

PAPER

An Investigation of Adaptive Pen Pressure Discretization Method Based on Personal Pen Pressure Use Profile

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SUMMARY Continuous pen pressure can be used to operate multi-state widgets such as menus in pen based user interfaces. The number of levels into which the pen pressure space is divided determines the number of states in the multi-state widgets. To increase the optimal number of divisions of the pen pressure space and achieve greater pen pressure usability, we propose a new discretization method which divides the pen pressure space according to a personal pen pressure use profile. We present here four variations of the method: discretization according to personal/aggregation pen pressure use profile with/without visual feedback of uniform level widths and the traditional even discretization method. Two experiments were conducted respectively to investigate pen pressure use profile and to comparatively evaluate the performance of these methods. Results indicate that the subjects performed fastest and with the fewest errors when the pen pressure space was divided according to personal profile with visual feedback of uniform level widths (PU) and performed worst when the pen pressure space was divided evenly. With PU method, the optimal number of divisions of the pen pressure space was 8. Visual feedback of uniform level widths enhanced performance of uneven discretization. The findings of this study have implications for human-oriented pen pressure use in pen pressure based user interface designs.

key words: human-computer interaction, pen pressure, discretization method, pen pressure profile, pen-based interfaces

1. Introduction

Compared with other input devices such as keyboards and mice, pens have advantages of portability, outdoor availability, short-time practice, and convenience for drawing. As a result, pens have gradually become favored and are widely used in Tablet PCs, PDA, and mobile phones. On the other hand, pens are inferior to keyboards and mice in input capacity. A pen tip's x-y information is mapped to the cursor position in traditional WIMP interfaces (in human-computer interaction, WIMP stands for "window, icon, menu, and pointing device", denoting a style of interaction using these elements). Although binary buttons are provided on the pen barrel, unwanted pen tip movement caused by button press often influences the pen manipulation.

In addition to the usual x-y position and binary button press information, most pens provide continuous pressure input and thus the pen input capacity is raised. This pressure input may be used to operate a widget that has several discrete states. The optimal number of levels into which the pen pressure space is divided within human control ability determines the number of states in the multi-state widget. If

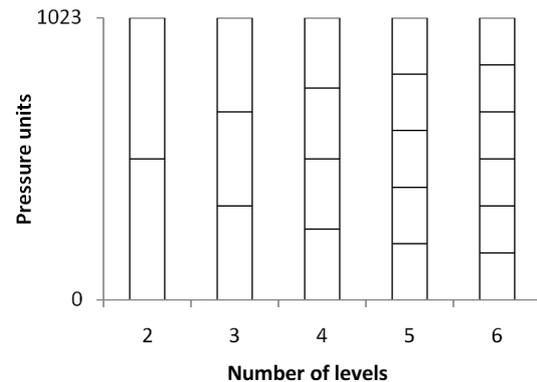


Fig. 1 Schematic diagram of even discretization method.

the number of pen pressure levels is less than the required number of discrete states of the widget, some states in the multi-state widget cannot be achieved.

Ramos et al. [1] explored the design space of pressure-based interactions with styli. They divided the whole pressure space into equal levels (Fig. 1) and found that 6 levels resulted in optimal controllability. However, even discretization will not likely afford optimal usability because human ability to control different levels of pen pressure varies over all levels, i.e., some pen pressure levels may be easier to control than others.

In order to increase the discernible number of pen pressure levels and make the discretization more suitable for user manipulation, we proposed an adaptive pen pressure discretization method based on pen pressure use profiles. We predicted that better performance could be achieved through discretization based on personal pen pressure use profiles than through even discretization. We also wanted to investigate whether 7 or more pen pressure levels could be discriminated by use of our discretization method.

2. Related Work

Research on pressure could be traced back to the last century. Herot et al. [2] investigated force input by detecting finger pressures on a pressure-sensitive digitizer and asserted that touch and pressure sensing opened a rich channel for immediate and multi-dimensional interaction. Buxton et al. [3] investigated touch-sensitive tablet input and presented examples such as painting with pressure sensing to suggest ways in which touch tablets could be used.

Literature related to pen pressure emerged mainly after

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the new Millennium, and most of them focused on novel interactive application designs. Mizuno et al. [4] implemented a virtual sculpting system by converting pen pressure to carving depth and angle. Ramos et al. [5] proposed a concept prototype designed for use with pressure-sensitive digitizer tablets to fluidly navigate, segment, link, and annotate digital videos; created the Zlider [6] that users can use pen pressure to achieve fluid zooming while sliding the pen; and developed pressure marks [7] that allowed users to perform a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time. Oshita [8] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure.

Some research focused on increasing the input bandwidth by means of pen pressure. Harada et al. [9] used pen pressure as an input modal to augment simultaneous input capacity. Ren et al. [10] proposed the Adaptive Hybrid Cursor to facilitate target selection performance by automatically adjusting cursor size according to pen pressure. Yin and Ren [11] proposed a zoom-based technique to improve pixel-target selection, in which the pressure is used as a mode switch.

Besides, some studies have utilized pen pressure as a clue that supports special analysis. To assist in biometric personal identification and digital signature verification, Hook et al. [12] added pressure sensors to a pen for 3D pressure analysis of handwritten characters, words and signatures. Oviatt et al. [13] investigated implicit user adaptive engagement via speech amplitude and pen pressure cues and found that users tended to clarify engagement by increasing the pen pressure.

There were also some published studies that focused on exploring 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. Mizobuchi et al. [14] further explored the force-based input on handheld devices and found subjects distinguished five to seven input levels within the set of ten force ranges actually used. Li et al. [15] 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.

On the other hand, some studies augmented traditional mice with pressure sensors to enhance input. Cechanowicz et al. [16] investigated the technique of augmenting a mouse with pressure sensors to increase input vocabulary and found that 64 modes could be controlled by users using a dual-pressure augmented mouse. Shi et al. [17] improved the control of discrete pressure-based input by using a fish-eye method, reducing error rates significantly.

Although the above mentioned studies reported the benefits of pressure as an alternative input channel, they also reported high error rate resulting from pressure-based input. According to previous research, the optimal number of divisions of the pen pressure space was 6. However, in a con-

crete pen based user interface design, more divisions may provide more flexibility. Also even division of pen pressure space may not result in optimal usability. In this light, we are motivated to find a new discretization method to both increase discernable pen pressure level number and make division of pen pressure space more suitable for user manipulation.

3. Design Framework and Method Elaboration

The exploration reported here includes the following work: investigating pen pressure use profiles for subjects in a natural writing and drawing experiment; dividing the pen pressure space into 2 to 12 levels according to personal pen pressure use profiles; and evaluating performance of the new proposed pen pressure discretization method.

Frequency of each pen pressure unit for each subject was calculated according to the results of the natural writing and drawing experiment. Then, the total pen pressure space was divided according to personal pressure use profiles. The first level started from pressure unit 0 and each level accounted for same pressure use frequency. For example, if the pen pressure space is divided into 8 levels, each level will account for 12.5% of pen pressure use frequency according to the results of the natural writing and drawing experiment. If the pen pressure use frequency from pressure unit 0 to 358 accounts for 12.5%, the first level will start at pressure unit 0 and end at pressure unit 358, and the other levels follow analogously. Figure 2 is a schematic diagram of the discretization of pen pressure space with the new proposed method.

The theory underlying the proposed method is based on the hypotheses that 1) higher frequency of pressure unit in natural writing and drawing experiment indicates that subjects use pressure more inherently in that pressure unit and thus they have stronger ability to control that pressure unit; 2) higher frequency of pressure unit gives users more experience, which further enhances the ability to control that

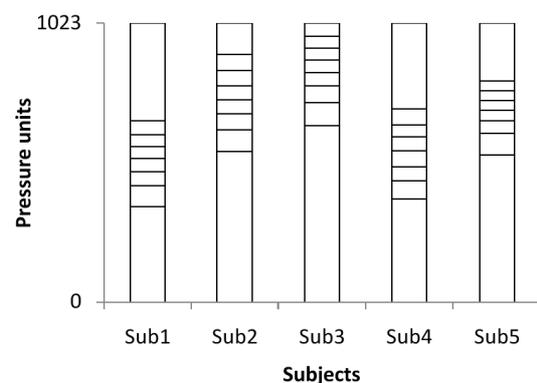


Fig. 2 Pen pressure space was divided into 8 levels according to the pen pressure distributions of five subjects. In experiment 2, targets were defined as the adjacent rectangles shown in the figure, which presented the pen pressure levels. The variable level width division for each subject resulted from uniform divisions of pen pressure use frequency.

pressure unit. As a result, levels containing pen pressure units with higher use frequencies should be allocated fewer pressure units.

In order to achieve the optimal number of pen pressure space divisions, we explored the performance of dividing pen pressure space into 2 to 12 levels. Taking into account that varied level widths may give users varied degrees of tension, we also investigated performance with visual feedback in the form of uniform level widths: although the discretization of pen pressure space was based on personal pressure profile, the presentation of each level was in the same visual width. In this situation, the real widths of each level were varied but the level widths which subjects saw were uniform. On the other hand, sometimes personal pen pressure profile may not be obtained in time, so we also explored the performance of pen pressure discretization based on the aggregation profile of all subjects. Thus, we explored 5 different discretization methods: AN (dividing the pen pressure space according to the aggregation profile of all subjects); AU (dividing the pen pressure space according to the aggregation profile of all subjects with visual feedback of uniform level widths); PN (adaptively dividing the pen pressure space according to personal profile); PU (adaptively dividing the pen pressure space according to personal profile with visual feedback of uniform level widths); and EV (dividing the pen pressure space evenly).

4. Experiment 1 - Pen Pressure Use Profile Investigation

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.

4.2 Equipment

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used. The Cintiq 21UX quantifies the pressure that the user acts on the stylus tip in the range from 1 to 1023 units.

4.3 Task and Procedure

This experiment investigated pen pressure use profiles when the subjects naturally wrote or drew on the tablet display surface. The subjects sat in front of the interactive display tablet which was placed in the horizontal plane. First, the subjects were instructed to write three types of characters on the tablet display. The characters included symbols (@, ☆, &, ×) and letters (S, E, M, B). Then the subjects were asked to draw freehand strokes (e.g. arbitrary curves and straight lines) in a natural manner, for a period of 3 minutes. Pen pressure was sampled every 10 ms while the pen was in contact with the display surface.

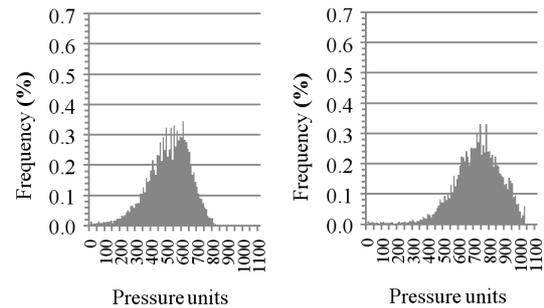


Fig. 3 Pen pressure profiles of two subjects.

4.4 Results

Univariate analysis of variance revealed a significant difference in average pressure ($F_{1,8} = 449.94, p < .001$) and in standard deviation of pressure ($F_{1,8} = 1405.28, p < .001$) among subjects. The average pressure for all subjects was 752.75 with standard deviation 192.04. Figure 3 shows examples of the pen pressure use profiles of two subjects.

Results indicate that each subject has a unique pen pressure use profile. This suggests that suitable pressure and the controllability of different pressure units should differ by subjects. As a result, even discretization method of pen pressure space should be ineffective.

5. Experiment 2 - Discretization Method Evaluation

5.1 Participants and Equipment

The same 9 individuals who participated in Experiment 1 took part in Experiment 2. And the same equipment was used as in Experiment 1.

5.2 Task and Procedure

Subjects were seated in front of a display tablet placed in the horizontal plane. 1024 pen pressure units were mapped to a spatial distance of 520 pixels in the screen. A serial target acquisition and selection task was used. The targets were a set of adjacent rectangles which presented pen pressure levels according to the pen pressure use profiles and the number of pen pressure divisions (Fig. 2). During each trial, one of the targets was highlighted in red. If the pen pressure was controlled within the range of a certain level, the corresponding rectangle was colored grey. Subjects were instructed to apply the appropriate amount of pressure to match the target pressure level as quickly and accurately as possible. If the pen pressure was controlled within target pressure level, the target color switched to green. Target selection was performed by a space key press on the keyboard. If a misselection was made, a failure icon appeared and an audio tip was given to the subject.

A within-subject full factorial design with repeated measures was used. Five kinds of pen pressure discretization methods (AN, AU, PN, PU, and EV) were investigated.

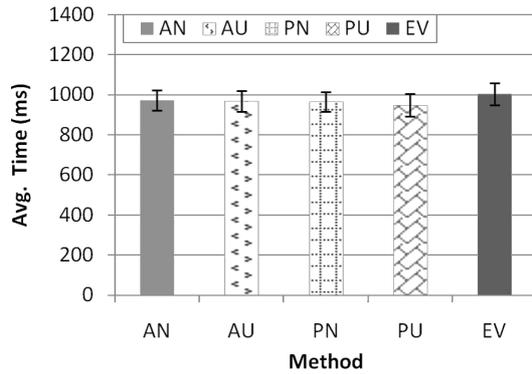


Fig. 4 Average selection time per method.

A Latin Square was used to counterbalance the order of appearance of methods. We explored number of levels, or *nLevels*, from 2 to 12 ($2 + 3 + 4 + \dots + 12 = 77$ pen pressure level targets in total). In order to investigate the learning effect, trials were grouped in “blocks”. Each subject was asked to perform 3 blocks of trials for each method. Each block consisted of the 77 different selection tasks described above. Trials were repeated 2 times under the same condition for reliability within each block. Presentation of trials within a block was randomized. In total, the experiment consisted of:

- 9 subjects ×
- 5 methods ×
- 3 blocks ×
- 77 level targets ×
- 2 repetitions
- =20790 target selection trials

5.3 Results

5.3.1 Selection Time

Selection time is defined as the time from when the pen comes into contact with the tablet’s surface until the subject executes target selection by pressing the space key on the keyboard. In selection time analysis, trials in which the subjects committed selection and release errors were excluded. Repeated measures analysis of variance showed a significant main effect on selection time for method ($F_{4,32} = 4.10$, $p < .01$) and *nLevels* ($F_{10,80} = 97.00$, $p < .001$). However, there was no significant interaction effect on selection time for method × *nLevels* ($F_{40,320} = 1.18$, $p = 0.22$). Figure 4 and 5 illustrate the results. Error bars in the figures of this paper indicate the standard errors (the standard deviations of the sampling distribution of the means).

Post hoc pairwise comparisons showed significant differences between method pair (AU, EV) ($p < .05$), (PN, EV) ($p < .05$), and (PU, EV) ($p < .01$). Subjects performed fastest using PU method, and performed slowest using EV method. *Post hoc* pairwise comparisons found significant difference ($p < .05$) between all *nLevels* pairs except (7, 8) ($p = 0.28$), (8, 9) ($p = 0.14$), and (10, 11) ($p = 0.67$).

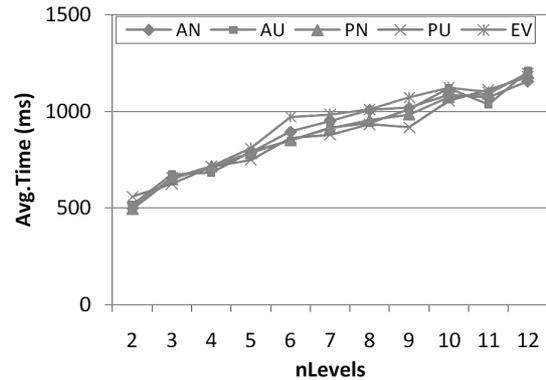


Fig. 5 Average selection time per method × *nLevels*.

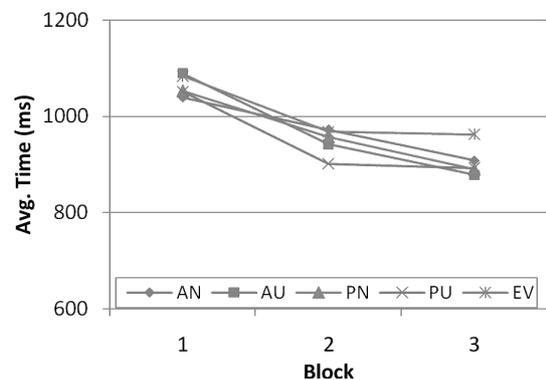


Fig. 6 Average selection time per block × method.

A repeated measures analysis of variance showed that block had a significant effect on selection time ($F_{2,16} = 13.42$, $p < .001$). *Post hoc* analysis also found that in block 1, selection time was significantly longer than in other two blocks ($p < .01$) for all discretization methods. Subjects exhibited learning. Figure 6 illustrates the results.

5.3.2 Selection Error

Selection error rate was defined as the percentage of trials in which the subjects made erroneous selections. Repeated measures analysis of variance showed a significant main effect on selection error rate for method ($F_{4,32} = 2.99$, $p < .05$) and *nLevels* ($F_{10,80} = 34.76$, $p < .001$). However, there was no significant interaction effect on selection error rate for method × *nLevels* ($F_{40,320} = 0.86$, $p = 0.72$). *Post hoc* pairwise comparisons found that subjects committed significantly more selection errors using EV method than using PN method ($p < .05$) and than using PU method ($p < .05$). Subjects committed the fewest selection errors (9.92%) using PU method and the most selection errors (13.51%) using EV method. Figure 7 and 8 illustrate the results.

Results showed that selection error rate for EV method was over 10% when the *nLevels* was more than 5. This is basically consistent with the statement of [1] that dividing pressure space into 6 levels resulted in best perfor-

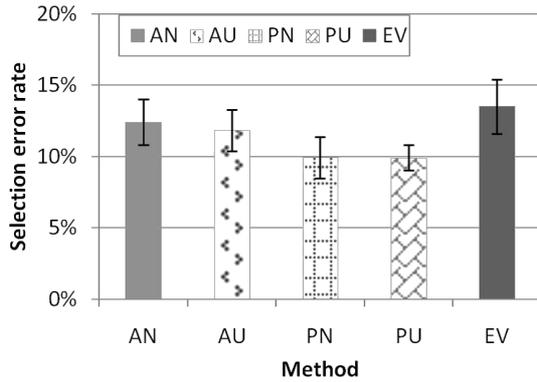


Fig. 7 Selection error rate per method.

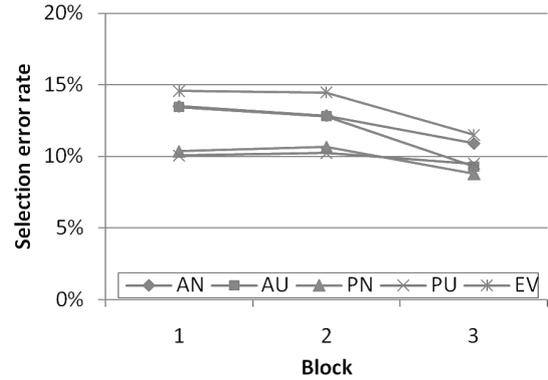


Fig. 10 Selection error rate per block x method.

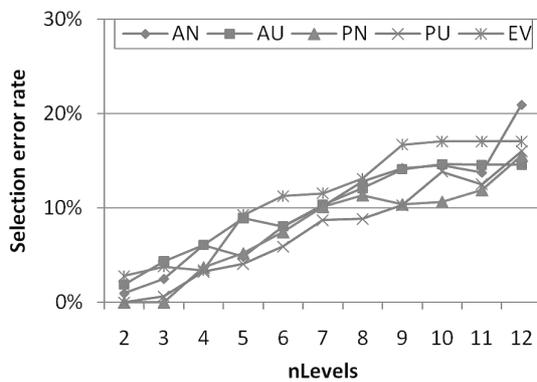


Fig. 8 Selection error rate per method x nLevels.

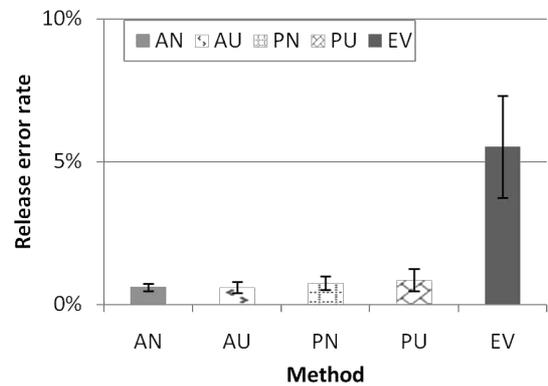


Fig. 11 Release error rate per method.

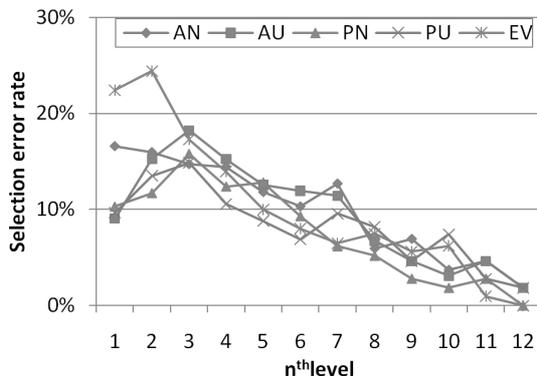


Fig. 9 Selection error rate per method x nth level.

mance. However, for the PU method, selection error rate was less than 10% when nLevels <= 8 and was 10.3% when nLevels = 9, which indicates PU method surpassed EV method in the respect of selection error rate.

A further analysis indicates that the subjects committed significantly more errors in first and second level selections using EV method (Fig. 9). Moreover, during the experiment, some subjects also complained that lower pen pressure was quite difficult to control.

A repeated measures analysis of variance showed that block had no significant effect on selection error rate ($F_{2,16} = 3.33, p = 0.06$). Nevertheless, selection error

rate gradually decreased while block number increased. Figure 10 illustrates the results.

5.3.3 Release Error

Subjects sometimes lifted the pen tip and broke contact with the tablet surface when trying to select a low pressure level. Before a selection is performed, if the pen tip does not remain in contact with the surface, a release error is counted and the subject must perform the task again. Repeated measures analysis of variance showed a significant main effect on release error rate for method ($F_{4,32} = 8.06, p < .001$). However, there was no significant main effect on release error rate for nLevels ($F_{10,80} = 0.70, p = 0.73$) and no significant interaction effect on release error rate for method x nLevels ($F_{40,320} = 1.37, p = 0.07$). *Post hoc* pairwise comparisons found that the release error rate for EV was significantly higher than for all other methods ($p < .05$). Figure 11 and 12 illustrate the results.

Further analysis found that most of release errors were committed in first and second level selections when using EV method. This again indicates that lower pressure was difficult for user to control. However, using the methods we newly proposed, release error rate was dramatically dropped in first and second level selections. Figure 13 illustrates the results.

A repeated measures analysis of variance showed that

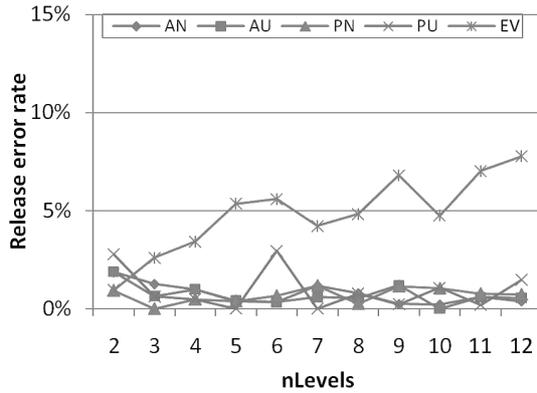


Fig. 12 Release error rate per method x nLevels.

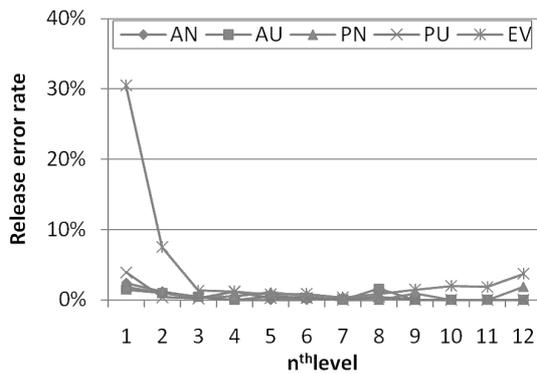


Fig. 13 Release error rate per method x nth level.

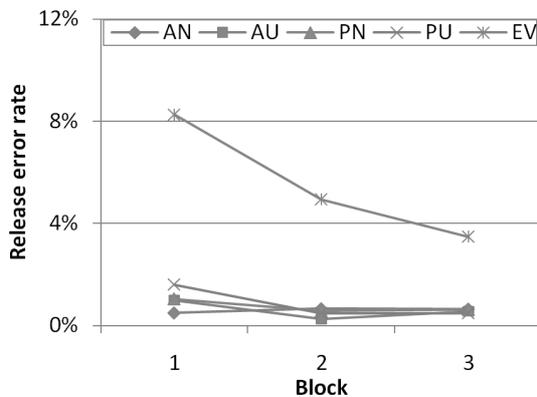


Fig. 14 Release error rate per block x method.

block had no significant effect on release error rate ($F_{2,16} = 2.59, p = 0.11$). Nevertheless, release error rate decreased while block number increased when using EV method. Figure 14 illustrates the results.

5.3.4 Number of Crossings

When searching for a target, subjects sometimes crossed the target more than once. Number of crossings, NC, is defined as the number of times subjects controlled pen pressure inside or outside a target in a particular trial, minus 1. Re-

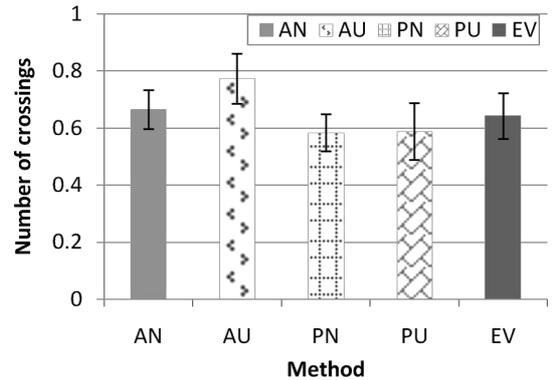


Fig. 15 Number of crossings per method.

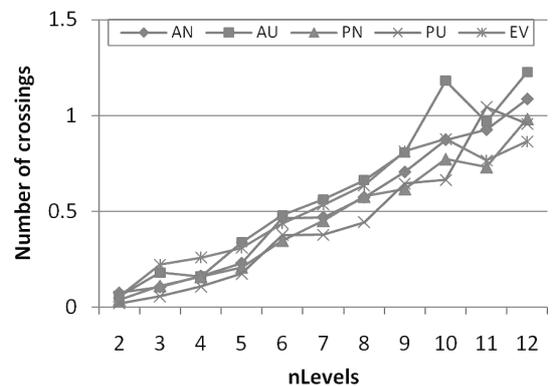


Fig. 16 Number of crossings per method x nLevels.

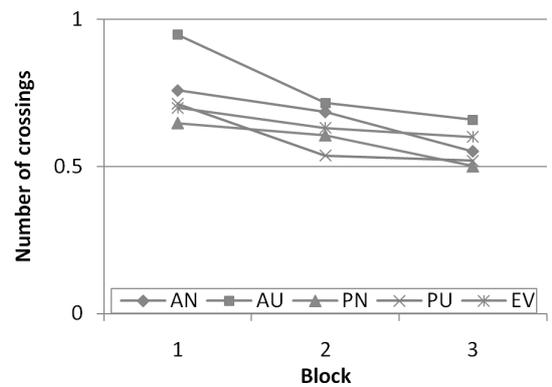


Fig. 17 Number of crossings per method x block.

peated measures analysis of variance showed a significant main effect on NC for method ($F_{4,32} = 2.78, p < .05$) and nLevels ($F_{10,80} = 75.44, p < .001$). Moreover, there was a significant interaction effect on NC for method x nLevels ($F_{40,320} = 1.70, p < .01$), which revealed an interaction effect of method and nLevels on NC. When dividing pen pressure space into 10 levels, a sharp increase of NC was found in the AU method case but was not found in the PU method case. This was probably because personal profile was more appropriate for pen pressure space discretization than aggregation profile of all subjects. *Post hoc* pairwise comparisons found that the NC for AU method was signifi-

cantly higher than for PN method ($p < .05$). Figure 15 and 16 illustrate the results.

A repeated measures analysis of variance showed that block had a significant effect on NC ($F_{2,16} = 9.82, p < .01$). *Post hoc* pairwise comparison showed significant difference between all block pairs ($p < .05$). Figure 17 illustrates the results.

6. Discussion

Our results show that the different discretization methods have significantly different effects on the usability of pen pressure for performing discrete selection tasks. In terms of quantitative measures (selection time, selection error rate, release error rate, and NC), PU enabled the fastest performance with the fewest errors, whereas EV the slowest with the most errors. Our results indicate that PU is a feasible discretization method that may be used to advantage in pen-based user interface design.

6.1 Discernable Number of Pen Pressure Levels

One of the main targets of this research has been to achieve the optimal number of pen pressure levels (ONPL) for different discretization methods. ONPL here was defined as the maximum number of pressure levels that users are able to manipulate with optimum performance. ONPLs were determined from the quantitative measure results. For selection time, ONPL was the maximum number of pressure levels where no significant differences were found between adjacent nLevels pairs. For selection error rate and NC, we set the same acceptability ranges as in [1]: selection error rate less than 8% and NC less than 1. As Ramos et al.'s study [1] did not investigate release error, we determined the release error rate acceptability range by applying the two standard deviations rule [19] to this set of data, yielding the rule of release error rate less than 4.55%. Finally, the General ONPL for each discretization method was obtained from the minimum value among ONPLs. Table 1 illustrates the results.

According to the above analysis, the General ONPL for EV method is 4, which is not in agreement with the results of [1]. This is probably because we used a different selection technique, key press, in our experiment. This does not influence the performance comparison between discretization methods since the same selection technique was used throughout the experiment. It is noteworthy that using PU

method, the General ONPL was 8, which means that more pen pressure levels were discerned with PU method than with traditional even discretization methods.

6.2 Influence of Visual Feedback

As was anticipated at the design stage, visual feedback of uniform level widths enhanced performance of uneven discretization in all quantitative measures except NC. The reason for this performance difference might be nervous tension resulting from varied level widths in a given discretization task. Subjects also reported that varied level widths made the discretization look chaotic and the narrower levels induced psychological pressure before selection. Visual feedback of uniform level widths provided a feasible solution to subjective discomfort. On the other hand, visual feedback of uniform level widths may have caused an undesirable illusion. Some subjects reported that because some target levels were visually enlarged, they believed that they had a wider tolerance to select the levels, which may be the reason for higher NC with uniform level widths visual feedback than with varied level widths visual feedback.

6.3 Pen Pressure User Experience

According to the results of experiment 2, more selection errors and release errors were committed at lower pressure levels in EV method. Some possible reasons are: 1) according to the Web's Law [18], it is almost impossible for users to distinguish pen pressure stimulus change when the change is below the JND (Just Noticeable Difference) threshold, thus lower pen pressure is difficult for users to control; and 2) the pen has its own weight. We measured the pressure produced by the weight of the pen used in the experiments and found that the default pressure was about 185 when the pen tip was perpendicular to the display tablet surface with no extra force exerted on the pen tip. When the pen barely came into contact with the tablet surface, the user did actually lift the pen, and the pen pressure was reported as 0. Moreover, the user had to lift the pen, provided detected pen pressure was less than the pen weight. In this situation, the user had to lift the pen and maintain the pen tip in contact with the surface at the same time, which increased the difficulty of pen pressure control. However, when the pen pressure was greater than the pen weight, the user did press the pen tip. The switch from lifting to pressing the pen further increased the difficulty of pen pressure control.

Therefore, the improvement of performance at lower pressure levels is critical. Using our discretization method, error rate at lower pressure level selection was significantly reduced. Moreover, subjects also reported that using PU method, the first and second levels were no longer difficult to select. Some subjects also said, "It was convenient to select a given target with PU method." We also believe that PU is a more suitable discretization method for user manipulation because the discretization is based on a personal pen pressure use profile.

Table 1 Optimal number of pen pressure levels (ONPL) for all discretization methods.

Quantitative Measure Discretization Method	ONPL for Selection time	ONPL for Selection error	ONPL for Release error	ONPL for NC	General ONPL
AN	5	6	12	11	5
AU	8	6	12	9	6
PN	11	6	12	12	6
PU	8	8	12	10	8
EV	5	4	4	12	4

Although the aggregation profile was used in AN and AU methods, better performances were achieved than with EV method. In particular, AU method has the same General ONPL as PN method, which verified the feasibility of using aggregation profile as a substitute for personal profiles. Although using aggregation profile did not achieve the best performance, the difficulty in lower pressure control was remedied. Moreover, the methodology of constructing a transfer function from an aggregated user profile to substitute for personal ones may spread to other pen input modalities, e.g. pen tilt input, which we will further explore in future work.

On the other hand, subjects committed the fewest errors at the last level of all discretization methods. The reason for this is that the subjects could press the pen tip with arbitrarily high pressure greater than the penultimate level boundary and as a result they could ensure correct selections. Furthermore, according to Fig. 9, the subjects made fewer selection errors at higher levels. This might indicate that users could control higher pressures more precisely than expected. If higher pressures were appropriately exploited, the error rate might be reduced.

6.4 Effective Profiles Achievement

In this study, the pen pressure use profiles were derived from a natural writing and drawing experiment. However, we are also aware that the investigation of pen pressure use profile might not be comprehensive and appropriate because pen manipulation types are numerous, including writing, drawing, steering, tracing, and intentionally navigating the pressure space. As a result, for more effective pen pressure based interface designs, it is better to derive personal pen pressure use profiles according to performance of concrete tasks.

7. Conclusion

To increase the optimal number of divisions of the pen pressure space and achieve greater pen pressure usability, a new discretization method which divides the pen pressure space according to a personal pen pressure use profile is proposed here. We explored here four variations of the method: discretization according to personal/aggregation pen pressure use profile with/without visual feedback of uniform level widths and the traditional even discretization method. This paper firstly explored the pen pressure use profile of the subjects and then comparatively evaluated performance of the five methods. According to the quantitative measures (selection time, selection error rate, release error rate, and NC), subjects performed fastest and with the fewest errors when the pen pressure space was divided according to personal profile with visual feedback of uniform level widths (PU) and performed slowest with the most errors when the pen pressure space was divided evenly. Moreover, dividing pen pressure space according to the aggregation profile of all subjects also resulted in better performance than dividing pen pressure space evenly. With PU method, the optimal

number of divisions of the pen pressure space was 8. Visual feedback of uniform level widths enhanced performance of uneven discretization. Our exploration indicates that PU is a feasible discretization method that may be useful in pen-based user interface design.

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