Acquiring and Pointing: An Empirical Study of Pen-Tilt-Based Interaction

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ABSTRACT
Research literature has shown that pen tilt is a promising input modality in pen-based interaction. However, the human capability to control pen tilt has not been fully evaluated. This paper systematically investigates the human ability to perform discrete target selection tasks by varying the pen stylus' tilt angle through two controlled experiments: tilt acquiring (Experiment 1) and tilt pointing (Experiment 2). Results revealed a decreasing power relationship between angular width and selection time in Experiment 1. The results of Experiment 2 confirmed that pen tilt pointing can be modeled by Fitts' law. Based on our quantitative analysis, we discuss the human ability to control pen tilt and the implications of pen tilt use. We also propose a taxonomy of pen tilt based interaction techniques and showcase a series of possible pen tilt technique designs.

Author Keywords
Pen-based interfaces, pen tilt input, pen tilt techniques.

ACM Classification Keywords
H5.2 User Interfaces: Input devices and strategies.

General Terms
Design, Experimentation, Human Factors.

INTRODUCTION
The pen is favored over other input devices such as keyboards and mice in mobile computing environments due to its portability, outdoor accessibility, short-time learning curve, and ease of manipulation. Consequently, research into pen-based interaction has intensified in recent years (e.g., [12, 27, 16]).

Typically, only x-y pen tip movement is used for interaction, but this unnecessarily limits the communication bandwidth between pen and computer, and restrains users from taking advantage of the great expressiveness of a pen. Fortunately, tablets these days can accurately detect pen pressure, and pen tilt and rolling angles. A trend in pen computing is towards fully utilizing these extra degrees of freedom. Rigorous studies have been conducted to investigate users' ability to control pen pressure [24] and rolling [2].

Among the various characteristics of a pen, tilt has unique properties compared to pen pressure and rolling: the tilt anlge of a pen is tightly related to the workplane-orientation [3], and the pen barrel can visually indicate the tilt angle of a pen anytime during pen use, which could be beneficial for eye-free interaction. Thus, pen tilt is a promising input modality [21, 32].

In spite of its potential, the human ability to control pen tilt has been overlooked and it has become a timely issue. Comprehensive evaluation will help guide developers/ researchers to design effective tilt-based interfaces.

We, therefore, systematically invesitigate the human ability to control pen tilt through two controlled experiments: (1) tilt acquiring and (2) tilt pointing. According to the aforementioned previous works, current pen-tilt-based interaction techniques can be classified into two types: (1) *Tilt acquiring*: users adjust the pen to a designate tilt angle either before or after placing the pen tip on the surface (e.g., using pen tilt to control the cursor [36] or to choose a pen mode once the pen tip contacts the tablet), and (2) *Tilt pointing*: users tilt the pen from one angle to another only after the pen tip is in contract with the surface (e.g., "tilt menu" [33], controlling a virtual human figure [21], 3D navigation [4, 31]). Based on the study results, we discuss the implications for designing pen-tilt-based user interfaces.

RELATED WORK
The tilt of an interactive device has been widely explored as an additional input channel. Research literature has presented plenty of compelling interaction techniques based on the physical manipulation of a small screen device such as a PDA. Earlier work by Fitzmaurice et al. [9] investigated the use of positions and tilting actions based on the Chameleon system. They explored the potential of the tilting action as a natural way to issue commands, e.g., to scroll up or down. Rekimoto [25] presented an interaction technique that uses variations in the tilt of a small screen device as input commands to build several interaction techniques for

navigating menus, maps, and 3-D scenes. During operation, only one hand was required to both hold and control the device, which was especially useful for field workers. TiltType [22] and TiltText [34] are text entry techniques for mobile devices. The tilt direction and angle of a mobile device were used to aid character selection from a range of given candidates. Rekimoto and Sciammarella [26] proposed the ToolStone that can sense physical manipulations of the device itself such as rotating, flipping or tilting to expand the functionalities of a single input device.

Harrison et al. [11], Fishkin et al. [6], Hinckley et al. [13], Small and Ishii [30], and Bartlett [1] used tilt sensors to scroll through and select information on a hand-held device. Eissele et al. [5] used tilt operations to achieve successive scroll and link-step actions. Wigdor and Balakrishnan [34] proposed a new technique, TiltText, for entering text into a mobile phone: the phone could be 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. [22] and Sazawal et al. [28]. Tilt and orientation have also been used to allow spatially aware display. Fitzmaurice et al. [8] studied how artists took advantage of their ability to reorient their work surface while sketching and writing. They also introduced and explored many issues relating to Rotating User Interfaces (RUIs) including applications and toolkits for pen-based computing systems that take into account work-plane orientation, angle of rotation relative to the user around the axis perpendicular to the user's work surface. Rahman et al. [23] analyzed the design space of wrist-based interactions and the level of wrist control. By investigating the factors that could influence tilt control, they concluded that users could comfortably control at least 16 levels on the pronation/supination axis. Leitner et al. [19] compared the performance of a multi-touch surface with a pen based tilting surface and presented the different usages of tilt change.

In addition to the studies and techniques exploring the tilt of interactive devices in which sensors were mounted on the screens (or devices), there was a sizable amount of research focused on pen tilt. Blaskó et al. [3] presented two complementary methods to achieve more fine-grained awareness of user-to-device orientation for a hand-held writing surface, one using computer vision techniques, the other based on stylus-pose. Kuroki and Kawai [17] observed that people hold three physical tools (a syringe, a pen, and a cutter) differently and proposed that the use of tilt information for pen interfaces should be based on this observation. Oshita [21] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Tian and colleagues [32, 33] showed that using pen tilt information could improve the stimulus-response compatibility and their "Tilt Cursor" utilized pen tilt to extend selection capability. Futhermore, Zhou and Ren [36] showed that tilt input performed relatively better than pressure input for cursor control. Bridson [4] used both translation and tilt of a pen to control viewpoint in a 3D scene, treating the pen as a handle attached to a selected point on the surface.

Despite the sizable amount of research integrating pen tilt into normal pen interfaces, no literature quantitatively investigated the human ability to control pen tilt in acquiring and/or pointing tasks. This paper is aimed at shedding some light in this area.

EXPERIMENT 1: TILT ACQUIRING

This experiment was to investigate how well a user can acquire a target using an absolute pen tilt angle. The user can adjust the pen tilt either before or after landing the pen tip on the surface.

Participants

Twelve participants (2 females, 10 males), ranging in age from 20 to 33, participated in the experiment. To minimize experimental bias caused by handedness, we ensured that all participants were right-handed according to self-report.

Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used in the experiment. The Cintiq 21UX can detect the tilt angle of the stylus in the range from 30° to 90°. 90° tilt angle means that the stylus is perpendicular to the tablet surface. The experimental program was designed in the Java Environment and ran on a 2.13 GHz Intel Core2 CPU PC with Windows XP Professional SP2. The resolution of the display was set to 1280 by 1024 pixels at 96 dpi (0.27 mm per pixel).

Task and Procedure

Figure 1 is the schematic diagram of the experimental tool. As shown in Figure 1, we extended the pen tilt range from [30°, 90°] to [30°, 150°] using pen azimuth angles. The tilt angle is within the range [30°, 90°] if the azimuth angle is between 0°, 179°, while it is within [91°, 150°] if the azimuth angle is between [180°, 359°]. As a result, the tilt angle range in our experiment is from 30° to 150° (120° wide).

The pen tilt angle was mapped uniformly to a circumferential angle with a radius of 300 pixels on the screen. (e.g., 80° pen tilt is mapped to an 80° circumferential angle). Pen tilt was utilized to guide the rotation movement of a pink cursor around a fixed point, either clockwise or anticlockwise. A set of equal and consecutive sectors which presented the targets' angular width were drawn by dashed lines around a fixed point on the screen. Subjects were seated in front of the display tablet which was placed in the horizontal plane. The display edge was parallel to the subject's torso. In our pilot studies, we found that the preferred display-table angle varied for different users. Thus, we decided to place the tablet horizontally to eliminate potential effects caused by different display-table angles. The horizontal angle is also a common tablet usage, e.g., where users flatten a tablet laptop and place it on their laps or on a desk.

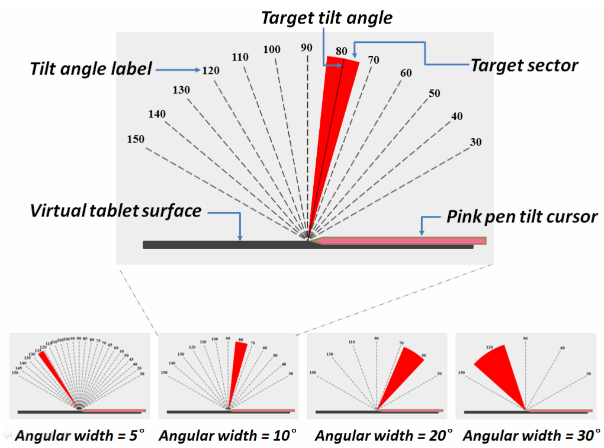

Figure 1. Schematic diagram of the tilt acquiring experiment.

During each trial, one of the target sectors was highlighted in red. The pink cursor indicating the pen tilt angle was displayed once the pen was in contact with the tablet surface. Subjects were instructed to land the pen on the tablet surface with the appropriate amount of pen tilt to guide the pink cursor to the desired target. The tilt cursor indicated the pen tilt angle at any time the pen was in contact with the tablet surface. For example, if a user landed the pen with the tilt angle of 80°, the tilt cursor jumped to 80°. When the pink cursor entered the target sectors, the target sector color changed to green. The subject confirmed the selection by pressing the space bar with the non-dominant hand on the keyboard. Subjects were told to strive for both accuracy and speed. If an incorrect selection was made, a failure "ding"' sound cue was given to the subject.

A within-subject full factorial design with repeated measures was used. The independent variables were *angular width* (5°, 10°, 20°, and 30°) and *target tilt angle* (35°, 57°, 79°, 101°, 123°, 145°). The target tilt angle refers to the angle between the middle line of the target sector and the 0 degree line (Figure 1). A Latin Square was used to counterbalance the order of the appearance of the targets. To explore the learning effects, 5 blocks of trials were completed by each subject. Each block consisted of 24 target acquiring tasks repeated once. Presentation of trials within a block was randomized. In total, the experiment consisted of:

12 subjects ×
4 angular widths ×
6 target tilt angles ×
5 blocks ×
2 times
=2880 target selection trials

Results

Selection Time

Selection time is the elasped time from the moment the pen tip comes into contact with the tablet's surface until the moment the subject confirmed the selection by pressing the space bar. Results showed that the narrower the angular width, the more time subjects needed to select the target. A further regression analysis of *angular width* × *target tilt angle* on selection time showed strong fits to the power relationship of $MT = a{*}W^b$ with a correlation of $R^2 > 0.98$ where MT is selection time, W is angular width, and a, b are empirical constants. Figure 2 illustrates the results.

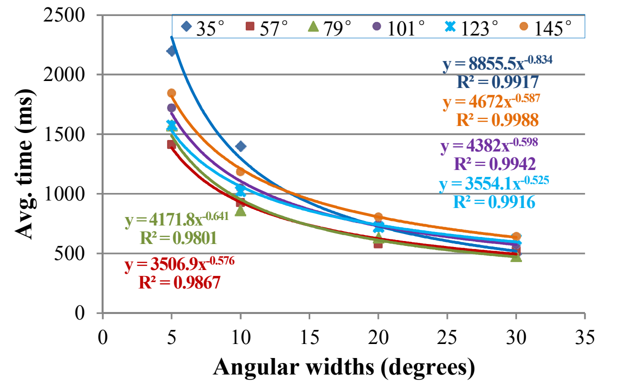

Figure 2. Average selection time per angular width × target tilt angle.

Repeated measures analysis of variance showed a significant main effect on selection time for *target tilt angle* ($F_{5, 55} = 6.27$, $p < .001$) and *angular width* ($F_{3, 33} = 61.30$, $p < .001$). Moreover, there was a significant interaction effect on selection time for *target tilt angle* × *angular width* ($F_{15, 165} = 4.05$, $p < .001$). On average, participants selected the targets in the shortest selection time when the *target tilt angle* was 57°. The second shortest selection time was achieved when the *target tilt angle* was 79°. The *target tilt angle* of 145° produced the longest time. This result is consistent with the finding from our pilot studies in which participants were asked to naturally and comfortably place the pen tip on the tablet surface. Pilot studies revealed that the comfortable and natural range for pen tilt was 58.8° with an *SD* of 8.6°.

In Experiment 1, we also observed that participants encountered trouble selecting targets with *target tilt angle* 35° because the pen was obstructed by the hand when the pen tail was oriented towards the participant's arm. Even when the angular width of a target increased to 10°, the selection time was still very long, indicating the strong influence imposed by hand obstruction. *Post hoc* pair-wise comparisons showed significant differences between all angular width pairs ($p < .005$) and target tilt angle pairs (35°, 57°), (35°, 79°), (57°, 145°), (79°, 101°), and (79°, 145°), (all $p < .01$). The significant *target tilt angle* × *angular width* interaction for time indicates that the adverse impact of hand occlusion was obviously reduced when angular width increased.

Selection Error

Selection error rate was defined as the percentage of trials in which subjects made erroneous selections. Subjects committed the fewest errors (3.33%) when angular width was 30°, and the most errors (32.38%) when angular width was 5°. For *target tilt angle*, subjects committed the fewest errors when the target tilt angle was 145°, and the most errors when the target tilt angle was 101°. Repeated measures analysis of variance showed a significant main effect on error rate for *target tilt angle* ($F_{5, 55} = 7.46$, $p < .001$) and *angular width* ($F_{3, 33} = 341.42$, $p < .001$). Moreover, there was a significant main effect on error rate for *target tilt angle* × *angular width* ($F_{15, 165} = 2.28$, $p < .01$). Figure 3 illustrates the results.

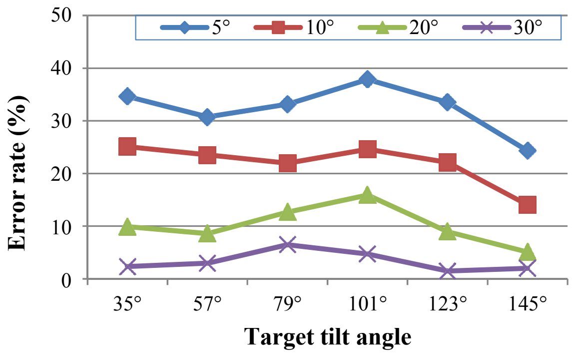

Figure 3. Error rate per angular width × target tilt angle.

Post hoc pairwise comparisons showed significant differences between all angular width pairs ($p < .001$) and target tilt angle pairs (35°, 145°), (57°, 145°), (79°, 145°), (101°, 123°), and (101°, 145°), ($p < .005$). The significant interaction effect of *target tilt angle* × *angular width* on time indicates that with the increase of angular width, subjects tended to commit a similar number of errors for different target tilt angles.

Number of Crossings

When rotating the pink tilt cursor to select a target, subjects sometimes crossed the target more than once. Number of crossings, NC, is defined as the number of times the pink tilt cursor enters or leaves a target for a particular trial, minus 1. Repeated measures analysis of variance showed a significant main effect on NC for *target tilt angle* ($F_{5, 55} = 10.25$, $p < .001$) and *angular width* ($F_{3, 33} = 61.52$, $p < .001$). Moreover, there was an interaction effect on NC for *target tilt angle* × *angular width* ($F_{15, 165} = 3.96$, $p < .001$).

As illustrated in Figure 4, a narrower angular width leads to a higher number of NC. In particular, subjects managed to select the target without extra crossings when angular width was 30°.

Analyzing NC by *target tilt angle*, subjects crossed the target with the least NC when target tilt angle was 145°; the largest NC occurred when the target tilt angle was 101°. These results indicate that NC increases as the pen becomes perpendicular to the tablet surface. *Post hoc* pairwise comparisons show significant differences between all angular width pairs ($p < .001$) and target tilt angle pairs (35°, 79°), (35°, 101°), (57°, 101°), (79°, 145°), (101°, 123°), and (101°, 145°) (all $p < .005$).

Learning effect

We collected 5 blocks of data to investigate the learning effect. Results showed that the selection time dropped as the block number increased.

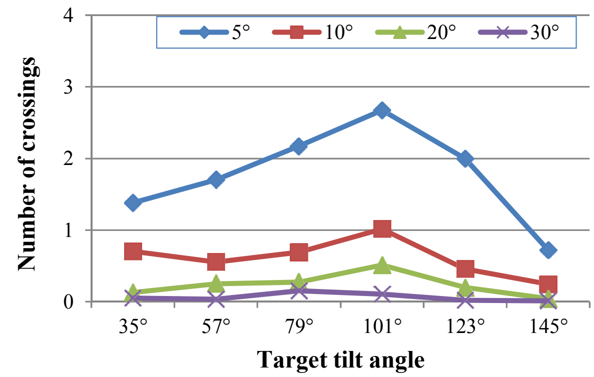

Figure 4. Number of crossings per angular width × target tilt angle.

Repeated measures analysis of variance showed a significant main effect for *block* on selection time ($F_{4, 44} = 10.55$, $p < .001$) and on NC ($F_{4, 44} = 4.31$, $p < .01$). Pairwise mean comparisons showed significant differences between block 1 and each of the other blocks (all $p < .05$). However, no significant differences were found between blocks 2, 3, 4 and 5 in pairs, indicating that participants reached a steady performance after the first block. No significant main effect was found for *block* on Error rate. Figure 5 illustrates the results.

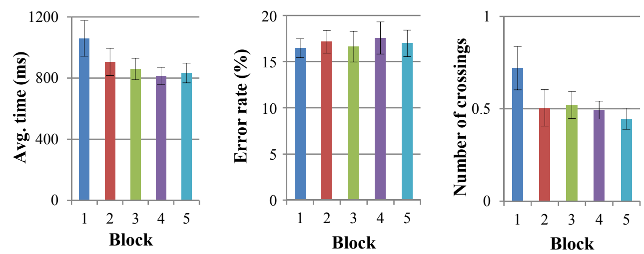

Figure 5. Learning effects of selection time, error rate, and NC × block.

Subjective Evaluation

At the end of the experiment, a questionnaire was administrated to gather subjective opinions. Participants were asked to rate *angular width* and *target tilt angle* on 7-point Likert Scales regarding *difficulty*, *stress*, and *fatigue*.

The final *preference* ratings were based on the average value of the answers given by the subjects (1 = lowest preference, and 7 = highest preference). Repeated measures analysis of variance showed a significant main effect on *angular width* ($F_{3, 33} = 61.40$, $p < .001$). The preference and the standard deviation values of *angular widths* 5°, 10°, 20°, and 30° were (2.72, 1.58), (4.97, 0.97), (6.44, 0.41) and (6.89, 0.30) respectively. 5° was rated the lowest and 30° the highest. A significant main effect on *target tilt angle* was found ($F_{5, 55} = 13.39$, $p < .001$). The preference and the standard deviation values of target tilt angles 35°, 57°, 79°, 101°, 123°, and 145° were (3.31, 2.03), (5.50, 1.18), (6.03, 0.94), (5.36, 1.58), (4.39, 1.15), and (2.44, 1.09) respectively. 145° was rated the lowest and 79° the highest.

Discussion

One main objective of this study was to investigate the comfort zones for pen tilt. Our results indicate that users performed experimental tasks efficiently during the tilt range [30°, 150°] with angular width >=30°, and tilt range [30°, 80°] & [100°, 150°] with angular width >=20°. We highly recommend these ranges as "comfortable zones" for pen tilt. Within these ranges, the selection times are all less than 1 second with error rate<=10% and NC<=1. Once the angular width drops to 10°, the error rate drastically increases to above 20%. Utilizing the tilt angle within these "comfortable zones" will lead to shorter performance time and lower error rate.

We observed that participants adjusted the pen tilt angles using the following two approaches: 1) by roughly tilt the pen in the air, and finely adjust the tilt angle after landing the pen on the tablet; 2) by not adjusting the tilt angle until the pen tip is in contact with the tablet. Since our purpose is to investigate how users naturally tilt the pen, participants could freely choose either of these two approaches during the experiment. Interestingly, most of the pen tilt adjustments fell within the approach #1, especially for tilt angles within [90°, 180°]. This is probably because approach #1 allowed participants to see both the pen tip and visual objects most of the time. The pen tip is occluded when the tilt angel falls within [90°, 180°] in approach #2.

EXPERIMENT 2: TILT POINTING

This experiment investigated the human ability to control pen tilt when the pen tip is in contact with the tablet. Also, we planned to test whether tilt-based pointing tasks can be modeled by Fitts' law [7].

Participants and Apparatus

The same 12 individuals who participated in Experiment 1 took part in Experiment 2. The same apparatus with the same experimental setup was used as in Experiment 1.

Task and Procedure

Figure 6 is the schematic diagram of the tilt pointing experimental tool. Pen tilt was utilized to control the rotation movement of a pink cursor around a fixed point, either clockwise or anticlockwise. As in Experiment 1, the pen tilt angle was mapped to the circumferential angle of the pink cursor in a one-to-one manner (e.g., 80° pen tilt is mapped to an 80° rotation). A set of equal and consecutive sectors presenting targets with various angular widths were drawn using dashed lines around the fixed point on the screen. During each trial, two of the target sectors were highlighted in red and yellow respectively. Subjects had to land the pen tip in the input area and apply the appropriate amount of pen tilt to rotate the pink cursor into the first desired target, the red one. When the pink cursor entered the first target, the target sector color changed to green. The subject confirmed the selection by pressing the space bar with the non-dominant hand on the keyboard. After the first selection, the color of the first target sector changed to gray and the color of the second target sector changed to red. The subject had to tilt the pen to select the second target. The subject could not select the second target without correctly selecting the first target. Subjects were told to strive for both accuracy and speed. An error was defined as selecting the second target wrongly. If an incorrect selection was made, a failure "ding" sound cue was given to the subject.

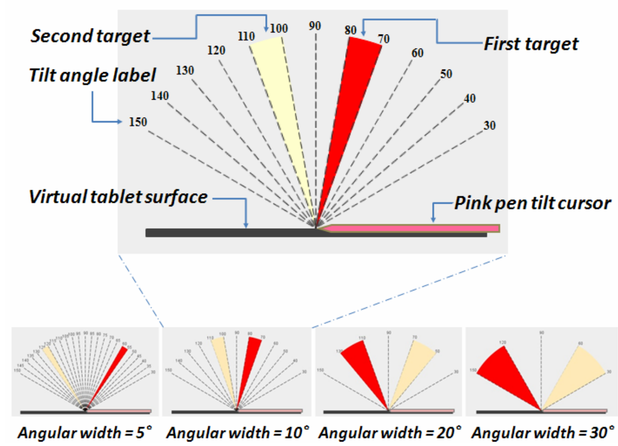

Figure 6. Schematic diagram of the tilt pointing experimental tool.

A within-subject full factorial design with repeated measures was used. The independent variables were angular widths, *ID* (index of difficulty), and tilt directions (left-to-right, and right-to-left). To ensure that the targets were symmetrical along the vertical line of the tablet and the ID values were relatively decentralized, we designated the following values of angular widths and angular distances (see Table 1). The *ID* values were calculated according to $ID = log_2\ (Angular\ distance/Angular\ width+1)$.

Angular Width	5°			10°			20°			30°		
Angular Distance	25°	65°	115°	30°	70°	110°	20°	60°	100°	30°	60°	90°
ID	2.58	3.81	4.58	2	3	3.58	1	2	2.58	1	1.58	2

Table 1. Angular widths vs. angular distances in Experiment 2.

A Latin Square was used to counterbalance the order of the appearance of angular widths and angular distances. To explore the learning effects, 5 blocks of trials were completed by every subject. Each block consisted of 24 target acquiring tasks repeated once. Presentation of trials within a block was randomized. Before the formal experiment, subjects were allowed to perform a warm-up practice session until they could understand the task and perform it correctly. In total, the experiment consisted of:

12 subjects ×
4 angular widths ×
3 angular distances ×
2 tilting directions ×
5 blocks ×
2 times
=2880 target selection trials

Results

Selection Time

Selection time is elapsed time from the moment when the subject confirmed the first target selection correctly until the time when the subject executed the second target selection by pressing the space bar on the keyboard. Similar to the results of the first experiment, the narrower the angular width, the more time subjects needed to select the target. The subjects generally tilted the pen from the left to the right side (right pointing, towards the dominant hand) faster than from the right to the left side (left pointing, towards the non-dominant hand).

Repeated measures analysis of variance showed a significant main effect on selection time for *angular width* ($F_{3,\,33}$ = 176.86, $p < .001$), *tilting direction* ($F_{1,\,11}$ = 5.45, $p < .05$) and *ID* ($F_{7,\,77}$ = 47.52, $p < .001$). However, there was no significant effect on selection time for *angular width* × *direction* ($F_{3,\,33}$ = 2.69, p = 0.062) and *ID* × *direction* ($F_{7,\,77}$ = 0.682, p = 0.687). *Post hoc* pairwise comparisons showed significant differences between all angular width pairs ($p < .001$).

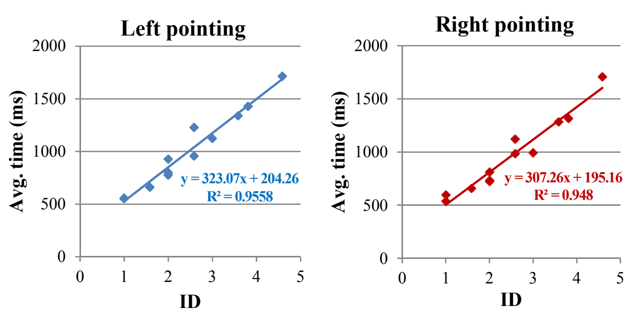

Figure 7. Selection time of left and right pointing for each ID.

As shown in Figure 7, linear regression of the experimental data *MT* by *ID* showed high correlations with Fitts' law. In both left and right pointing, R-Squares were greater than 0.94. We also performed linear regression of *MT* by *ID* separately with each angular width. R-Squares were all greater than 0.90. These results show that pen tilt-controlled target pointing tasks obey Fitts' law. For right-handed subjects, left pointing was a closer fit to Fitts' law than right pointing.

Selection Error

The error rate was defined as the percentage of trials in which the subjects made erroneous selections of the second target. Results indicate that narrower angular widths lead to higher error rates. ANOVA showed a significant main effect on error rate for *angular width* ($F_{3,\,33}$ = 5.86, $p < .005$) and *ID* ($F_{7,\,77}$ = 3.11, $p < .01$). However, there were no significant effects on error for *tilting direction*, angular width × *direction* and *ID* × *direction*.

Number of Crossings

The NC was calculated in the second target selections. Repeated measures analysis of variance showed a significant main effect on NC for *angular width* ($F_{3,\,33}$ = 82.62, $p < .001$) and *ID* ($F_{7,\,77}$ = 16.81, $p < .001$). However, there were no significant effects on NC for *tilting direction*, angular width × *direction* and *ID* × *direction*.

Learning effect

The experimental results showed a sight learning effect for tilt pointing. Selection time decreased as the number of blocks increased. Repeated measures analysis of variance showed a significant main effect on selection time for *block* ($F_{4,\,44}$ = 7.08, $p < .001$). Pairwise mean comparisons showed significant differences between block 1 and each of the other blocks (all $p < .05$). However, no significant differences were found between blocks 2, 3, 4 and 5 in pairs, indicating that participants reached a steady performance after performing block 1. This result showed that the leaning effect was minor and participants could quickly learn tilt pointing operations. Moreover, there was a significant interaction effect on selection time for *tilt direction* × *block* ($F_{4,\,44}$ = 3.17, $p < .05$). Subjects achieved a better learning effect in tilting to the left than in tilting to the right. In block 5, subjects used almost the same time to accomplish the target selections.

For error rate, repeated measures analysis of variance showed no significant effect on error rate for *block*. Moreover, there was no significant interaction effect on error rate for *tilt direction* × *block*.

For NC, repeated measures analysis of variance showed no significant effect on NC for *block* ($F_{4,\,44}$ = 0.087, p = 0.986). Moreover, there was no significant interaction effect on NC for *tilt direction* × *block*. Figure 8 illustrates the results.

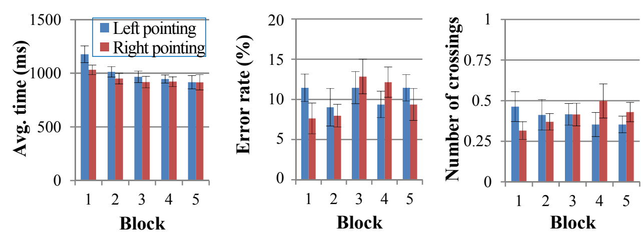

Figure 8. Learning effects of selection time, error rate, and NC for block × tilting direction.

Subjective Evaluation

At the end of the experiment, a questionnaire was administrated to gather subjective opinions. Participants were asked to rate *tilting direction*, *angular distance* and *angular width* on 7-point Likert Scales regarding *difficulty*, *stress*, and *fatigue*.

The final *preference* ratings were based on the average value of the answers given by the subjects (1 = lowest preference, and 7 = highest preference). Repeated measures analysis of variance showed a significant main effect on *angular width* ($F_{3,\,33}$ = 55.99, $p < .001$). The preference and the standard deviation values of *angular widths* 5°, 10°, 20°, and 30° were (2.61, 1.48), (4.92, 1.08), (6.49, 0.38) and (6.75, 0.29) respectively. The *angular distances* were classified as "far", "middle", and "near". A significant main effect on *angular* *distances* was found ($F_{2, 22} = 12.86$, $p < .001$). The preference and the standard deviation values of *angular distances* “far”, “middle”, and “near” were (3.79, 1.18), (4.20, 1.63), and (5.67, 0.86) respectively. However, no significant main effect was found on *tilting direction*.

Discussion

Experimental results indicate that users can control pen tilt well when angular widths are equal or above 20°. Regarding selection time, subjects selected the target within 0.8 second for tilt angular widths of 20° and 30°, but very close or above 1 second when tilt angular width is 10° or 5°. The selection times in the 5th block for tilt angular widths 5°, 10°, 20°, and 30° were 1.34s, 0.99s, 0.77s, and 0.59s, respectively. For error rate, subjects committed less than 10% errors for angular widths 10°, 20°, and 30° in the 5th block. The average NCs were less than 1 except for angular width 5°. In the 5th block, the NCs for all target tilts were less than 1. Right pointing (towards the dominant hand) leads to better performance than Left pointing (towards the non-dominant hand) in terms of selection time, error rate, and NC.

Though the tilt-based pointing task in Experiment 2 was different from the traditional pointing tasks, interestingly, experimental results indicate that the tilt pointing task can also be modeled by Fitts’ law in both left pointing and right pointing. Thus, the related applications and theories of Fitts' law could be widened to include tilt pointing tasks.

GENERAL DISCUSSION

Implications for Design

Experiments 1 and 2 investigate the user’s ability to control tilt acquiring and pointing tasks respectively. The experimental results lead to the following important implications for pen tilt based interface design:

- The results reveal the comfort zones (tilt range [30°, 150°] with angular width >=30°, and tilt range [30°, 80°] & [100°, 150°] with angular width >=20°) for pen tilt in both *target-acquiring* and *target-pointing* situations. Since users can achieve high performance in these zones, we recommend their use for common pen tilt interaction. For example, if pen tilt angle is used to trigger mode switches, these angles should be distributed within the range [30°, 150°], and the angular width of each mode should be at least 20° wide. If pen tilt is used to control a virtual human figure [21] or for 3D navigation [4], using tilt angels within the “comfortable zones” could lead to better performance.
- The results give guidance to the continuous pen tilt space discretization. Study results show that users performed *tilt pointing* tasks with good performance when the angular width was equal or above 20°. Therefore, to obtain high performance, the angular width of a discrete unit should be equal to or above 20°.
- Selection time for acquisition by tilting can be modeled as a power relation while selection time for tilt pointing can be modeled by Fitts’ law. These results can help designers improve design, e.g., to adjust the number of items in a pen-tilt-based pie menu.

We note that a direct input device was used in our experiments. The results might vary slightly in different situations such as with the use of indirect devices and in mobile postures. Furthermore, though absolute mapping was used in the experiment, (e.g., if the user lands the pen with the tilt angle of 80 degrees, the tilt cursor jumps to 80 degrees), we believe that the human ability to control pen tilt will not be changed even when using a relative mapping function. However, using different mapping functions like [29, 35] in pressure studies should be investigated in future work.

Method for conforming selection

How to conform the target selection in both tilt acquiring and pointing tasks is a key issue. At the design stage of the study, we conducted a series of experiments to decide the target selection technique. The five candidates considered were 1) Barrel-Button-Click: pressing the stylus' barrel button; 2) Dwell: keeping the tilt cursor within the target for 1 second; 3) Quick-Release: quickly lifting the pen from the tablet's surface; 4) Stroke: quickly drawing a circle; and 5) Key-Pressing: pressing a key on the keyboard using the non-dominant hand.

The results indicated that the Key-Pressing method was the most appropriate for investigating pen tilt control for the following reasons: 1) Barrel-Button-Click [20] and Stroke [15] often caused inadvertent pen-tip movement and easily led to pen tilt changes. Besides, subjects often rotated the stylus, thus the button may not always be in a position that facilitates pressing; 2) Dwell requires subjects to maintain pen tilt for a given time, which may lead to user fatigue and pen tilt change. Ramos et al.'s study [24] also showed that the time cost for Dwell was high; 3) Quick-release method requires the user to lift pen tip up after the selection. This method is a poor fit for the “tilt pointing” task because the user had to select the first and the second targets in succession, in which case he/she had to keep the pen tip in contact with the surface. 4) Previous work indicated that better performance in selection time and error rate could be achieved with bi-manual rather than with uni-manual interaction [8, 10, 14, 28].

We also asked the subjects to evaluate the five selection techniques according to fatigue, difficulty, nervousness, and preference on a 7-point Likert scale. Key-Pressing was ranked best, followed by Quick-Release, Barrel-Button-Click, Dwell, and Stroke. Because our purpose was to investigate the human ability to control pen tilt, it was necessary to minimize the factors that affected the results. Thus in this study, we regarded the space bar selection method as optimal. We note that pressing a button may not always be available in real applications which only involve one-handed operation, thus other selections method should be considered.

An alternative is to confirm the selection by pressing the pen tip. However, since a tablet can not reliably detect the pen pressure at a large pen tilt angle and exerting force on the pen tip could affect the tilt angle which might compromise the experiments, we did not use this method in our experiments.

Effects of Handedness

To avoid bias caused by handedness, we deliberately choose right-handed participants in our experiments. Since the structures of left and right hands are symmetrical, we expect that findings in our studies also apply to left-handed users by symmetrically adjusting the coordinate system. In our experiment, tilt angle range [30°, 90°] is mapped to azimuth angle range [0°, 179°]. For left-handed users, most of the conclusions still hold if the tilt angle range [30°, 90°] is mapped to the azimuth angle range [180°, 359°]. Investigating how handedness affects the human ability to control pen tilt is one of our future research directions, but it is not within the scope of the current paper.

PEN TILT INTERACTION TECHNIQUES

As an additional input modality, pen tilt can be used in both discrete selections, e.g., choosing an item from a list or a pie menu, and consecutive variant manipulations, e.g. varying brush size in a painting system. Moreover, in a concrete pen based interface, pen tilt changes can be mapped either to displace a cursor in the interface, or to change the angle/orientation of a target, or to adjust the granularity of a manipulation of a parameter. Taking into account the factors mentioned above, we developed a taxonomy of pen tilt utilization which describes the characteristics of the pen tilt techniques we proposed (see Table 2).

	Manner of Pen tilt manipulation	
	Discrete	Consecutive
Target	Fan menu 3D manipulation Sub-objects creation	Granularity widget 3D manipulation
Cursor	Magic Pen Mode switching	Projection cursor

Table 2. A taxonomy for the design of pen tilt techniques.

Based on our experimental results, a series of interactive techniques are proposed to demonstrate the potential of pen tilt to enhance pen-based interactions (see Figure 9).

Fan menu

A pie menu is divided into different sectors and each sector is mapped to a certain range of pen tilt angle (Figure 9a). By changing pen tilt angle with the pen tip in contact with the tablet, users can switch between different menu items. Moreover, the pen tilt could also be used in a marking menu [18] to extend the number of available items. According to the results of our experiment, it is better to set the sector in a tilt menu no smaller than 20° to achieve more comfortable manipulation.

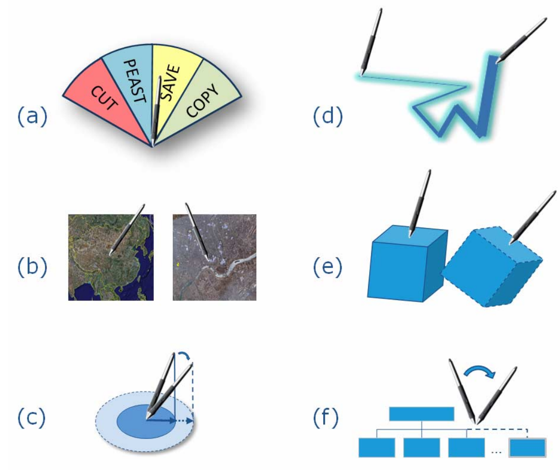

Figure 9. The conceptual designs of pen tilt techniques: (a) Fan menu; (b) Granularity widget; c) Projection cursor; (d) Magic Pen with implicit mode switching; (e) 3D manipulation; (f) Sub-objects creation.

Granularity widget

Pen tilt can be used to manipulate a parameter with varied precision. A slider is an object in a GUI with which the user sets a value by moving an indicator. The slider can be augmented with pen tilt (Figure 9b) so that the sliding action is produced by varying the pen tip x-y coordinate position, and the granularity of the sliding is adjusted by controlling pen tilt. As indicated in the experimental results, pen tip displacement could be found when the pen is tilted. In order to achieve accurate manipulation, a special procedure to reduce the influence of displacement is recommended. This mechanism can be used to adjust the granularity of a control such as the number of steps in scrolling, or the speed of the fast forward function in a video replay. For example, in map navigation, the reader can easily navigate the map to either coarse or fine scale by adjusting the pen tilt.

Projection cursor

As the pen tilt angle changes, its projected shadow varies accordingly. We proposed a projected cursor whose size changes according to the pen's tilt angle (Figure 9c). The cursor size shrinks as the pen is tilted towards the line perpendicular to the tablet surface, while the size of a cursor expands when it is tilted towards the tablet surface. This cursor is useful for selecting multiple targets, or for specifying an area. Also, the cursor size provides user visual feedback about the pen tilt angle.

Magic Pen with implicit mode switching

Mode switching is always challenging in pen interface design. Pen tilt has the potential to smooth the mode switching process. For example, in our Magic Pen design (Figure 9d), a digital pen has two painting modes ("hard" pen and "soft" pen). In drawing tasks, a large pen tilt angle results in a "hard" pen mode in which stroke width is consistent. A small pen tilt angle invokes "soft" pen in which stroke width varied according to pen pressure. Our experimental results show that a target angle near 90° is difficult to acquire. Since hard pen mode is seldom used in pen design, we suggest mapping this area (e.g., [80°, 100°]) to "hard pen" mode.

3D manipulation

Through the manipulation of a 3D object with pen tilt, more intuitive interaction may be achieved (Figure 9e). For example, a 3D object could be rotated according to variations in pen tilt. If the azimuth angle of a pen is also used to control the azimuth angle of the rotated target, the user can manipulate multiple degrees-of-freedom simultaneously.

Sub-objects creation

Since users can tilt a pen without moving the pen tip position drastically, using pen tilt can ease the sub-objects creation process in the drawing of an organizational chart or a flowchart. For example, we can slide the pen tip downward to create subordinates or left & right to create colleagues. During a pen sliding process, we can also tilt the pen to determine the number of sub-objects (Figure 9f). Because our experimental results indicate that an angle of more than 20° in width is identifiable, the pen tilt space [30°, 150°] can be divided into six regions at most thus reflecting the maximum number of sub-objects in one instance of pen tilting. If more sub-objects are needed, we can use a multiple-tilting method: after the first tilt is finished, the pen can be slid upwards over a threshold distance and the pen can be tilted again to continue sub-object creation.

CONCLUSIONS

This paper presented two controlled experiments, pen tilt target acquiring and pointing, that empirically investigated the human ability to use pen tilt to perform discrete target selection tasks. Results revealed a decreasing power relationship between angular width and selection time. This paper also verified the applicability of Fitts' law in the pen tilt pointing experiment. Results also indicate that 20 degrees of angular width presented the optimal performance regarding selection time, error, number of crossings, and number of tilt divisions. The human ability to control pen tilt and the implications of pen tilt utilization are discussed. In addition, a taxonomy of pen tilt based techniques along with a series of possible pen tilt scenarios is given. This paper presents a general understanding of pen tilt utilization, which may be useful in pen-based user interface design.

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