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An exploration of pen tail gestures for interactions

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Abstract

In this paper, we performed an exploration on the design and evaluation of pen tail gesture, an interaction method that allows the use of pen tail movement to initiate interactions. Based on our interviews with some designers and researchers who regularly used pen-based tools, we conducted three experiments to establish baseline criteria to distinguish intentional pen tail gestures from incidental pen tail movements, and to understand the basic movement behaviors in pen tail gestures. We developed designs and recognition methods of pen gestures, and implemented three application prototypes based on them. Our research can inspire some new designs of pen-based tools and enrich the design repertoire of pen-based user interfaces.

Keywords: Pen stroke gesture; Pen input

1. Introduction

Pen gestures play a very important role in pen-based user interfaces and have been incorporated into various applications, such as text editing, 3D modeling, and sketching interface. Pen strokes are used in different ways in user interface design, as an operation, an associated operand, or necessary parameters (Rubine, 1991). Research has shown that users think gestures are powerful, efficient, and convenient (Long et al., 1997). With the increasing availability and popularity of pen-based devices, pen gestures are expected to play more important roles in daily interactions.

Tools based on pen gestures become more and more efficient at the system level, thanks to research on recognition algorithms (Rubine, 1991; Kristensson and Zhai, 2004; Wobbrock et al., 2007), learnablity and memorability (Long et al., 2000), and quantitative models of human performance (Cao and Zhai, 2007; Isokoski, 2001), but designing pen gesture tools at the interaction level still faces challenges. The overload of multiple functions onto the pen tip may result in highly-modal designs with many UI widgets. To solve this problem, researchers have explored other input dimensions of pen for command selections in inking mode, such as pressure (Ramos and Balakrishnan, 2007), hover (Grossman et al., 2006), rolling (Bi et al., 2008) and tilting (Tian et al., 2008). However, how to increase the interaction bandwidth of the stylus remains an interesting research issue.

As an attempt to improve the intuitiveness and flexibility of pen-based input, we present pen tail gesture, an interaction method that lets people use the trajectory of pen tail in 3D space for gesture-based interaction. By leveraging the other degrees of freedom as means of gestural interaction, pen tail gestures are potentially independent of interactions, which helps user perform secondary interaction tasks while the pen tip is designated to a primary task (Fig. 1). To understand the value and limitation of pen tail gestures, we performed an exploration with an interview and two experiments. Based on the

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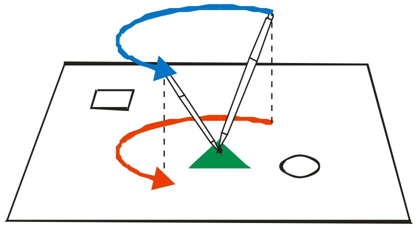

Fig. 1. A user makes a gesture stroke (blue) in 3D space by moving the pen tail while the pen tip is occupied for sketching. The red stroke illustrates the 2D projection of the 3D gesture on the screen surface (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

results of these studies, we designed and implemented an application prototype to support pen tail gestures.

This paper is structured as follows. We first review relevant literature, and then describe our interviews with pen-based UI users and three experiments on user's ability to perform pen tail movements. Next, we report the design, development, and limitation of pen tail gestures. After discussing the results of our research, we conclude the paper with future research directions.

2. Related work

Much research has been done to improve user performances with pen gestures. Rubine (Rubine, 1991) and (Wobbrock et al., 2007) studied gesture recognizers that can be easy to build and with high accuracy. Long et al. (2000) investigated the ‘‘learnablity’’ and ‘‘memorability’’ of pen gestures by examining gestures that are perceived by users as similar. Isokoski (2001) proposed a line-segment model for stroke gestures to predict gesture production time. The CLC model (Cao and Zhai, 2007) is a quantitative human performance model for the production time of making single-stroke pen gestures within certain error constraints. Zone and Polygon menus are two new variants of multi-stroke marking menus that consider both the relative position and orientation of strokes (Zhao et al., 2006). There has also been research on 3D pen gestures, such as the 3-Draw system (Sachs et al., 1991) and CavePainting (Keefe et al., 2001). Different from our research, these two systems are focused on pen-tip gestures in free 3D space for virtual worlds.

Modern digital pens provide not only 2D positions of the pen tip, but also other information like pressure, hovering states, and 3D orientation and rotation of pen body. Some research has considered pen pressure and hovering information in design (Grossman et al., 2006; Ramos and Balakrishnan, 2007). Inking and gesturing are two primary modes users rely on in pen-based user interaction. Users often need to frequently switch between these two modes. Li et al. (2005) investigated five techniques for this mode-switching. An inferred-mode interaction protocol was proposed to determine the user intent based on pen trajectory and context (Saund and Lank, 2003). Other research explored selection-action patterns (Hinckley et al., 2005; Ramos and Balakrishnan, 2007), command selection merging, and direct manipulation (Guimbretière et al., 2005; Tian et al., 2008). Different from above designs, our pen tail gestures utilize pen tail in interaction without requiring the intentional involvement of pen tip.

Pen rolling, shaking and tilting, gestures that are independent of pen tip, have also been applied in design. For example, Bi et al. (2008) used pen rolling (around its axis) to support such tasks as object rotation, multi-parameter input, and mode selection. Suzuki et al. (2007) used an accelerometer to detect pen shaking gestures (up and down along its axis) in designing a color-switch tool. In our previous work, we designed pen-based cursor (Tian et al., 2007) and menu (Tian et al., 2008) tools by using pen tilting information. Gesture-based tools offer more flexible movements of pen, and may enrich interaction possibilities. Our pen tail gesture approach differs from these existing interface designs and widgets by examining a new gesture space – pen tail.

3. Interviews with pen-based UI users

To obtain insight into pen tail gestures, we first interviewed twelve UI designers and researchers who used pen-based tools (e.g., Wacom^{TM} tablets) regularly in their work. To help interviewees have a sense about pen tail gestures, we first asked them to perform twelve gestures by moving the tail of a digital pen, each for three times. These gestures were chosen from existing pen-gesture systems, such as Microsoft Windows XP Tablet PC Edition^{TM}, SILK (Landay and Myers, 2001), Tivoli (Pedersen et al., 1993), Apple Inkwell^{TM}, Newton^{TM}, and Mindjet Mindmanager^{TM}. These gestures include various single-stroke shapes (Fig. 2).

When asked about their opinions about pen tail gestures, most interviewees were positive about this potential interaction method. They indicated that pen tail gestures could simplify various tasks, such as mode switching, and drag-n-drop. Meanwhile, they also offered the following suggestions on designing pen tail gesture tools.

3.1. Distinguish intentional and incidental actions

During drawing or writing, pen tail orientation is unstable because of pen body movement. It is important to reliably distinguish intentional pen tail gestures from incidental pen tail movements.

Fig. 2. Gestures used in interview.

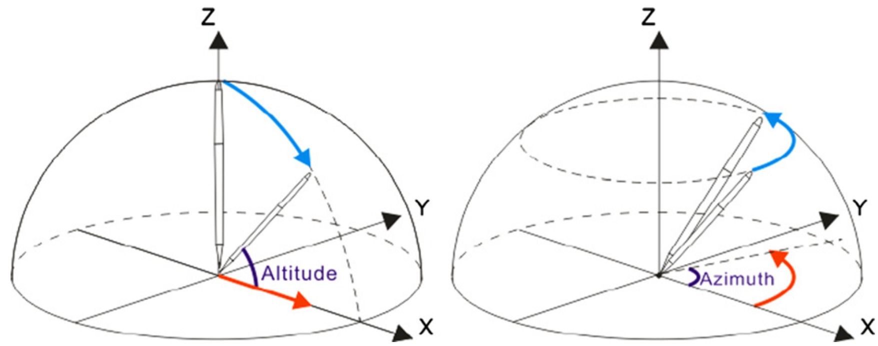

Fig. 3. Tilting (left) and panning (right) (Blue strokes are 3D movements, and red strokes are their 2D projections) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

3.2. Simplify pen tail movements

Complicated 3D curves are hard to draw with the pen tail, so movements involved in pen tail gestures should be simple. *It was suggested that only two basic pen tail movements be offered: tilting and panning*, shown in Fig. 3. Tilting refers to an action to change the altitude angle of a pen, and corresponds to using the pen tail to draw along the longitude lines of the imaginary hemisphere spanned by the pen tail; panning is an action to change the azimuth angle of the pen, and corresponds to using the pen tail to draw along the latitude lines of the hemisphere. Another related suggestion was that, *to improve the learnability and accuracy of actions, tilting and panning actions should be limited to a few azimuth angles.*

3.3. Consider natural pen-holding posture

Interviewees mentioned that *the exact spatial magnitude of a given tilting or panning action is difficult for them to control.* Therefore, to perform pen tail gestures, users should have little concern with the spatial scale of a gesture, as long as the angular trajectory of the gesture is valid. On the other hand, pen orientation in a natural pen-holding posture is easy for people to remember and replicate, given their daily writing habits. They suggested that *the azimuth angle of the natural pen-holding posture should be considered as one of the valid tilting directions in the design of pen tail gestures.* In addition, they pointed out that tilting should avoid the direction that a pen is naturally tilted in the pen-holding posture (Fig. 4), because it was very difficult to perform further tilting along this direction.

3.4. Match pen tail gestures with 2D pen gestures

Some interviewees indicated that a one-to-one mapping between 3D pen tail gestures and existing 2D gestures can help them to learn and remember pen tail gestures by referring to familiar 2D pen gestures (Fig. 5).

Inspired by interview results, we conducted two controlled experiments to investigate some important quantitative factors to guide the design of pen tail gestures.

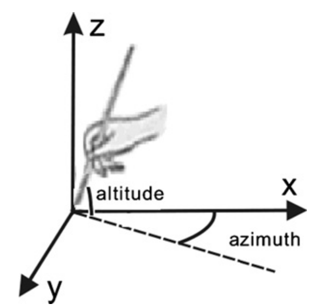

Fig. 4. Pen-holding posture.

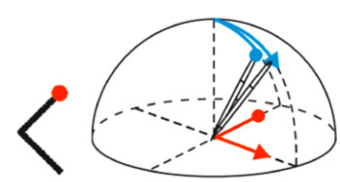

Fig. 5. A 2D pen gesture and a pen tail gesture mapped.

4. Experiment 1: incidental pen-tail movements and natural pen-holding posture

In recognizing pen tail gestures, it is important to differentiate whether a user is intentionally making a gesture, or incidentally moving the pen tail while performing other tasks with the pen tip. The goal of this experiment is to explore the performance of incidental tilting and panning movements, which will allow us to further study the critical threshold that distinguishes intentional tilting and panning from incidental movements in following explorations. Also, we are interested in knowing the natural pen-holding posture during typical pen operations.

4.1. Participants and apparatus

Twelve people (five female, seven male) participated in the experiment. Participants were all right-handed and familiar with computers and Chinese/English writing. Seven of them had prior experience with pen interaction systems. The experiment was run on a 19″ LCD screen with the resolution of 1440×900 pixels and a Wacom Intuos3 $6'' \times 11''$ (30.4×30.4 cm) digitizing tablet with a stylus pen (13.8 cm). A Tilt Cursor (Tian et al., 2007) was used to provide feedback about the position, altitude, and azimuth angle of the pen.

4.2. Task and procedure

We sought to explore the characteristics of incidental pen tail movements accompanying three representative pen tasks: freeform drawing, line tracing, and writing. Participants were asked to do these tasks at their natural speeds.

4.2.1. Free drawing (FD)

We chose eight sketch examples, shown in Fig. 6, for free-drawing. These sketches were chosen to cover different types of stroke (line, curve, arc, etc.) in different length. Eight sketch examples were printed on the paper and handed to participants. In a trial, a participant was asked to draw freely based on these sketches. The order of these sketch presented to participants was randomized. The scale of a sketch and the stroke order of a sketch were not particularly specified. Participants could draw freely in their own styles.

4.2.2. Line tracing (LT)

A straight line tracing task was chosen to represent trajectory-based interactions such as dragging or menu navigation. In each task a straight line was displayed on the screen, accompanied by a red circle as the start point and a green circle as the end point (Fig. 7). Participants traced the line from the start to the end using the pen tip. Straight lines used in the study varied in tracing direction (N, E, S, W, NE, NW, SE, and SW) and length (50 pixels (1.5 cm), 100 pixels (3 cm), 200 pixels(6 cm) and 350 pixels(10.5 cm)). Different direction and length combinations were presented in random order.

4.2.3. Writing (WR)

The writing task was to transcribe sentences displayed on the top of the screen with the pen tip. This task represents typical pen interaction tasks such as handwriting text input or note taking. Participants pressed the barrel button to start and end a task. Sentences were in two languages – English and Chinese, and were presented in random order. Eight sentences (four English sentences, four Chinese sentences) were chosen in writing tasks, as shown in Fig. 8. Sentences are simple and familiar to participants.

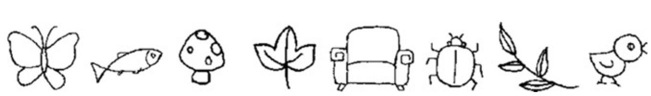

Fig. 6. Eight sketch examples in free drawing tasks.

Fig. 7. Line tracing task. Each black arrow is a tilt cursor, and its head and tail correspond to the 2D projections of the pen tip and tail (a) task initiated, (b) task in progress and (c) task completed.

Hello world.
Can I help you?
Goodbye, see you.
Could you please give me a book?
文章的语言很富感染力。
这是春天里的第一场雨。
一片树叶经不起雨水的拍打。
我喜欢没有风的下雨天。

Fig. 8. Eight sentences chosen in writing tasks.

4.2.4. Measurements

For each trial, the following measurements were collected:

- *Tilting range*: the maximum range of tilting, measured as the difference between the maximum and minimum altitude angle during the trial.
- *Tilting speed*: the average velocity of the change in altitude angle, calculated by averaging the unsigned instant velocities during the trial.
- *Panning range*: the maximum range of panning, measured as the difference between the maximum and minimum azimuth angle during the trial.
- *Panning speed*: the average velocity of the change in azimuth angle, calculated by averaging the unsigned instant velocities during the trial.
- *Natural pen-holding posture*: the average attitude and azimuth angle at which the pen was held during the trial.

It should be noted that in addition to the range of tilting and panning, we also measured the instant speed of pen tail tilting and panning, which are important to the investigation of the action properties of pen tail, especially in supporting the discovery of the thresholds to distinguish intentional tilting and panning from incidental movements.

4.3. Design

A within-subject factorial design was adopted. The order of the free drawing, line tracing and writing tasks was counterbalanced across participants. Each participant had a total of 112 trials: eight free drawing trials, 96 line tracing trails (4 line lengths $\times$ 8 directions $\times$ 3 trials), and 8 writing trials (eight sentences: four English and four Chinese). Before the experiment began, each participant had 5 min to practice using pen to draw. The experiment lasted approximately 20 min for each participant. Participants could take a two-minute break between tasks.

4.4. Results

4.4.1. Incidental tilting & panning

Fig. 9 shows the mean tilting ranges of freeform drawing, line tracing and writing $-5.27°$, $4.86°$ and $2.93°$ respectively – and their standard errors (For other figures in the rest of paper, if error bars are displayed, they are all standard errors.). Repeated measures analysis of variance showed a significant main effect for task type in tilting range ($F_{2,22}=182.00$, $p<0.001$). Pairwise comparisons also indicate that the tilting range of writing is significantly shorter than that of others ($p<0.001$), and no significant differences were found between freeform drawing and line tracing ($p=0.02$).

Fig. 10 shows the mean tilting speeds of freeform drawing, line tracing and writing, which are $29.24°/s$, $27.14°/s$, and $37.64°/s$, as well as their standard errors. Repeated measures analysis of variance showed a significant main effect for task type in tilting speed ($F_{2,22}=26.33$, $p<0.001$). Pairwise comparisons also indicate that the tilting speed of writing is significantly faster than that of others ($p<0.001$), and no significant differences were found between the tilting speeds of freeform drawing and line tracing ($p=0.32$).

The mean panning ranges of freeform drawing, line tracing and writing are $18.61°$, $12.93°$ and $8.32°$, respectively (Fig. 11). Repeated measures analysis of variance showed a significant main effect for task type in panning range ($F_{2,22}=182.41$, $p<0.001$). Pairwise comparisons also indicate that the panning range of writing is significantly shorter than that of other two ($p<0.001$), and the panning range of line tracing is significantly shorter than that of freeform drawing ($p<0.001$).

The mean panning speeds of freeform drawing, sketch tracing, line tracing and writing are $41.73°/s$, $29.34°/s$, $77.65°/s$, respectively (Fig. 12). Repeated measures analysis of variance showed a significant main effect for task type in tilting range ($F_{2,22}=55.01$, $p<0.001$). Pairwise comparisons also indicate that the panning speed of writing is significantly faster than that of others ($p<0.001$), and no significant differences is found between freeform drawing and line tracing ($p=0.06$).

The tilting and panning speeds in writing are both significantly faster than those in drawing and tracing ($p<0.001$), and the tilting and panning ranges in writing are also both significantly shorter than those in drawing and tracing ($p<0.001$). Our results are consistent with the findings from other research (Accot and Zhai, 1997; Bi et al., 2008), which show that writing, as delicate actions with many turns, leads to higher-frequency and shorter-range pen tail movements. In contrast, drawing and line tracing are closed-loop tasks, requires a more constant

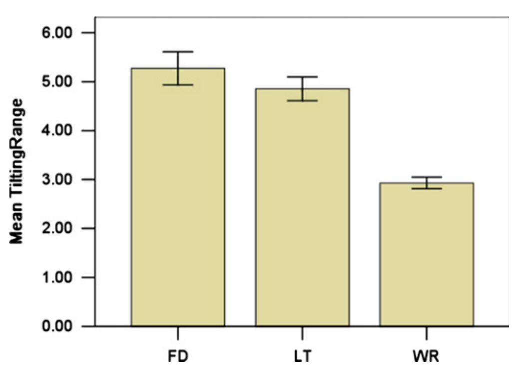

Fig. 9. Mean and standard error of tilting range of the freeform drawing, line tracing and writing.

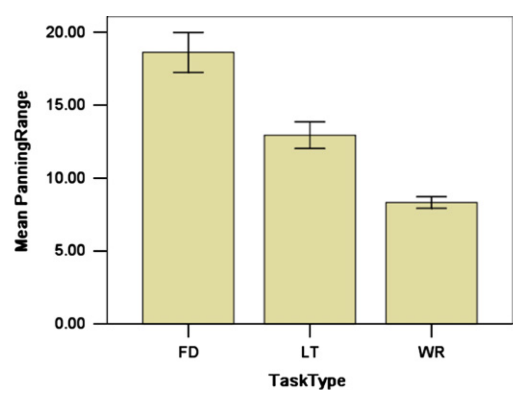

Fig. 11. Mean and standard error of panning range of the freeform drawing, line tracing and writing.

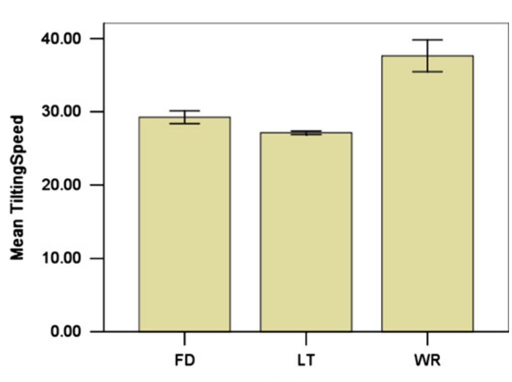

Fig. 10. Mean and standard error of tilting speed of the freeform drawing, line tracing and writing.

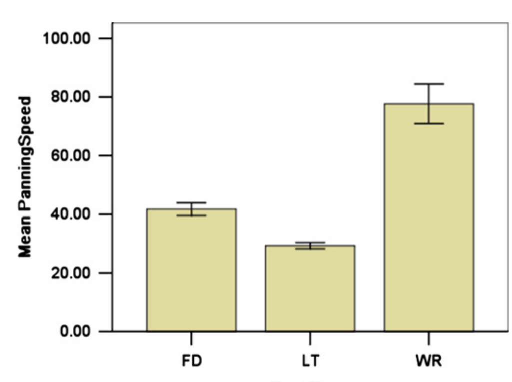

Fig. 12. Mean and standard error of panning speed of the freeform drawing, line tracing and writing.

holding of the pen, and involves no turns. Thus, pen tail movement tends to be slower and longer-range.

Furthermore, in the line tracing task, tilting and panning ranges increase with the line length. The mean tilting ranges for 50, 100, 200 and 350 pixels were 3.28°, 5.72°, 7.72° and 14.45°, respectively and the difference is significant ($F_{3, 33}=102.07$, $p<0.001$). The mean panning ranges of the three lengths were 8.05°, 16.01°, 22.06°, and 25.82°, and they differ significantly ($F_{3, 33}=53.82$, $p<0.001$). Meanwhile, the mean tilting speeds for 50, 100, 200 and 350 pixels were 26.39°/s, 27.52°/s, 27.95°/s, and 34.00°/s, respectively. It indicates that tilting speed slows down with line length ($F_{3, 33}=20.31$, $p<0.001$). Similarly, the mean panning speeds of the five lengths were 27.78°/s, 29.31°/s, 33.09°/s, and 50.59°/s, and panning speed also slows down with line length ($F_{3, 33}=53.82$, $p<0.001$).

We further analyzed the relation between tilting/panning ranges and stroke length of all four kinds of tasks. We found that tilting range increases with the distance from the start point of a stroke (Pearson correlation coefficient $r=0.26$, $p<0.001$), and panning range increases with the distance from the start point of a stroke (Pearson correlation coefficient $r=0.32$, $p<0.001$).

These results might be because longer stroke lengths require more change of the pen posture to span. We found that panning speed increases with the distance from the start point of a stroke (Pearson correlation coefficient $r=0.019$, $p<0.001$), but the correlation between tilting speed and tilting distance was not found significant (Pearson correlation coefficient $r=0.002$, $p=0.55$).

4.4.2. Natural pen-holding posture

The mean altitude angles of the freeform drawing, line tracing and writing are 53.77°, 52.43° and 56.58°, as shown in Fig. 13. Repeated measures analysis of variance showed a significant main effect for task type in altitude angle ($F_{2, 22}=170.83$, $p<0.001$). Pairwise comparisons also indicate that the altitude angle of each task type is significantly different from others ($p<0.001$).

The mean azimuth angles of the freeform drawing, sketch tracing, line tracing and writing are 25.30°, 32.17°,

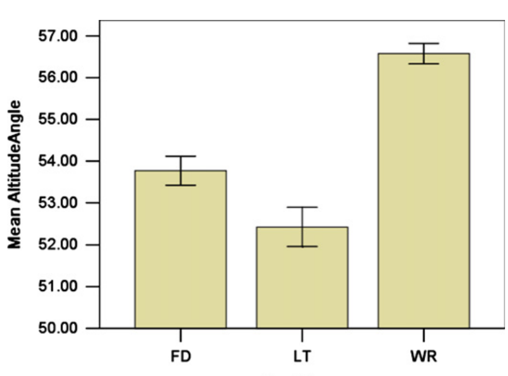

Fig. 13. Mean and standard error of altitude angle of the freeform drawing, line tracing and writing.

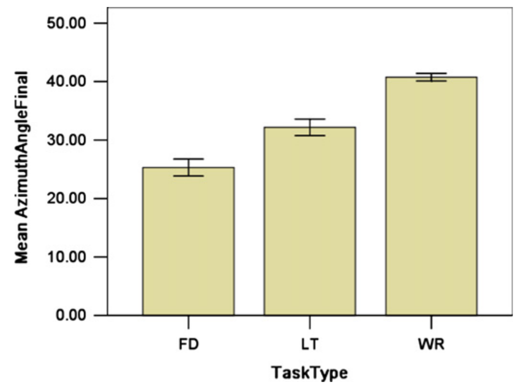

Fig. 14. Mean and standard error of azimuth angle of the freeform drawing, line tracing and writing.

and 40.74°, shown in Fig. 14. Repeated measures analysis of variance showed a significant main effect for task type in altitude angle ($F_{2, 22}=207.43$, $p<0.001$). Pairwise comparisons also indicate that the azimuth angle of each task type is significantly different from others ($p<0.001$).

Further analysis of the relation between altitude/azimuth angles and stroke length of all four kinds of tasks shows that (a) altitude angle increases with the distance from the start point of a stroke (Pearson correlation coefficient $r=0.07$, $p<0.001$) and (b) panning range increases with the distance from the start point of a stroke (Pearson correlation coefficient $r=0.09$, $p<0.001$).

4.5. Discussion of Experiment 1

The data distribution of tilting range and tilting speed are shown in Fig. 15. For tilting range, data show that 99.70% had a tilting range smaller than 20°, and 99.99% had a tilting range smaller than 30°. For tilting speed, data show that 87.8% of the trials had a tilting speed smaller than 30°/s, and 90.2% of the trials had a tilting speed smaller than 35°/s.

The data distribution of panning range and panning speed are shown in Fig. 16. For panning range, data show that 88.08% had a panning range smaller than 30°. For panning speed, data show that 84.4% of the trials had a panning speed smaller than 40°/s, and 89.1% of the trials had a panning speed smaller than 50°/s.

These relatively small values of tilting/panning speed and tilting/panning range suggest that users not tilt a pen dramatically when performing regular tasks. Furthermore, we will continue our exploration in intentional tilting and panning actions to investigate where their values of tilting/panning speed and tilting/panning range live. From all the results, we can finally infer the thresholds to distinguish intentional tilting and panning from incidental movements.

5. Experiment 2: free intentional tilting behaviors exploration in eight directions

In this section and the two sections that follow, we focus on exploring the intentional tilting/panning actions.

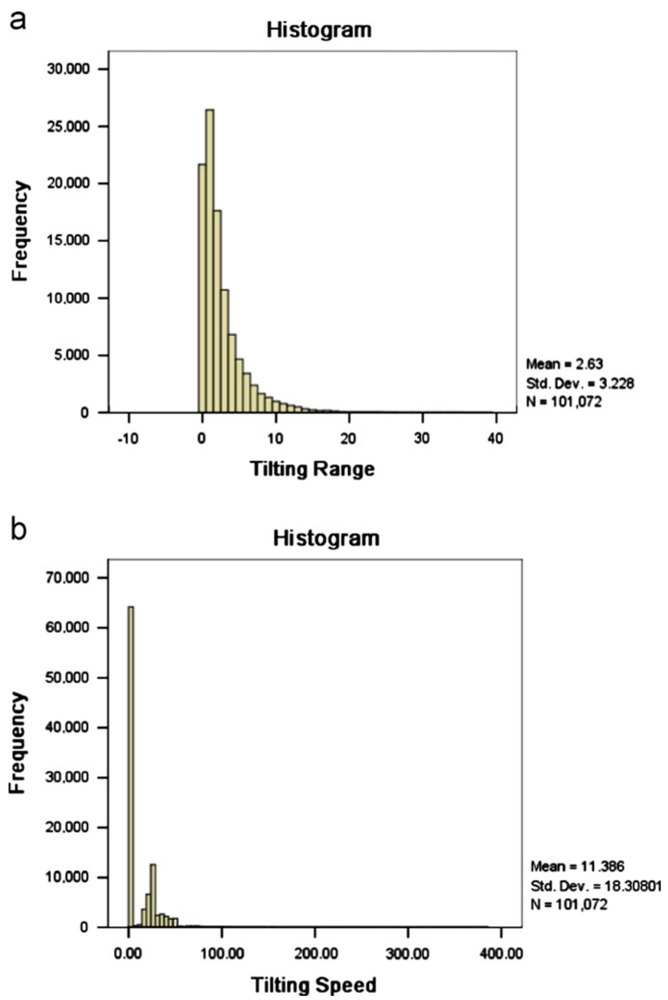

Fig. 15. (a) The distribution of tilting range and (b) the distribution of tilting speed.

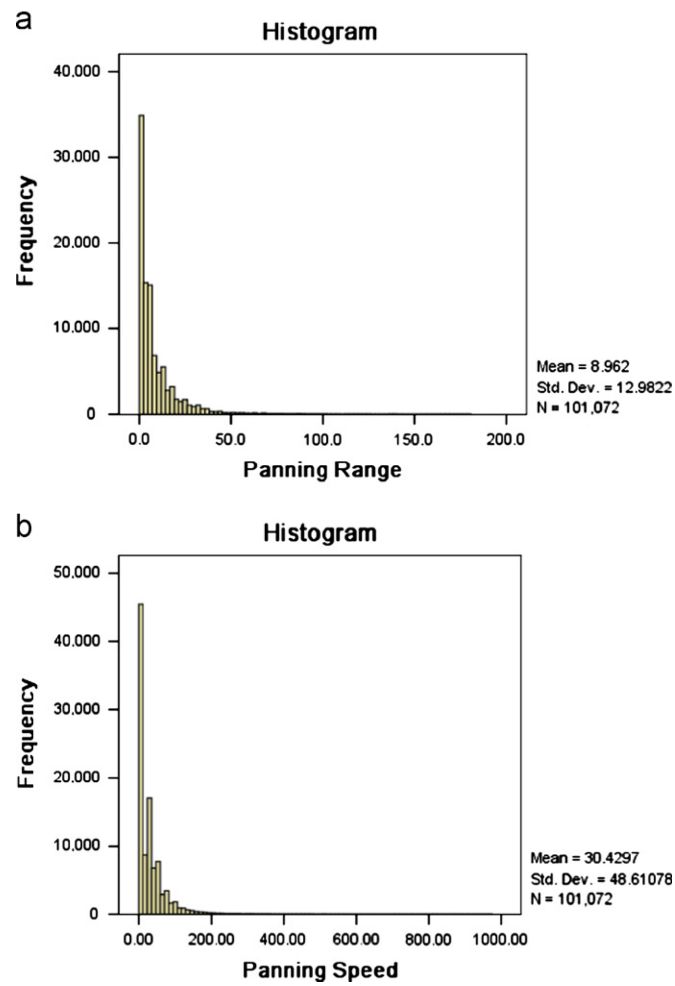

Fig. 16. (a) The distribution of panning range and (b) the distribution of panning speed.

Firstly, two questions need to be answered: (1) how many tilting directions are appropriate and (2) which directions are them. The answers to these two questions will lay the foundation for the further exploration for pen tilting behaviors.

For the first question, previous research (Tian et al., 2008) has indicated that there will be apt to error-prone when tilting directions are over 8, and more than four directions of pen tilting could lead to significant performance variances among tilting directions. Thus, this experiment focused on studying which four tilting directions are better for gesture interaction.

5.1. Task and procedure

We designed eight tilting tasks to investigate user performances in intentionally tilting eight directions: north (N), northeast (NE), east (E), southeast (SE), west (W), southwest (SW), south (S), and northwest (NW). We chose these eight directions based on the feedback from our interview, which said tilting and panning actions should be easy to learn and limited to a few azimuth angles. It should be note that tilting magnitudes were not explored in this experiment, which will be discussed in Section 6.5.5. The same group of participants and the same apparatus as in Experiment 1 were used for this experiment.

The task was to tilt the pen according to the tilting directions shown on the screen. The tilting range is not defined in the tasks. Participants were asked to perform tilting action as quick as possible according the direction shown. When a task began, a participant saw a starting circle and an arrow to indicate the tilting direction. The starting circle was in green, appearing at the center position on the screen (Fig. 17a). The radius of the circle is 5°. Participants could put the pen freely on the pad at any position.

We used the tilt cursor (Tian et al., 2007) to provide feedback information of pen tail movement in this and the following experiment. We used the tilt cursor because it easily provides all necessary pen information we needed in our study, which other existing cursors for pen-based tools cannot offer. Considering our focus on pen tail gestures, we did not explore new cursor designs specifically for pen tail.

As the participant placed the pen vertically on the touch pad, a tilt cursor (Tian et al., 2007) in the shape of an

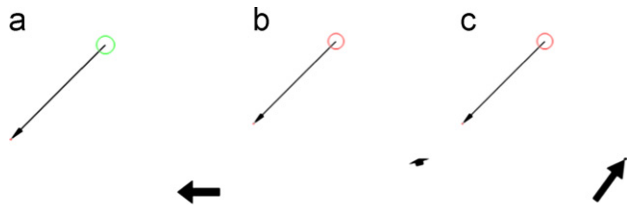

Fig. 17. Free intentional tilting tasks.

arrow appeared, and the starting circle turned to red (Fig. 17b). In tilting actions, the orientation of the tilt cursor's tail represented the azimuth angle of the pen (Fig. 17c). The participant lifted the pen tip to complete a tilting action. During the experiment, participants were not told the total number of possible tilting directions.

5.1.1. Measurements

For each trial, the following measurements were collected:

Task completion time: the time of a tilting action was calculated from the time when the starting circle turned to red to the time when the pen tip was lifted.
Tilting range: the maximum range of tilting, measured as the difference between the maximum and minimum altitude angle during a trial.
Tilting speed: the average velocity of the change in altitude angle, calculated by averaging the unsigned instant velocities during a trial.
Panning range: the maximum range of panning, measured as the difference between the maximum and minimum azimuth angle during the trial.
Panning speed: the average velocity of the change in azimuth angle, calculated by averaging the unsigned instant velocities during a trial.
Pen tip movement: the distance the pen tip traversed from the moment it touched the screen to the time it was lifted.

5.2. Design

A within-subject factorial design was adopted. Each participant performed a total of 96 trials, which consisted of 16 practice trials and 80 test trials (10 trials × 8 directions). Before the experiment began, each participant had 5 min to practice. The experiment lasted approximately 15 min for each participant.

5.3. Results

The average completion times for eight directions (N, NE, E, SE, W, SW S, NW) are 1.68 s, 1.52 s, 1.62 s, 1.67 s, 1.67 s, 1.48 s, 1.61 s, and 1.66 s. Repeated measures analysis of variance shows no significant main effect for task types in completion time ($F_{7,77}=0.99$, $p=0.44$).

The average tilting ranges for eight directions (N, NE, E, SE, W, SW S, NW) are 48.57°, 46.44°, 38.80°, 40.67°, 47.06°, 54.83°, 49.25°, and 48.68°. Repeated measures analysis of variance shows a significant main effect for task type in tilting range ($F_{7,77}=26.40$, $p<0.001$). Pairwise comparisons indicate that the tilting range of SW is significant larger that that of the others ($p<0.001$).

The average tilting speeds for eight directions (N, NE, E, SE, W, SW S, NW) are 58.10°/s, 56.77°/s, 47.00°/s, 40.35°/s, 58.07°/s, 74.78°/s, 59.08°/s, and 53.82°/s. Repeated measures analysis of variance shows a significant main effect for task type in tilting speed ($F_{7,77}=10.66$, $p<0.001$).

The average panning ranges for eight directions (N, NE, E, SE, W, SW S, NW) are 95.60°, 78.62°, 78.27°, 85.44°, 105.87°, 128.10°, 130.01°, and 112.97°. Repeated measures analysis of variance shows a significant main effect for task types in tilting range ($F_{7,77}=22.11$, $p<0.001$).

The average pen tip movements for eight directions (N, NE, E, SE, W, SW S, NW) are 0.10, 0.10, 0.11, 0.11, 0.11, 0.12, 0.12, and 0.11 cm. Repeated measures analysis of variance shows a significant main effect for task types in pen tip movement ($F_{7,77}=1.16$, $p<0.04$).

We further analyzed the average deviation of pen tail strokes drawn comparing with the original tilting directions, which was calculated by least square fittings. The average deviations for eight directions (N, NE, E, SE, W, SW S, NW) are 0.10 cm, 0.12 cm, 0.13 cm, 0.14 cm, 0.11 cm, 0.15 cm, 0.11 cm, and 0.16 cm. Repeated measures analysis of variance shows a significant main effect for task type in deviation ($F_{7,77}=3.98$, $p<0.001$).

5.4. Discussion of Experiment 2

5.4.1. Tilting direction chosen

Based on the criteria of easy to remember and manipulate, we select two options of tilting directions (shown in Fig. 18): Option 0 (E, N, W, S) and Option 1 (SE, NE, NW, SW). We conducted a further performance analysis for two Options.

The average completion times for two Options are 1.65 s and 1.58 s. Pairwise comparisons indicate that no significant differences between eight directions ($p=0.23$). The average tilting ranges for two Options are 45.92° and 47.61°. Pairwise comparisons indicate that the tilting range of Option 0 is significant shorter that that of Option 1 ($p=0.03$). The average tilting speeds for two options (Option 0 and Option 1) are 55.57°/s and 58.09°/s. Pairwise comparisons did not find significant differences among eight directions ($p=0.23$). The average panning ranges for two options (Option 0 and Option 1) are 102.40° and 101.13°, but pairwise comparisons failed to find significant differences among eight directions ($p=0.71$). The average pen tip movements for two options are 0.11 and 0.11 cm. Pairwise comparisons did not show significant differences among eight directions ($p=0.66$).

From the above results, we can conclude that the performances of two options are nearly similar. The only significant difference between two options is the average tilting range. The tilting range of Option 0 is significant shorter that that of option 1 ($p=0.03$). Considering that the difference in the average completion time between two options is not found significant, we believe that the larger tilting range may not influence the performance of tilting actions. Instead, the larger tilting range can make less the ambiguity of incidental/intentional tilting actions (Normally the tilting range of intentional tilting actions are larger than that of incidental tilting actions.). Based on the result of our user interview about considering the hand-holding postures, we chose Option 1 for performing pen tilt gestures, in which the direction SE is closest to the azimuth value of hand-holding postures. For conveniences, we use N′, E′, W′, S′ directions to replace NW, NE, SW, and SE, as shown in Fig. 19.

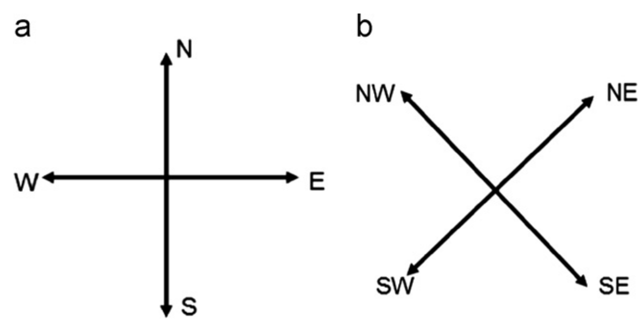

Fig. 18. Two options of tilting direction: (a) Option 0 and (b) Option 1.

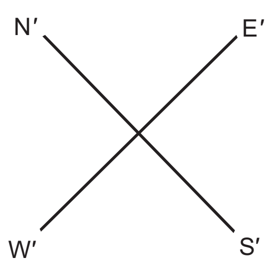

Fig. 19. Four tilting directions in pen tail gestures. (a) Four pairs of tilting actions (two movements with opposite directions as a pair). (b) Four pairs of panning actions.

Based on the above results, we define (intentional) tilting as a set of eight specific actions, including *outbound* and *inbound* tilting in four directions. Similarly, we define (intentional) panning as a set of eight actions: clockwise and counterclockwise panning between adjacent pairs of the four tilting directions. Eight basic tilting movements, and eight basic panning movements, as shown in Fig. 20.

5.4.2. Tilting range of intentional tilting actions

The data distribution of tilting range is shown in Fig. 21. As shown, 96.0% intentional tilting actions had a tilting range larger than 20°, and 92.5% had a tilting range larger than 30°. From the discussion of Experiment 1, we know that 99.7% of incidental tilting actions had a tilting range smaller than 20°, and 99.99% had a tilting range smaller than 30°. Based on these results, we chose tilting range 20° as one part of the threshold to discriminate incidental or intentional tilting actions.

6. Experiment 3: tilting and panning behaviors

In Experiment 2, we investigated the behavior performance when users performed intentional tilting actions in eight directions freely. We could define four basic tilting directions and 16 basic pen tail movements. With these basic pen tail movements, we conducted another experiment to investigate whether these movements are easy to use and how these movements may interfere with each other or with pen tip movements.

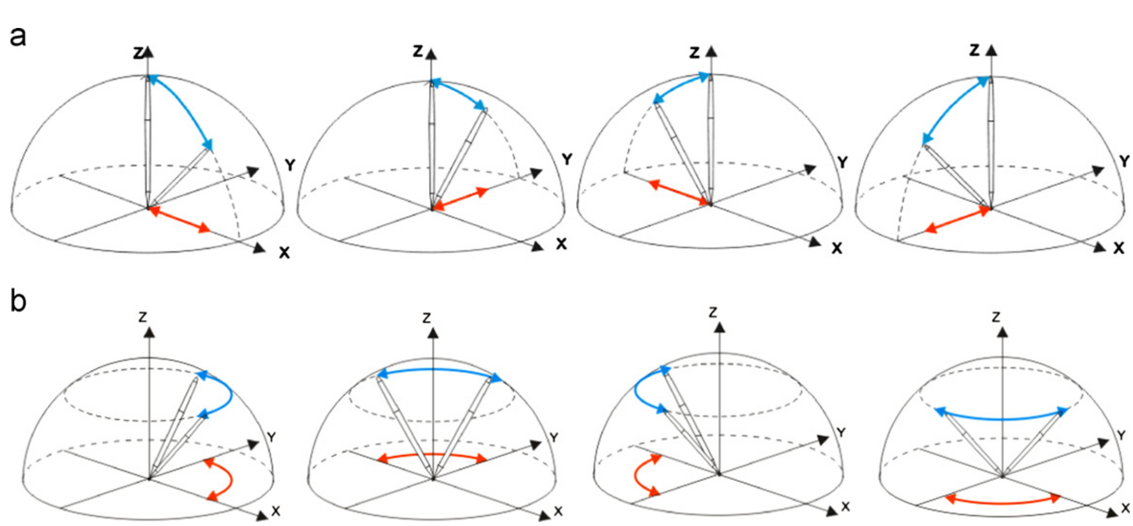

Fig. 20. Basic movements for pen tail gestures.

6.1. Participants and apparatus

Twelve people (eight female, four male) participated in the experiment. Participants were all right-handed and familiar with computers. Six of them had prior experience with pen interaction systems. The experiment was run on a 19″ LCD screen with the resolution of 1024×768 pixels and a Wacom Intuos3 $6'' \times 11''$ digitizing tablet with a stylus pen. A Tilt Cursor (Tian et al., 2007) was used to provide feedback about the position, altitude, and azimuth angle of the pen.

6.2. Task and procedure

We designed two tasks to investigate user performances in tilting and panning. We chose to use constant tilting and panning magnitudes in this experiment. This decision was made based on observation of user behaviors and user interview in Experiment 1, in which participants generated pen gestures with different movement magnitudes. Some participants drew large symbols, while some produced small ones. In our interview, participants also indicated that the magnitude of pen movement varied from person to person, so this parameter should not be considered in defining pen gestures.

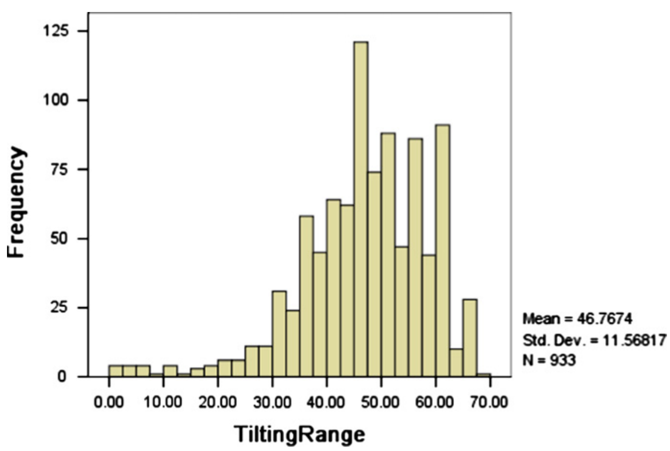

Fig. 21. The distribution of tilting range in intentional tilting actions.

6.2.1. Arc reaching via tilting

The first task was to tilt the pen tail to reach an arc target and then to tilt the pen tail back. Each task consisted of an outbound tilting action followed by an inbound tilting action. When the task began, a participant saw a starting circle and a 90° arc, both in green, appearing at a random position on the screen (Fig. 22a). The radius of the circle was chosen to represent the incidental tilting threshold (20°) found in Experiment 1, and the radius of the arc represented the mean altitude angle (53°) of the natural pen-holding posture.

As the participant placed the pen vertically into the starting circle, a tilt cursor (Tian et al., 2007) in the shape of an arrow appeared, and the starting circle turned to red (Fig. 22b). Tilting the pen tail, the tilt cursor grew in length to represent the amount of tilting, and the orientation of its tail represented the azimuth angle of the pen (Fig. 22c). As soon as the tail of the tilt cursor reached the arc target, the arc turned to red, signaling the completion of the outbound tilting action (Fig. 22d). Then, the participant needed to return the cursor to the starting circle by tilting back immediately (Fig. 22e). The circle became blue when the whole cursor fell into the circle (Fig. 22f). The participant lifted the pen tip to complete the inbound tilting action.

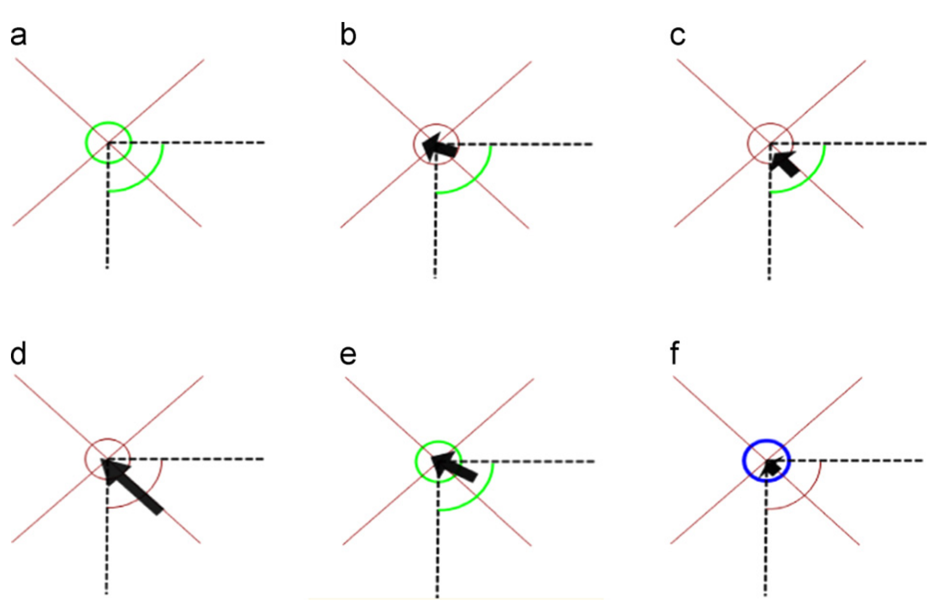

Fig. 22. Arc reaching via tilting.

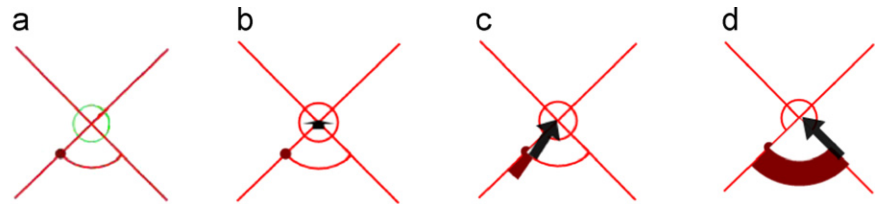

Fig. 23. Arc traversing via panning.

It should be noted that outbound tilting tasks and inbound tilting tasks are different. The outbound tilting tasks have a large target region, while inbound tilting tasks have a small one. This design is based on users normally perform outbound/inbound tilting actions.

6.2.2. *Arc traversing via panning*

The second task was to traverse an arc target by panning the pen tail. Similar to the tilting task, the participant saw a green starting circle and a 90° arc target appearing at a random position on the screen at the beginning of the task (Fig. 23a). The radius of the starting circle and the arc target chosen in this task were the same as in the tilting task. This ensured the results from both tasks were compatible, and could be combined to guide pen tail gesture designs composed of both tilting and panning actions.

A dot was displayed at one end of the arc, indicating the starting point of traversing. The participant needed to first initiate a tilt cursor by placing the pen vertically into the circle (Fig. 23b), and then to tilt the pen to align the cursor tail with the traversing starting point (Fig. 23c). Panning the pen tail, the participant made the cursor scan the arc, and the portion of the arc that had been scanned was thickened (Fig. 23d). The task was completed when the whole arc was traversed. The angular thresholds about outgoing and returning targets was 90°.

It should be noted that because of the basic panning actions defined by Experiment 2, we did not design the task as a tunneling task and investigate performances in different levels. Instead, we are interested in user performances in eight separate panning actions, which can help us choose appropriate panning actions in designing pen tail gestures.

6.2.3. *Measurements*

In both tasks, participants were asked to complete the task as quickly and accurately as possible. For each trial, the following measurements were collected:

6.2.3.1. Task completion time. For the arc reaching task, we collected the task completion time separately for the outbound and inbound tilting actions. Outbound tilting completion time was between the moment the a participant placed the cursor inside the starting circle (Fig. 22b) and the moment the target arc was reached (Fig. 22d). Inbound tilting completion time was between the moment the arc was reached (Fig. 22d) and the moment the pen tip was lifted (Fig. 22f). For the arc traversing task, the completion time was between the moment when a pen was placed into the starting circle and the moment a traversing was over. Here, we did not include the time span of overshoot in the task completion time of outbound or inbound tilting actions. We chose the moment when the target arc was forth reached by the tilt cursor as the end time of outbound tilting actions, and the moment when the target arc was back reached by the tilt cursor as the start time of inbound tilting actions.

6.2.3.2. Error rate (ER). For arc reaching tasks, an error was recorded if the pen tip was lifted before the completion of a task, or the tilting actions were wrong (e.g., the tilt cursor hit two dotted lines). For arc traversing tasks, the tilt cursor should stay outside of the starting circle during the traversing. An error was counted if the cursor returned to the starting circle before a task was finished, i.e., the tilt cursor never hit the target line.

6.2.3.3. Pen tip movement. We recorded the distance pen tip traversed from the moment it touched the screen to the time it was lifted.

6.2.3.4. Incidental tilting and panning. For each task, we collected all pen tail movement data as we did in above experiments to analyze the co-variations between tilting, panning, and pen tip movement.

6.3. *Design*

A within-subject factorial design was used for each task. In the arc reaching task, an arc target could be at one of four possible quadrants, making 8 possible pen tilting directions—outbound and inbound in E′, N′, W′, and S′. A Latin square design was applied to counterbalance the order of appearance of these tilting directions. The same approach was adopted in the arc traversing task, which also had eight task conditions corresponding to eight possible panning directions: E′–N′, N′–W′, W′–S′, S′–E′, E′–S′, S′–W′, W′–N′, N′–E′.

For every task, each participant performed a total of 100 trials, which consisted of 20 practice trials and 80 test trials (10 trials $\times$ 8 directions). Participants took a break between the two tasks. The experiment lasted approximately 30 min for each participant.

6.4. Results

6.4.1. Arc reaching via tilting

For the arc reaching task, the average task completion time was 1.26 s; the average error rate was 4.17%; and the average tilting speed was 60.74°/s. With repeated measures ANOVA, we could not find significant effects of tilting direction on task completion time ($F_{7,77}=1.89$, $p=0.067$), error rate ($F_{7,77}=0.12$, $p=0.997$), or tilting speed ($F_{7,77}=0.57$, $p=0.777$).

In terms of the impact of tilting actions on incidental pen tip movement and panning, the average pen tip movement was 2.98 mm, and the average panning range was 15.69° during each trial. We found a significant main effect of tilting direction on pen tip movement ($F_{7,77}=3.936$, $p<0.001$) (Fig. 24). Post-hoc pair-wise comparisons showed that when the pen is tilted in the directions of N′ and W′, both outbound and inbound, pen tip movements are significantly larger than in other directions. We did not find a significant main effect of tilting on incidental panning range ($F_{7,77}=0.225$, $p=0.979$).

6.4.2. Arc tracing via panning

The average completion time in arc tracing tasks was 1.76 s; the average error rate was 7.90%; and the average panning speed was 79.43°/s. Repeated measures ANOVA showed a significant main effect of panning direction on completion time ($F_{7,77}=2.560$, $p=0.013$) (Fig. 25), error rate ($F_{7,77}=5.429$, $p<0.001$) (Fig. 26), and panning speed ($F_{7,77}=3.425$, $p=0.001$) (Fig. 27). Post-hoc pair-wise comparisons indicated that the completion time of panning in the direction of E′–S′ was significant longer than in other directions; panning in the directions of E′–S′ and S′–E′ led to significantly higher error rates than in other directions; and panning speed in the E′–S′ direction was significantly lower than in other directions.

In terms of the incidental tilting and pen tip movement, during the panning task trials the average tilting range was 10.47°, and the average pen tip movement was 3.04 mm. We observed a significant main effect of panning direction on incidental tilting range ($F_{7,77}=5.716$, $p<0.001$) (Fig. 28), as well as on pen tip movement ($F_{7,77}=5.075$, $p<.001$) (Fig. 29). Post-hoc pair-wise comparisons indicated that the incidental tilting range was significantly larger in the panning direction of E′–S′ than in other directions, and pen tip movement was significantly larger in the panning direction of W′–N′ than in others.

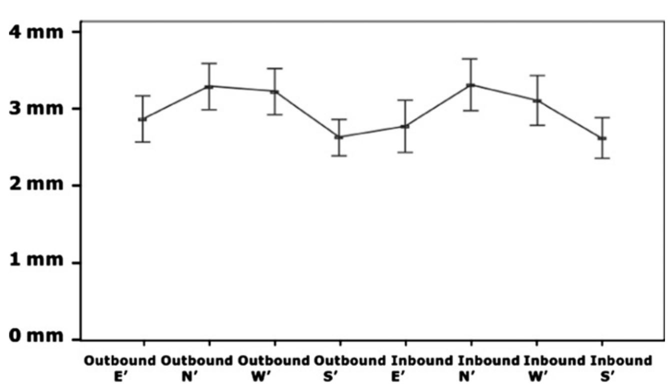

Fig. 24. Mean and standard error of incidental pen tip movements vs. tilting directions.

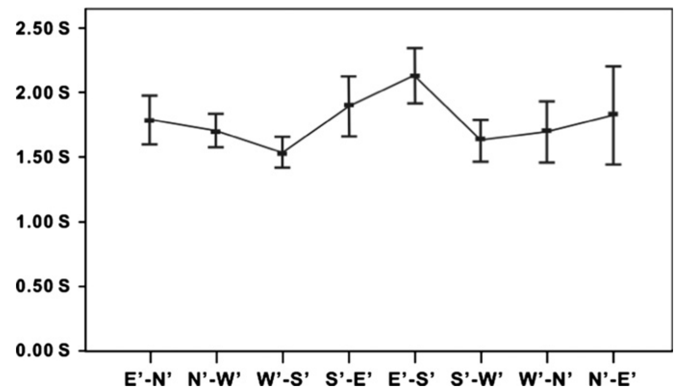

Fig. 25. Completion time vs. panning directions.

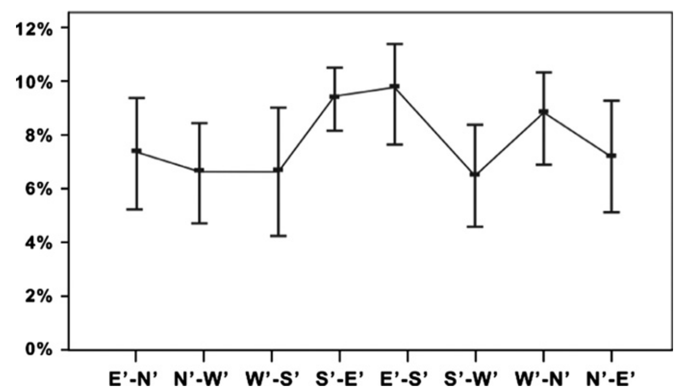

Fig. 26. Mean and standard error of error rate vs. panning directions.

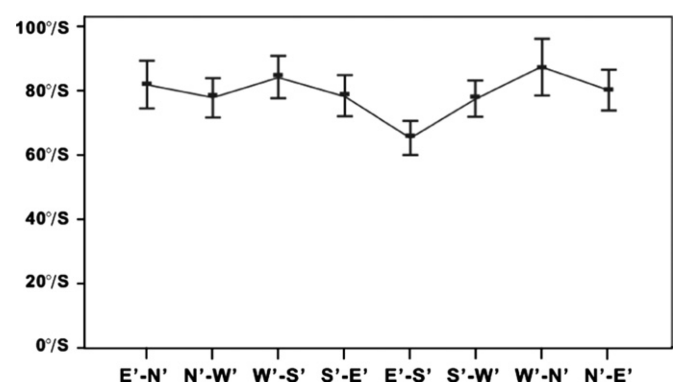

Fig. 27. Mean and standard error of panning speed vs. panning directions.

6.5. Discussion of Experiment 3

6.5.1. Tilting behavior

The results indicate that tilting direction tends not to influence user performances. This is similar to the study

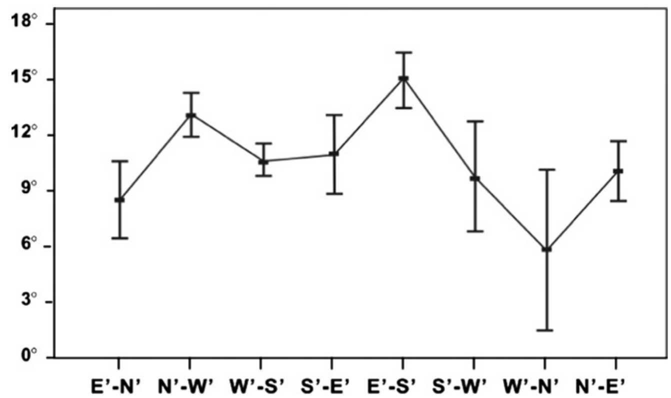

Fig. 28. Mean and standard error of incidental tilting vs. panning directions.

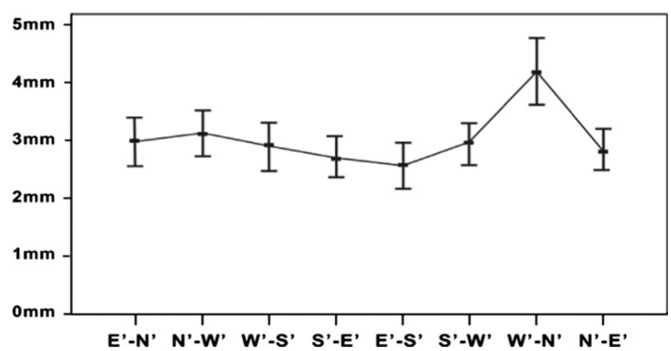

Fig. 29. Mean and standard error of incidental pen tip movement vs. panning directions.

findings with the Tilt Menu (Tian et al., 2008). Meanwhile, our results show that tilting actions cause incidental co-variations in the panning and pen tip movement. The panning range in tilting actions is lower than 16°, well under the 30° threshold we set according to Experiment 1, and can be successfully classified as incidental panning. Thus, we consider that this co-variation tends not to interfere with the recognition of tilting actions. For the co-variation between tilting actions and pen tip movement, our data show that the incidental tip movement is under 3.5 mm. Tilting in the directions of N′ and W′ tend to cause the largest pen tip movement. This implies that in designing a pen tail gesture tool, if it is critical to minimize the pen tip movement, we should avoid the tilting directions of N′ and W′.

6.5.2. Panning behavior

Our data show that panning along the direction of E′–S′ tends to be slow and panning in both the E′–S′ and S′–E′ directions cause more errors. Thus, in choosing panning actions for pen tail gesture design, the E′–S′ and S′–E′ directions should be given a lower priority.

Meanwhile, our results show that the panning actions can cause incidental co-variations in tilting as well as pen tip movement. For incidental tilting, our data indicate that the tilting range is lower than 15°, which is under the 20°

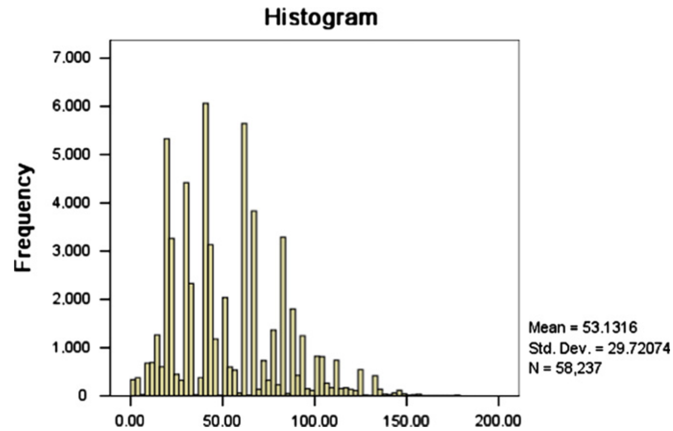

Fig. 30. The distribution of tilting speed.

threshold we set according to Experiment 1 and can be successfully classified as incidental tilting. Thus, we consider that this co-variation tends not to interfere with the recognition of panning actions. For incidental pen tip movement, the largest value is about 5 mm and the most vulnerable panning direction is W′–N′. Therefore, pen tail gesture designs should discourage panning in this direction if 5 mm of pen tip movement is unacceptable.

6.5.3. Threshold of incidental/intentional tilting action

In the discussion of Experiment 2 (Section 5.4.2), we chose tilting range 20° as one part of the threshold to discriminate incidental or intentional tilting actions. For tilting speed, the data distribution is shown in Fig. 30. As shown, 78.1% of intentional tilting actions had a tilting speed larger than 30°/s, and 65.5% of the trials had a tilting speed larger than 35°/s. From the discussion of Experiment 1, we know that 87.8% of incidental tilting actions had a tilting speed smaller than 30°/s, and 90.2% of the trials had a tilting speed smaller than 35°/s. Based on these results, we chose tilting speed 30°/s as the other parameter to discriminate incidental or intentional tilting actions.

Therefore, we define identify an intentional tilting gesture with a tilting action with a tilting range larger than 20° and a tilting speed above 30°/s. All other tilting actions are treated as incidental.

6.5.4. Threshold of incidental/intentional panning action

In our experiments, we only choose four tilting directions, making the angular range of an intentional panning action around 90°. From the discussion of Experiment 1, we know that 88.08% of incidental panning actions had a panning range smaller than 30°. Therefore, we could choose panning range 30° as one of the parameter to discriminate incidental from intentional panning actions. For panning speed, the data distribution is shown in Fig. 31: 99.9% of the trials had a panning speed faster than 50°/s. From the discussion of Experiment 1, we know that 84.4% of incidental panning actions had a panning

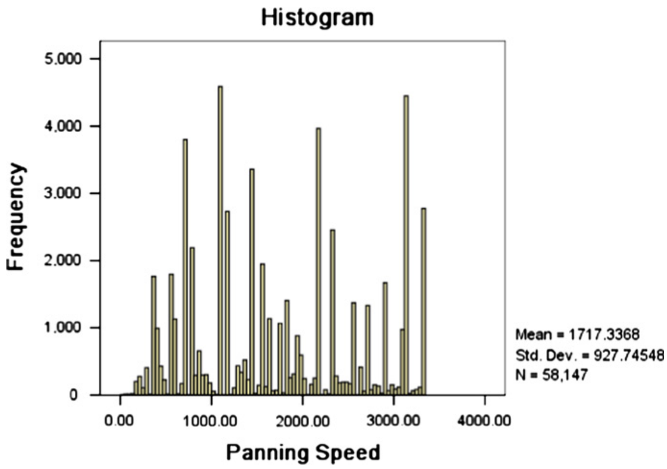

Fig. 31. The distribution of panning speed.

speed smaller than 40°/s, and 89.1% of incidental panning actions had a panning speed smaller than 50°/s. Thus, we chose tilting speed 50°/s as the other parameter to discriminate incidental or intentional panning actions.

Therefore, we define an intentional panning gesture as a gesture with a panning speed larger than 50°/s and a panning range larger than 30°. All other panning actions are treated as incidental.

6.5.5. Tilting magnitudes

As for the performance of tilting magnitudes, some research has been done. The most related work is from Xin et al. (2012). They studied the performance of discrete target selection by varying the pen stylus' tilt angle through two controlled experiments: tilt acquiring and tilt pointing. Their result revealed a decreasing power relationship between angular width and selection time, and confirmed that pen tilt pointing can be modeled by Fitts' law. From that, we could deduce that the shorter tilting range will result in higher performance. However, the tilting range cannot be shorter than 20°, which is the discrimination of incidental or intentional tilting actions.

7. Design & implementation of pen tail gestures

Results from the above three experiments laid out the foundations for the design and implementation of pen tail gestures. This section describes some issues we consider important to designing pen tail gestures.

7.1. Design properties

Pen tail gestures create an additional interaction layer while keeping the pen tip on primary work. With pen tail gestures, the division of gesturing and other functionalities between the pen tail and the pen tip may eliminate the burden of mode switch. Then, users can combine pen tip gestures and pen tail gestures to perform an interactive task that requires multiple steps or multiple operation parameters. This approach can expand the design space in pen-based UIs.

Different from mouse-based interactions (or those emulated by a pen), which all happen at the point of the cursor, regular pen gestures inevitably need to span some screen space to be made. This non-localized input paradigm can often pose problems. For example, when the gesture spans across multiple objects, it becomes ambiguous as to which object should receive the gesture command. It also becomes tricky when the user tries to perform a gesture near the boundary of the display. By migrating the gesturing space from 2D screen into 3D space, pen tail gestures enable truly localized input. The user can generate gesture inputs without noticeably moving the pen tip, therefore being able to indicate an unambiguous interaction focus, and evading the limitation of the screen size.

7.2. Projecting pen tail gestures to 2D

Given that the pen tip remains static, a gesture by the pen tail can be considered as a 3D trajectory on the surface of an imaginary hemisphere, which is centered at the pen tip, and has a radius equal to the length of the pen. Any 3D trajectory on the hemisphere therefore has a unique 2D projection on the base plane. Fig. 32 illustrates a pen tail gesture in the 3D Cartesian coordinates and its 2D projection on the base plane.

This one-to-one mapping between a 3D pen tail trajectory and its 2D projection is a key to the design of pen tail gestures, because a 2D gesture can always be mapped back into a 3D counterpart. Simple gestures like drawing an arc or a straight line in 2D can be directly mapped to one of the 16 basic pen tail actions we defined (Fig. 20). For more complex gestures like those we used in our interview (Fig. 2), we can decompose them into a collection of simple arc or line segments, and then map these segments to those basic pen tail actions respectively. By doing so, we create a bridge between pen tail gestures and traditional 2D pen gestures, and allow users to leverage their existing skills to smoothly migrate to pen tail gestures. Fig. 33 shows two realistic 2D pen gestures and their corresponding pen tail gestures.

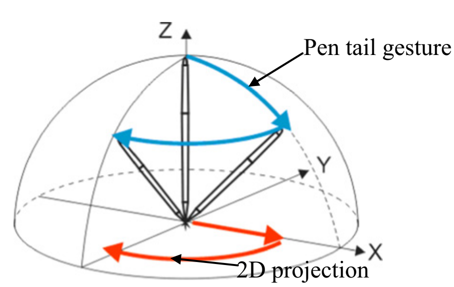

Fig. 32. A pen tail gesture in 3D space and its 2D projection.

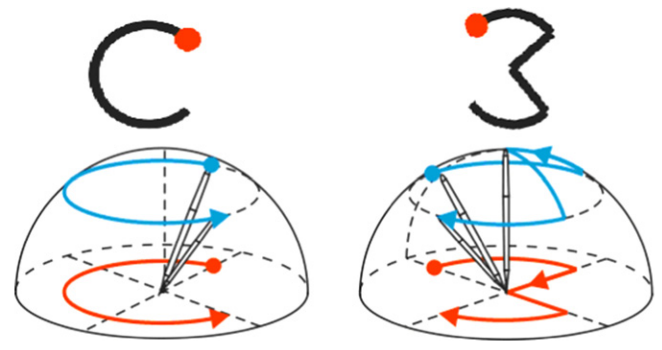

Fig. 33. 2D gestures and their pen tail gesture counterparts (Red dot indicates starting point of the gesture.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

7.3. Gesture recognition

We adopted a simple template matching approach in recognizing pen tail gestures, similar to that of the Shark[2] (Kristensson and Zhai, 2004), $1 gesture recognizer (Wobbrock et al., 2007), and Protractor (Li, 2010). The first step is to convert a pen tail gesture into a 2D stroke sample. When the pen tail moves, its 3D trajectory is captured and projected to the 2D screen plane as a 2D stroke. The 2D stroke is then translated and scaled so that its bounding box is centered at (0, 0) and has a unit size. This ensures that the user can perform the gesture with an arbitrary scale, a requirement expressed in our initial interviews. Then the stroke is re-sampled to a predetermined number (64) of sample points.

With a collection of gesture templates that are generated in the same way, a template that most closely matches the sample stroke can be identified and used as the recognition result. Furthermore, a pen tail gesture consists of tilting and panning elements, and each element can be regarded as a movement within one of the four quadrants (N′, E′, W′, S′). Our gesture recognition tolerates slight rotations ($<45^\circ$) of the gestures, as long as each movement element still stays within its quadrant. This is particularly important, given that each user may have a slightly different natural pen-holding posture to start from. To achieve this goal, we first generates 18 variations of the sample stroke by rotating it by 5, 10, 15, 20, 25, 30, 35, 40, and 45° clockwise and counterclockwise, and then matches these 19 samples (including the original one) with gesture templates to get the recognition result.

We conducted a preliminary performance to test the recognition rate of our algorithm. Twelve pen tail gestures were selected based on how they are composed to different basic pen tail movements, as shown in Fig. 34. The same group of participants and the same apparatus as in Experiment 3 were used for this experiment. Each participant was asked to input each gesture randomly shown on the screen in three times. There are 19 recognition error among 432 gestures input. The recognition rate is higher than 95%.

Fig. 34. Twelve pen tail gestures tested.

7.4. Activation and visualization

To distinguish pen tail gestures from incidental pen tail movements, a pen tail gesture is considered valid only if the magnitude and speed of the tilting/panning exceed their corresponding thresholds as defined previously according to previous experiments. Otherwise, the system considers the pen tail movement as incidental. A similar approach was seen in (Bi et al., 2008). A pen tail gesture is recorded for the whole duration of intentional pen tail movement. Therefore, there is no ambiguity in start and end points. In particular, if the usage scenario of a gesture requires the user to be continuously performing other actions (e.g. sketching) immediately before and after the activation, gesture should start and end at the natural pen-holding posture to avoid false activation. To assist the performance of the gestures, we used a Tilt Cursor (Tian et al., 2007), the shape of which is dynamically updated based on the pen position, to provide a visual cue of the pen tail. When a pen tail gesture is activated, the tail of the Tilt Cursor will produce a thick and red stroke dynamically following the movement of pen tail until the gesture is performed. This stroke gives users a real-time feedback about the activation state and a trajectory of movements.

8. Application prototypes

Based on the above implementation, we developed three application prototypes to demonstrate the usage of pen tail gestures. Each of these prototypes attempts to address an existing challenge in current pen-based interfaces.

8.1. Modeless control in sketching

In sketching applications, a user often needs to draw freeform strokes, as well as to manipulate these strokes through commands such as copying and deleting. Conventional systems allow the user to trigger these operations either by interface buttons/menus or by pen gestures. If pen gestures are used in a system, it often has two operation modes: one for sketching and one for gesturing. To switch between these two modes, the user needs to give explicit commands, often again involving the use of buttons/menus. This approach results in interruptions in task flow. Pen tail gestures enable modeless interactions in such situations. The user can perform the gestures without interrupting the sketching activities. In our prototype, we used six pen tail gestures – , , , , , and – to represent the six action commands: "delete", "copy", "scale down", "scale up", "collapse ink structure" and "expand ink structure". Figs. 35 and 36 show an example of a scale-down gesture being performed.

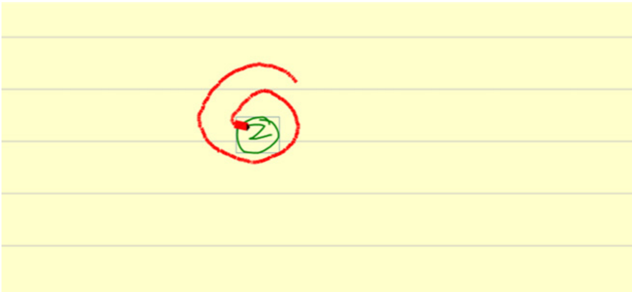

Fig. 35. A scale-down gesture is applied to strokes.

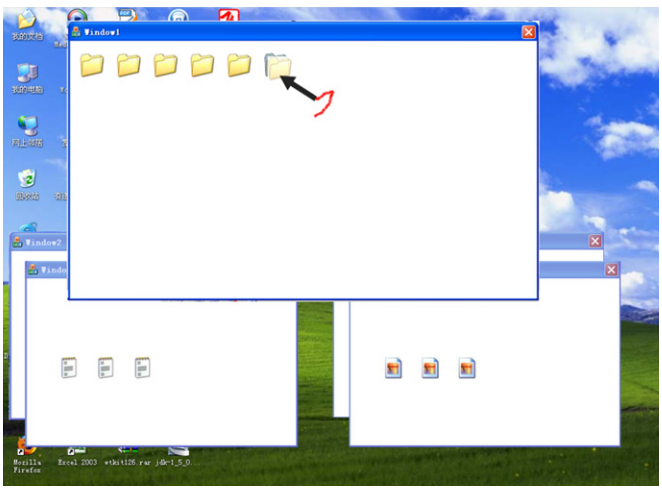

Fig. 36. Pen tail gesture to switch between windows.

8.2. Drag–and-drop between overlapping windows

Dragging and dropping an object into an occluded window is a challenge in pen-based UI. Several solutions have been available, including rearranging the windows first, or using cut-and-paste instead of drag-and-drop. Researchers have also explored new techniques such as “fold-and-drop” gestures (Dragicevic, 2004) to fold up a window and reveal other windows underneath. However, most of these solutions still require lifting or moving the pen tip, which might interfere with the drag-and-drop operation itself.

Different from these techniques, pen tail gestures allow the user to issue commands to switch to the target window with the pen tip staying on top of the object of interest. Once the user selects the object with the pen tip, she can use two pen tail gestures, “ ” and “ ”, to traverse back and forth through a stack of overlapping windows, and then drag the object into the target window. The complete operation can be done in a single fluid sequence without lifting the pen in the middle.

8.3. Arc drawing technique

In addition to issuing discrete gestures, we also consider the control of multiple continuous parameters by compositing the basic actions of tilting and panning. We demonstrate this by an intuitive technique for drawing arcs.

Current CAD systems often require users to specify multiple parameters in sequence for constructing geometric shapes. For example, to create an arc, a user usually needs to set the center point first, then to specify the desired radius, and finally indicate where the arc starts and ends respectively. Such a seemingly simple task requires several discrete operations, often separated by mode switches. Inspired by the use of physical compasses, we created a fluid arc drawing technique, using tiling and panning pen tail gestures to intuitively indicate different parameters in a continuous operation. Fig. 37 shows the key action steps, with corresponding on-screen visualizations as a pair of compasses. This technique is merely an example of a rich set of interaction designs that could be supported by continuous pen tail movements.

9. Preliminary study in using pen tail gestures

To have an initial understanding of how pen tail gestures perform within application contexts, we invited six participants to use three prototypes mentioned above each for 20 minutes. We observed participants using these tools, and asked them about their opinions and suggestions on the three prototypes after they finished. Subjective feedbacks from participants favored pen tail gestures.

For tasks involving heavy model switching, participants liked the division of inking and gesturing functionalities between the pen tip and the pen tail. Compared with pen tail gestures, participants indicated that the traditional mode-switching techniques required a “round-trip” of the pen that slowed them down considerably. Although some techniques simplified the mode-switching operation with a secondary input, the very existence of different modes inevitably caused confusions when the same pen tip is used for both actions, evidenced by the error analysis above. While pen tail gestures could allow people to perform with a speed comparable with some state-of-art techniques, and at the same time produce fewer errors by eliminating explicit mode switches.

As for the drag and drop between overlapping windows, all participants felt comfortable using pen tail gestures to switch between overlapping windows. They also indicated the pen tail gestures for going through overlapping windows (“>” and “<”) were easy to remember and use, and pen tail gestures could be used to bring an invisible window on the top easily.

As for the tasks of arc drawing, participants mentioned that in traditional arc drawing tasks like compass geometric construction, they had to remember exactly what state has been chosen in order to construct arcs correctly. In comparison, with the pen tail gestures, they could merge all steps under one coherent pen action. Results also indicate that this new design improve the user experience

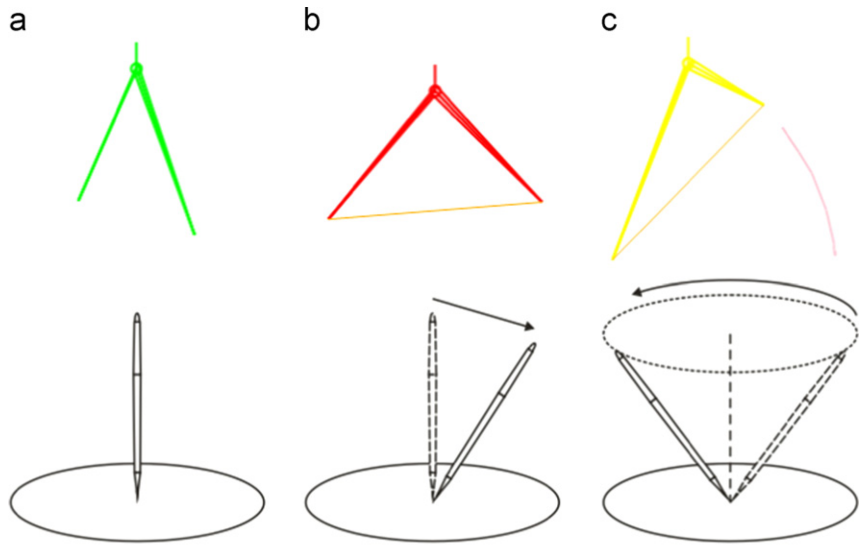

Fig. 37. Arc drawing with pen tail gestures: (a) setting the center point by the pen tip, b) setting the radius and starting point by pen tail tilting and c) drawing the arc by pen tail panning.

in geometry construction. Participants thought the tool was smooth and fun to use.

10. Limitations

Although results of the preliminary evaluation showed that pen tail gesture is well received and performed by users as a promising new interaction method. Some limits of pen tail gestures still exist.

10.1. Incidental pen tip movements

The incidental pen tip movement may be a weakness for drawing applications. We recognize it as a common problem in designs utilizing additional pen input dimension (see (Bi et al., 2008) for a similar case) and may reduce the precision of strokes in freeform drawing. Experiment 2 was precisely to understand this so that we could reduce its negative impact by careful gesture design. For example, we suggest gesture designs should discourage tilting and panning in some directions if certain pen tip movements are unacceptable.

In this paper we focused on pen tail gestures that are performed whilst keeping the pen tip static. One would naturally think of extending this to gestures that include simultaneous pen tip and tail movements. However, as our experiments showed, *movements of pen tip and pen tail are highly correlated, so it would be difficult for users to control both movements independently*. As such, when developing such gestures, we need to carefully design within the motor control constraints to ensure the gestures could be comfortably performed by users.

10.2. Magnitude of the tilting and panning

Although the smaller magnitude of the tilting and panning may results in better performance, we do not leverage different magnitudes to design pen tail gestures, which will reduce the variety of gestures. However, in addition to initial interview feedback, our decision is incidentally supported by research on handwriting (Hollerbach, 1981), which showed that different sizes of the same letter take approximately the same amount of time to produce. People do not seem to have an explicit mental model to differentiate pen actions performed in different scales, as they are considered semantically equivalent. Gestures made by the pen tail are likely to follow a similar trend, to be further validated by future investigations.

10.3. Thresholds identification of incidental/intentional actions

In this paper, we identified the thresholds of incidental/intentional actions based on the analysis of the data distribution about the range and speed of tilting and panning actions. Though few errors were found in using those thresholds to activate intentional tilting/panning actions, how to find the optimal methods in identification of incidental/intentional actions is still an open question.

As a preliminary step, we adopted naive Bayesian classifier to further analyze the factors of tilt range, tilt speed, pan range and pan speed in identifying incidental/intentional actions. Eighty percent of data are used for obtaining the prior probabilities required for Bayesian classification. The other data are used for testing.

First, we used tilting ranges to classify incidental/intentional inputs. As for data in incidental tilting actions

(Experiment 1), the maximal tilting range of each stroke is utilized. As for data in intentional tilting actions (Experiment 2), the maximal tilting range of each action is used. Results show that the classification accuracy of the intentional tilting actions is 92.47%, and all testing data from the incidental tilting actions (Experiment 1) is classified correctly.

We then tried to use tilt speeds to distinguish between incidental input and intentional inputs. The tilt speed of each point in the collected dataset is considered as a sample for Bayesian classifier. The accuracy of incidental tilting actions is 81%, while the accuracy of intentional tilting actions is 78.32%.

As for the panning range, we adopted the maximal pan range of each stroke for incidental panning actions as features. The maximal pan range for each intentional panning action is used as features. Results show that the accuracy of incidental panning actions is 99.41% and the accuracy of intentional panning actions is 80.11%.

Lastly, we analyzed panning speed as features for incidental/intentional action identification. The accuracy of incidental panning actions is 98.46% and the accuracy of intentional panning actions is 63.79%.

From the results, we know that tilting range and panning range could be used as key features in incidental/intentional action identification, and are more reliable factors than tilting speed and panning speed. However, when other pen features, such as pen tip movement speed, pen pressure, and pen rolling speed, are also involved in the design, it may be unclear whether tilting range and panning range can still reliably identify intentional gestures. Further research would be needed.

11. Conclusion and future work

In this paper, we presented pen tail gestures, a technique using the pen tail while the pen tip is occupied by other tasks. This new type of pen gestures has shown good potential, especially in terms of enabling modeless and localized gesture input. Our experimental explorations provided guidelines for designing pen tail gestures. We also developed three initial prototypes to demonstrate pen tail gestures in different application contexts. Preliminary evaluation results showed these designs are promising.

Our major finding can be classified into two categories: the identification of intentional pen tail gestures and the suggestions for pen tail gesture tools. To distinguish intentional pen tail gestures from incidental ones, our results show that:

- intentional pen tail gestures, tilting and panning, can be better defined by gesture range than gesture movement;
- for tilting gestures, an intentional tilting gesture is one with a tilting range larger than 20°, and if tilting speed is also considered, a tilting speed above 30°/s; and
- for panning gestures, an intentional panning gesture is one with a panning range larger than 30°, and if panning speed is considered together, a panning speed larger than 50°/s.

Our design suggestions for pen tail gesture tools primarily concern how pen tail gestures may affect the stability of pen tip, which is usually involved in a task when pen tail gestures are performed. Because of our natural pen-holding posture, the impacts of pen tail gestures in different directions on pen tip movement are unequal. To reduce the potential pen tip movement caused by pen tail gestures, we should consider the following two rules:

- avoiding the two tilting directions of N′ and W′ shown in Fig. 19; and
- avoiding the W′–N′ direction in pen tail panning.

There are several directions that can be pursued to extend the current work. Firstly, the current design of pen tail gestures is based on the experiment results for right-handed users. It would be interesting to explore whether the results for left-handed users are symmetric to that of right-handed users. Also, it would be useful to allow the user to adapt relevant parameters of the gestures based on their own natural pen-holding posture. Secondly, we are interested in developing a quantitative model for the user performance using pen tail gestures. The Steering Law (Accot and Zhai, 1997) may provide a good analogy for exploring in this direction, given that pen tail gestures are essentially trajectory-based tasks in 3D space. Thirdly, our experiments were conducted on an ordinary tablet, where the separation between input and display may lead to mismatches in terms of user perception. It would be valuable to investigate whether our current results apply to direct-touch devices such as a Tablet PC or a pen-enabled interactive surface.

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