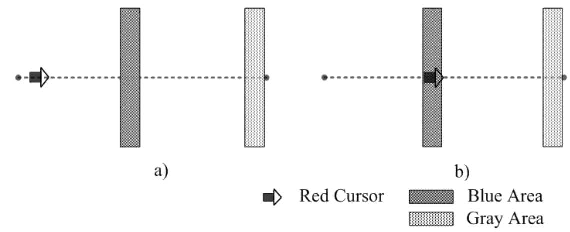

Fig. 2 Experiment 1 setup. a) Start status b) Adjust pressure or tilt to drive the arrow cursor into the target.

was done by clicking the "0" key on the keyboard. After the confirming key click, the colors were switched; the blue target became gray, while the gray target became blue. The user again applied the appropriate amount of pressure or tilt to move the red arrow cursor into the new blue target, and then clicked the "0" key to confirm selection (see Fig. 2). An audible beep provided error feedback if a selection was made outside the target.

4.4 Procedure and Design

Participants were randomly assigned to 2 groups of 5 participants each. The within-subject factors were Input (pressure input vs. tilt input), Tasks (26 target selection tasks). The 26 tasks were chosen such that targets were appropriately distributed throughout the potential target space. Because we were also interested to see if these pressure-controlled or tilt-controlled target acquisition tasks obey Fitts' law, we computed the values of (A/W) for the 26 tasks (2, 3, 4, 5, 6, 7, 8, 9, 10), i.e., the index of difficulty (ID) for the 26 tasks (1, 1.58, 2, 2.32, 2.58, 2.81, 3, 3.17, and 3.32).

The participants in Group 1 first performed a pen pressure input task, while those in Group 2 did a pen tilt input task first. For each input, participants were asked to complete 5 blocks trials. Each block consisted of trials for all 26 target selection tasks; each task consisted of 5 target selections (clicks). The first selection could not be used for data analysis because the starting point of the pointing movement and the duration of the pointing act were not known. In summary, the experiment consisted of: 26 target selection tasks × 4 repeats × 5 blocks × 10 participants × 2 inputs = 10400 target selection trials.

In the 5 target clicks, when the right side target on the display was to be clicked, users had to increase pressure on the pen tip or increase the pen angle by rotating the pen so that it tilted 150 degrees, depending on the modality being tested. Conversely, when the left target on the display was to be clicked, users had to decrease pressure on the pen tip or decrease the pen angle by rotating the pen so that it tilted 30 degrees. The participant was instructed to complete the task as fast and as accurately as possible. Participants could take breaks between changes of input modality. The experiment lasted approximately 80 minutes for each participant. A short questionnaire was administered at the end of the experiment to gather subjective opinions.

4.5 Results

4.5.1 Conformity with Fitts' Law

Most target selection tasks tend to follow Fitts' law, where pointing time (T) is modeled by the following relationship:

$$T = a + b\log_2(A/W + 1) \tag{1}$$

A is the distance between the center of the two targets, and W is the width of the targets. The logarithmic term is called the index of difficulty (ID) for the target acquisition task. For experiment 1, linear regression of TT by ID for each input technique indicated high correlations with Fitts' law for Pressure-left ($R^2 = 0.97$), Pressure-right ($R^2 = 0.91$), and Tilt-left ($R^2 = 0.91$), but poorer correlation for Tilt-right ($R^2 = 0.75$). For the Tilt-right input, this is perhaps not surprising since all the subjects are right-handed. When a pen is rotated in Tilt-Right, the hand holding the pen may obstruct the rotation of the pen.

A more interesting phenomenon observed in Experiment 1 was that linear regression of MT by ID for each input technique indicated high correlations with Fitts' law for Pressure-left ($R^2 = 0.95$), Pressure-right ($R^2 = 0.92$), Tilt-left ($R^2 = 0.94$), and Tilt-right ($R^2 = 0.9$).

Although AT varied irregularly with increasing A and ID, AT decreased with increasing W. This indicated that the more levels that pressure or tilt was divided into, the longer the adjustment time took.

4.5.2 Total Time (TT)

Mean TT for pressure-controlled and tilt-controlled input were respectively 2324.46 and 1610.96 ms. For pressure input, a significant learning effect ($F_{4,99} = 7.46, p < .00001$) were observed. TT was significantly different across directions ($F_{1,99} = 14.55, p = 0.0002$) with left and right directions respectively 2531.1 and 2117.8 ms, which showed that the process of decreasing pressure was more difficult to control than that of increasing pressure. For tilt input, there was no significant learning effect and effect of direction. These mean that pressure input technique needs learning process, but tilt input doesn't. Even by learning, pressure input still spends more total time than tilt input does (see Fig. 3).

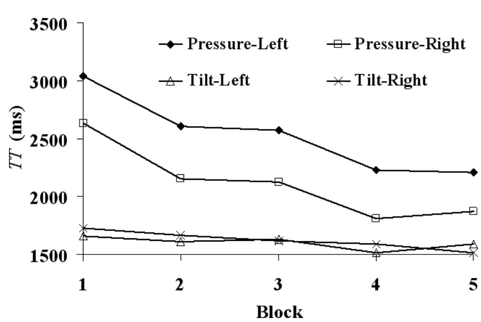

Fig. 3 TT for pressure and tilt input in Experiment 1.

4.5.3 Movement Time (MT)

Mean MT for pressure-controlled and tilt-controlled input were respectively 1145.85 and 1023.36 ms, which were 49.3% and 63.5% of their TT respectively. For pressure input, a significant learning effect ($F_{4,99} = 4.38, p = .00028$) were observed. For tilt input, the same statistical analysis results as TT were observed (see Fig. 4). From Fig. 4, we can see that by learning, pressure input can attain the almost same movement time as tilt input can.

4.5.4 Adjustment Time (AT)

Mean AT for pressure-controlled and tilt-controlled input were respectively 1178.61 and 587.6 ms, which were 50.7% and 36.5% of their TT respectively. For pressure input, a significant learning effect($F_{4,99} = 4.93, p = 0.001$) were observed. AT was significantly different across directions ($F_{1,99} = 26.93, p < .00001$) with left and right directions respectively 1379.3 and 977.9 ms. For tilt input, the same statistical analysis results as TT were observed on AT (see Fig. 5). From Fig. 5, we can see that even by learning, pressure input still spends more adjustment time than tilt input does.

4.5.5 Error Rate (ER)

Mean ER for pressure-controlled and tilt-controlled input were respectively 16.37% and 8.71%. For pressure input, an ANOVA showed a significant direction effect ($F_{1,99}$ =

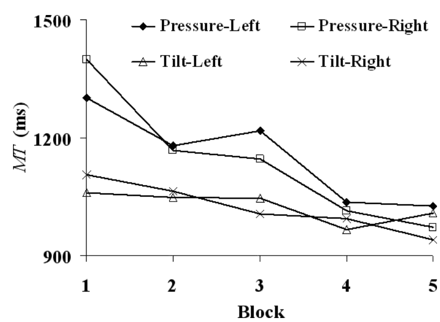

Fig. 4 MT for pressure and tilt input in Experiment 1.

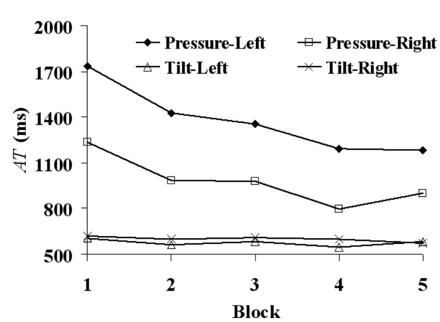

Fig. 5 AT for pressure and tilt input in Experiment 1.

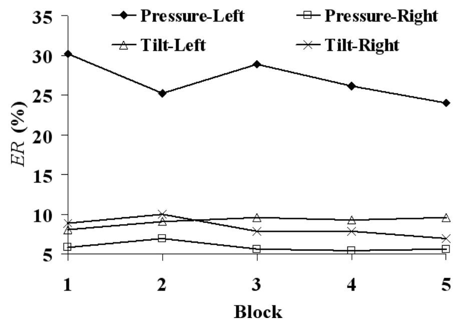

Fig. 6 *ER* for pressure and tilt input in Experiment 1.

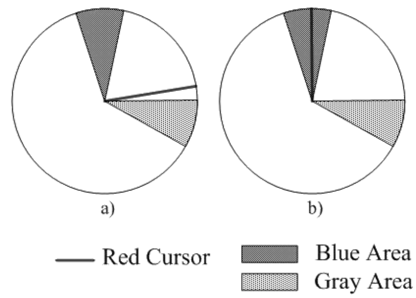

Fig. 7 Experiment 2 setup. a) Start status b) Adjust pressure or tilt to rotate the needle into the target sector.

76.08, $p < .00001$) upon *ER* with the left and the right directions respectively 26.88% and 5.85%, indicating that decreasing pressure on the pen tip to select a target resulted in more errors. For tilt input, the same statistical analysis results as TT were observed on *ER* (see Fig. 6).

4.5.6 Number of Crossings (*NC*)

Mean *NC* for pressure-controlled and tilt-controlled input were respectively 1.2 and 0.6. For pressure input, an ANOVA showed a significant direction effect ($F_{1,99} = 94.22, p < .00001$) upon *NC* with left and right directions respectively 1.82 and 0.57. For tilt input, the same statistical analysis results as TT were observed on *NC*.

In terms of *ER* and *NC*, both pressure input and tilt input don't show significant learning effect.

5. Experiment 2-Coupling to Cursor Angle

5.1 Subjects

Ten subjects (1 female and 9 male, aged from 20 to 36, with an average age of 24.9) participated in the experiment. The participants performed the test using their preferred hand (all right handed) and had little prior experience using pressure or tilt sensitive pen. Two subjects in this experiment had also participated in Experiment 1.

5.2 Cursor Angle Mapping

The cursor used in the second experiment was an imaginary red needle with the position of 3 o'clock representing zero degrees. This angle corresponded to a pressure value of 0 or a pen tilt value of 30 degrees. The needle rotated according to the amount of pressure or tilt applied to the pen. When the current pen pressure or tilt values increased, the needle rotated in the counter-clockwise direction; when the values decreased, the needle rotated in the clockwise direction.

5.3 Task

A series of target acquisition and selection tasks were used. Pen pressure or pen tilt was used to control the rotation of the needle in a circle. 1024 pressure values or 120 tilt values were mapped uniformly to a complete circle (i.e. 360 degrees). A set of consecutive circular sectors were drawn in the circle. The size of the sectors was experimentally predetermined. Only two sector targets were visible on the Wacom display during the experiment (see Fig. 7). The angular width of the sector targets were determined by the levels that 1024 pressure values or 150 tilt values were divided into (4, 6, 8, 10, or 12 levels) and the total mapping degrees (360 degrees here). The angular distance between two target sectors was chosen by the same method as in Experiment 1 (26 tasks). The experimental process was the same as for Experiment 1, the only difference being that the user's task was to apply the appropriate amount of pressure or tilt to rotate the needle into the blue target sector.

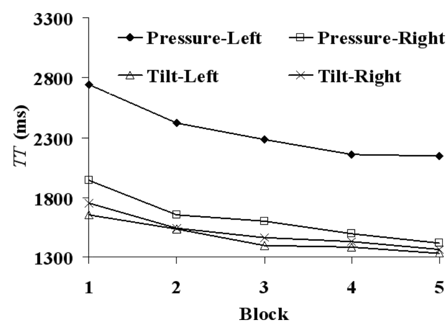

Fig. 8 TT for pressure and tilt input in Experiment 2.

The procedure and design in this experiment were the same as for Experiment 1.

5.4 Results

5.4.1 Total Time (TT)

Mean TT for pressure-controlled and tilt-controlled input were respectively 1986.67 and 1485.91 ms. For pressure input, a significant learning effect ($F_{4,99} = 7.89, p < .00001$) were observed. TT was significantly different across directions ($F_{1,99} = 105.08, p < .00001$) with left and right directions respectively 2349.7 and 1623.7 ms. For tilt input, a significant learning effect ($F_{4,99} = 6.88, p < .00001$) were observed (see Fig. 8).

5.4.2 Movement Time (MT)

Mean MT for pressure-controlled and tilt-controlled input were respectively 899.54 and 810.28 ms, which were 45.3% and 54.5% of their TT respectively. For pressure input, a significant learning effect ($F_{4,99} = 6.45, p = .00013$) were observed. MT was also significantly different across directions ($F_{1,99} = 36.52, p < .00001$). Similarly for tilt input, significant learning effect ($F_{4,99} = 7.39, p < .00001$) and effect of direction ($F_{1,99} = 26.91, p < .00001$) were observed on MT.

5.4.3 Adjustment Time (AT)

Mean AT for pressure-controlled and tilt-controlled input were respectively 1087.14 and 675.63 ms, which were 54.7% and 45.5% of their TT respectively. For pressure input, a significant learning effect ($F_{4,99} = 3.71, p = 0.0077$) were observed. AT was significantly different across directions ($F_{1,99} = 75.18, p < .00001$) with left and right directions respectively 1352.0 and 822.2 ms. For tilt input, a significant learning effect ($F_{4,99} = 3.48, p = 0.01$) were observed. AT was significantly different across directions ($F_{1,99} = 4.29, p = 0.04$).

Different from Experiment 1, tilt input technique showed significant learning effect in terms of time in the cursor angle mapping experiment.

5.4.4 Error Rate (ER)

Mean ER for pressure-controlled and tilt-controlled input were respectively 17.58% and 6.12%. For pressure input, an ANOVA showed a significant direction effect ($F_{1,99} = 67.79, p < .00001$) upon ER. For tilt input, there was no learning effect and effect of direction upon ER.

5.4.5 Number of Crossings (NC)

Mean NC for pressure-controlled and tilt-controlled input were respectively 1.3 and 0.73. For pressure input, an ANOVA showed a significant direction effect ($F_{1,99} = 81.08, p < .00001$) upon NC with left and right directions respectively 2.01 and 0.67. Similarly for tilt input, ($F_{1,99} = 6.85, p = 0.01$) with the left and right tilt directions respectively 0.84 and 0.62.

Similar to Experiment 1, in terms of ER and NC, both pressure input and tilt input don't show significant learning effect.

6. Experiment 3-Coupling to Cursor Scale

6.1 Subjects

Ten subjects (1 female and 9 male, aged from 20 to 36, with an average age of 25.7) participated in the experiment. The participants performed the test using their preferred hand (all right handed) and had little prior experience using pressure or tilt sensitive pen. Two subjects in this experiment had participated in both Experiments 1 and 2, two other subjects had participated in Experiment 1 and one other subject had participated in Experiment 2.

6.2 Cursor Scale Mapping

The cursor used in the third experiment was a red, zoomable, circle cursor with an original radius of 5 pixels, and the maximum radius of 453 pixels. The circular cursor zoomed in or zoomed out according to the amount of pressure or tilt applied on the pen. When the current pen pressure or tilt values increased, the circular cursor became visibly larger; conversely, when the values decreased, the circular cursor became visibly smaller.

6.3 Task

A series of target selection tasks were used. Pen pressure or pen tilt was used to control the zoom size of the circular cursor. 1024 pressure values or 120 tilt values were mapped uniformly to correspond to varying radii from 5 pixels (original circle cursor) up to a maximum radius of 453 pixels. A set of consecutive concentric rings were drawn at intervals along the maximum radius. The size of the concentric rings was experimentally predetermined. Only two concentric rings were visible on the Wacom display at any time during the experiment (see Fig. 9). Similarly, the width of the target rings were determined by the levels that 1024 pressure values or 150 tilt values were divided into and the total mapping distances ($448 = 453 - 5$ pixels here), and distance between two concentric target rings were determined according to the same methods as in Experiments 1 and 2 (26 tasks). The experimental process was the same as for Experiment 1, the only difference being that user's task was to apply the appropriate amount of pressure or tilt to zoom the circular cursor into the blue concentric rings.

The procedure and design in this experiment were the same as for Experiment 1.

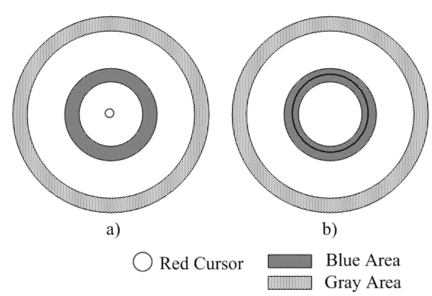

Fig. 9 Experiment 3 setup. a) Start status b) Adjust pressure or tilt to zoom the cursor into the target.

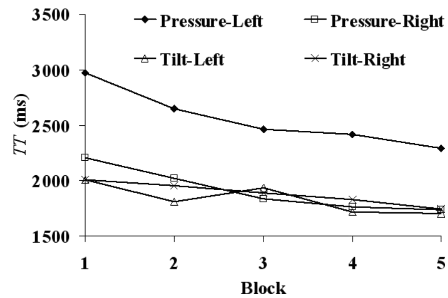

Fig. 10 TT for pressure and tilt input in Experiment 3.

6.4 Results

6.4.1 Total Time (TT)

Mean TT for pressure-controlled and tilt-controlled input were respectively 2236.13 and 1861.32 ms. For pressure input, a significant learning effect ($F_{4,99} = 7.03, p < .00001$) were observed. TT was significantly different across directions ($F_{1,99} = 69.83, p = 0.0002$) with left and right directions respectively 2558.9 and 1913.3 ms. For tilt input, there was no significant learning effect and effect of direction upon TT (see Fig. 10).

6.4.2 Movement Time (MT)

Mean MT for pressure-controlled and tilt-controlled input were respectively 1026.06 and 1068.49 ms, which were 45.9% and 57.4% of their TT respectively. For pressure input, MT was significantly different across directions ($F_{1,99} = 13.45, p = .00042$). For tilt input, there was no significant learning effect and effect of direction upon MT.

6.4.3 Adjustment Time (AT)

Mean AT for pressure-controlled input and tilt-controlled input were respectively 1210.06 and 792.8 ms, which were 54.1% and 42.6% of their TT respectively. For pressure input, a significant learning effect ($F_{4,99} = 4.53, p = 0.002$) were observed. AT was significantly different across directions ($F_{1,99} = 58.78, p < .00001$). For tilt input, there was no significant learning effect and effect of direction upon AT.

Similar to Experiment 1, tilt input technique didn't show significant learning effect in terms of time in the cursor scale mapping experiment.

6.4.4 Error Rate (ER)

Mean ER for pressure-controlled input and tilt-controlled input were respectively 14.31% and 5.77%. For pressure input, an ANOVA showed a significant direction effect ($F_{1,99} = 87.27, p < .00001$) upon ER. For tilt input, there was no significant learning effect and effect of direction upon ER.

6.4.5 Number of Crossings (NC)

Mean NC for pressure-controlled and tilt-controlled input were respectively 1.3 and 0.98. For pressure input, a significant learning effect ($F_{4,99} = 3.38, p = 0.01$) were observed. NC was significantly different across directions ($F_{1,99} = 83.62, p < .00001$). For tilt input, there was no significant learning effect and effect of direction upon NC.

7. Discussion

This study abstracts the three visual attributes as the one-dimensional live cursor's position, the needle cursor's angle and the circular cursor's scale respectively to compare pen-pressure input and pen-tilt input. From the three experimental results, we can see that pen pressure input and tilt input led to different performances. A common conclusion is drawn from the three experimental results: decreasing pressure input resulted in very poor performance compared to tilt input and compared to increasing pressure input. The reason might be that when reducing the pen pressure, there is no resistance and it is therefore harder to change the pressure with distinct increments. Conversely, increased pressure is more easily applied incrementally because there is consistent resistance from the tablet surface. Thus, in the following discussion, we limit our discussion to increasing pressure input and tilt input techniques regarding the three experiments.

In the "Position" experiment (Experiment 1), tilt input resulted in generally better performance than pressure input for controlling cursor position. The tilt input technique spent shorter TT, MT and AT, and received higher subjective ratings than the increasing pressure input technique. The reason for this might be that the direction of the pen's swing is consistent with the direction of the one-dimensional live cursor's movement, which can be seen as in harmony with both hand and eye movements. In addition, tilt input permitted smoother and steadier changes in the cursor's position than pressure input. Some subjects said that pressure input "does not permit the user to easily stop the movement of the live cursor", "The live cursor always moves back and forth under pressure-controlled input". The reason may be that tactile change of pen pressure is too sensitive for users relative to their perceptive ability, and this is a limitation of the human ability to control pressure precisely enough. Tilt reflects the posture of holding a pen. People tend to keep a certain habitual posture when holding a pen for writing and drawing in everyday life, so they are able to control pen tilt better than pen pressure. Another reason is that there is no learning effect for the tilt input technique, and users don't need practice controlling tilt input. The tilt input technique resulted in higher ER and had almost the same NC as increasing pressure input. The reason that a higher ER resulted from tilt input might be that all the subjects were right-handed, the right hand blocked the movement of the pen, especially at the right extreme when users rotate the pen to the right side. In addition, pressure-controlled and tilt-controlled target selection tasks also follow Fitts' law in terms of TT and MT.

In the "Angle" experiment (Experiment 2), tilt input generally resulted in a little better performance than pressure input in terms of time for controlling the needle cursor's angle, but the advantages of tilt input are not so significant here as they were in the "Position" experiment. One explanation may be that tilt input technique also showed significant learning effect in terms of time, which is different from the "Position" experiment. In this experiment, the rotation movement of the needle cursor in the "disk" (visual stimulus) is not consistent with the swing movement of the pen, which leads to visual confusion and fatigue. While the pen barely moves in the increasing pressure input technique, less visual confusion is caused by the pressure input. This can be explained by Stimulus-Response Compatibility [3] (i.e., the up-elevator button is never put below the down-elevator button). In terms of ER, tilt input still leads to a little higher ER than increasing pressure input. In terms of NC, because of the inconsistency of pen swing movement and visual stimulus, NC caused by tilt input and increasing pressure input rose, but the gap between these two input techniques was still very small.

In the "Scale" experiment (Experiment 3), tilt input and increasing pressure input each have their own advantages and disadvantages. In terms of TT, the gap between these two input techniques was very small. In terms of MT, increasing pressure input was better than tilt input. The reason for this might be that the direction of pen swing movement and the zoom of the circular cursor can not achieve Stimulus-Response compatibility. Some of the subjects said that "it was more natural to use pressure on the pen tip to make the circular cursor larger". In terms of AT, tilt input was better than increasing pressure input. The reason for this might be that pressure control is not as stable as tilt control. The tilt input resulted in higher NC and had almost the same ER as increasing pressure input.

We also analyzed the discernable number of pressure and tilt levels, $nLevels$, users can discriminate at a satisfactory level of performance. The results showed that ER and NC rise with increased $nLevels$. When $nLevels <= 8$ ER ranged from 0~6.8% and $NC < 0.78$ under increasing pressure input and tilt input techniques for all the three experiments. This indicates that 8 levels of pressure and tilt is a reasonable number that can be reliably differentiated with continuous visual feedback. This number of levels is different from that obtained in Ramos et al.' study (6 levels) [17], the reason may be that start state of pressure or tilt input control was predetermined in our experiments so as to measure the user performance more precisely.

According to the above analysis and discussion, several implications for pen user interface design are listed as follows:

For widget positioning, it is better to use the tilt input technique. The UI designers should note the consistency that exists between hand movement and widget movement; that is to say, if the direction of the pen swing is consistent with the direction of the widget movement, human performance will improve. For some extreme angles, i.e., the angles near 30 or 150 degrees, we can consider using them as mode switches since they are not easy to use based on human physical conditions.

To manipulate the angle of a widget, neither tilt input nor increasing pressure input are good input techniques. Tilt input tends to cause significant visual confusion and fatigue. Other input modalities of pens, such as pen azimuth, may be further investigated.

To control the scale of a widget, it is better to use the pen tilt input technique from the point of view of control stability.

8. Conclusion

We have presented three experiments that investigated the human ability to use pen pressure and tilt mapping to cursor position, angle and scale to perform target selection tasks and compared pressure input and tilt input. Experimental results showed that decreasing pressure input resulted in very poor performance and could not be considered a viable input technique. "Experiment 1-Coupling to Cursor Position" benefits more from the tilt input technique, even though it results in a slightly higher error rate than increasing pressure input techniques. "Experiment 2-Coupling to Cursor Angle" benefits a little from the tilt input technique in time performance. In "Experiment 3-Coupling to Cursor Scale", the tilt input technique performed a little better than increasing pressure input in terms of adjustment time, but a little worse in terms of the degree of control that users experienced.

Based on the results of our experiments, we have inferred several design implications and guidelines. Future work includes investigations of other issues which may affect the pen operation, such as human wrist movement and so on.

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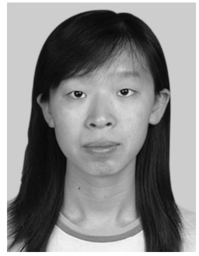
References

[1] W. Buxton, R. Hill, and P. Rowley, "Issues and techniques in touch sensitive tablet input," Proc. ACM SIGGRAPH Conference1985, pp.215–224, 1985.

[2] P.M. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement," J. Experimental Psychology, vol.47, pp.381–391, 1954.

[3] P.M. Fitts and C.M. Seeger, "S-R compatibility: Spatial characteristics of stimulus and response codes," J. Experimental Psychology, vol.46, pp.199–210, 1953.
[4] C. Herot and G. Weinzapfel, "One-point touch input of vector information for computer displays," Proc. ACM SIGGRAPH Conference1978, pp.210–216, 1978.
[5] K. Hinckley, P. Baudisch, G. Ramos, and F. Guimbretiere, "Design and analysis of delimiters for selection-action pen gesture phrases in scriboli," Proc. CHI2005, pp.451–460, 2005.
[6] T. Kuroki and S. Kawai, "An interface technology for pen devices using tilt information," Proc. Interactive Systems and Software VII, pp.1–6, 1999.
[7] G. Kurtenbach and W. Buxton, "The limits of expert performance using hierarchical marking menus," Proc. CHI1993, pp.35–42, 1993.
[8] J. Lai, R. Anderson, and Y. Li, "Donuts: A chinese input technique using pressure-sensitive marking menus," Conference Supplement to UIST2005, 2005.
[9] Y. Li, K. Hinckley, Z. Guan, and J.A. Landay, "Experimental analysis of mode switching techniques in pen-based user interfaces," Proc. CHI2005, pp.461–470, 2005.
[10] S. Mizobuchi, S. Terasaki, T. Keski-Jaskari, J. Nousiainen, M. Ryynanen, and M. Silfverberg, "Making an impression: Force-controlled pen input for handheld devices," Ext. Abstracts CHI2005, pp.1661–1664, 2005.
[11] M. Oshita, "Pen-to-mime: A pen-based interface for interactive control of a human figure," EUROGRAPHICS Workshop on Sketch-Based Interfaces and Modeling, pp.43–52, 2004.
[12] K. Partridge, S. Chatterjee, V. Sazawal, G. Borriello, and R. Want, "TiltType: Accelerometer-supported text entry for very small devices," Proc. UIST2002, pp.201–204, 2002.
[13] I. Poupyrev, M. Okabe, and S. Maruyama, "Haptic feedback for pen computing: Directions and strategies," Ext. Abstracts CHI 2004, pp.1309–1312, 2004.
[14] G. Ramos and R. Balakrishnan, "Fluid interaction techniques for the control and annotation of digital video," Proc. UIST2003, pp.105–114, 2003.
[15] G. Ramos and R. Balakrishnan, "Zliding: Fluid zooming and sliding for high precision parameter manipulation," Proc. UIST2005, pp.143–152, 2005.
[16] G. Ramos and R. Balakrishnan, "Pressure marks," Proc. CHI2007, pp.1375–1384, 2007.
[17] G. Ramos, M. Boulos, and R. Balakrishnan, "Pressure widgets," Proc. CHI2004, pp.487–494, 2004.
[18] G. Ramos, A. Cockburn, R. Balakrishnan, and M. Beaudouin-Lafon, "Pointing lenses: Facilitating stylus input through visual-and motor-space magnification," Proc. CHI2007, pp.757–766, 2007.
[19] X. Ren and S. Moriya, "Improving selection performance on pen-based systems: A study of pen-input interaction for selection tasks," ACM ToCHI, vol.7, no.3, pp.384–416, 2000.
[20] X. Ren, J. Yin, S. Zhao, and Y. Li, "The adaptive hybrid cursor: A pressure-based target selection technique for pen-based user interfaces," Proc. Eleventh IFIP TC13 International Conference on Human-Computer Interaction, INTERACT 2007, pp.310–323, Rio De Janeiro, Brazil, Sept. 2007.
[21] F. Tian, X. Ao, H. Wang, V. Setlur, and G. Dai, "The tilt cursor: Enhancing stimulus-response compatibility by providing 3D orientation cue of pen," Proc. CHI2007, pp.303–306, 2007.
[22] D. Wigdor and R. Balakrishnan, "TiltText: Using tilt for text input to mobile phones," Proc. UIST2003, pp.81–90, 2003.
[23] J. Yin and X. Ren, "ZWPS and pressure scroll: Two pressure-based techniques in pen-based interfaces," IPSJ J., vol.48, no.12, pp.3750–2761, 2007.
[24] S. Zhai and P.O. Kristensson, "Shorthand writing on stylus keyboard," Proc. CHI2003, CHI Letters, vol.5, no.1, pp.97–104, 2003.



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