PAPER

A Study of Inherent Pen Input Modalities for Precision Parameter Manipulations during Trajectory Tasks

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SUMMARY Adjustment of a certain parameter in the course of performing a trajectory task such as drawing or gesturing is a common manipulation in pen-based interaction. Since pen tip information is confined to x-y coordinate data, such concurrent parameter adjustment is not easily accomplished in devices using only a pen tip. This paper comparatively investigates the performance of inherent pen input modalities (*Pressure*, *Tilt*, *Azimuth*, and *Rolling*) and *Key Pressing* with the non-preferred hand used for precision parameter manipulation during pen sliding actions. We elaborate our experimental design framework here and conduct experimentation to evaluate the effect of the five techniques. Results show that *Pressure* enabled the fastest performance along with the lowest error rate, while *Azimuth* exhibited the worst performance. *Tilt* showed slightly faster performance and achieved a lower error rate than *Rolling*. However, *Rolling* achieved the most significant learning effect on *Selection Time* and was favored over *Tilt* in subjective evaluations. Our experimental results afford a general understanding of the performance of inherent pen input modalities in the course of a trajectory task in HCI (human computer interaction).
key words: *human computer interaction, pen input, inherent pen input modalities, multi-scale navigation, pen-based interfaces*

1. Introduction

In pen-based user interfaces, adjustment of a parameter as well as its granularity, or manipulation of a value besides x-y cursor movement, is usually required, such as changing a rectangle's scale with different levels of granularity and adjusting the color of a line while drawing. However, compared with that of other input devices such as keyboards and mice, the input throughput capacity of pens is less because the pen input channel is restricted to x-y coordinate data. Thus it is generally difficult to use the pen to adjust both a parameter and the granularity without other input modalities.

In this background, research has been conducted on the use of inherent pen input modalities such as pen pressure, tilt, azimuth and rolling to enhance the pen input capacity. Some of these studies, for example [1], focused on human ability to control these modalities, while others, for example [2], designed novel interaction techniques based on the pen modalities. However, most of these studies investigated only one or two pen input modalities. In particular, regarding precision parameter manipulation, only performance using pen pressure has been investigated [3]. Utilization of other inherent pen input modalities to achieve precision parameter manipulation during trajectory task remains unexplored. This gap in the literature motivates us to systematically evaluate performance using pen input modalities to realize precision parameter manipulations during trajectory tasks.

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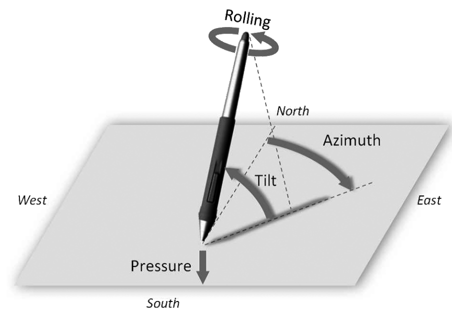

Fig. 1 Schematic diagram of pen input modalities.

In this study, four kinds of inherent pen input modalities, *Pressure*, *Tilt*, *Azimuth*, and *Rolling*, used for high-precision parameter manipulation were comparatively investigated by both qualitative and quantitative analysis. Here *Pressure* means the pressure exerted on the stylus pen tip by the user. *Tilt* means the angle between the tablet surface and the pen body. *Azimuth* is the angle from the north direction on the tablet surface to the vertical projection of the pen on the tablet surface. *Rolling* means the angle the user rolls the pen around its longitudinal axis. Figure 1 is a schematic diagram of these pen input modalities.

We conducted experimentation to evaluate the performance of these pen modalities and compared them with *Key Pressing* using the non-preferred hand. We elaborate the experimental design, present the results, and discuss the advantages and disadvantages of each pen modality. This paper provides pen-based interface designers with a general understanding of pen input modality choice for precision parameter manipulation during trajectory tasks.

2. Related Work

Literature related to pen pressure emerged mainly after the new Millennium, and most of them focused on novel interaction technique designs. Mizuno et al. [4] implemented a virtual sculpting system by converting pen pressure to carving depth and angle. Ramos et al. [2] proposed a concept prototype designed for use with pressure-sensitive digitizer tablets to fluidly navigate, segment, link, and annotate digital videos; created the Zlider [3] that users can use pen pressure to achieve fluid zooming while sliding the pen; and developed pressure marks [5] that allowed users to perform a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time. Similarly, Harada et al. [6] used pen pressure as an input modal to augment simultaneous input capacity. Ren et al. [7] proposed the Adaptive Hybrid Cursor to facilitate the target selection tasks by automatically adapting the size of the cursor based on pen pressure input. Yin and Ren [8] proposed a zoom-based technique to improve pixel-target selection, in which the pressure is used as a mode switch.

There were also some published studies that focused on pen pressure characteristics and/or explored the human ability to control pen pressure. Ramos et al. [1] investigated the human ability to perform discrete selection tasks by controlling stylus pressure and found that dividing pressure space into 6 levels resulted in optimal controllability. Li et al. [9] investigated five techniques for switching between ink and gesture modes in pen interfaces, including a pen pressure based mode switching technique that allowed implicit mode transitions. Zhou et al. [10] comparatively investigated the performance of pen pressure and tilt in a cursor control experiment.

Compared to the studies on pen pressure, few studies that focused on the exploration of pen tilt, azimuth, and rolling were found. Tilt Cursor [11] provided users with 3D pen orientation as visual cues. Another technique, Tilt Menu [12], extended the selection capabilities of pen-based user interfaces using 3D pen orientation information. Oshita [13] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Bi et al. [14] explored pen rolling around the longitudinal axis of the pen and determined the intentional and incidental pen rolling while users manipulating a pen.

Although the aforementioned works explored the utilization of pen input modalities to widen the stylus input vocabulary available to the user, only two are close to our current inquiry. One, the Zlider [3], is a high precision parameter mechanism for fluid integrated manipulation of zooming via pen pressure input during pen sliding. But a major different point from this study is that their study only employed pen pressure modality, while this study fully investigated four different pen input modalities. The other study [10], evaluated cursor control from pen input modalities with the pen tip stationary, while this study focuses on precision parameter manipulation with the pen tip moving, which should have broader relevance to practical utilization of digital pens.

3. Design Framework

In order to investigate the performance of pen input modalities for precision parameter manipulation during trajectory tasks, we designed a widget that incorporates the pen sliding mechanism and a precision parameter that users can ma-

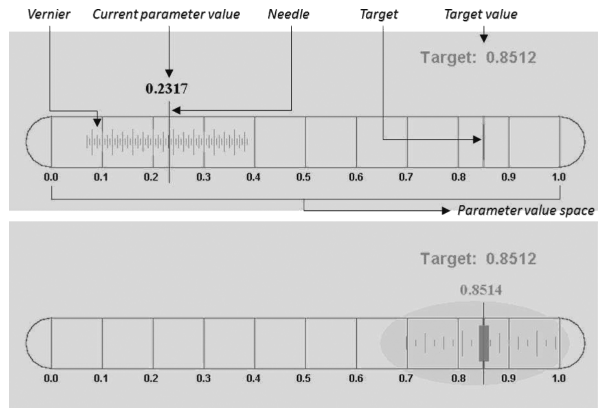

Fig. 2 The widget (upper: a target is displayed in the center of a light gray rectangle. The user can move the needle along the vernier by sliding the pen horizontally. Lower: the user can change the granularity level of pen sliding as well as the target width for ease of target selection.).

nipulate it at different levels of granularity (Fig. 2). Sliding action was produced by varying the pen tip x-y coordinate position. The granularity of the sliding is adjusted by variation of the values of the different pen input modalities or by number of key presses during pen sliding. At all times a needle indicates the value of the parameter being manipulated, and a vernier shows the granularity level.

The widget consists of a rectangular working area. Users can slide the needle within the parameter space of [0.0, 1.0]. At the beginning of each trial, the needle was displayed at the start point of the workspace on the left and a target was displayed in a light gray rectangle which had three possible widths: *0.0004*, *0.0026* and *0.0060*, referred to as narrow, medium and wide target areas respectively. The target could be located at three different distances from the start point of the workspace on the left: *0.1680*, *0.4478* and *0.8512*, presenting near, mid and far distances respectively.

The subjects were instructed to slide the pen to control the needle to locate and select the given targets as quickly and accurately as possible. The subject could slide the pen to control the needle at a coarse granularity level so that the needle approached the target quickly. As the needle neared the target, if the target width was too small for easy selection, the subject could change the granularity level of sliding in five different ways: increasing the pressure exerted on the pen tip, increasing the pen tilt[†], rotating the pen counterclockwise, rolling the pen clockwise, and pressing constantly on the right arrow key to manipulate at finer granularity levels, or by doing the reverse of any of those actions. We use an exponential function similar to that in the Zlider [3], of the form $base^{f(p)}$, $base^{f(t)}$, $base^{f(a)}$, $base^{f(r)}$, or $base^{f(num(k))}$ to calculate the granularity level, where *f(p)*, *f(t)*, *f(a)*, *f(r)*,

[†]The farther left of pen terminal, the larger the tilt angle. In the experiment, we extended the tilt range from [30, 90] to [30, 150] degrees depending on pen azimuth. [30, 90] degrees tilt angle is supported by [0, 179] degrees azimuth, and [91, 150] degrees tilt angle is supported by [180, 359] degrees azimuth.

and *f(num(k))* were functions of detected pen pressure, tilt, azimuth, rolling angle and the number of presses of the left or right key with the user's non-preferred hand.

To enable impartial comparisons, the same start and end value for each function were set. In order to determine the natural and preferable pen tilt, azimuth, and rolling manipulation modes, we performed a set of informal pilot experiments along with questionnaire surveys. Results showed that for the condition of pen tip to remain stable, the Northeast-Southwest direction tilting was optimum whereas for the condition of pen sliding, the horizontal direction was preferred. Thus we chose horizontal orientation to realize tilt manipulation. Results also showed that for azimuth, a counter-clockwise rotation was preferred and for rolling, a clockwise rolling around the longitudinal axis of the pen was preferred. Thus we chose counterclockwise pen azimuth rotation or clockwise pen rolling to realize the precision parameter manipulation.

To make the widget more easily understood and manipulated, several types of visual feedback were provided in the widget. A numeric label indicated the current value of the parameter being manipulated. When the pen pressure, tilt, azimuth, rolling angle or the number of key presses exceeded the thresholds, a gray opaque ellipse would appear. Meanwhile, the granularity of the vernier changed according to pen pressure, tilt, azimuth, rolling angle or the number of key presses, and the charcoal gray clone target area also expanded or contracted accordingly. If a misselection was made, a failure icon appeared and a sound tip was given to the subject.

4. Experiment

4.1 Participants

Two female and seven male volunteers from a native university campus, ranging in age from 21 to 32, participated in the experiment. All of them were right-handed according to self-report. Five had the experience of using pen tablet, and others had no prior experience with such devices.

4.2 Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet with a wireless stylus with an isometric tip was used in the experiment. The experimental software was designed in 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 120 dpi.

The Cintiq 21UX can detect the pressure that a user exerts on the stylus pen tip from 1 to 1023 levels which corresponds to the force range of 0 to 4 Newtons. If the pressure level is over 1023, it is recognized as 1023. The Cintiq 21UX can also detect the tilt angle of the stylus which ranges from 30 degrees to 90 degrees (When the stylus is perpendicular to the tablet surface, the tilt value is 90 degrees). The azimuth of the pen can also be detected by the Cintiq 21UX ranging from 0 to 359 degrees clockwise from the northerly direction. The rolling angle of the pen can be detected ranging from 0 to 359 degrees according to counterclockwise pen rolling. Moreover, the pen rolling angle being detected is related to current pen azimuth. When the pen tail orientates the southerly direction, the rolling angle is reported 0.

4.3 Task Design

A within-subject full factorial design with repeated measures was used. The independent variables were *Technique* (*Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing*), *Width* (*0.0004*, *0.0026* and *0.0060* scale values), and *Distance* (*0.1680*, *0.4478* and *0.8512* scale values from the start point). A Latin Square was used to counterbalance the order of the appearances of techniques. To explore the learning effects, 6 blocks of trials were completed by every participant. Trials under same condition were repeated 2 times. Presentation of trials within a block was randomized. In total, the experiment consisted of:

9 participants ×
5 techniques ×
6 blocks ×
3 width conditions ×
3 distance conditions ×
2 repetitions
=4860 target selection trials

5. Results

This experiment took an average of 1.16 hours per participant. After each block, subjects were allowed an optional 10-minute break.

5.1 Selection Time

For *Selection Time*, it fitted in accordance with the Fitts' law [15]: the farther and the narrower the target was, the more time was needed to select the target. Repeated measures analysis of variance showed a significant main effect on *Selection Time* for *Width* ($F_{2,16} = 69.01$, $p < .001$) and *Distance* ($F_{2,16} = 74.40$, $p < .001$). Furthermore, there was also a significant main effect on *Selection Time* for *Technique* ($F_{4,32} = 4.68$, $p < .01$) and *Technique* × *Width* ($F_{8,64} = 2.58$, $p < .05$). However, there was no significant main effect on *Selection Time* for *Technique* × *Distance* ($F_{8,64} = 1.54$, $p = 0.22$). *Post hoc* pairwise comparisons showed significant differences between all pairs of *Techniques* across all levels of the *Width* condition or all levels of the *Distance* condition. It is worth noting that in the narrowest *Width* condition *0.0004*, *Pressure* performed significantly better than other pen input modalities and even better than *Key Pressing*. Figure 3 and 4 illustrate the results.

Since we recorded data for all 6 blocks, we expected to see a learning effect. A repeated measures analysis of

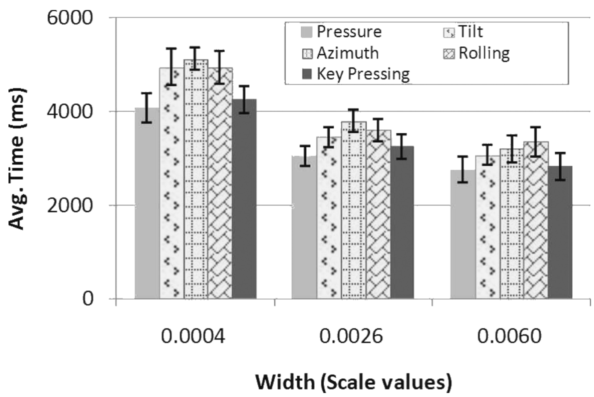

Fig. 3 Average selection time per technique × width.

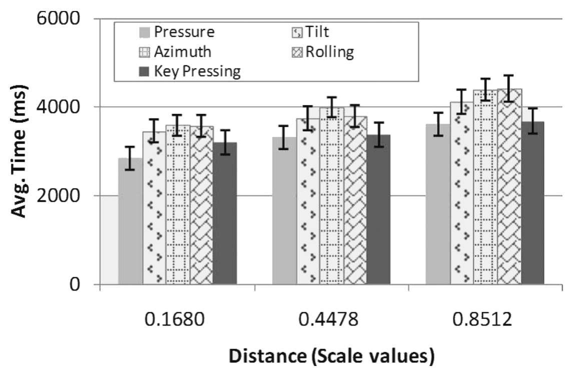

Fig. 4 Average selection time per technique × distance.

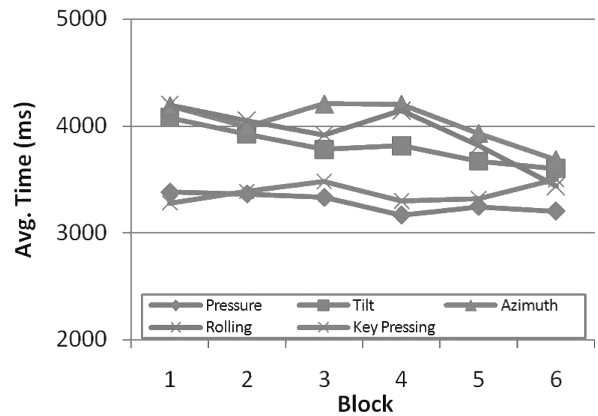

Fig. 5 Average selection time per block × technique.

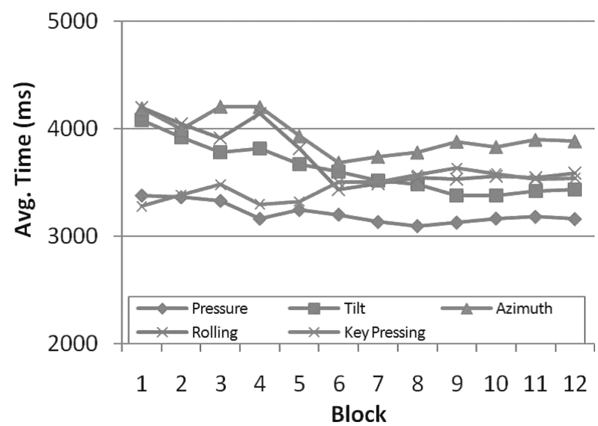

Fig. 6 Average selection time per block × technique.

variance showed that block had a significant effect on *Selection Time* ($F_{5,40} = 3.31$, $p < .05$). *Post hoc* analysis also found that in block 6, for all pen input modalities, *Selection Time* was significantly shorter than in other blocks ($p < .05$), whereas for *Key Pressing*, *Selection Time* was longer than in other blocks.

The overall decreases of *Selection Time* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were 176.66 ms, 477.37 ms, 504.08 ms, 759.87 ms and −222.24 ms respectively, which indicated that participant performance improved the most with *Rolling* (Fig. 5). On the other hand, with *Key Pressing*, performance worsened. A possible explanation for this is that using two hands diverted users' attention from target selection and also caused user fatigue.

As can be seen in Fig. 5, selection time for some of the pen modalities still decreased after 6 blocks of trials. In order to explore the learning effect in more detail, the subjects were asked to perform another 6 blocks of trials to further investigate the learning effect. As shown in Fig. 6, *Pressure* enabled the fastest selection, while *Azimuth* exhibited the slowest selection. Performance with *Tilt* was slightly faster than with *Rolling*.

5.2 Error Rate

Repeated measures analysis of variance showed a significant main effect on *Error Rate* for *Width* ($F_{2,16} = 19.29$, $p < .001$). However, there was no significant main effect on *Error Rate* for *Technique* ($F_{4,32} = 1.09$, $p = 0.38$) and *Distance* ($F_{2,16} = 0.76$, $p = 0.48$). Furthermore, there was also no significant main effect on *Error Rate* for *Technique* × *Width* ($F_{8,64} = 0.54$, $p = 0.82$) and for *Technique* × *Distance* ($F_{8,64} = 1.35$, $p = 0.23$). Subjects committed the fewest errors (4.41%) while using *Pressure* and *Tilt*, and the most errors (6.87%) while using *Azimuth*. Figure 7 and 8 illustrate the results.

Post hoc pairwise comparisons found that in the *0.0004 Width* condition, the *Error Rate* was significantly higher than in the other two *Width* conditions. Ordinarily, if a target tolerance width is narrower than the granularity of pen tip moving, it is impossible for users to achieve fine target selection using only pen tip x-y coordinate information: the fine target selection must be supplemented by means of some other input modalities, methods or techniques. The results indicate that *Pressure* and *Tilt* are good candidates.

Repeated measures analysis of variance showed that block had no significant effect on *Error Rate* ($F_{5,40} = 0.60$, $p = 0.70$). The overall decreases of *Error Rate* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were −0.62%, 1.85%, 3.09%, −3.09%, 4.32% re-

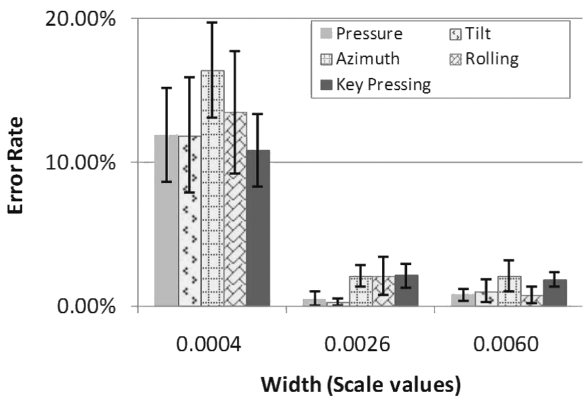

Fig. 7 Average error rate per width × technique.

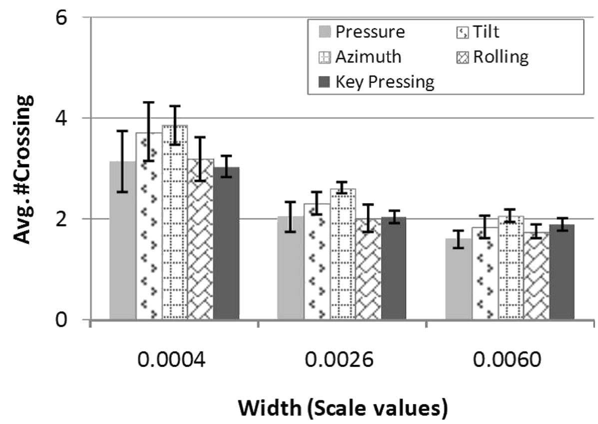

Fig. 9 Average crossings per width × technique.

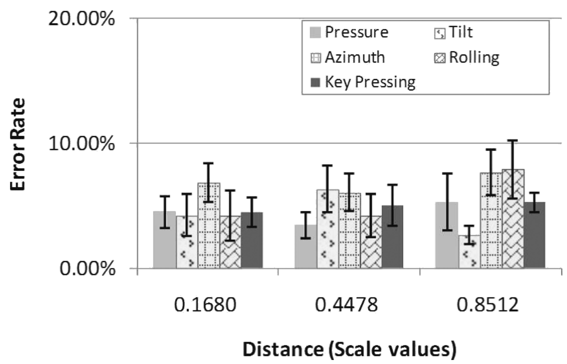

Fig. 8 Average error rate per distance × technique.

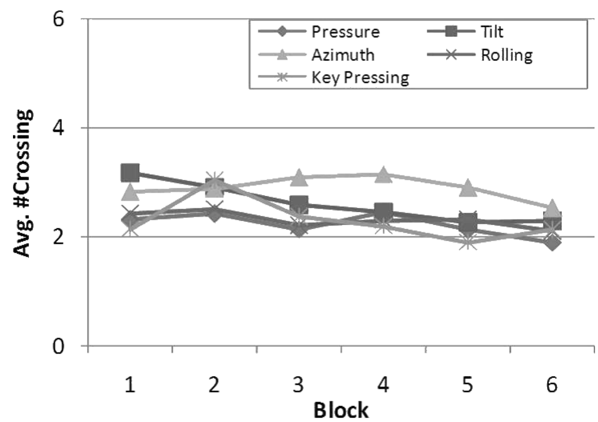

Fig. 10 Average crossings per block × technique.

spectively.

5.3 Number of Crossings

When searching for targets, subjects sometimes crossed the targets more than once. This reflects some subjective factors such as subjects trying to bring the target area within the range of visual attention, and subjects inadvertently sliding too fast. On the other hand, multiple crossings also give information about the suitability, feasibility and stability of a certain pen input modality in our experimental tasks.

Repeated measures analysis of variance showed a significant main effect on *Number of Crossings* for *Width* ($F_{2,16} = 32.40$, $p < .001$). However, there was no significant main effect on *Number of Crossings* for *Technique* ($F_{4,32} = 1.94$, $p = 0.13$) and for *Distance* ($F_{2,16} = 1.91$, $p = 0.18$). Moreover, there was also no significant main effect on *Number of Crossings* for *Technique* × *Width* ($F_{8,64} = 0.90$, $p = 0.52$) and for *Technique* × *Distance* ($F_{8,64} = 1.38$, $p = 0.22$). Subjects crossed targets the fewest times on *Pressure* (2.26 on average) and the most times on *Azimuth* (2.85 on average). Figure 9 illustrates the results.

An analysis of *Number of Crossings* across experimental blocks showed a strong learning effect ($F_{5,40} = 5.98$, $p < .001$). *Post hoc* analysis also found that in blocks 5 and 6, the *Number of Crossings* was significant fewer than in the other blocks. The overall decreases of *Number of Crossings* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were 0.41, 0.90, 0.30, 0.32, and 0.02 respectively. Figure 10 illustrates the results.

5.4 Effective Width

Although tolerance widths of targets were given, users still performed the selections nearer the targets than the given tolerance widths because they preferred more accurate selections. In our experiment, we calculated *Effective Width* of each *Technique* so that the accuracies of successful targets selections could be identified.

Repeated measures analysis of variance showed a significant main effect on *Effective Width* for *Width* ($F_{2,16} = 96.27$, $p < .001$) and *Technique* ($F_{4,32} = 1.94$, $p < .01$). Moreover, there was also a significant main effect on *Effective Width* for *Technique* × *Width* ($F_{8,64} = 2.13$, $p < .05$). *Post hoc* pairwise comparisons found that *Pressure* had the narrowest *Effective Width* while *Azimuth* had the widest. Thus, using *Pressure* resulted in the most accurate target selections. Figure 11 illustrates the results.

A further regression analysis of *Effective Width* vs. *Target Width* yielded a strong fit to the Power relationship with correlation of R-Squares greater than 0.99 for all the pen input modalities.

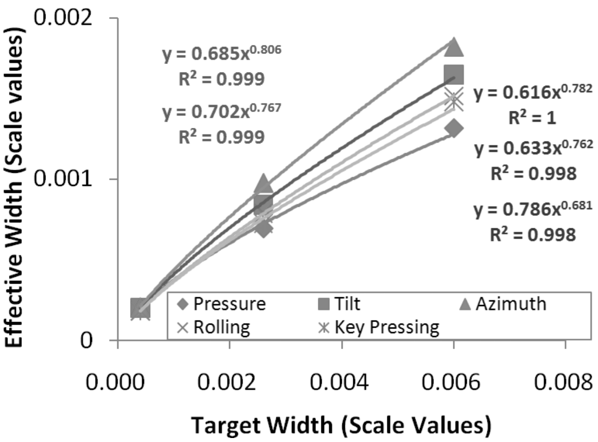

Fig. 11 Effective width vs. target width for each technique. Power regression lines are shown.

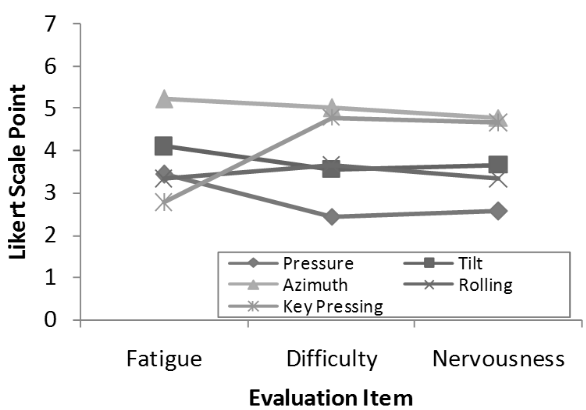

Fig. 12 Subjective evaluations with 7-point likert scale.

5.5 Subjective Evaluation

After subjects had completed the experiment, a questionnaire was given to them to evaluate the techniques. Techniques were ranked for *Fatigue*, *Difficulty*, and *Nervousness* on 7-point Likert Scales (Fig. 12). Moreover, the subjects were asked to rank the techniques in terms of *Preference*.

In general, subjects regarded *Pressure* as the best technique while *Azimuth* the worst according to *Fatigue*, *Difficulty*, and *Nervousness* evaluation results. That was consistent with the *Preference* results. However, participant opinion was not uniform. Five participants ranked *Pressure* as their most preferred technique, two *Tilt*, one *Rolling* and one *Key Pressing*.

5/9 subjects preferred *Pressure*. They reported that using *Pressure* was "subconscious" and "natural" because when looking for an unknown target or trying to see an object more clearly, they naturally wanted to press harder on the pen tip. "Pen pressure is easier to control in the experiment," and "it was simple to use pressure." Furthermore, they believed that using pen pressure brought almost no accidental pen tip movement while tilt, azimuth, and rolling often caused accidental pen tip movement. However, long time pen tip pressing also made subjects tired. Moreover, subjects often unconsciously changed pen pressure while sliding the pen, thus causing an unwanted scale granularity variation. In order to avoid unwanted pressure change, subjects must continuously monitor pen pressure by tactile sense as well as by the visual feedback presented in the interface of our experimental widget. Some subjects complained that "changing pressure only according to tactile sense is not easily perceived;" "Pressure made me nervous because it is too sensitive;" And "maintaining stable pressure made my arm sore and tired."

Tilt and *Azimuth* were regarded as easily causing fatigue. Possible reasons for this include: 1) users have to frequently tilt or rotate the pen to adjust the granularity while sliding the pen; 2) if the expected granularity was achieved, users often kept a fixed pen gesture until they finished the selection. Several subjects complained that "my hand and forearm often hang up when I used tilt and azimuth, and thus my arm felt sore and tired." Moreover, "tilting the pen while sliding, particularly to an uncommon angle, violated the naturalness of pen use habit;" "For some special pen tilt or azimuth, it was almost impossible for me to keep it steady;" "For long time manipulations, I will not choose tilt and azimuth." However, subjects also reported that tilt and azimuth provided them with inherent visual feedback from which they could be roughly aware of the present scale granularity.

Most subjects believed that *Rolling* was a promising technique. After practice, users could usually control pen rolling fluently as they wanted. "*Rolling* gave me the feeling of a radio tuner," thus "it was easy to grasp the technique".

Those who had little experience of using a stylus pen preferred using their non-preferred hands. They reported that "the task was separated in two parts: adjusting the scale granularity and sliding the pen. Thus both of my hands could work together;" And "parallel bimanual manipulation made the task easy." On the contrary, those who had more pen use experience, especially more than 2 years, advocated that using only the pen with the dominant hand rather than both hands was more rational and simple because the non-preferred hand was free. They complained that "using both hands was troublesome."

6. Discussion

According to the quantitative measures (*Selection Time*, *Error Rate*, *Number of Crossings*, and *Effective Width*) and subjective evaluations, *Pressure* enabled the fastest performance and, remarkably, even surpassed bimanual manipulation. Adjusting a parameter while sliding the pen is a common manipulation in pen-based interaction, so even tiny improvements may result in significant benefits to users. On the other hand, although performance of inherent pen input modalities other than *Pressure* did not surpass bimanual manipulation, they did have specific advantages. As well, the non-preferred-hand-free concurrent manipulation was positively rated by users, preferred to bimanual manipulation.

6.1 Advantages and Disadvantages of Pen Modalities

Our experimental results indicate that *Pressure* consistently performed satisfactorily. The possible reasons for this include: 1) adjusting pen pressure while sliding the pen is more natural and intuitive to users than adjusting other pen modalities; 2) users can take up any pen posture as they want and need not attend to pen posture when using pen pressure, since pen pressure is not influenced by different pen postures. However the other pen modalities are influenced by different pen postures; 3) unlike *Tilt* and *Azimuth*, *Pressure* typically did not produce unintentional pen tip movement, and thus speed and accuracy were better in the pressure experimental task. On the other hand, subjects reported difficulty remaining aware of the pressure level through only tactile sense because the pen did not provide them with inherent visual feedback on pressure value. Moreover, pen pressure value has the characteristics of 0-started and 0-ended. It is impossible for users to achieve a non 0 pressure value immediately after putting down the pen. It is also impossible for users to maintain a non 0 pressure value while lifting the pen.

Adjusting pen tilt and azimuth required extra time. In addition, the subjects sometimes had to maintain an unnatural pen gesture to use pen tilt or pen azimuth while sliding the pen; this also caused user fatigue. However, as for *Error Rate*, *Tilt* was excellent. In the *0.0004* and the *0.0026 Width* conditions, users committed the fewest errors with *Tilt*, as expected for high precision parameter manipulation tasks. With decreased *Width* scale, *Tilt* was very stable. This was likely because subjects could maintain a designated tilt angle more consistently than a designated pressure value, due to the visibility of pen tilt. We regard the visibility of pen tilt or azimuth as advantageous because it seemed that this feature could be used in many different application scenarios, e.g., users could directly invoke different menu items in a pie menu by simply positioning the pen at a certain tilt or azimuth angle. Besides, significant learning effects occurred with *Tilt* and *Azimuth*. With increased use experience, users gradually became comfortable with using the *Tilt* and *Azimuth*. In block 6, the *Selection Time* gaps between *Pressure* and *Tilt/Azimuth* were markedly reduced.

Unlike *Pressure*, *Tilt* and *Azimuth* can achieve a non-0 value through different user pen gestures. Moreover, when the pen is lifted, *Tilt* and *Azimuth* need not return to any default values. Thus using pen tilt or azimuth can invoke either a monotonous increase or a monotonous decrease after the pen is put down as a result of simply tilting the pen forward or back, or adjusting the pen azimuth clockwise or counterclockwise, which can be mapped onto zooming in and zooming out respectively.

To most subjects, *Rolling* was acceptable; they reported that it caused almost no fatigue. Some users reported enjoying *Rolling* because they found rolling the pen was quite similar to rotating a tuner knob. Moreover, users thought that accidental pen tip movement caused by rolling didn't significantly affect accuracy. At any rate, the accidental pen tip movement caused by *Tilt*, *Azimuth* and *Rolling* can be compensated for in real applications via specific technical treatment.

For users who had little pen use experience, using the non-preferred hand was welcomed. Although bimanual performance gave good results, it is not the ideal technique either since it requires using two hands at the same time.

Although we have discussed the advantages and disadvantages of pen modalities in precision parameter manipulations during trajectory tasks, it should be noted that the advantages and disadvantages may vary according to different tasks. Choice of effective pen input modality should be based on task type. If the user has to control an orientation parameter, *Azimuth* may be more intuitive and convenient for user manipulation. Besides, in real applications, two or more pen input modalities are often used in tandem. If a task requires the control of more than one parameter simultaneously, combined use of multiple pen modalities may be more appropriate. We regard the combination use of pen input modalities as promising and worthy of exploration in future work.

6.2 Users' Habits and Expectations

According to user preference, uni-manual manipulation was favored over bi-manual manipulation. Users wanted to achieve improved manipulation using only a pen so that they could accomplish the experimental tasks with only their dominant hands.

On the other hand, users also hoped that uni-manual manipulation could be simpler and more effective. Thus *Pressure* was the most highly rated technique because of its "natural" and "simple" characteristics. We also found that subjects often paid attention to additional overhead factors which influenced the results of their performing. For example, when using *Tilt*, *Azimuth*, or *Rolling* during pen sliding actions, unwanted pen tip movement often occurred, which was complained about by most of the subjects thus again *Pressure* was highly rated.

Subjects exhibited learning. When a new technique was first presented, subjects were often not used to the new technique. However, after a period of practice, most of them could find a unique and appropriate operation method in order to perform the given task. Once they acquired the knack, they could easily perform the task and enjoy the knack. Moreover, if they found something was really helpful to them, e.g. after they found that the inherent visual feedback of *Tilt* and *Azimuth* made selection easier, they would generally make full use of that feature.

7. Conclusion

In this paper, four kinds of inherent pen input modalities (*Pressure*, *Tilt*, *Azimuth*, and *Rolling*) used for high precision parameter manipulation during pen sliding were comparatively investigated. We conducted an experiment to evaluate their performance and compared them with *Key Pressing* using the non-preferred hand. Our results indicate that subjects performed fastest and with the fewest errors when using *Pressure*. However, performance with *Azimuth* was the worst, and subjects evaluated *Azimuth* as unsuitable for the experimental tasks because of it conflicted with their pen use habits. *Tilt* showed slightly faster performance and achieved lower error rate than *Rolling*. Moreover, *Tilt* achieved the lowest error rate in some *Width* and *Distance* conditions. Nevertheless, participant performance improved the most with *Rolling*, and *Rolling* was favored over *Tilt* in subjective evaluations. Our experimental results verify the feasibility of concurrent pen manipulations based on pen input modalities and provide pen-based interface designers with a general understanding of pen input modality choice for precision parameter manipulation during trajectory tasks.

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