Mode Switching Techniques through Pen and Device Profiles

Huawei Tu
Kochi University of Technology, Kochi, Japan
ren.xiangshi@kochi-tech.ac.jp

Xing-Dong Yang
University of Alberta
Alberta, Canada
xingdong@cs.ualberta.ca

Feng Wang
Kunming University of Science and Technology
Yunan, China
wf@cnlab.net

Feng Tian
Institute of Software
Chinese Academy of Sciences, Beijing, China
tf@iel.iscas.ac.cn

Xiangshi Ren
Kochi University of Technology, Kochi, Japan
ren.xiangshi@kochi-tech.ac.jp

ABSTRACT
In pen-based interfaces, inking and gesturing are two central tasks, and switching from inking to gesturing is an important issue. Previous studies have focused on mode switching in pen-based desktop devices. However, because pen-based mobile devices are smaller and more mobile than pen-based desktop devices, the principles in mode switching techniques for pen-based desktop devices may not apply to pen-based mobile devices. In this paper, we investigated five techniques for switching between ink and gesture modes in two form factors of pen-based mobile devices respectively: PDA and Tablet PC. Two quantitative experiments were conducted to evaluate these mode switching techniques. Results showed that in Tablet PC, *pressure* performed the fastest but resulted in the most errors. In PDA, *back tapping* offered the fastest performance. Although *pressing and holding* was significantly slower than the other techniques, it resulted in the fewest errors in Tablet PC and PDA. *Pressing button on handheld device* offered overall fast and accurate performance in Tablet PC and PDA.

Author Keywords
Pen interface, mobile devices, mode switching, ink, gesture.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces—*Interaction techniques*

INTRODUCTION
As a familiar tool and a precise input device, the pen has been widely used in Tablet PCs and mobile phones. One of the most common tasks in pen-based handheld devices is to record information by inking [12], which is the prominent feature of this handheld product. Considering the situation where the user quickly records information and wants to change font style or font color to highlight the content, it is beneficial to use an efficient switching technique to switch between the ink task and the gesture task.

Previous studies mainly focused on mode switching in pen-based desktop devices. Li et al. [5] systemically analyzed five mode switching techniques in a Tablet PC fixed on a desktop. Lank et al. [4] investigated the non-preferred hand mode manipulation in a Tablet PC which was fully opened and placed on a desk. Liu and Ren [6] applied pen tilt and azimuth to mode switching in a pen-based desktop device. Unlike desktop devices, handheld devices are mobile and miniature, so the conclusions drawn by previous studies may not apply to pen-based handheld devices.

Mode switching is more urgent issue in pen-based handheld devices than in pen-based desktop devices. As mentioned in [5], the usual methods to alleviate modes in pen-based interfaces are designed by using system defined gestures and appropriate interface layout. However, because of hardware limitations in handheld devices, the ability to discern gestures from other ink strokes in freeform sketches is not as strong as in that of desktop devices. In addition, the small input area also restricts icon size in pen-based devices, which makes mode switching more difficult in pen-based handheld devices. Simple and effective explicit mode switching techniques are needed to provide users advanced mode switching mechanisms in pen-based handheld devices.

Six mode switching techniques were examined in this study. Four of these techniques, *pressing the barrel button on the pen*, *pressing and holding*, *pressing the button on the handheld device* and *using pressure* were previously proposed and examined as they applied to pen-based desktop devices by Li et al. [5]. The other two techniques, *jerking movement* and *back tapping* are proposed in this study based on the features of pen-based handheld devices. The aim of this study is to compare these mode switching techniques and to find

APCHI'12, August 28–31, 2012, Matsue-city, Shimane, Japan.

the most suitable mode switching technique in two typical sizes of pen-based handheld devices: PDAs and Tablet PCs.

The paper is structured as follows. In the following section, the six mode switching techniques are described. Next, two empirical experiments are reported and the experimental results are analyzed. Finally, several design principles for mode switching techniques and directions for future research are discussed.

RELATED WORK

We reviewed previous studies related to the six techniques used in our study, with consideration of how to better employ these techniques in mobile devices for mode switching. In addition, we reviewed some other mode switching techniques which would be beneficial to the technique design in our study.

Using Pressure

The availability of pressure in pen-based devices has been explored by a number of researchers. Ramos et al. [10] carried out the first systematic investigation of the human ability to select a discrete target by varying stylus pressure under full and partial visual feedback. Ramos et al. [11] designed pressure marks, which employed pressure as a feature for selection and action simultaneously.

Employing pressure is an effective input method for mobile devices. Varying levels of pressure can be used, for example, to convert the case of letters [2]. Miyaki and Rekimoto [7] proposed a single-handed UI scheme to realize multi-state input using pressure sensing.

Stylus pressure can be used to switch input mode from inking to gesturing [5],[6]. Inking is a more common task than gesturing in stylus input, so the normal pressure space can be employed in inking mode and the heavier pressure space can be employed in gesturing mode.

A preliminary experiment was conducted to set a suitable pressure spectrum for gesturing mode and inking mode. Four participants, two males and two females, were asked to do the pie crossing task (described in the section "Experimental Design") which included four blocks for each orientation (one block included four red pie slices and four black pie slices). Participants were asked to draw with their normal pressure to cross the black pie and with their heavier pressure to cross the red pie. No visual feedback other than pressure sensitive ink thickness was given. The stylus pressure in one pie crossing task was recorded per 10 milliseconds.

The formula proposed in [5] was used to calculate the maximum average pressure which is defined as the maximum of the average pressure of one pie crossing task. The average pressure at the time t_i is measured as:

$$\mathrm{AP}_{\mathrm{t_i}} = \frac{1}{i+1}\sum_{j=0}^{i} P_j,\ P_j \text{is the pressure at the time } t_j$$

We set a pressure threshold which was higher than most average pressures in normal input conditions and lower than most average pressures in heavy input conditions. The pressure threshold for Tablet PC and PDA will be given in the section "Experiment One" and "Experiment Two" respectively.

Pressing and Holding

Pressing and holding is a widely used technique in pen-based devices such as PDA and Tablet PC. *Pressing and holding* requires the user to hold the pen tip on the screen for a predefined time, then mode switching feedback is given. The user can lift the pen tip to choose a menu item or move the pen tip to draw a gesture on the screen.

According to the method proposed by Li et al. [5], we designed a *pressing and holding* technique for this study. For a drawing trajectory, the first point was set as the base point. The holding time was defined as the duration from the moment the base point was produced to the moment the pen was moved out of the scope of a circle whose center was the base point and radius was 7 pixels. If the holding time was longer than 1 second, a red circle with a radius of 7 pixels appeared around the pen tip. If the holding time was shorter than 1 second, the subsequent point of the base point would be chosen as the new base point and the holding time would be recalculated. In the case when a red circle appeared, to perform mode switching the participant had to move the pen out of the circle within 800 ms. Otherwise, the red circle would disappear; meanwhile the current pen point would be set as the base point and the holding time would be recalculated.

Pressing the Barrel Button

Pressing the barrel button of the stylus is a commonly used technique, in which the barrel button serves the function of a mouse. Mode switching can be achieved by pressing the barrel button.

Pressing the Button on Handheld Devices

Physical buttons on handheld devices can be used to switch interfaces or functions. Pressing and then releasing the button can be used to affect mode switching.

Back Tapping on the Device

Back operation is an effective way to enhance input capability in handheld devices. Users can input information by fully utilizing the back of the device. Sugimoto and Hiroki [15] mounted a touchpad to the rear surface of a PDA and proposed a new technique called HybridTouch. Yang et al. [20] designed a Dual-Surface technique by means of mounting a touchpad at the back of a PDA, and systematically investigated the ability of backside operation via two experiments. Tapping input was an embedded interaction method for mobile devices [13]. Back tapping was used to trigger a continuous mode in mobile devices [14]. Wobbrock et al. [18] analyzed the performance of pointing tasks with respect to the interaction with one and two hands, thumbs and index fingers, horizontal and vertical movements, and front- and back-of-device manipulation in a mobile device respectively. The results showed that the index finger offered good performance on both the front and the back of the device, and that the thumb performed worse on the front of the device.

In this study, we used a prototype similar to that in [20] where we attached an Ergonomic USB touchpad [?] on the back of the experimental device. Participants were asked to tap on the touchpad to perform mode switching using the index finger of the non-dominant hand.

Jerking Movement

In a noteworthy study, Roudaut [14] used a jerking movement to activate a mode that helped to reach the last opened window. In this study, we used vibration acceleration to detect jerking movements.

Considering the vibration difference is usually small while inking input, we set the normal vibration difference space for inking and large vibration difference space for gesturing.

To determine the jerking direction for *jerking* technique, a pilot study was conducted with four participants, two males and two females. Participants were requested to jerk two handheld devices, PDA and Tablet PC over x, y and z axis respectively (ten times for each exis) by their non-preferred hand. They were asked over which axis the jerking task was easier and fastest to accomplish. For the Tablet PC, all participants reported that the jerking task was easy to accomplish over the z axis. Regarding the PDA, three participants reported that the jerking task was easy to accomplish over the z axis, and a female participant said it was easier to accomplish over the y axis but she admitted that it was faster over the z axis. According to their reports, jerking a handheld device over the z-axis (forward or backward) was the preferred method to perform the mode switching task.

A Phidget Accelerometer 3-Axis [9] which can detect vibration with $\pm$ 29.4 m/s^2 change per axis, was used to measure the vibration over the z-axis. Jerking movement was detected by calculating the difference between the smallest acceleration value and the largest acceleration value in an experimental trial. The acceleration difference is defined as:

$AD = Max(A_i) - Min(A_j), 0 \leq i, j \leq t$, A_i and A_j are the acceleration values in time i and j, t is the total task time of an experimental trial.

A preliminary experiment was conducted to set a suitable acceleration difference spectrum for gesturing mode and inking mode. Four people, two males and two females, were required to do the pie crossing task (described in section "Experimental Design") which had four blocks for each orientation (one block included four red pie slices and four black pie slices). If a red pie appeared, participants were asked to jerk the device with comfortable jerking movement over the z-axis (forward or backward) and then perform the pie crossing task. If a black pie appeared, participants only needed to do the pie crossing task. The value of device acceleration in one pie crossing task was recorded per 10 milliseconds.

We set an acceleration difference threshold which was higher than most acceleration difference values in the non-jerking condition and lower than most acceleration difference values in the jerking condition. The acceleration difference thresholds for Tablet PC and PDA will be given in "Experiment One" and "Experiment Two" respectively.

Other Mode Switching Techniques

Bi et al. [1] explored how to use pen rolling in pen-based interactions, including the task of mode switching. Pen tilt can also be employed to perform mode switching [19]. We did not use pen rolling or pen tilt in this study as these two input techniques are not available in current mobile devices. The combination of finger gesture on the pen barrel plus device tilt can produce a sense of natural and seamless operation for mode switching [16]. Motion gesture on mobile devices can produce better mode switching for word input [17]. Inspired by the above two techniques proposed in [16] and [17], we designed and tested a technique named *Jerking Movement* in our study.

EXPERIMENTAL DESIGN

Experimental Task

Our experimental design was based on the experimental paradigm proposed in [5]. As shown in Figure 1a, a pie slice was shown with its symmetry axis corresponding to one of the eight major geographical directions. Pie crossing task was the process of crossing a pie slice from its inner edge to its outer edge with the requirement of high speed.

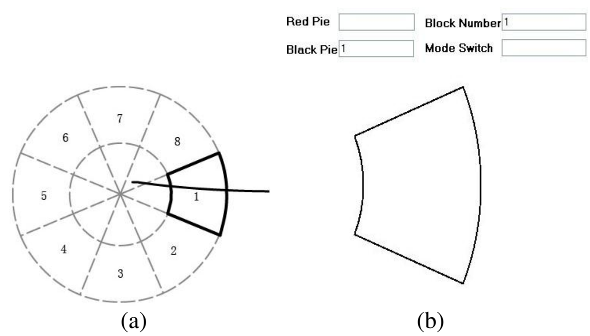

Figure 1. The experimental interface. (a)A ring is equally divided into 8 slices. Supposing the center point of the ring is the origin of the coordinate, the first slice is axial symmetry with x-axis. (b) The numbers and the dashed lines were not shown in the experiment, and only one pie slice appeared each trial.

The experiment consisted of two kinds of tasks: mode switching task and non mode switching task. In the non mode switching task, a black pie was shown in the screen and participants only needed to perform the pie crossing task (see Figure 1b). In the mode switching task, a red pie was shown on the screen. Participants were required to complete the mode switching task before the drawing exceeded the inner edge of the pie target. In both mode switching and non mode switching tasks, the pie color would turn green if mode switching was performed and the mode could not be canceled until pie crossing task was finished. In order to avoid the predictable mode switching [4], the presentation order of black pies and red pies was randomized in each block. Task time in a trial was defined as the time from when the pie slice appeared until the moment the pen was lifted from the screen.

Error Classification

Similar to [5], errors in the experiment were divided into three categories: mode errors, crossing errors, and out-of-target errors. Mode errors included mode-in errors and mode-out errors; mode-in error was crossing a red pie without mode switching and mode-out error was crossing a black pie with mode switching. Crossing errors happened when the trajectory crossed a target slice from a side, or from outer to inner. Out-of-target error means trajectory did not cross the target.

If a participant finished a pie crossing task with an error, a beep sound and a new pie slice with bold edge would be given to remind the participant to redo this task.

EXPERIMENT ONE - MODE SWITCHING IN TABLET PC

Five mode switching techniques, *using pressure, pressing the barrel button, pressing and holding, pressing the button on the Tablet PC* and *jerking movement* were tested in a medium-sized pen-based handheld Tablet PC. *Back tapping* technique was not examined because it was difficult to tap the Tablet PC's back with the non-dominant hand when the participant was holding the device.

Apparatus

The experiment was conducted with a Fujitsu FMV-STYLISTIC Tablet PC running Windows XP Tablet PC Edition. The weight of the device was approximately 1.48 kg. The tablet PC has a Pentium III 933MHz processor and 256MB RAM. The resolution of the screen is 1024x768 pixels with each pixel approximately 0.2055mm. The stylus recognizes 256 levels of pressure and is equipped with a barrel button.

A Phidget Accelerometer 3-Axis [9] was mounted on the top of the Tablet PC's back and connected to the Tablet PC for the detection of jerking movements.

The Tablet PC ran custom software written in C# using Microsoft's Tablet SDK and Visual Studio .NET.

Set Pressure and Acceleration Threshold for Mode Switching

The pressure threshold for mode switching was set as the value of 185 which was higher than 89% maximum average pressure in the normal condition and lower than 89% maximum average pressure in the heavy condition.

We set the acceleration difference threshold for mode switching as 0.3 m/s^2 which was higher than 97% acceleration difference in the non-jerking condition and lower than 99% acceleration difference in the jerk condition.

Participants

Ten right handed volunteers (5 females, 5 males) ranging in age from 25 to 30, participated in this experiment. Two participants reported that they had experience with *using the barrel button*. Two participants had experienced *pressing and holding*. Four participants had experienced *using pressure*. However, none of them had used *jerking movement* before. Participants were asked to sit in a chair and hold the device by the non preferred hand when performing the experimental task with a stylus which was held in the preferred hand.

Procedure

The experiment consisted of a training phase and an experimental phase. Two mode switching trials and two non mode switching trials in each orientation were performed in the training phase. In the experimental phase, each participant performed the pie crossing task for 8 orientations. Each orientation trial included 6 blocks; for each block, the participant performed 4 pie crossing tasks with mode switching and 4 pie crossing tasks without mode switching. The participant could take a break after finishing a block. A Latin-square design was used to balance the order of the five techniques between the participants. The whole experimental session lasted about 1 hour. In summary, the experiment consisted of:

10 subjects ×
5 mode switching techniques ×
8 orientations ×
6 blocks of trials ×
8 pie-crossing tasks
=19200 pie-crossing tasks

9600 mode switches were performed in total. The dependent variables measured were task time for mode switching trials and for non mode switching trials, mode-in error, mode-out error, crossing error, and out-of-target error.

RESULTS

Performance Stability over Experimental Blocks

Mode switching time was measured by subtracting the mean non mode switching task time from the mean mode switching task time. Repeated measures analysis of variance showed that there was no significant learning effect on mode switching time for block ($F_{5,45}$ = 2.15, p = 0.08). Chi-square analysis revealed that no significant learning effect was found on error rate for block (χ^2_5 = 2.27 , p = 0.81). Therefore, we believed that after the training phase, participants were able to stably perform the five mode switching techniques in the following experimental blocks.

Mode Switching Time

A significant main effect was found on mode switching time for the five techniques ($F_{4,36}$ = 209.20, $p < 0.001$) (see Figure 2a).

Post Hoc Tests with the Bonferroni adjustment were applied to multiple comparisons. The smallest mode switching time was the time of *using pressure* with a mean 228ms. Post hoc comparisons showed there was no significant difference (p = 0.14) between *using pressure* and *pressing button on Tablet PC* (Mean = 304ms), and no significant difference (p = 0.18) between *using pressure* and *barrel button* (Mean = 374ms). However, there was a significant difference ($p < 0.01$) between *using pressure* and *jerking*. It was found that *jerking* (Mean = 435ms) had no significant difference from *barrel button* (p = 1.00), but a significant difference from *button on Tablet PC* ($p < 0.01$). Post hoc comparisons also showed there was no significant difference ($p = 1.00$) between *button on Tablet PC* and *barrel button*. *Pressing and holding* was the slowest technique with a mean of 1414ms ($p < 0.001$).

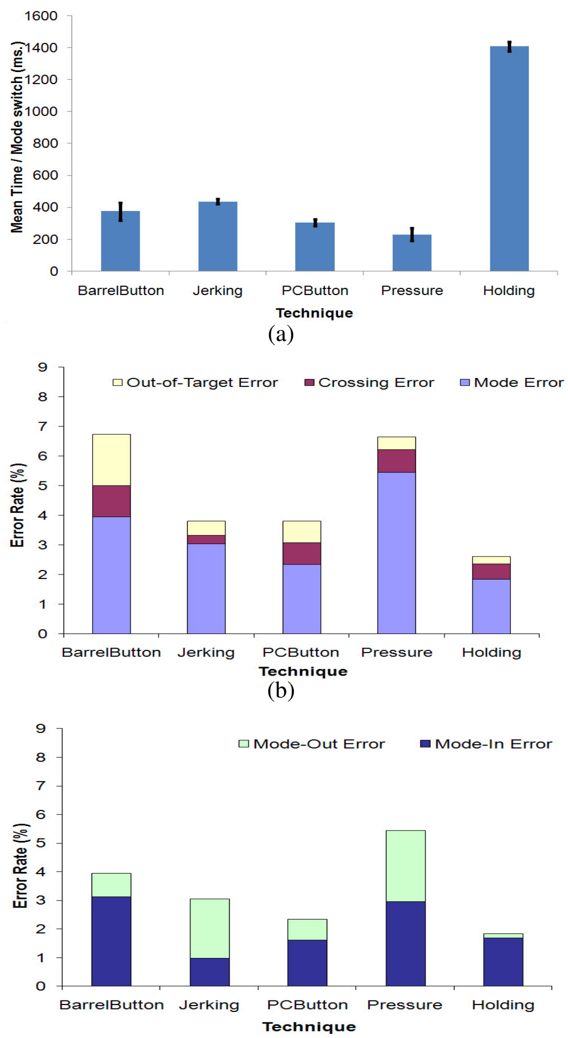

Figure 2. (a) The mean mode switching time of five techniques. Error bars represent 0.95 confidence interval. (b) The error rate on each pie-crossing. (c) The error rate of mode-in and mode-out errors on each pie-crossing.

Error Analysis

Chi-square test revealed that there was a statistically significant relationship between the number of errors and techniques ($\chi^2_4 = 113.53$, $p < 0.001$). *Pressing and holding* resulted in few errors with a standardized residual at -6.0. *Jerking* (z = -2.6) and *pressing PC Button* (z = -2.6) led to the same errors. *Using pressure* resulted in more errors than these three techniques (z = 5.5). *Barrel button* committed the most errors (z = 5.8).

Frequencies of each type of error when using the five different techniques were further analyzed. Chi-square test showed that there was a significant relationship between the five techniques and four types of errors ($\chi^2_{12} = 161.00$, $p < 0.001$).

The results showed that mode errors, including mode-in and mode-out errors, were the main errors for the five techniques. As shown in Figure 2c, *using pressure* led to the most mode errors, and *pressing and holding* resulted in the least mode errors. *Barrel button* committed more mode-in errors (z = 0.6), and *jerking* resulted in fewer mode-in errors (z = -3.3). *Using pressure* led to more mode-out errors (z = 3.3), and *pressing and holding* resulted in fewer mode-out errors (z = -4.0).

It should be noted that some crossing errors and out-of-target errors occurred along with mode errors. This is because while engaging in a crossing task, subjects accidentally lifted the pen tip to cancel the drawing if they found a mode error happened, even though they were required to continue the pie crossing task. Regarding crossing error, *barrel button* led to more crossing errors (z = 0.5), and *jerking* resulted in fewer crossing errors (z = -2.1). For out-of-target error, *barrel button* resulted in more out-of-target errors (z = 4.4), and *pressing and holding* committed fewer out-of-target errors (z = -1.6) (see Figure 2b).

EXPERIMENT TWO - MODE SWITCHING IN PDA

The aim of this experiment was to compare five mode switching techniques in a small scale pen-based handheld device, PDA. Five mode switching techniques, *using pressure*, *pressing and holding*, *pressing the button on PDA*, *back tapping* and *jerking movement*, were investigated in this experiment. We did not test*Pressing the barrel button* in this experiment, because most styluses for PDA did not have a barrel button.

Apparatus

PDA and Host Computer

We conducted the experiment with an HP iPAQ PDA running Windows Mobile 2003. The weight of the device is 164.4g. The PDA has a PXA270 520MHz processor, 65MB RAM and Wi-Fi card. The resolution of the screen is 240 $\times$ 320 pixels with each pixel measuring approximately 0.24mm.

A Tablet PC which has a wireless network card was used as the host computer to receive data from sensors and to send data to the PDA through the wireless network. The sensors were used to detect back taping, pressure and jerking.

Back Tapping Detection Device

A prototype similar to that in [20] was built. In the prototype, an Ergonomic USB touchpad was attached on the back of the PDA and connected to the host computer. A tapping action was detected as a pressing down action on a mouse.

Pressure Detection Device

A device for pressure detection was constructed based on [7] and [8]. Four Force Sensitive Resistor (FSR) sensors

[3], which can detect 1024 levels of pressure, were attached on the bottom of an acrylic cover. The FSR was connected to the host computer via a single-board microcontroller Arduino. The PDA was put on the sensors and the average pressure value of the four pressure sensors was calculated to approximately represent the stylus pressure.

Jerking Detection Device

To detect jerking movement, we mounted a Phidget Accelerometer 3-Axis [9] on the PDA's back and connected it to the host computer.

Experiment software was designed in C# and Visual Studio .NET.

Set Pressure and Acceleration Threshold for Mode Switching

The pressure threshold for mode switching was set to the value of 80 which was higher than 96% maximum average pressure in the normal condition and lower than 89% maximum average pressure in the heavy condition.

We set the acceleration difference threshold for mode switching as 0.7 m/s^2 which was higher than 97% acceleration difference in the non-jerk condition and lower than 98% acceleration difference in the jerk condition.

Participants

Ten right handed volunteers (4 females, 6 males) ranging in age from 25 to 32, participated in the experiment. Six of them had participated experiment one. The other four participants reported that they had no experience using the stylus before. In the experiment, participants were asked to sit in a chair and hold the device in the non preferred hand, while performing the experimental task with a stylus held by the preferred hand.

Procedure

The experiment procedure was similar to that in experiment one. We recorded the task time in mode switching trials and non mode switching trials, mode-out error, mode-in error, crossing error and out-of-target error.

RESULTS

Performance Stability over Experimental Blocks

Mode switching time was measured by subtracting the mean of non mode switching task time from the mean of mode switching task time. Repeated measures analysis of variance showed that there was no significant learning effect on the mode switching time between six blocks ($F_{5,45} = 2.04$, $p = 0.09$). Chi-square analysis also revealed that no significant learning effect was found on error rate between six blocks ($\chi^2_5 = 2.40$, $p = 0.79$). The overall results showed that the learning effect was minor and participants had already reached a steady performance from block one.

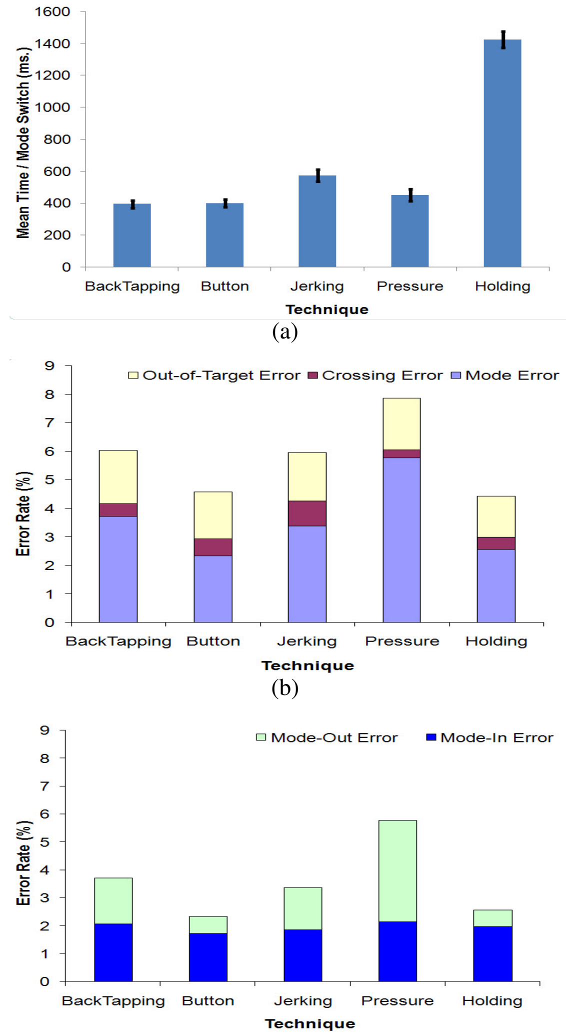

Figure 3. (a) The mean mode switching time of five techniques. Error bars represent 0.95 confidence interval. (b) The error rate on each pie-crossing. (c) The error rate of mode-out and mode-out errors on each pie-crossing.

Mode Switching Time

Repeated measures analysis of variance was performed on mode switching time for five techniques. Mauchly's test indicated that the assumption of sphericity had been violated (chi-square = 17.98, p < 0.05), therefore degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (epsilon = 0.86). A significant main effect was found on mode switching time for the five techniques ($F_{3.458,31.118} = 288.61$, $p < 0.001$) (see Figure 3a).

Post Hoc Tests were performed using the Bonferroni adjustment for multiple comparisons. *Back tapping* produced the smallest mode switching time with a mean 393ms. Although *back tapping* had no significant difference with *pressing button on PDA* (Mean = 399ms, $p = 1.00$), it had a significant difference with the three other techniques(*jerking* (Mean = 572ms, $p < 0.05$), *using pressure* (Mean = 450ms, $p < 0.05$) and *pressing and holding* (Mean = 1424ms, $p < 0.001$)). *Pressing button on PDA* also had a significant difference with *jerking* ($p < 0.05$), *using Pressure* ($p < 0.05$) and *press-*

ing and holding ($p < 0.001$), which means that *pressing button on PDA* and *back tapping* resulted in the similar mode switching times. Post hoc comparisons showed there was no significant difference ($p = 0.85$) between *jerking* and *pressure*, indicating that these two techniques can be grouped on their efficiency in switching modes. *Pressing and holding* produced the largest mode switching time than the other four techniques.

Error Analysis

A Chi-square test revealed that there was a statistically significant relationship between the number of errors and the technique ($\chi^2_4 = 51.26$, $p < 0.001$) (see Figure 3b). *Pressing and holding* resulted in few errors with a standardized residual at -3.5. And *Pressing the button on PDA* led to few errors (z = -3.1). *Jerking* resulted in many more errors than these two techniques (z = 0.5). *Back tapping* made almost the same error as *jerking* (z = 0.68). *Using pressure* resulted in more errors (z = 5.4) than the other techniques.

Frequencies of each type of error were further analyzed. The Chi-square test showed that there was a significant effect between five techniques and four types of errors ($\chi^2_{12} = 103.20$, $p < 0.001$).

Mode errors, including mode-in and mode-out errors, were the main errors for the five techniques. *Using pressure* led to the most mode errors, and *pressing button on PDA* resulted in the least mode errors. *Using pressure* resulted in more mode-out errors (z = 5.8), and *pressing the button on PDA* resulted in fewer mode-out errors (z = -3.6). *Using pressure* resulted in more mode-in errors (z = 1.0). *Pressing button* (z = -1.9) resulted in fewer mode-in errors (see Figure 3c).

In this experiment, some crossing errors and out-of-target errors occurred along with mode errors. This is because while engaging in a crossing task, participants accidentally lifted the pen tip to stop the drawing if they found a mode error happened. In addition, the slippery screen and small stylus made it difficult for participants to control the trajectory. As shown in Figure 3b, *jerking* led to more crossing errors (z = 2.9), and *using pressure* resulted in fewer crossing errors (z = -3.1). *Back tapping* resulted in more out-of-target errors (z = 2.2), and *pressing and holding* resulted in fewer out-of-target errors (z = -0.8).

DISCUSSION

Regarding Tablet PC, *using pressure* allowed users to smoothly switch between gesturing and inking, so it offered the fastst performance. However, this technique resulted in more errors. We set the pressure threshold according to the pressure data from four participants, so personalized pressure profiles may reduce the error rate for *using pressure*. Some participants felt it uncomfortable to press the button on Tablet PC for mode switching while holding the experimental device, and this may lead to a longer mode switching time. *Using Barrel button* resulted in the most crossing errors and out-of-target errors, suggesting that this technique may be difficult to use in handheld devices. Some participants complained that the Tablet PC was too heavy to jerk, so *jerking technique* may perform slower than other techniques except *pressing and holding*. However, *jerking* resulted in fewer errors than other techniques except *pressing and holding*, indicating that it can serve as a promising mode switching technique.

With respect to PDA, *back tapping* performed faster than *pressing button on PDA*, which is consistent with the results in [18]. However, *back tapping* resulted in more errors than *pressing button on PDA*. In the experiment, we found that many errors were caused by inadvertently touching the touchpad. An optimal input area for *back tapping* technique may reduce errors and keep high efficiency for mode switching. In further study, we will investigate the performance of *back tapping* technique in different input areas for mode switch. *Using pressure in PDA* did not perform as well as in Tablet PC, which may be due to the fact that it is difficult to use the small stylus on the smooth PDA screen. *Jerking technique in PDA* led to larger mode switch time than *jerking technique in Tablet PC*. Jerking the PDA was performed by using the wrist as a fulcrum, while jerking the Tablet PC required the use of the elbow as a fulcrum; jerking the Tablet PC may be easier to perform for participants.

Overall, *pressing button on handheld device* performed faster and more accurately on the Tablet PC and the PDA, which was consistent with the results in [5]. Although *pressing and holding* technique resulted in longer mode switching time than the other techniques, it led to fewer errors. Furthermore, this technique requires the least hardware support, so it has been widely used in handheld devices.

Jerking technique and *back tapping* are two techniques proposed in this paper with a view to better meeting the requirement of efficient mode switching for mobile devices. Although these two techniques did not perform as well as we expected, the results still shed some light on the use of these two techniques in mode switching technique design. First, regarding *jerking technique*, we found that the mode switching time for the tablet PC was shorter than that for the PDA. This is an interesting result: although the tablet PC is heavier than the PDA, it seems that users feel more control over the tablet PC. This indicates that *jerking technique* is more suitable in large scale mobile devices for mode switching tasks. Second, although the area of the touchpad used in *back tapping* is larger than that of the button in *pressing button on handheld device*, *back tapping* did not produce significant shorter mode switching times than *pressing button on handheld device*. This may be due to the differences between one handed and two handed input; *back tapping* is a two-handed input technique but *pressing button on handheld device* is a one-handed input technique. Mode switching technique design should pay attention to the use of one-handed and two-handed input. Last, *pressing the barrel button on the pen*, *pressing and holding*, *pressing the button on the handheld device*, *using pressure* and *back tapping* were performed on a 2D surface, such as the touch screen and the button surface. Unlike the above techniques, *jerking technique* is a motion-based technique. This technique did not perform well in the sitting posture, but due to its distinct property, it may be useful in other postures, such as walking. Future study will explore the impact of user posture (sitting, standing and walking) on the performance of mode switching.

CONCLUSION

In this paper, we investigated five mode switching techniques in two typical pen-based handheld devices respectively: a PDA and a Tablet PC. Two experiments were conducted to evaluate the performance of these techniques. Some interesting results were found here. For the PDA, *back tapping* offered the fastest performance. *Pressing the button on PDA* technique was slower than *back tapping* technique, but there was no significant difference between them. Regarding Tablet PC, *pressure* led to shorter time but more errors than the other four techniques. *Pressing button on Tablet PC* technique was slower than *pressure* technique, but there was no significant difference between them. *Jerking* resulted in fewer errors than the other techniques except *pressing and holding*. In both devices, *pressing and holding* was significantly slower but less prone to error. *Pressing button on handheld device* offered overall fast and accurate performance in both the Tablet PC and the PDA. Two methods proposed here, *back tapping* and *jerking* are two promising mode switching techniques, which should be deeply explored in future study. The experimental results can be beneficial to the design of mode switching techniques in pen-based handheld devices.

ACKNOWLEDGMENTS

This study has been partially supported by Grant-in-Aid for Scientific Research (No. 23300048) in Japan and NSFC of China (No. 61063027). We thank the members of Ren Lab in Kochi University of Technology for their assistance.

REFERENCES

1. Bi, X., Moscovich, T., Ramos, G., Balakrishnan, R. and Hinckley, K. An exploration of pen rolling for pen-based interaction. In *Proc. UIST 2008*, ACM Press (2008), 191-200.
2. Brewster, S. A. and Hughes, M. Pressure-based text entry for mobile devices. In *Proc. MobileHCI 2009*, ACM Press (2009), 1-4.
3. Interlink electronics: Force Sensing Resistors, http://www.interlinkelectronics.com/force_sensors.
4. Lank, E., Ruiz J. and Cowan, W. Concurrent bimanual stylus interaction: a study of non-preferred hand mode manipulation. In *Proc. GI 2006*, ACM Press (2006), 17-24.
5. Li, Y., Hinckley, K., Guan, Z. and Landay,J.A. Experimental analysis of mode switching techniques in pen-based user interfaces. In *Proc. CHI 2005*, ACM Press (2005), 461-470.
6. Liu C. and Ren, X. Experimental analysis of mode switching techniques in pen-based user interfaces. *International Journal of Innovative Computing, Information and Control, 6*, 4(2010), 1983-1990.
7. Miyaki T. and Rekimoto J. GraspZoom: zooming and scrolling control model for single-handed mobile interaction. In *Proc. MobileHCI 2009*, ACM Press (2009), 1-4.
8. Mizobuchi, S., Terasaki, S., Keski-Jaskari, T., Nousiainen, J., Ryynanen M. and Silfverberg, M. Making an impression: force-controlled pen input for handheld devices. *Ext. Abstracts CHI 2005*, ACM Press (2005), 1661-1664.
9. Phideget: PhidgetAccelerometer 3-Axis, http://www.phidgets.com/.
10. Ramos, G. A., Boulos, M. and Balakrishnan, R. Pressure widgets. In *Proc. CHI 2004*, ACM Press (2004), 487-494.
11. Ramos, G. A. and Balakrishnan, R. Pressure marks, In *Proc. CHI 2007*, ACM Press (2007), 1375-1384.
12. Ren, X. and Moriya, S. Improving selection performance on pen-based systems: a study of pen-based interaction for selection tasks. *TOCHI, 7,* 3(2000), 384-416.
13. Ronkainen,S., Häkkilä,J., Kaleva, S., Colley A. and Linjama, J. Tap input as an embedded interaction method for mobile devicess. In *Proc. TEI 2007*, ACM Press (2007), 263-270.
14. Roudaut, A., Baglioni M. and Lecolinet, E. TimeTilt: Using Sensor-Based Gestures to Travel through Multiple Applications on a Mobile Device. In *Proc. INTERACT 2009*, Springer Press (2009), 830-834.
15. Sugimoto M. and Hiroki K. HybridTouch: an intuitive manipulation technique for PDAs using their front and rear surfaces. In *Proc. MobileHCI 2007*, ACM Press (2007), 137-140.
16. Sun, M., Cao, X., Song, H., Izadi, S., Benko, H., Guimbretiere, F., Ren, X. and Hinckley, K. Enhancing naturalness of pen-and-tablet drawing through context sensing. In *Proc. ITS 2011*, ACM Press (2011), 83-86.
17. Wang, J. Zhai, S. and Canny, J. SHRIMP - solving collision and out of vocabulary problems in mobile predictive input with motion gesture. In *Proc. CHI 2010*, ACM Press (2010), 15-24.
18. Wobbrock, J.O., Myers B.A. and Aung, H.H. The performance of hand postures in front- and back-of-device interaction for mobile computing. *Int. J. Hum.-Comput. Stud, 66*, 12(2008), 857-875.
19. Xin, Y., Bi, X. and Ren, X. Acquiring and pointing: an empirical study of pen-tilt-based interaction. In *Proc. CHI 2011*, ACM Press (2011), 849-858.
20. Yang, X.D., Mak, E., Irani P. and Bischof, W.F. Dual-Surface input: augmenting one-handed interaction with coordinated front and behind-the-screen input. In *Proc. MobileHCI 2009*, ACM Press (2009), 1-10.