2013

Understanding and Rejecting Errant Touches on Multi-touch Tablets

Ke SHU
Singapore Management University, ke.shu.2010@msis.smu.edu.sg

Understanding and Rejecting Errant Touches on Multi-touch Tablets

by

SHU Ke

Submitted to School of Information System in partial fulfillment
of the requirements for the Degree of Master of Science in Information Systems

Thesis Committee:

Richard DAVIS (Supervisor/Chair)
Assistant Professor of Information Systems
Singapore Management University

Rajesh BALAN
Assistant Professor of Information Systems
Singapore Management University

Daniel VOGEL
Assistant Professor of Computer Science
University of Waterloo

Singapore Management University
2013

Understanding and Rejecting Errant Touches on Multi-touch Tablets

SHU Ke

Abstract

Given the pervasion of multi-touch tablet, pen-based applications have rapidly moved onto this new platform. Users draw both with bare fingers and using capacitive pens as they would do on paper in the past. Unlike paper, these tablets cannot distinguish legitimate finger/pen input from accidental touches by other parts of the user's hand. In this thesis, we refer it to as errant touch rejection problem since users may unintentionally touch the screen with other parts of their hand.

In this thesis, I design, implement and evaluate new approaches, bezel-focus rejection, of preventing errant touches on multi-touch tablets. I began the research by conducting a formal study to collect and characterize errant touches. I analyzed the data collected from the study and the results are guiding me to design rejection techniques. I will conclude this research by developing bezel-focus rejection and evaluate its performance. The results show that bezel-focus rejection yields high rejection rate of errant touches and make users more inclined to rest hands on tablet than comparison techniques.

This research has two major contributions to Human Computer Interaction (HCI) community. First, my proposed errant touch rejection approaches can be applied the other pen-based note-taking applications. Second, my experimental results can serve as a guide to other developing similar techniques.

Table of Contents

Acknowledgments

Thanks to my supervisor, Assistant Professor Richard C. Davis from Singapore Management University, for his support, help and advice in the past three years.

Thanks to my collaborator, Assistant Professor Daniel Vogel from University of Waterloo, for his guide on this project in the past year.

Thanks to my committee member, Assistant Professor Rajesh Balan from Singapore Management University, for his time and comments on my thesis.

Thanks to the administrators of Post-graduate Research Program, Ong Chew Hong and Seow Pei Huan from Singapore Management University, for their kind assistance in the past three years.

Thanks to my post-graduate classmates and colleagues: Zhang Zhi, Ren Jing, Qiu Minghui, Du Jiali, Xie Wei, Tan Biying, Cheng Zhiyong, Ding Ying, Liu Jun, Shi Jie, Zhang Zequn, Guan Chaowen, Lu Meng, Qiao Qiming, Wang Shaowei, Huang Jianhui, Liu Weijie and Chen Qijia from Singapore Management University, for their help in the user study.

Thanks to my post-graduate colleague, Gao Ming from Singapore Management University, for his assistance on statistical analysis.

Dedication

I dedicate this thesis to my mam, dad, grandma, grandpa and gran-nanny. I wish you all healthy and happy every day. I love you all!

I also dedicate this thesis to my grand-daddy, the loved one who left us in March 18th 2012. Rest in peace, grand-daddy!

Chapter 1: Introduction

1.1 Motivation

Given the pervasion of multi-touch tablet, pen-based applications have rapidly moved onto this new platform. Users draw both with bare fingers and using capacitive pens as they would do on paper in the past. Unlike paper, these tablets cannot distinguish legitimate finger/pen input from accidental touches by other parts of the user's hand.

Consider the following scenarios in which the problem of accidental touch could happen to tablet users:

1. User A is taking notes on a multi-touch tablet in a college class. He sees many important notes that the professor leaves on the blackboard and he writes them all on his tablet. When he takes notes, his fingers drag on screen while reaching out to touch buttons on the toolbar. Sometimes this accidentally invokes a two-finger gesture (e.g zoom out). User A needs an approach to reduce, if not eliminate, the chance of making accidental touches on the tablet.
2. User B is also taking notes on a multi-touch tablet. User B understands the errant touch problems and knows that he cannot rest his hand on the tablet when he is writing. Therefore, he arches his wrist in order to avoid accidentally touching the tablet. Since he takes note for a long time, his wrist begins to ache. User B needs to solution that allows him to rest his wrist on the tablet just as he does when he writes on real paper.

3. User C is an advanced tablet user. He found that some note-taking applications can reject errant touches automatically, for example *Penultimate*[1], if his hand is firmly placed on the screen, but it does not work for accidental knuckle or pinkie touches. Another application provides an explicit "cover sheet" where he can rest his hand without creating accidental marks. However, he finds the cover sheet distracting and hard to drag with his wrist.

Errant touch problem on multi-touch tablet are also observed in research community. These scenarios motivate me to design, implement and evaluate new approaches to preventing errant touches on multi-touch tablets. I began this research by conducting a formal study to collect and characterize errant touches. I analyzed the data collected from the study and the results are guiding me to design rejection techniques. I will conclude this research by implementing and evaluating three rejection techniques. My thesis statement is the following:

An exploratory study of errant touches would reveal patterns that would help to design better errant touch rejection techniques.

1.2 Research Objectives

This thesis aims to address the problem of errant touches on multi-touch tablet. It has two major research objectives which are:

1. *To understand the properties and patterns of errant touches on multi-touch tablets*. To reach these goals, we investigate a series of primary research

[1] http://evernote.com/penultimate/

problems as follows:

a. How do errant touches vary with different input styles (finger or stylus)?
b. How do errant touches vary with different tasks (tapping, dragging, writing or drawing)?
c. Is it possible to automatically differentiate from intended touches using variables such as contact size, pressure, event time or positions relative to another touch?
d. Do errant touch positions follow a pattern that can be used to design effective errant touch rejection techniques?

To answer these questions, we conduct a formal study to collect errant touch in a controlled environment. The formal study investigates errant touches in either capacitive stylus or bare finger condition. In the capacitive stylus condition, participants are requested to complete tasks by a capacitive pen. On other hand, participants are requested to complete tasks by their fingers in the bare finger condition. In each condition, we investigate errant touch according to four types of task that is, tapping, dragging, writing and drawing. The detail of the study will be described in the methodology section. The result from the formal study is useful in designing geometric models which are able to block the area where errant touches are occurred according to the position of intended touches.

2. *To design techniques for rejecting errant touches on multi-touch tablets.* Motivated by results from the formal study, I present *bezel-focus rejection* technique, a new approach that supports bi-manual and uni-manual interaction

seamlessly for errant touch rejection. Bezel-focus rejection creates an *Ink Start Area (ISA)* where new touches will be recognized as ink. The position of the ISA is manipulated by interacting with the bezel using the non-dominant hand. Errant touches that are invoked outside of ISA are rejected, and hence allows users to safely rest their hand on the tablet when writing or drawing. Finally, I conduct a formal experiment to evaluate the performance of bezel-focus rejection technique. I found that bezel-focus rejection yields high rejection rate of errant touches and make users more inclined to rest hands on tablet than comparison techniques.

This research will make two contributions. Firstly, the data of errant touches which are collected from an experimental study can guide further developing errant touch rejection techniques. To my knowledge, this is the first comprehensive study which investigates errant touches on multi-touch tablets. Secondly, the bezel-focus rejection proposed in this thesis can be applied to current researches and tablet applications.

This thesis is organized as follows: In chapter 2, I summarize the relate works on errant touch problem and errant touch rejection techniques. In chapter 3, I present a formal study for collecting errant touches and present the study results. In chapter 4, I propose a mixed explicit and implicit rejection approach, bezel-focus rejection. In chapter 5, I describe a formal experiment to evaluate the performance of bezel-focus rejection and presented the experimental results. In chapter 6, I concluded the study and discuss future work.

Chapter 2: Related Work

In this section, I categorize the errant touches related works by three research purposes: emphasizing errant touch problem, understanding user behaviors and solutions to errant touch problem. Here I will use errant touch rejection and palm rejection interchangeably in order to coordinate with existing research since errant touch rejection problem is often referred to as palm rejection in pen-based community.

2.1 Errant Touch Problem

Grosky et al. [1] defined palm rejection as "disambiguating a finger used in conjunction with a pen from a palm placed on the surface to support the hand while drawing with a pen". They go on to explain that "the research community (of pen-based centric computing) has gone beyond basic pen input to consider multimodal issues, such as multi-touch and hybrid speech systems." Palm rejection problem is considered as one of the fundamental problems on touch-based input devices, but not be solved in [1].

Hinckley et al. [2] defined errant touches as the false input of pen in simultaneous pen-and-touch interaction. They proposed a technique called pen + touch, in which pen and touch are used for different purposes. One of the potential problems of pen + touch is caused by errant touches because pen + touch misrecognized them as a legitimate input from pen. Hinckley et al. also observed that users may rest their hands on the drawing surface, causing unintended operations. To overcome this problem, they regarded touches with a large contact area as incidental palm touches. However, they claimed that this did not solve errant touch rejection problem. A robust method for handling errant touches remains an important research area.

2.2 Writing Behavior

Schmidt et al. [3] conducted an empirical study to compare the performance of direct and indirect multi-touch input on large surfaces. They observed that participants often hovered their hands over the surface to avoid errant touches when selecting targets. This resulted in both selection time and less comfort. Schmidt et al also recommended further investigation into errant touch rejection techniques that allow users to rest their hands on the surface for interaction.

Other researchers have observed that users tend to rest their hands on surfaces when using pen input due to fatigue [4]. Hancock and Booth [5] claimed that the resting position reduced fatigue and increased users'ability to acquire targets utilizing wrist movement instead of arm movement. Siio and Tsujita [6] noticed that users secure paper with their palm to keep it from moving while writing or drawing something on a sheet of paper. Matulic and Moira [7] also indicated that palm resting on surface will result better pen precision.

2.3 Solutions of Errant Touch Problem

Current solutions to errant touch problem can be classified into two groups: hardware-based solutions and software-based solutions. The hardware-based solution depends on applying specified hardware devices or technologies (e.g. digitizer pen and advanced pressure-sensing screen etc) on multi-touch tablets and tablet users. On the other hand software-based solution solves the errant touch problem without any of those devices.

2.3.1 Hardware-based Solutions

In the academic community, Kim et al. [8] designed a new pressure sensitive capacitive stylus which supports simultaneous pen and touch inputs. A pressure sensor at the middle of the pen is used for recognizing the pressure level and differentiates whether the current input is pen or touch. Rosenberg and Perlin [9] created a multi-touch input device called UnMousePad that was capable of distinguishing the pressure profiles of hand and other objects (e.g. pen tip) based on a new pressure-sensing principle. It can accurately measure entire images of pressure with continuous bilinear interpolation, permitting both high-frame-rate and high-quality imaging of spatially variant pressure upon a surface. Lopes et al. [10] proposed an approach to distinguish touches by different body parts (e.g. fingers, knuckles, fingernails, punches etc) by their acoustic signatures. Gregorio [2] introduced a novel capacitive sensor glove that allowed the wearer to interact only with fingers with no interference from other parts of hand.

In industry, Cregle [3] introduced a specialized stylus called iPen, which is claimed to be the first active stylus for iPad, along with an external receiver. The external receiver is used to plug into iPad dock connector so that it only

[2] *Capacitive Sensor Gloves*. 2010, Immersion Corporation US.
[3] http://www.cregle.com/

communicates information with the pen and hence support errant touch rejection while writing. The similar products of stylus and receiver, like Studio pen[4] (by Byzero), Apen[5] (by EFUN) and MyNote pen[6] (by Aiptek) are also active in market. Ten One Design[7] presented a pressure-sensitive pen called Pogo Connect on iPad by utilizing Bluetooth technology without external receivers. Using Blue Tiger, the iPad application only responds to the pen tip but ignores fingers or wrist at once.

One of significant limitations of the solutions discussed above is that all of them are not capable of supporting errant touch rejection without preventing simultaneous pen and touch inputs. To overcome it, N-trig[8] proposed the DuoSense digitizer which employs grid-based capacitive technology to support simultaneous pen and touch input. Along with DuoSense digitizer, N-trig developed a digitizer pen, the DuoSense pen, so that it is able to differentiate the touch of pen from fingers. N-trig also claimed that DuoSense digitizer supports palm rejection by ignoring large-sized contacts. Wacom also presented new multi-touch tablets (e.g. Intuos5[9] and Cintiq 24HDT pen and touch display[10]) in combination of digitizer stylus. Those tablets came with a set of APIs which build in errant touch rejection through the use of confidence bits. A confidence bit is a

[4] http://www.by-zero.com/?page=studiopen

[5] http://www.apenusa.com/

[6] http://www.mynote.eu/mynotepen-en.html

[7] http://tenonedesign.com/home.php

[8] http://www.n-trig.com/

[9] http://www.wacom.com/en/creative/products/pen-tablets/intuos/intuos5-touch-medium

[10] http://www.wacom.com/en/creative/products/pen-displays/cintiq/cintiq-24hd-touch

flag for a single finger's touch data that indicates whether the tablet driver thinks the touch is intentional or accidental. In general, touches that are in the vicinity of the pen location would be deemed non-confident. It is also flagged non-confident when a touch contact is too large, where "too large" is approximately anything over the size of a normal finger contact. To our knowledge, the performance of rejecting errant touches for those products has not been investigated.

Hardware-based solutions are fairly effective for rejecting errant touches, but they also bring with several major problems. First, those specialized devices are fairly costly and they are not affordable for every tablet user. Second, tablet users cannot lose or break those devices in order to enable errant touch rejection. Third, it diminishes the flexibility of interacting on tablet because it does not work for bare finger. Besides, the performance of hardware-based solution is widely in debate. In sum, hardware-based solution is a good choice but not applicable to everyone.

2.3.2 Software-based Solutions

The software-based solution can be categorized by two classes: implicit approach and explicit approach. We define the implicit approach as the one in which the system distinguishes errant touches from others by particular input parameters (e.g. contact size, pressure and position etc.) without external manipulations from users. In the academic community, Murugappan et al. [11] proposed an approach to reject errant touches by measuring the approximate shape of contact area on a tabletop surface. The approach succeeded on large surface but has not been evaluated on a multi-touch tablet.

In industry, Penultimate[11] has an implicit errant touch rejection technique called the wrist protection which allows users to rest their wrists on the tablet. The wrist protection can only exclude the errant touches from the palm if users keep it firmly on the tablet. The wrist protection is not capable of protecting the errant touches from other fingers. Furthermore, it results fatigue because users have to constantly place their hands on screen.

On the other hand, explicit approaches mainly focus on preventing errant touches through manipulation of interactive widgets. For example, SmartNote[12] introduced an errant touch rejection feature called the palm ignoring area. The palm ignoring area is basically a rectangle-shaped cover sheet that ignores any touch events that are invoked inside it. The size and location of the palm ignoring area is requested to customize from users. In doing so, users are able to rest their hands on the palm ignoring area with no interference to interface. However, problems are still remained in palm ignoring area. First, the palm ignoring area is not capable of auto-locating on canvas. Users have to drag it to the new location whenever their pens are starting over from a different position. Second, users hardly set the accurate size and location of palm ignoring area and consequentially miss excluding errant touches.

Implicit approaches are generally challenging for a capacitive stylus as input on multi-touch tablets, because it is not foolproof to differentiate pen from hand as a digitizer stylus does. In this regard, it is difficult to reject errant touches by ignoring the touches in the vicinity of pen.

[11] http://evernote.com/penultimate/

[12] https://itunes.apple.com/sg/app/smartnote/id362165952?mt=8

Chapter 3: Understanding Errant Touch Properties

I conducted a formal study to understand the properties and patterns of errant touches, and reported study results in this section.

3.1 Overview

We focused on user behavior in pen-based applications and were not as concerned with specific GUI widget manipulation. Each participant performed a series of tasks that could generate errant touches on tablet. To avoid participants hovering their hand intentionally, I encouraged participants to adopt a relaxed writing posture as they would do on real paper. I told them that “you can place your palm on the screen without any problems using our system” before they started the experiment. During the experiment, we recorded all touches made by users and any comments they made.

The experiment investigates the characteristics of errant touch in two different conditions, capacitive stylus condition and bare finger condition. In the capacitive stylus condition, participants are requested to perform all tasks with a capacitive pen. In the bare finger condition, participants are requested to complete the same tasks by their fingers. The condition order is counterbalanced across all participants. The entire experiment took about 1 hour to complete.

3.2 Participants

16 people (3 female, 13 male) with an average age of 25.9 (SD 2.8) participated. Participants were pre-screened for color blindness, in case it would prevent them from seeing any colored highlighted on the screen. I did not screen participants for hand dominance, but all participants were right handed. Left handed participants will be investigated in future study.

3.3 Apparatus

The experiment was conducted using an ASUS Eee Pad TF101 tablet running the Android OS. It has a 256 mm (10.1 inch) diagonal display, a resolution of 1280 by 800 px (218 by 136 mm), and a pixel density of 5.9 px/mm. We chose the ASUS Eee Pad TF101 tablet since it provides a reasonably large display that is suitable for general drawings or writings and is typical of the new breed of multi-touch tablets. We positioned the tablet flat on desk in portrait-orientation and allowed participants to adjust it to a comfortable angle.

We mounted a camera in front of participants to record their hand movement above the tablet. To distinguish correct touches from errant ones, we required participants to begin each touch in a designated area on the screen. Touches that began outside this area were considered errant. We correct the misclassification of errant touches by a post-processing which will be described in later section.

3.4 Tasks

Vogel et al. [12] differentiated between two styles of pen manipulation: short and singular interactions against long and localized interactions. Based on that, we defined two tasks: tapping and dragging that require short and singular interactions and two tasks: writing and drawing that require long and localized interactions in order to collect the real drawing behavior on a multi-touch tablet. In order to classify data either errant touches or correct touches, I designed a *legal touch area* in tap, drag, write and draw. If a touch-down is occurred inside of the legal touch area, it is considered as correct touch; otherwise, it is errant touches. However, since the legal touch area is not able to avoid false positive, the data is somehow misclassified between correct touch and errant touch. To correct such misclassification, I conducted a post-processing to clean the raw data. The post-processing will be illustrated in later section.

3.4.1 Tap

To complete the tapping task, participants selected a 14 mm circular target with a single tap. We defined 25 possible targets and the location of the target was varied across trials inscribed by a 5×5 grid. We were interested in tapping task since we observed that users sometimes smudged their drawings by hand when they attempted to click menu in writing or drawing application. Menus are often placed at the top, bottom or left edge of a display and second-level menus may be placed in the middle. Although it is less likely for a menu at the right edge of a pen-based application due to the predominant issue of hand occlusion for right-handed users, we still covered it in tapping task for completeness.

3.4.2 Drag

To complete dragging task, participants drag a 14 mm circular target from start position to stop position in a 5×5 grid. In the dragging task, we defined 16 targets (see figure 1) which formulates 44 pairs of start and stop target. We chose these tasks to cover a range of values for the following parameters.

1. *Location*

   We defined the targets at different horizontal and vertical locations

2. *Distance*

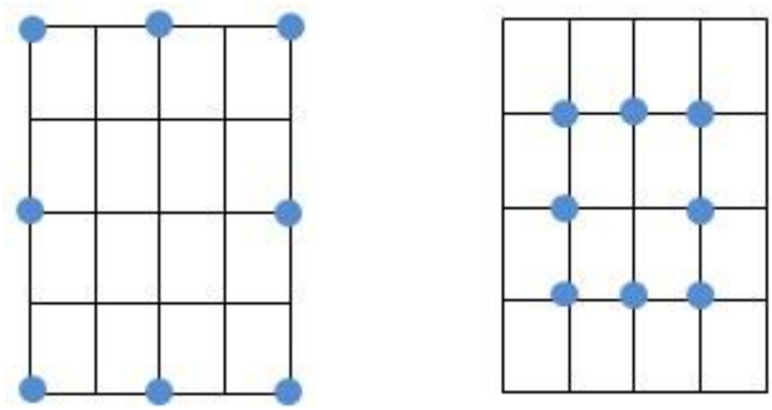
   The distance between two target falls into two categories, long and short. The long-distance pair is defined by target located at corners of the grid. The short-distance pair is the one with the same location of start target but half-distance location of stop target.

3. *Orientation*

   We define three orientations, horizontal, vertical and diagonal representing the connection between start and stop target in the grid.

4. *Direction*

   Given pair of targets, we define the backward pair by swapping the location of start and stop target. In the dragging task, we design 22 pairs of targets varied by location, distance and orientation. In addition to 22 backward pairs of targets, we have 44 pairs of tasks in total.



(a) (b)

Figure 1(a) shows the targets positioned at edge of a 5 × 5 grid and (b) shows the targets positioned inside the grid.

For each trial of dragging task, the start and stop target will be randomly selected from pre-defined library and appeared on tablet. In the case that participants accidentally start to drag the circular target from stop area, the system will interfere by launching an error sound. We are interested in dragging task since we feel that it somehow leads to the similar user behavior as sketching on tablet.

3.4.3 Write

To complete the writing task, participants wrote text-like scribbles on tablet. We defined three text-like patterns (see figure 2) in write task and they represented to participants in a random order. Given a text-like pattern, participants repeated it by three lines in a block. We defined three blocks placed at top, middle and bottom in the display of tablet and only one block would be visible to participants at one moment. To copy a text-like pattern in a line, participants are required to start their writings from legal start area. The legal start area will shift to the next line once participants started to write in the current line. After finishing a block, participants repeated the same text-like pattern in the next block as they did in the previous one.

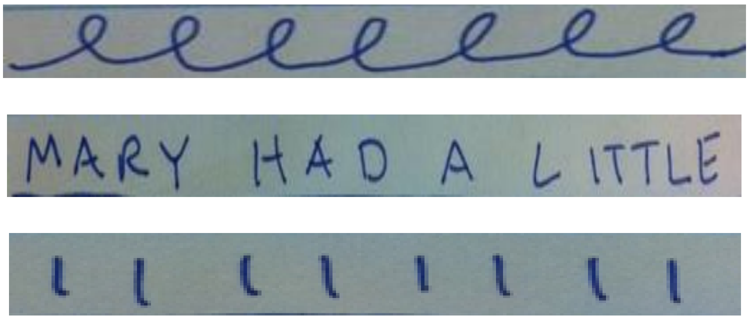
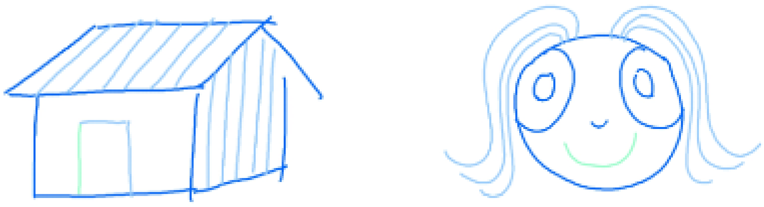


Figure 2 Text-like patterns used in write task

3.4.4 Draw

To complete the drawing task, participants traced out a drawing stroke by stroke. The stroke order of the required drawing is defined as the same order that we created it. In the drawing task, we defined two types of drawings (see figure 3), rectilinear and curvilinear.

We also defined two sizes, large and small for given type of drawing. The large-sized drawings positioned at top-center of screen and small-sized drawings positioned at either top-left for right-handed participants or top-right for left-handed participants. In doing so, we are able to maximize the chance of errant contact on tablet in the drawing task. For a given drawing, the target stroke is highlighted in greenish blue. The strokes that have been traced out are in dark blue. The strokes that are neither being finished nor targeted are in light blue (see figure 3). To trace out a target stroke, participants started from either end of the target stroke and finished it at the other end. The data collection system will proceed to the next target and drawing automatically after finishing the current drawing. We placed the large drawings at top and the small drawings at top-left corner to maximize the chance of palm contact on screen (since all participants were right-handed).



(a). Rectilinear (b). Curvilinear

Figure 3 (a) shows the rectilinear drawing and (b) shows the curvilinear drawing used in Draw task. The dark-blue lines represent the lines that have been completed. The light-blue lines represent the ones that have not been completed. The greenish-blue line represents the current target.

Participants performed all tasks with one style (finger or stylus) before mains to the next style. Four blocks of tasks were performed for each style: one unrecorded block followed by three recorded blocks. A block consisted of 25 trials of tapping task, 44 trials of dragging task, 9 trials of writing task and 4 trials of drawing task. Tasks are presented in increasing order of difficulty: tapping, dragging, writing and drawing. The order of styles was counterbalanced across participants. In summary, it has:

2 Conditions (Stylus, Finger) ×

3 Block ×

(25 trials of tapping task +

44 trials of dragging task +

9 trials of writing task +

4 trials of drawing task) = 492 data points per participant

In order to synchronize the video recorded by tripod-mounted camera and log data, we included visual time markers between tasks in the data collection. A time marker is a red square with a large number shown for 3 seconds. Participants tapped the time marker after 3-second delay and proceeded to the next task. The time maker number started from 1 and increased sequentially for stylus and finger condition.

3.5 Post Processing

To secure the validity of study results, we conduct a post-processing procedure following the formal study. The goal is to correct the misclassification of errant touches from event log intended touches. In the post processing, I used Scrubby (shown in figure 4), which is an efficient tool for log synchronizing, segmenting and annotating provided by Daniel Vogel13, to analyze touch events recorded from the formal study.

[13] http://www.nonsequitoria.com

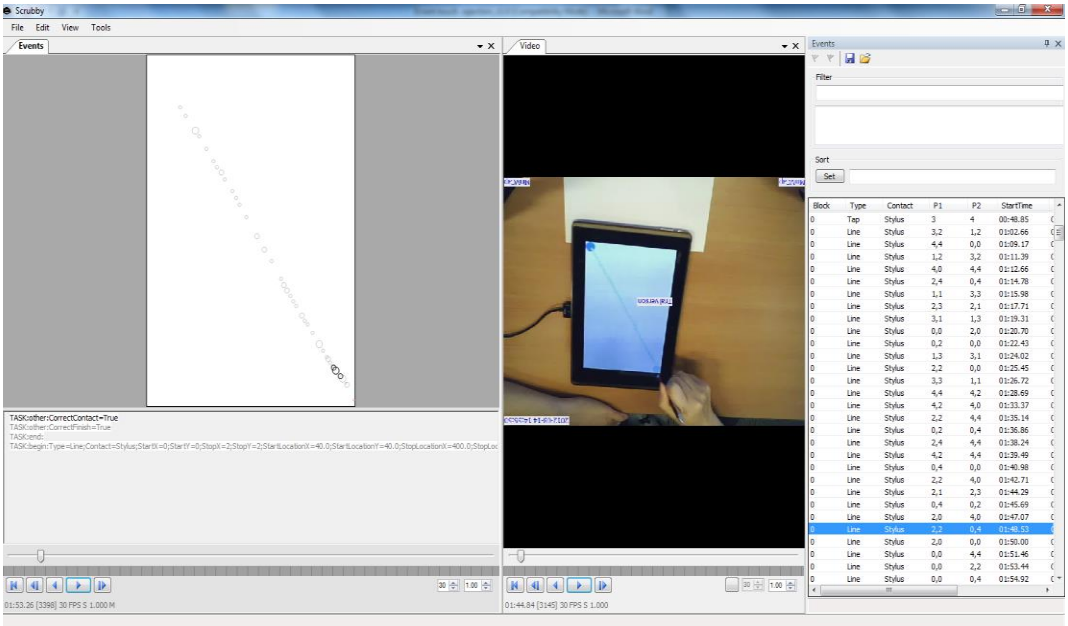


Figure 4 shows the user interface of Scrubby

3.5.1 Heuristic

I conducted a simple heuristic to analyze the logging data of writing task In the writing task, we did not control the legal touch-down area as rigorous as we did to other three tasks because we do not expect to change the way users are writing naturally. It reduced the bias of results but required effort on post-processing. To reduce the workload of post-processing, I applied a simple heuristic on touch events in the writing task and described it at below.

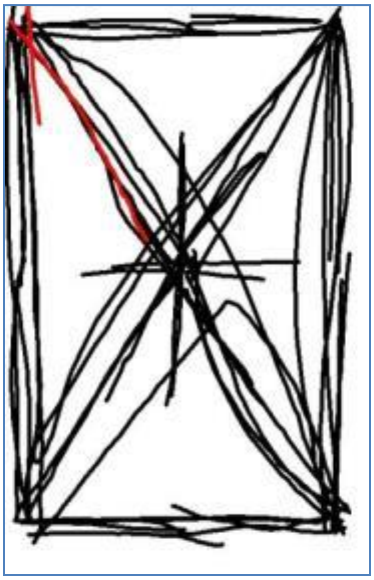
1. If the contact size of a touch input is no smaller than 2.0, it is an *errant* touch
2. If the touch input is occurred outside of the text area, it is an *errant* touch
3. If the horizontal position of a touch input is smaller than 300 pixels, it is a *correct* touch
4. If a touch input is not subject to any of these condition, it is flagged as an *undecided* touch

- It waits for the next touch if it is the first touch recorded by the tablet. If no more touches are received by end of the task, it is correct touch
- If an extra touch input is received, repeat from step 1). If this touch input is also an undecided touch, the left-most one is a correct touch

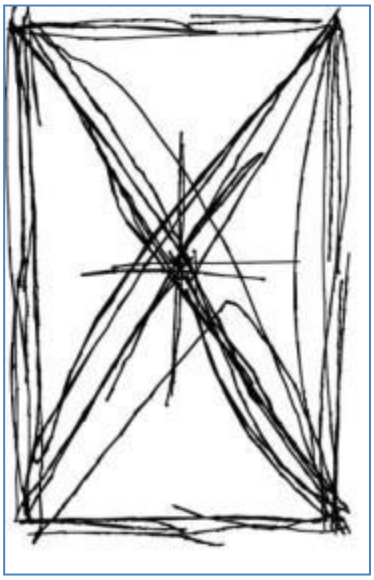
This heuristic helps to correct the misclassification to some extent and hence reduce the workload in manual clean which is discussed in the next section. This heuristic is an implicit approach for cleaning writing task, but not for rejecting errant touches in general cases because it considers a touch as an errant touch if it is out of the legal writing area, which is not existed in real scenarios.

3.5.2 Manual Clean

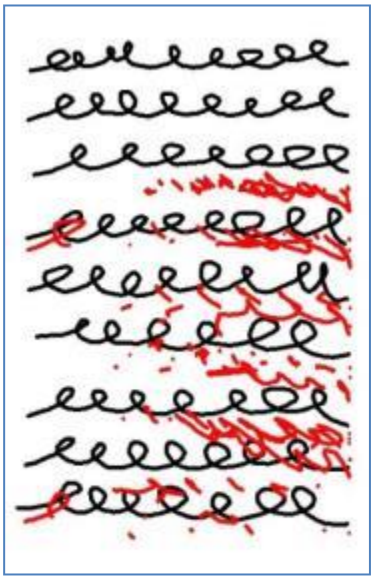
I manually correct misclassification of errant touches across all tasks. Since our heuristic cannot guarantee identifying errant touches completely, I manually checked and corrected the misclassification of errant touches by using Scrubby (see figure 5).



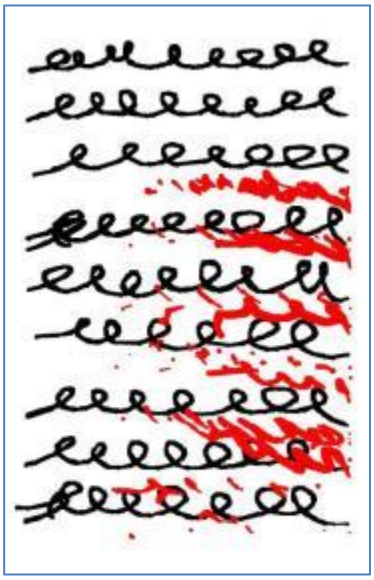
a.1 drag: before



a.2 drag: after

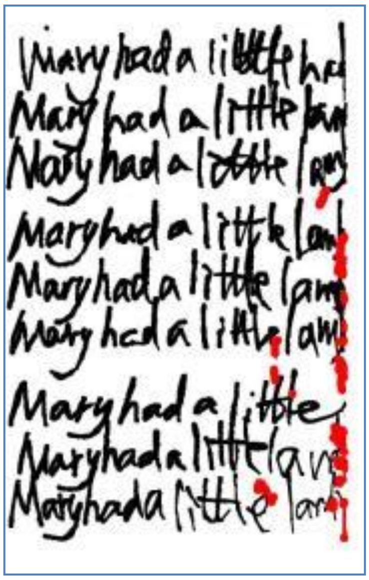


b.1 write 1#: before



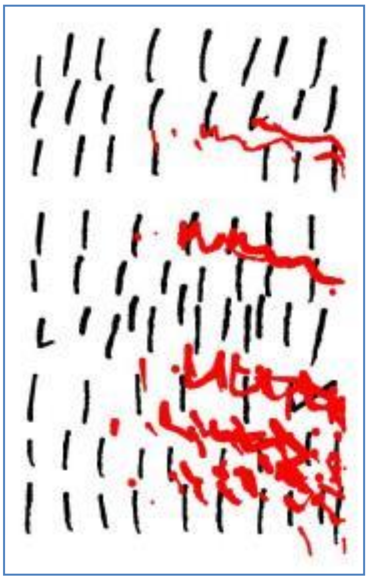
b.2 write 1#: after

c.1 write 2#: before

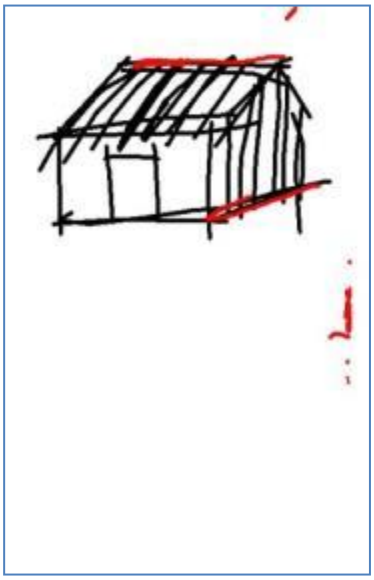


c.2 write 2#: after

d.1 write 3#: before



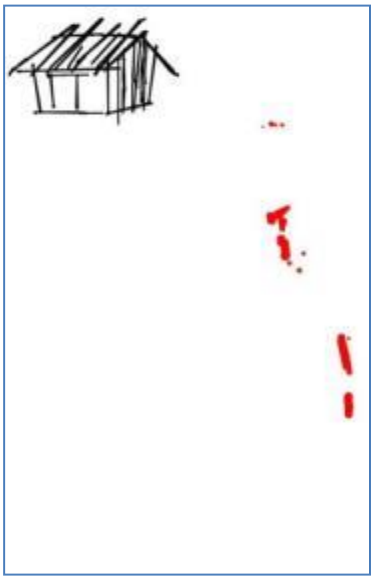
d.2 write 3#: after



e.1 draw 1#: before

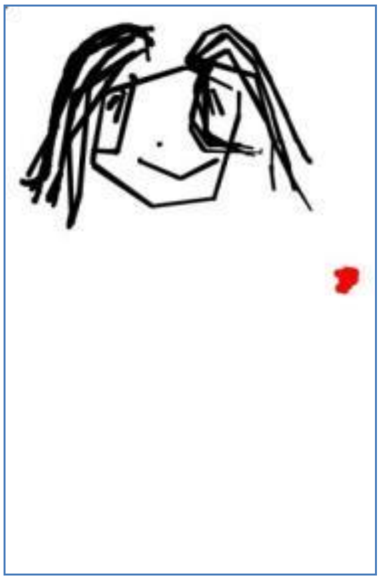
e.2 draw 1#: after

f.1 draw 2#: before



f.2 draw 2#: after

g.1 draw 3#: before



g.2 draw 3#: after

h.1 draw 4#: before

h.2 draw 4#: after

Figure 5 shows the example images of (a) dragging task, (b) - (d) writing task and (e) – (h) drawing task. For each pair of images, the left one presents the image before post-processing and the right after post-processin

3.6 Study Results

In this section, we present the results of errant touches from the formal study in terms of *errant rate*, *absolute position*, *contact size*, *touch order*, *time interval between touch events* and *errant touch pattern*.

3.6.1 Errant Rate

Our results show that 8.3% of tapping task, 8.4% of dragging task, 56.0% of writing task and 59.9% of drawing task has errant touch data being recorded in the stylus condition. The result is also consistent with the comments made by participants. Participant 1, 2 and 7 made comments that they "don't place palm on screen because the (tapping and dragging) task is way too easy", but participant 1, 3, 7 made comments that they "rest hand on screen since the (writing and drawing) task requires fine-grained drawing".

In the finger condition, the results show that 4.3% of tapping task, 3.7% of dragging task, 22.0% of writing task and 44.3% of drawing task has errant touch data being occurred. Based on the results, we found that errant rate is lower in the finger condition than the stylus condition. It may be caused by the different writing postures in which participants complete tasks by finger from stylus. In our study, all participants performed tasks by index finger in the finger condition. We observed that they generally straighted up their index fingers to touch the tablet to reduce ergonomic discomfort. In doing so, their hands basically hovered above the tablet and hence avoid the chance of making errant touches.

3.6.2 Absolute Position

In figure 6, we plotted the errant touches from tapping, dragging and writing task in the stylus and finger condition over the entire tablet display. We do not discuss the absolute position of errant touches in drawing task because we put the drawings at particular regions to increase the chance of collecting errant touches. The red dot represents the touch-down pointer which is initialized on tablet, and the grey one represents either touch-move or touch-up pointer that has been initialized from a touch-down pointer. In the tapping, dragging and writing task, the targets are placed fairly even over the entire display. Instead of finding where errant touches are, the more interesting thing that we expect from the absolution position of errant touches is where they are not located.

Based on the plots shown in figure 6, we find that the left area of display is fairly safe from errant touches for all tasks in both stylus and finger conditions. We have not measured the width of the “safe zone”, but it will be illustrated in the final thesis. More interestingly, we find that a right-top area is also safe from errant touches in the writing task for both stylus and finger. The “safe zone” can give us a rough idea of confident area that can be designed for user interaction without the interferences of errant touches. Note that this result is only applicable to right-handed users but I expect that the result would be mirrored for left-handed users. The left-handedness will be investigated in future work.

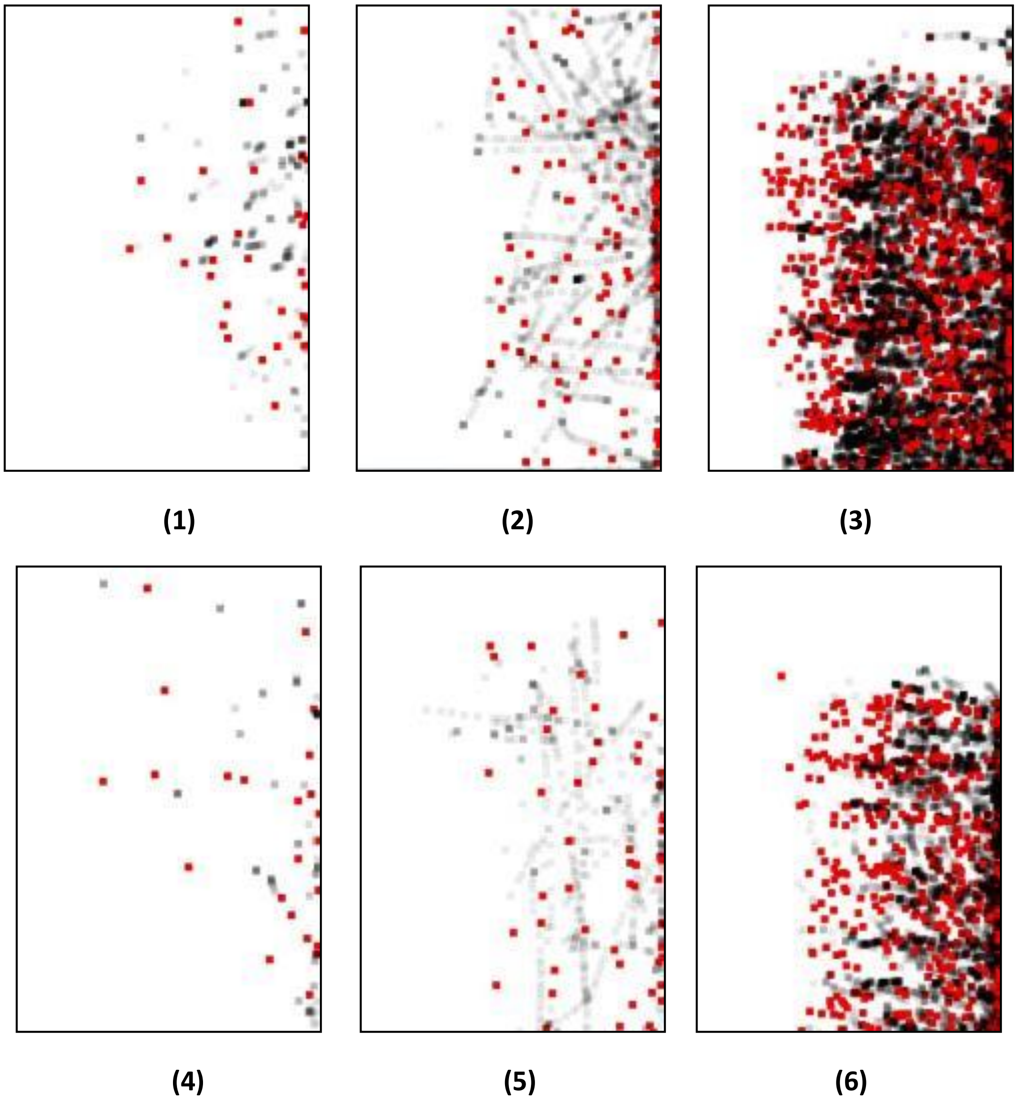
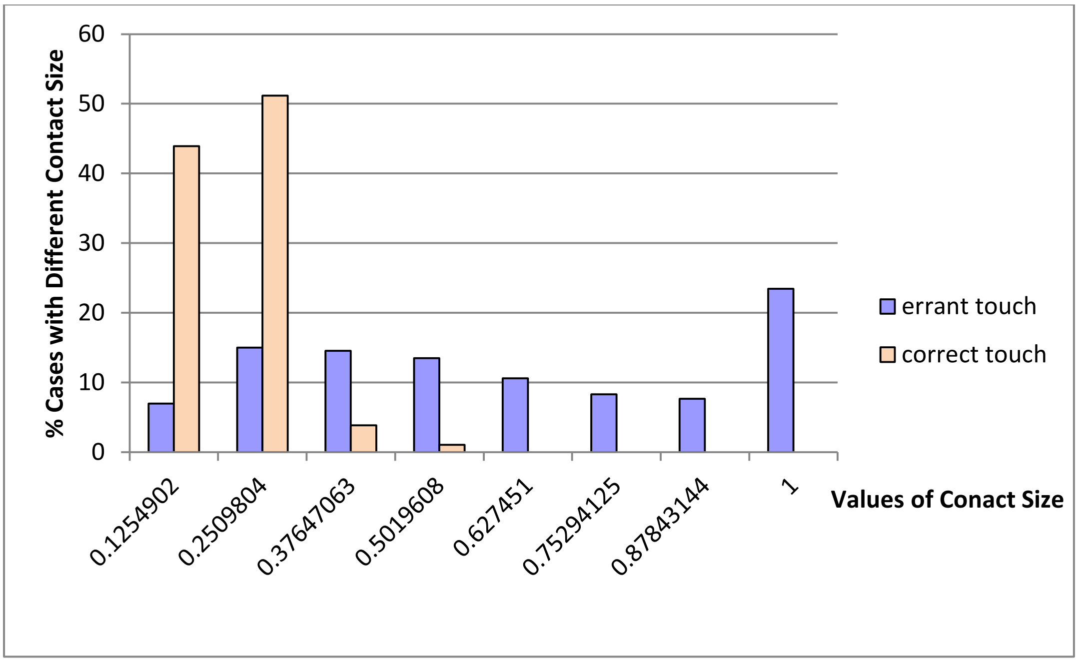


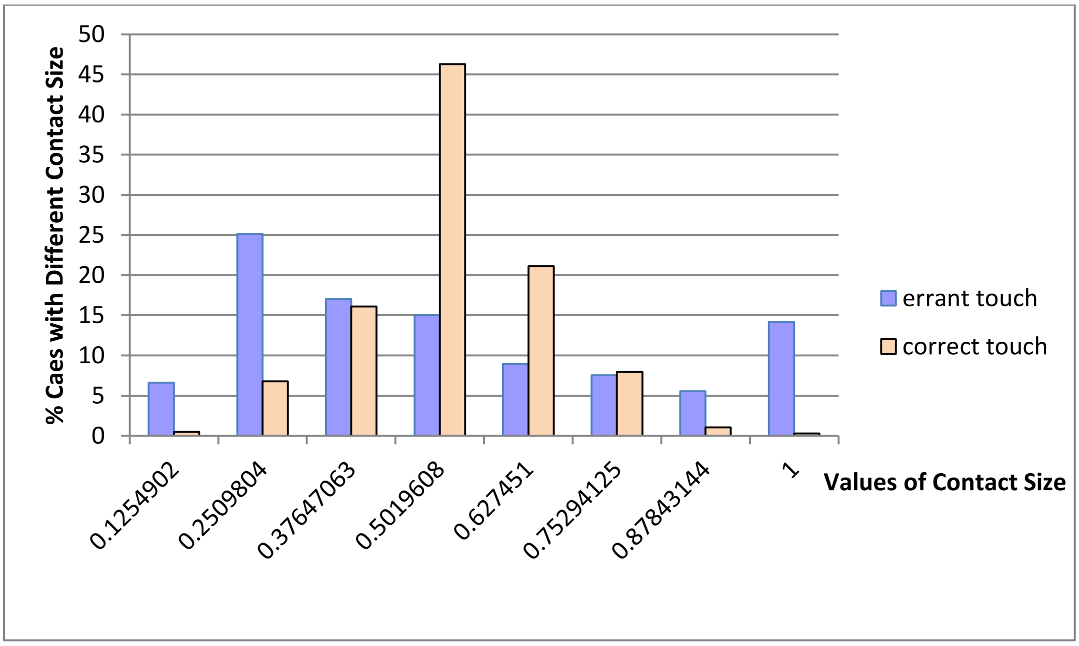
Figure 6 (1), (2) and (3) shows the errant touches from tapping, dragging and writing task respectively in the stylus condition. (4), (5) and (6) shows the errant touches from tapping, dragging and writing tasks in the finger condition.

3.6.3 Contact Size

The contact size of errant touches is important for errant touch rejection design. Hinckley et al. [2] and Zeleznik et al. [13] identified large-sized contacts as errant touches in their researches. They described that it somewhat solves the errant touch rejection problem but lacked of any further investigation. In our study, we analyzed the contact size of errant touches and presented them in figure 7.



(a) Stylus



(b) Finger

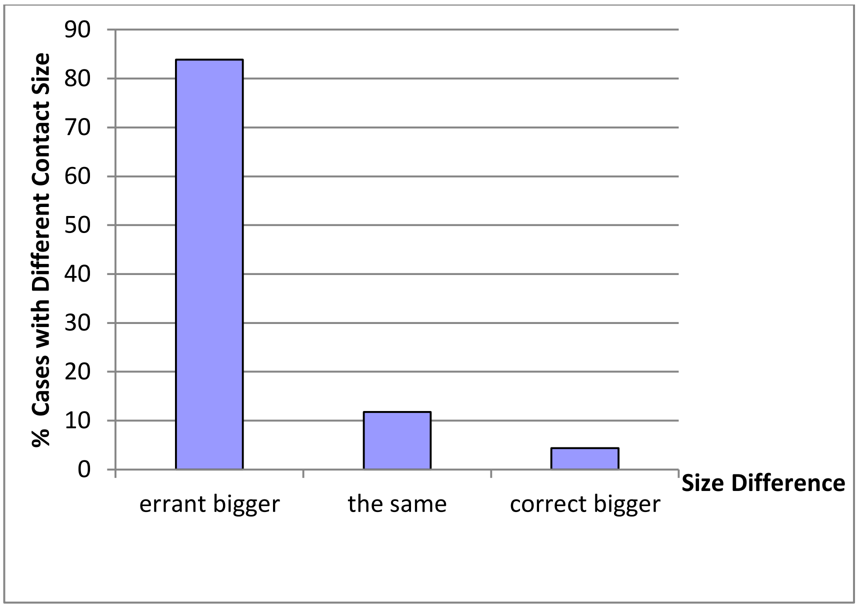
Figure 7 (a) and (b) show the percentage of errant touches over different sizes in the stylus and finger condition respectively

The contact size returned by the Android OS is a scaled value of the approximated size of touch input. It is device-dependent and ranges from

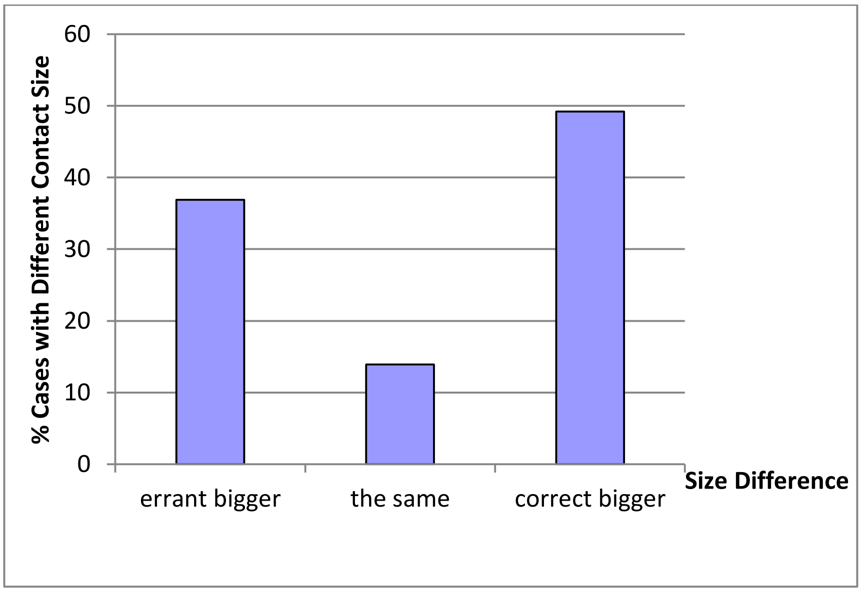
0.125(minimum round-up value) to 1.0. In this thesis, we define 0.627 and above as large contact size and verse vice as small contact size. Our results verify Hinckley and Zeleznik's statements since the errant touches are not necessarily large-sized contacts. From figure 5, we can see that 50% and 63.8% of errant touches are small-sized contacts in the stylus and finger condition. Furthermore, 7% and 6.6% of errant touches yield the minimum value of contact size by stylus and finger respectively.

We also find that the distribution of correct touch is different between stylus and finger condition. In the stylus condition, the contact size of pen touches is dependent on the elastic property of pen tip. To reduce the loss of generalization of results, we choose a capacitive stylus which is best sold in current market. We find that 95.1% of pen touches yield the contact size smaller than 0.3 by stylus and no large-sized contacts are generated in the stylus condition. They are all fairly confident sign of pen touches. We expect that the contact size could be an effective delimiter of identifying errant touches especially if the pen size is configured by users in real time, though it is not able to reject all errant touches. From the figure 7.a, we can see that the contact size of correct touch is no larger than 0.63. Therefore, 50% percent of errant touches can be rejected since their contact size are larger than or equal to 0.63. In the finger condition, however, the correct touch distributes normally.

Given a touch pointer, the contact size of this touch is generally varied by time since it is on tablet. It motivates us to investigate the contact size of an errant touch and its corresponding correct touch at given time. The results are presented in figure 8.



(a) Stylus



(b) Finger

Figure 8 (a) and (b) show the percentage of touches with different sizes at given time in the stylus and finger condition

From figure 8, we find that 95.7% of errant touches are larger than or equal to correct touches at given time in the stylus condition. By comparing the contact size of all touch pointer at given time, we can correct the misclassification of errant touches in real time.

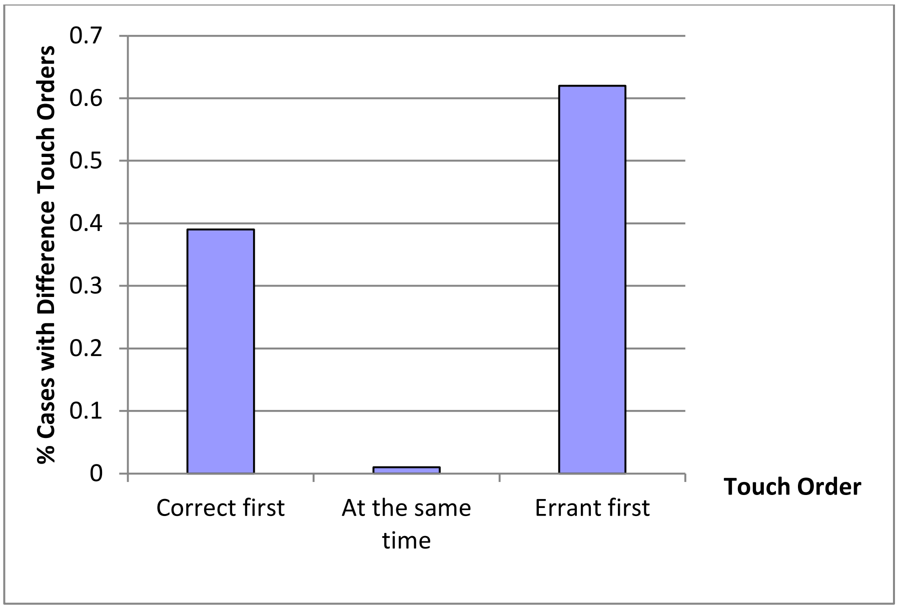
3.6.4 Order of touch events

We investigate the touch order because we are curious if users rest their hands on tablet before writing as they generally do on paper. If so, we can automatically generate the cover sheet according to the first touch on tablet. The results of touch order are presented in figure 9.

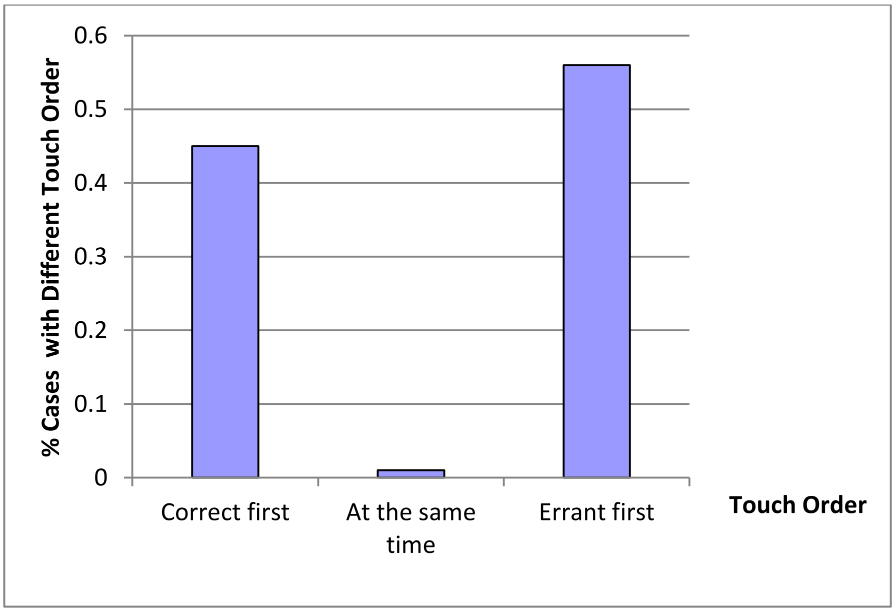
Unfortunately, our results show that it is not reliable to assume the first contact on tablet is generated by errant touches. From figure 7, we can find that only 62% and 56% of errant touches are invoked before correct touches in the stylus and pen conditions. This result demonstrates that *penultimate* is not capable to reject errant touches completely since it assumes users will always put their hands on tablet before writing.

3.6.5 Time Interval between Touch Events

We are interested at the interval of event time between an errant touch and its corresponding correct touch because we feel that it could be a very important variable for implicit errant touch rejection designs. The results of intervals of event time are shown in figure 10.

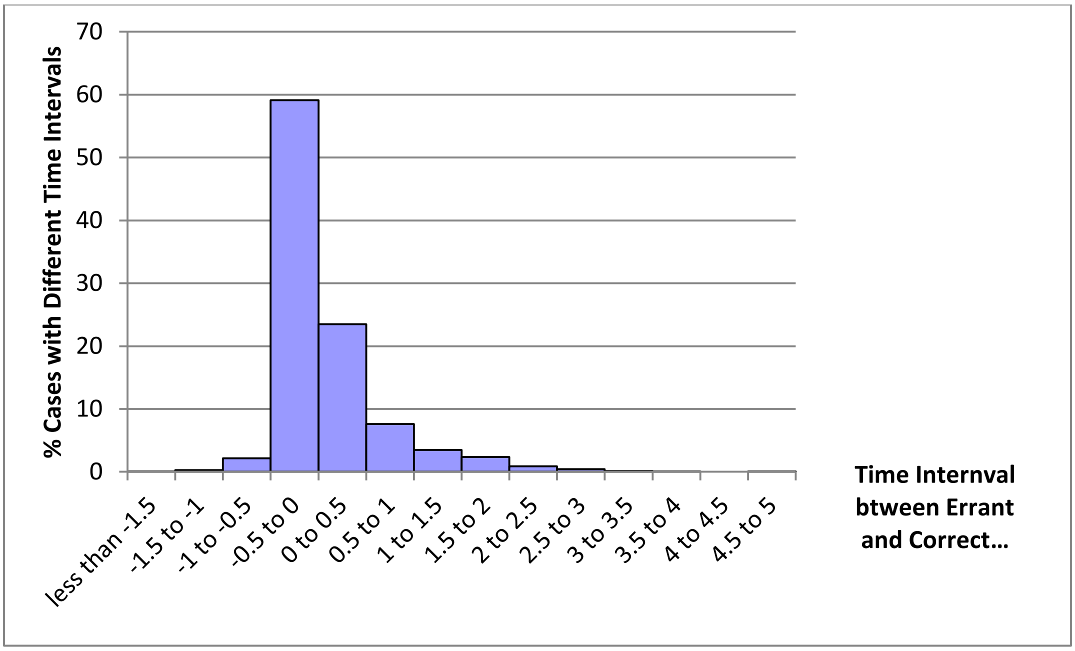


(a) Stylus

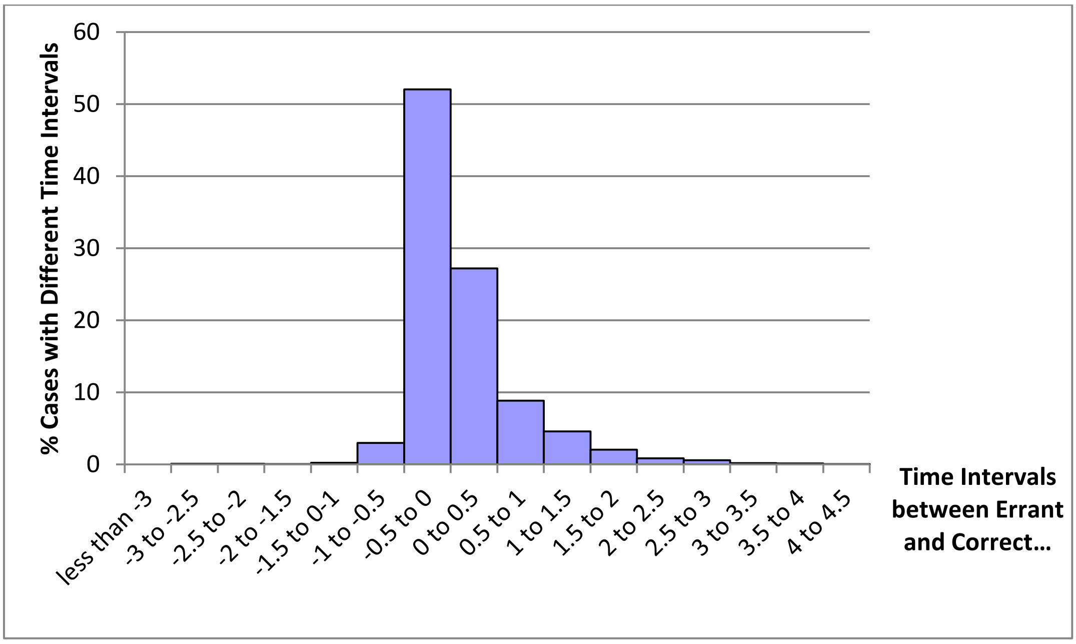


(b) Finger

Figure 9 (a) and (b) show the percentage of touch order in the stylus and finger condition



(a) Stylus



(b) Finger

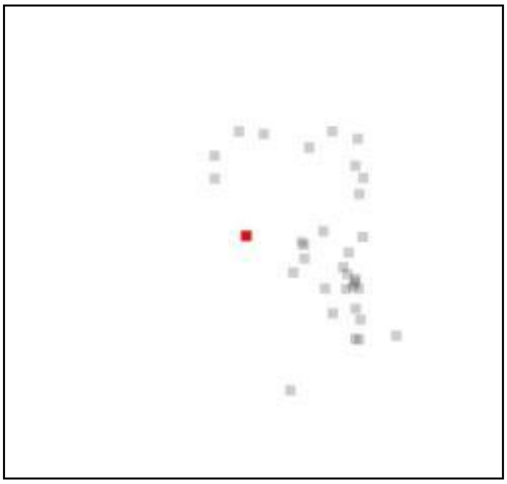
Figure 10 (a) and (b) show the interval of event time between an errant touch and it corresponding correct touch in the stylus and finger condition. The negative value represents the interval of an errant touch earlier than its correct touch. On the contrary, the positive value stands for the interval of an errant touch later than its correct touch.

The results show that the distribution of intervals in the stylus condition is similar to it in the finger condition. 82.6% and 79.3% of errant touches and their corresponding correct touches are occurred within 0.5 second in the stylus and finger condition. If there is a touch invoked more than 0.5 second later or earlier than a given correct pointer, it is probably an errant touch. To design a robust implicit rejection approach, I will investigate the intervals between two consecutive errant touches in future study.

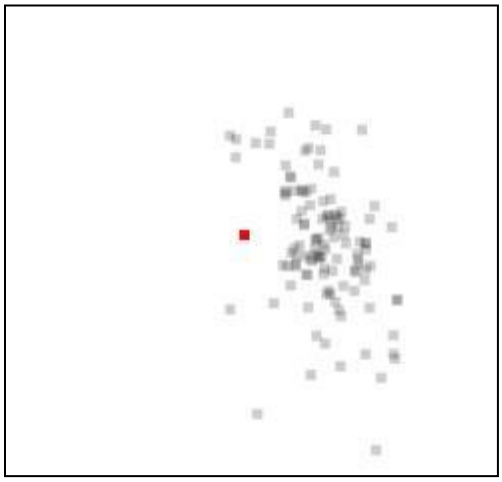
3.6.6 Errant Touch Patterns

The relative position to a correct touch is another important aspect to help understand characteristics of errant touches. In this thesis, I consider errant touches along with a corresponding correct touch as an errant touch pattern. In figure 11, I plotted the errant touch patterns in each task and condition.

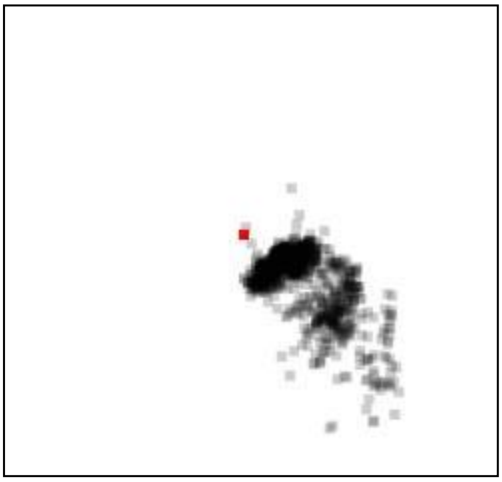
From figure 11, we can find that the errant touch patterns of tapping and dragging are sparsely spread in both stylus and finger condition. Apart from the low errant rate, we observed that it is mainly resulted from the inconsistent pen grip and hand posture adapted to complete those tasks. The errant touch patterns are compact in writing and drawing task by both stylus and finger. The errant touch pattern of drawing task is slightly different from writing task by stylus. In the drawing task, several errant touches are occurred above the correct touch but it is rarely a case in writing task by stylus.



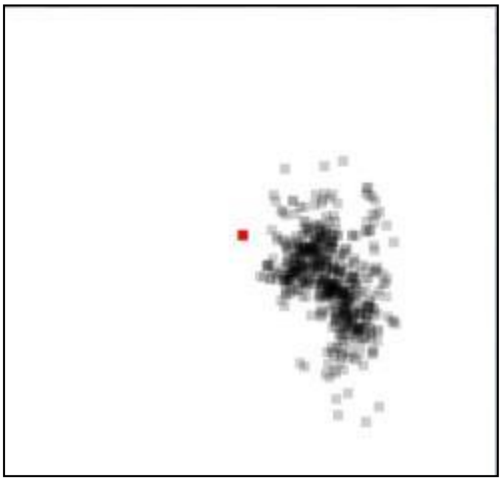
(a) stylus: tap



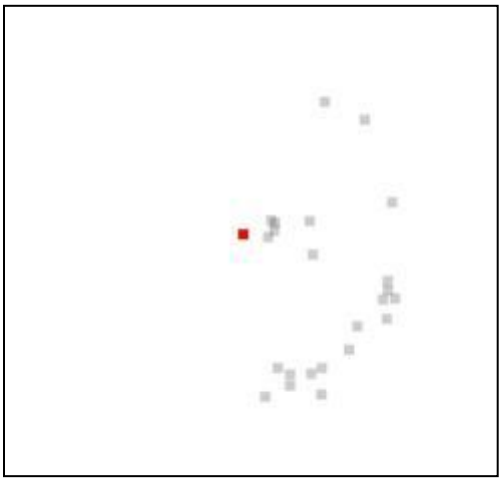
(b) stylus: drag



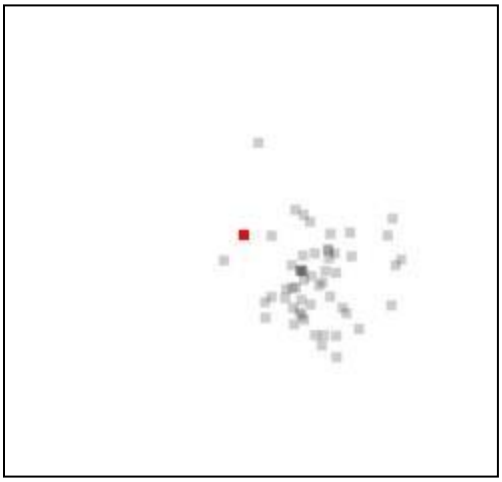
(c) stylus: write



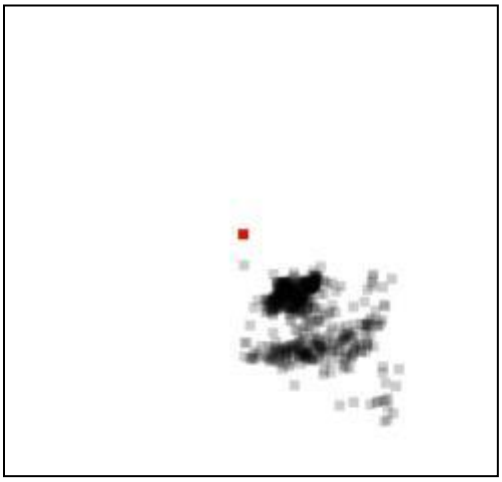
(d) stylus: draw



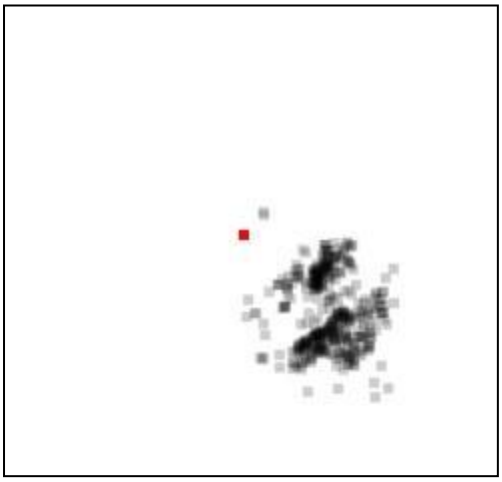
(e) finger: tap



(f) finger: drag



(g) finger: write



(h) finger: draw

Figure 11 (a), (b), (c) and (d) present the errant touch patterns from tapping, dragging, writing and drawing task respectively in the stylus condition. Similarly (e), (f), (g) and (h) present the errant touch patterns from tapping, dragging, writing and drawing task respectively in the finger condition. The red dot at the center stands for the correct touch and the grey dot represents errant touches.

3.7 Discussion

The goal of the formal study was to collect errant touches in general ink activities. In the section 3.5, I presented the findings from the aspects of errant rate, absolute position, contact size, order of touch event, time interval between time event and errant touch patterns. In this section, I will summarize the study results and discuss how they inform the design of errant-touch rejection techniques. I will separately consider two types of implicit techniques (single-parameter and multi-parameter) as well as explicit techniques.

3.7.1 Single-parameter Implicit Rejection

Based the study results, implicit errant-touch rejection designs are difficult and challenging. Currently, single-parameter implicit approaches are often applied to reject errant touches in research and practice. For example, Hinckley et al. [2] and Zeleznik et al. [13] identified large-sized contacts as errant touches in their researches. However, the study results demonstrate that it is difficult, if not impossible, to reject errant touches completely based on a single parameter (e.g. contact size, absolute position, relative position etc.). Besides, the errant-touch rejection accuracy of single-parameter is probably varied with the types of input (e.g. finger or stylus). The contact size is only helpful to reject errant touches if people are using a capacitive stylus. If people are using their bare fingers, the errant-touch rejection accuracy is low. Based on the errant touch patterns, I found the relative position of errant touches to the correct touch is also useful for implicit rejection design. For right-handed users, errant touches usually occur at the right-hand side of the correct touch.

3.7.2 Multi-parameter Implicit Rejection

In general, multi-parameter implicit rejections are more reliable than single-parameter approaches for rejecting errant touches since they can correct the possible misclassification made by single-parameter rejections. From the study results, I found the absolute position, relative position, time interval between touch events suitable for multi-parameter implicit approach of rejecting errant touches in both finger and stylus condition. The contact size is exclusively useful for multi-parameter implicit approach of rejecting errant touches in stylus condition. In this section, I presented a set of rules (for stylus only) that could hopefully help multiple-parameter implicit approach designs stylus input only:

1. If a touch yields a contact size that is large than the median of the contact size that tablet OS can provide, it considers as a large-sized touch. If a touch is in large size, consider it as an errant touch.
2. If multiple touches are recognized as errant touches but no touch is correct, evaluate the correctness of touches based on users' handedness: for the right-handed users, consider the left-most touch as correct touch.
3. Classify the first touch is a correct touch and subsequent touches are errant touches. Evaluate the correctness of touch classification in 0.5 seconds after the first touch is on based on rule 1# and rule 2#.
4. Generate a cover sheet subject to the geometric model of errant touch patterns relative to the correct touch. All touches that occur inside of the cover sheet will be rejected. The cover sheet could be either visible or invisible to users. If no touches occur in 3 seconds after the cover sheet is on, dismiss the cover sheet.

The values of parameters (e.g. contact size, the distance between two touches etc.) used in the implicit rejection are undefined, and the implicit rejection is not implemented in this thesis. It remains to be the work that I expect to address in future.

3.7.3 Explicit Rejection

The pure explicit approach rejects errant touches with a virtual "cover sheet" (as in SmartNote[14]). The position of this cover sheet can be set manually, but it may

[14] https://itunes.apple.com/sg/app/smartnote/id362165952?mt=8

also move as the user writes to reduce the need for manual positioning. The geometric design of cover sheet is related to the performance of an explicit rejection approach: if the cover sheet is too small, it will miss preventing errant touches; if it is too large, it will waste the limited real estates of display unnecessarily.

The results of my study can be used to choose a cover sheet shape. The position of errant touches relative to a correct touch is fairly predictable. As shown in figure 12, the position of these errant touches can be modeled as a trapezoid with four parameters:

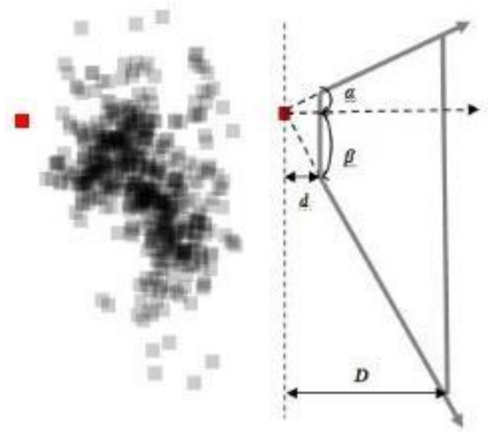


Figure 12 . shows the geometric model (right) according to the errant touch pattern (left) for right-handed users.

1. α: the angle from the upper edge to the horizontal line
2. β: the angle from the lower edge to the horizontal line
3. d: the distance from the baseline to the left edge
4. D: the distance from the baseline to the right edge

These four parameters could be increased to reduce the chance of errant touches or decreased to reduce the need for manual re-positioning of the cover sheet. The parameters could also be calibrated to individual users. I leave the problem of choosing appropriate parameters for future work.

Chapter 4: Bezel-focus Rejection Technique

In previous chapters, I investigated the properties of errant touches by a formal study. In this chapter, I present *bezel-focus rejection* technique, a new mixed explicit and implicit approach that supports bi-manual and uni-manual interaction seamlessly for errant touch rejection. Bezel-focus rejection technique is mainly inspired by two results from our exploratory study. First, pure implicit rejection is very difficult, if not impossible. Second, in the region around an intended touch, errant touches nearly always appear on the right (for right-handed users).

Bezel-focus rejection creates an *Ink Start Area (ISA)*, which is the unique area allowed inks on tablet when users are interacting the bezel of their non-dominant hand side. By manipulating ISA, bezel-focus rejection technique explicit rejects errant touches that are invoked outside of ISA and hence allows users to safely rest their hand on the tablet when writing or drawing. Inside of ISA, bezel-focus rejection technique implicitly rejects simultaneous multi-touches by their relative positions. Bezel- focus rejection also Bezel-focus rejection supports *tap*, *drag* and *pinch* gestures to invoke, relocate and resize ISA so that uses can choose an appropriate ISA in different ink scenarios. Bezel-focus rejection is also applied an implicit strategy to reject errant touches occurred within ISA based on users' handedness.

4.1 Storyboard of Bezel-focus Rejection

Bezel-focus rejection relies on touch interactions close to the tablet bezel on the non-dominant hand side of users. By interacting with the bezel of a tablet, users are able to control an *Ink Start Area* (ISA) which is the only area where new ink touches can begin. In figure 13, I present a simple storyboard to describe the idea of bezel-focus rejection.

1. The system is in NO-DRAW mode when no touches are on the tablet at the initial state.

2. Touch the bezel at the non-dominant hand of the tablet. In this storyboard, we consider right-handed users as an example. By touching the tablet bezel, the system generates an *Ink Start Area* (ISA) according to the position of touch-down.

3. Once ISA is on, any touches that are *initiated* outside will be rejected. ISA allows users to rest their hand securely on the tablet when they are writing or drawing. Do note that users are allowed to extend inks beyond ISA as long as they are started from ISA.

4. ISA will stay where it was when users are releasing their input finger or stylus, as long as there is whatever touch-down on the display of tablet.

5. To relocate ISA, drag it along bezel. In doing so, users are able to perform writing or drawing over the entire tablet.

Figure 13 the storyboard of bezel-focus rejection

The storyboard in figure 13 is briefly described how the bezel-focus is expected to work at very beginning. Based on the storyboard, I defined five key questions led to designing an efficient and reliable bezel-focus rejection. Question (1) to (5) determines the efficiency and question (6) concerns the reliability of bezel-focus rejection, respectively.

1. *Is ISA supposed to be enabled by a single finger or two fingers?*

It is enabled by one-finger tap gesture (see figure 14.a). In [14], Wagner et al. demonstrated that two-finger interaction is more difficult than one finger at the bezel of a tablet. It also reveals that one-finger bezel interaction is more preferable by users over two-finger interaction. In the proposed bezel-focus rejection technique, the position of one-finger tap determines the center of ISA in horizontal.

2. *What is the initial size of ISA?*

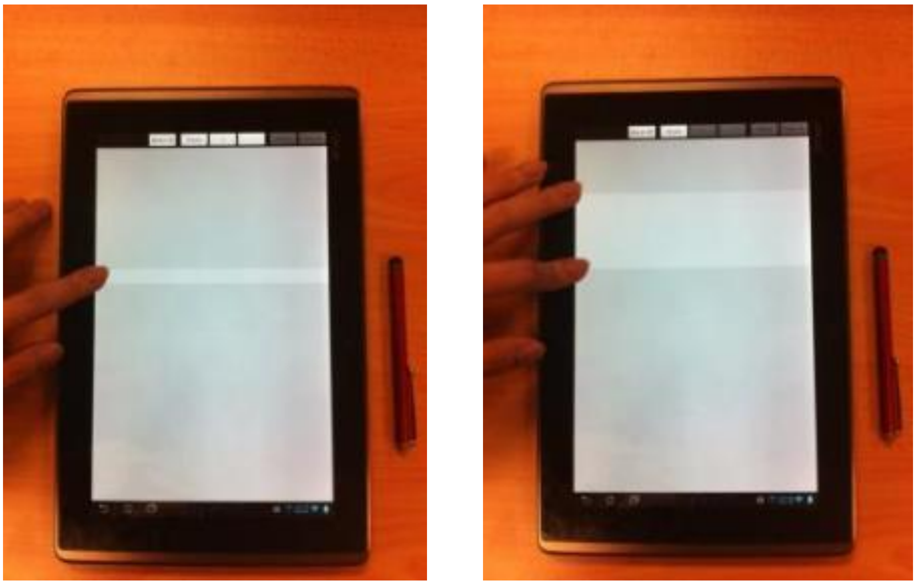
ISA is a rectangle-shaped cover sheet. It does not match the pattern of errant touches I found in my formal study. The reason that I choose it is that it is easy to manipulate. I define the default value of width of ISA as the full-width of the display (see figure 14.a) since the bezel-focus technique is mainly proposed for note-taking activity. Most of time people take note from the left to right over the entire display. For the default value of height of ISA, I set it as 10mm, which is generally as the same size as the diameter of a fundamental stylus's tip (see figure 14.b). From the results of errant touch patterns in formal study, I find numbers of errant touches are above the correct touch vertical. It reflects that it is possible that multiple touches could occur within ISA. To reduce the chance of co-occurrences of multiple touches in ISA, the height of ISA should be small.

(a) (b)

Figure 14 (a) one-finger tap on the bezel to enable ISA (the white rectangle). The grey area is the blocked area where any touches will be ignored. The width of ISA is the full-width of the display of the tablet. (b) The height of the ISA is at the same size as the diameter of the stylus' tip by default

3. *How does a user resize ISA if the initial size of ISA is not preferable?*

Bezel-focus rejection supports resizing ISA by two-finger pinch gestures. After enabling ISA by one-finger tap, users are allowed to put the second finger on bezel (see figure 15) to resize ISA. The top of ISA is set to upper touch position, and the bottom of ISA is set to the lower touch position. Once two fingers are on bezel, users can pinch the size of ISA.



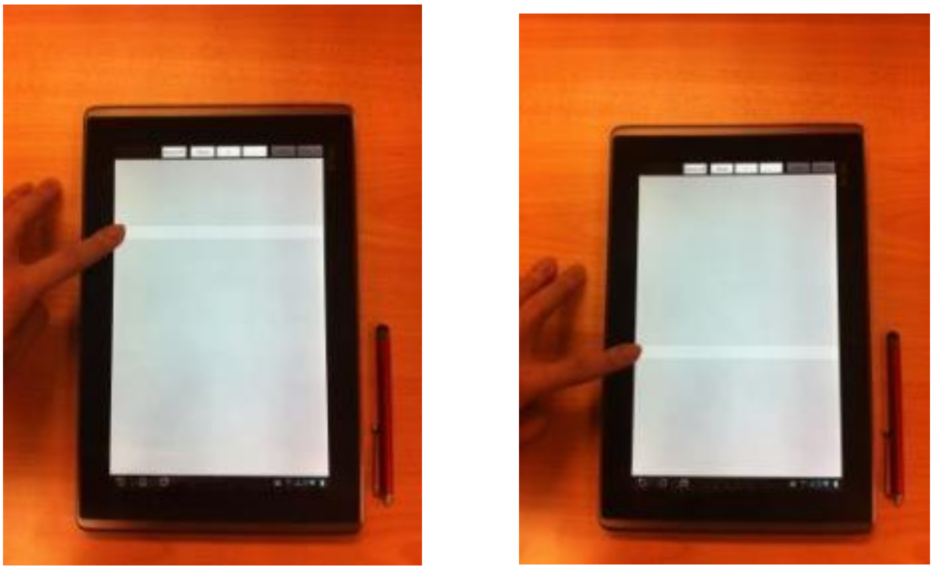
(a) (b)

Figure 15 (a) shows the one-finger tap gesture to enable ISA and (b) shows the two-finger tap gesture (put an extra finger at a new position of the bezel) to resize ISA

4. *How does a user relocate ISA to a new position?*

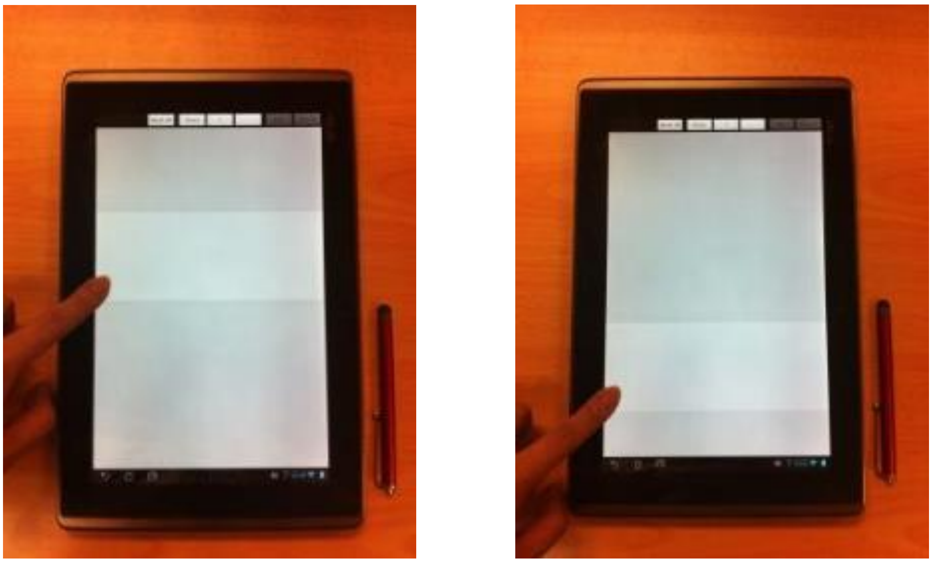
I defined three gestures, one-finger tap, one-finger drag and two-finger pinch to support ISA reposition in the bezel-focus rejection approach. One-finger tap gesture (see figure 16) allows users to relocate ISA by tapping a new position on the tablet bezel and the one-finger touch down determines the central line of ISA. The bezel-focus rejection technique also allows users to drag ISA (see figure 17) to a new position and it is commonly developed in current tablet applications. Besides, two-finger pinch not only can change the resize of ISA but also is able to change its position at the same time. (see figure 18).

The reason of supporting one-finger tap for ISA reposition is that we expect one-finger tap more efficient for drawing two parts of objectives far away from each other in drawing tasks. Two-finger pinch gesture is regarded as a shortcut of combining ISA resize and reposition by one movement.



(a) (b)

Figure 16. After turning on the ISA by default (see (a)), release the current touch and tap a new position on the bezel of relocate ISA (see (b)). The position of the finger determines the central line of the ISA in vertical



(a) (b)

Figure 17. When the ISA is on the tablet, tap inside of the ISA (see (a)) and drag it to change its position (see (b)).

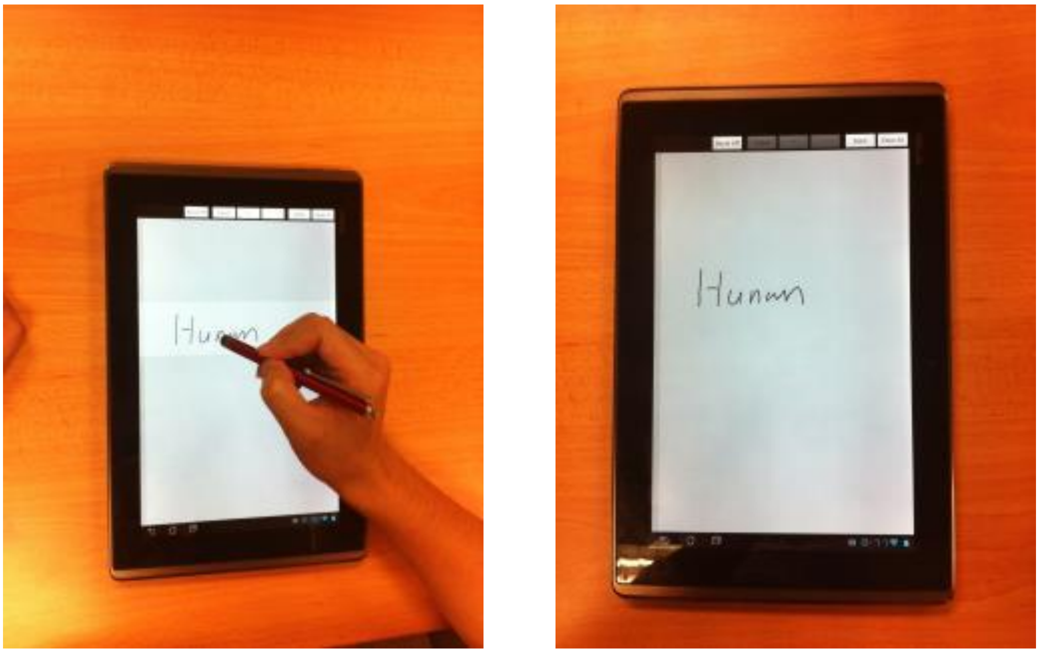
(a) **(b)**

Figure 18. By two-finger pinch gesture (see (a)), ISA is able to be resize and reposition at the same by move the two fingers on ISA (see (b)).

5. *How is the ISA dismissed?*

ISA is dismissed by a timer. In the bezel-focus rejection technique, I set a three-second timer at the point of time when the last touch-down is released from tablet. The ISA will be automatically dismissed and disappeared after three seconds if no new touch-down is received by tablet (see figure 19).

We expect that dismissing ISA by a timer is efficient assuming (1) users are inclined fast writings in writing task and (2) users who prefer errant touch rejection are accustomed rest their hands on tablet constantly.



(a) (b)

Figure 19. (a) shows the user is resting his hand on the tablet and writing. Please note that the user is not touching the bezel of tablet but the ISA is not disappeared because there are at least one touch-down caused by either stylus tip or hands on tablet. Once there is no touch-down on tablet, the ISA will be dismissed in three second (see (b))

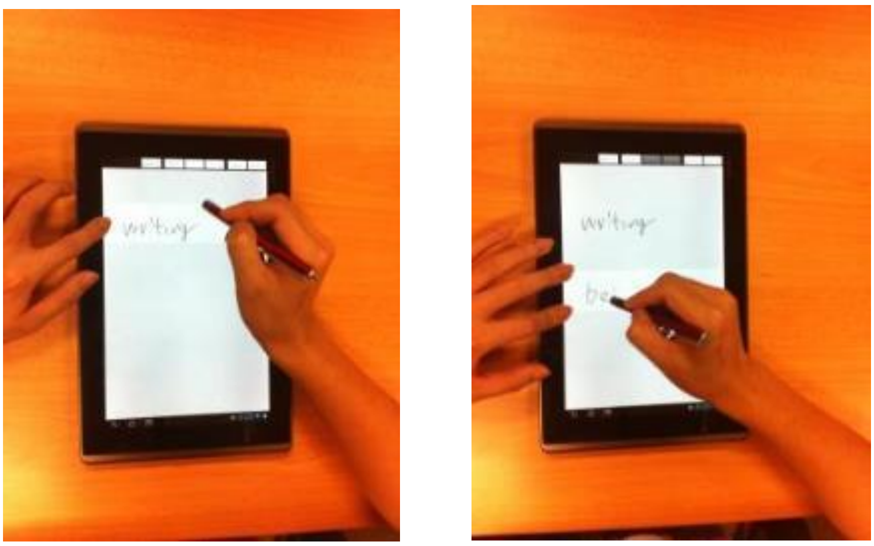
6. *How does ISA reject the errant touches if any are invoked inside of it?*

Based on the results of the errant touch patterns in formal study, I found that errant touches are consistently at the right-hand side of the correct touch for right-handed users. Inspired by that, I developed a simple approach to reject errant touches inside of ISA based on the handedness of users. For right-handed users, I reject any extra touch-down inside of ISA if it is at the right of the current touch-down. If the coming touch-down is at the left of the current one, bezel-focus rejection will consider the current touch-down as an errant touch and erase the ink created by it. The coming touch-down will be considered as a valid ink touch-down and start to generate inks. (For the current implement of bezel-focus rejection approach, I consider right-handed users only.)

There is one case that is not able to be rejected by bezel-focus rejection approach - an errant touch has made undesired inks but is released before users begin to write. This is the limitation of the bezel-focus rejection and we expect to evaluate how much it degrades the performance of bezel-focus rejection in a formal experiment, which is illustrated in the later section.

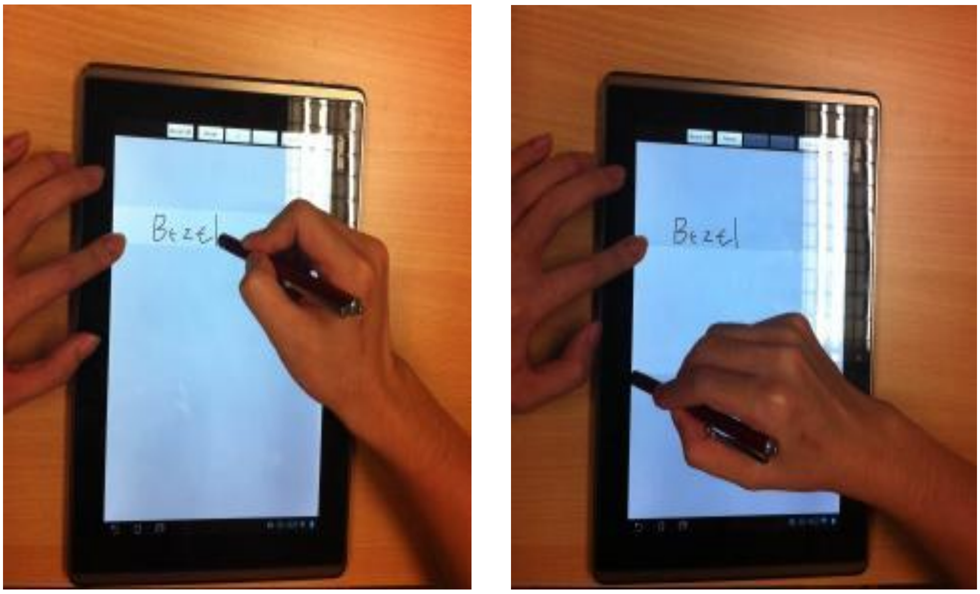
7. *Does bezel-focus rejection support bi-manual or uni-manual interaction?*

The bezel-focus rejection technique supports both bi-manual and uni-manual interactions. By bi-manual interactions, users are able to control ISA by their non-dominant hand when they are writing (see figure 20). Moreover, users are able to manipulate ISA by both non-dominant and dominant hand together (see figure 21).



(a) **(b)**

Figure 20 (a) and (b) demonstrates the bi-manual interaction: dominant hand for writing and non-dominant for manipulating the ISA

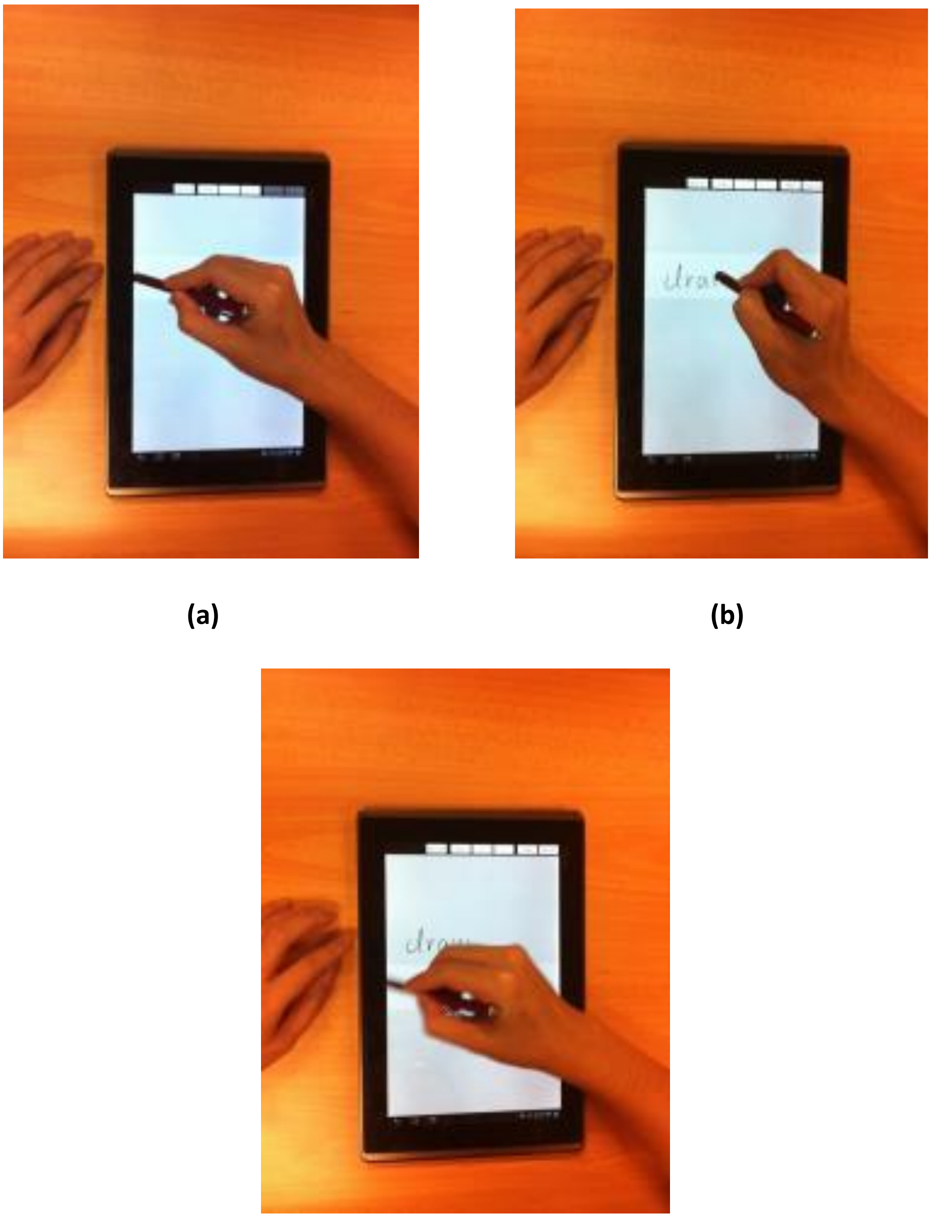


(a) (b)

Figure 21 (a) shows that the user is writing by dominant hand with a stylus and controlling the ISA with his non-dominant hand. (b) shows that the user is using non-dominant hand and dominant hand to perform two-finger pinch gesture on ISA

By uni-manual interactions, users are able to control ISA by their dominant hand before writing naturally (see figure 22). In this regard, the bezel-focus rejection is also acceptable when people cannot use their non-dominant hand.

In summary, bezel-focus rejection is a mixed explicit and implicit rejection approach. It rejects errant touches explicitly by ISA and implicitly based on users' handedness. It supports *tap*, *drag* and *pinch* gestures to invoke, relocate and resize ISA, and dismiss ISA by a three-second timer. In the next chapter, I will illustrate a formal experiment which intends to evaluate the performance of bezel-focus rejection in comparison to two existing rejection techniques.



(a) (b) (c)

Figure 22. (a), (b) and (c) shows that the user is enabling ISA, writing with ISA and dragging ISA by his dominant hand only.

Chapter 5: Evaluating Errant Touch Rejection Techniques

To evaluate the performance of bezel-focus rejection, I conducted a within-subject experiment to compare its performance with two existing ink interfaces (i.e. plain canvas and Note S canvas) in writing and drawing tasks by both finger and stylus. The experiment results show that our proposed technique can reject errant touches securely though it slightly slows down users' writing speed. The results also show that users are more inclined to put their hand on tablet when using the proposed technique and it is most preferred by users.

5.1 Experiment

In my previous formal study, I found that users are more inclined to rest their hand on tablet and leave errant touches in writing and drawing than tapping and dragging. Based on that, the bezel-focus rejection technique is mainly designed for rejecting errant touches in writing activity, but we expect it suitable in drawing as well. In this experiment, I evaluate the performance of bezel-focus rejection against two other errant stroke rejection techniques. The experiment has three main goals as follows:

1. Evaluate how well bezel-focus rejection prevents errant touches.
2. Test if bezel-focus rejection slow down users' writing or drawing speed
3. Collect user preference and feedback of bezel-focus rejection from users.

5.1.1 Apparatus

The experiment was run on an ASUS Eee Pad TF101 tablet with a 256 mm (10.1 inch) diagonal display, a resolution of 1280 by 800 px (218 by 136 mm) and a pixel density of 5.9 px/mm. We positioned the tablet flat on desk in portrait-orientation and participants are allowed to adjust it to a comfortable angle by their preference. In the experiment, I also only evaluate the portrait mode since the portrait mode is most-likely used for writing and drawing on tablet.

5.1.2 Comparison Interfaces

In this experiment, I compare the bezel-focus rejection technique with two existing techniques, the *PLAIN* technique and the *Note S* interface. PLAIN is an implicit rejection technique that rejects multiple touches whenever they occur. In such cases, the first touch will be initially identified as valid ink, but when the next touch begins, all will be rejected as errant touches (cancelling the ink generated by the first touch). I chose PLAIN as a comparison technique since it is the simplest approach to rejecting errant touches.

Note S is also an implicit rejection approach that is inspired by the Samsung Galaxy Note S interface. I chose this for comparison, because Note S is one of the few well-known ink applications that feature errant touch rejection. When multiple touches occur at the same time, this technique will attempt to classify one of them as valid ink. This contrasts with the *PLAIN* approach, which rejects any touch that occurs at the same time as another. To detect ink, *Note S* uses the following two rules which I observed in the Galaxy Note S interface:

1. *If the first touch is small-sized and slow-paced*

If the first touch is small and moves slowly, it will be accepted as ink on the page, and later touches will be rejected as errant touches. This rule accepts some ink while preventing accidental touches by hands when users are writing. The rationale behind requiring strokes to move slowly is unclear. Requiring strokes to be small may be an attempt to reject touches from the user's wrist.

2. *If the first touch is small-sized and slow-paced, and it is released after the second touch is on tablet*

Rule #1 accepts the first touch as ink, while the second touch is rejected. Rule #2 activates if the second touch is still active when the first touch is released. In this case, then the second touch will be accepted as ink from that time forward. However, any large-sized touches that begin after this point will cancel all ink accepted in this series of touches (including the first touch). The rationale behind these rules is unclear, but I observed them in the Note S interface.

If no touches can be accepted as ink using the two rules discussed above, *Note S* will reject the second touch and cancel the inks made by the first touch in the same way that *PLAIN* does. To sum up, *Note S* is a more advanced implicit rejection technique than *PLAIN* since it will attempt to classify some touches as ink when multiple touches are detected. I expected that these differences between *Note S* and

PLAIN would influence users' writing behavior and affect errant-touch rejecting performance.

To determine thresholds for "small" contact size and "slow" movement speed of touch pointers in *Note S*, I did a head-to-head experiment on Samsung Galaxy Note II tablet and ASUS Eee Pad TF101 tablet to estimate the value of parameters. I set the value of large size as 0.878 (*the second largest contact size value available on ASUS Eee Pad TF101*) and the movement speed of touch pointer as 300 pixels per second in *Note S* interface.

5.1.3 Tasks

In the experiment, I defined two types of free-hand task: *writing* and *drawing*. For the writing task, participants are required to start from the top area of tablet and copy a sample passage over the entire display of tablet. In order to prevent rush scribbles, I presented a nine-row grid on the display and request participants to copy a passage line by line. I chose all sample passages from *Pride and Prejudice* in order to keep all passages at same level of word complexity. I selected three types of passages varied their length for different sections in the experiment. For the training section, I selected simple passages in order to shorten the experiment process. For the formal section in finger condition, I selected the passages with less length of word than the ones used in stylus condition because people usually write bigger by finger than stylus.

For the drawing task, participants are required to trace a sample drawing with a set of small strokes shown on tablet. The sample drawing is placed at the upper-half part of the tablet since it is the area that most-likely to be drawn and results errant touches. For a drawing task, I did not specify the stroke order that participants are request to trace out. Instead, participants can trace a drawing by any order they prefer.

When participants are performing tasks, our system will log every touch event and button-click event in background. I developed UNDO, CLEAR ALL and DONE buttons at right-top area in PLAIN canvas, Note S canvas and bezel-focus rejection canvas. Participants are requested to remove errant inks by clicking either UNDO or CLEAR ALL button if they make any. They can also click the UNDO or CLEAR ALL button to remove their unsatisfied inks since we ask them to give the best ink performance as possible. After finish a task, participants click the DONE button to proceed to the next one.

5.1.4 Pilot Study

I conducted a pilot study before running the formal experiment. Two participants, aged 23 and 28, were recruited in the pilot study. The pilot study is a $3\times2\times2$ within-subject experiment with three variables: INTERFACE (PLAIN, Note S interface and bezel-focus rejection interface), TASK (writing and drawing) and INPUT (stylus and finger). The order of these three variables is counterbalanced across participants. Given an input type, participants complete both writing and drawing task for each interface. Given an interface, I defined 4 trials (1 practice trials and 3 formal trials) of writing task and 4 trials (1 practice trials and 3 formal trials) of drawing task as a block. Participants are request to complete three blocks of tasks in both finger and stylus condition. Participants took a five-minute break in between two tasks. To measure the completion time of writing tasks across different techniques, the writing tasks need to be of same length. The same is true for the drawing tasks. However, repeatedly using the same writing task and the same drawing task would ensure that tasks are comparable, but it has two problems:

- Repeating the same tasks increases the chance that learning effects could influence completion times, making later trials faster.
- Repeating the same tasks would be boring for participants, increasing their sense of fatigue and making later trials slower.

Therefore, I chose to compromise by using different but similar tasks for each trial in block 2 and the same task for each trial in block 3. For the writing task, the texts are all selected from *Pride and Prejudice*[15] with similar length. For the drawing tasks, there are similar in the number of strokes and the distribution of number of points in each stroke.

From the pilot study, we received two important feedbacks from participants as follows:

1) *The experiment took too long*. The pilot study approximately took 100 minutes by each participant. Participants felt exhausted after completing the entire experiment. In this regard, I will reduce the length of experiment in order to decrease the bias caused by fatigue in the formal experiment.
2) *Writing task is much more difficult than drawing tasks.* Both participants commented that writing task is much more difficult and tense than drawing task. It is possible that the drawing task right after writing tasks is poorly

[15] http://www.gutenberg.org/files/1342/1342-h/1342-h.htm

performed due to the effect of fatigue. In this regard, I will not counterbalance the order of writing and drawing task in the formal experiment, and alternatively keep them in a fixed sequence of drawing and writing.

5.1.5 Formal Experiment

To fix the issues of the pilot study, we fixed by the sequence of drawing and writing, while still counterbalancing the order of INTERFACE and INPUT across participants. The number of blocks is reduced to be three (one practice block and two formal blocks) in the formal experiment. Similar to the pilot study, I used the different similar texts or drawings in 2nd block and keep the text or drawing exactly same in the 3rd block in writing and drawing tasks. Participants took a five-minute break between two blocks of tasks. The texts used in the formal experiment are presented as follows:

- **Finger condition**
    - Block 1#
        - *When the party broke up, Lydia returned with Mrs. Forster to Meryton, from whence they were to set out early the next morning. The separation between her and her family was rather noisy than pathetic.*
        - *She had not been many hours at home before she found that the Brighton scheme, of which Lydia had given them a hint at the inn, was under frequent discussion between her parents.*

- *The others then joined her, and expressed admiration of his figure; but Elizabeth heard not a word, and wholly engrossed by her own feelings, followed them in silence. She was overpowered by shame and vexation*

* Block 2#
    - *Mr. Bennet had very often wished before this period of his life that, instead of spending his whole income, he had laid by an annual sum for the better provision of his children, and of his wife, if she survived him.*
    - *Between Elizabeth and Charlotte there was a restraint which kept them mutually silent on the subject; and Elizabeth felt persuaded that no real confidence could ever subsist between them again.*
    - *While she spoke, an involuntary glance showed her Darcy, with a heightened complexion, earnestly looking at her, and his sister overcome with confusion, and unable to lift up her eyes.*

* Block 3#
    - *She began now to comprehend that he was exactly the man who, in disposition and talents, would most suit her. His understanding and temper, though unlike her own, would have answered all her wishes.*

- **Stylus condition**
  - Block 1#
    - *Elizabeth, as they drove along, watched for the first appearance of Pemberley Woods with some perturbation; and when at length they turned in at the lodge, her spirits were in a high flutter.*
    - *On Saturday morning Elizabeth and Mr. Collins met for breakfast a few minutes before the others appeared; and he took the opportunity of paying the parting civilities which he deemed indispensably necessary.*
    - *The first week of their return was soon gone. The second began. It was the last of the regiment's stay in Meryton, and all the young ladies in the neighbourhood were drooping apace.*

  - Block 2#
    - *She could not think of Darcy's leaving Kent without remembering that his cousin was to go with him; but Colonel Fitzwilliam had made it clear that he had no intentions at all, and agreeable as he was, she did not mean to be unhappy about him.*
    - *Lady Catherine had many other questions to ask respecting their journey, and as she did not answer them all herself, attention was necessary, which Elizabeth believed to be lucky for her; or, with a mind so occupied, she might have forgotten where she was.*
    - *The tumult of her mind, was now painfully great. She knew not how to support herself, and from actual weakness sat down and cried for*

half-an-hour. Her astonishment, as she reflected on what had passed, was increased by every review of it.

- Block 3#
  - *Elizabeth could not see Lady Catherine without recollecting that, had she chosen it, she might by this time have been presented to her as her future niece; nor could she think, without a smile, of what her ladyship's indignation would have been.*

As same as the pilot study, those texts are all selected from *Pride and Prejudice* so that I expect the word complexity of each text is fairly similar. The length of text in each condition is also at similar level. The mean value of text length is 33.5 words (SD 1.22), 31.75 words (SD 2.06) and 43.5 words (SD 1.91) respectively in training, finger, and stylus conditions. I expect the small standard deviation will only have very trivial effects on experiment results. The drawings used in the formal experiment are shown in figure 23.

(a) draw 1# **(b) draw 2#**

(c) draw 3# **(d) draw 4#**

(e) draw 5# **(f) draw 6#**

(f) draw 7 **(g) draw 8#**

Figure 23 (a), (b) and c) are the drawings used in 2nd block in stylus condition. (d), (e) and (f) are the drawings used in the 2nd block in finger condition. (f) and (g) are the drawings used in the 3rd block in stylus and finger condition, respectively.

Similar to the text selected in writing tasks, I designed the drawings with a fairly high similarity in terms of number of strokes (see figure 24) and number of points in each stroke (see figure 25 and figure 26). From figure 25 and 26, I found that each image follows a similar distribution pattern at high level in terms of the number of points in each stroke. For stylus, I selected the drawings with more detailed strokes (*i.e., strokes with less than 30 points*) since the stylus is more suitable for detailed drawings than the finger.

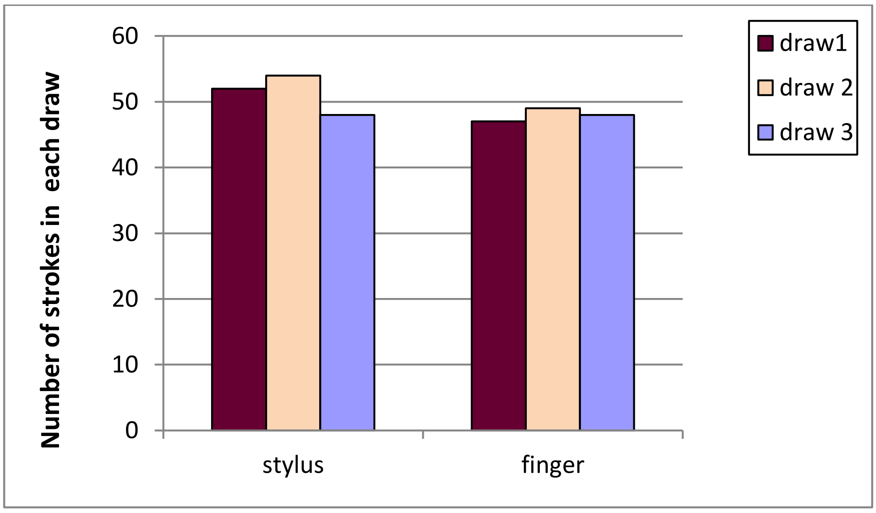
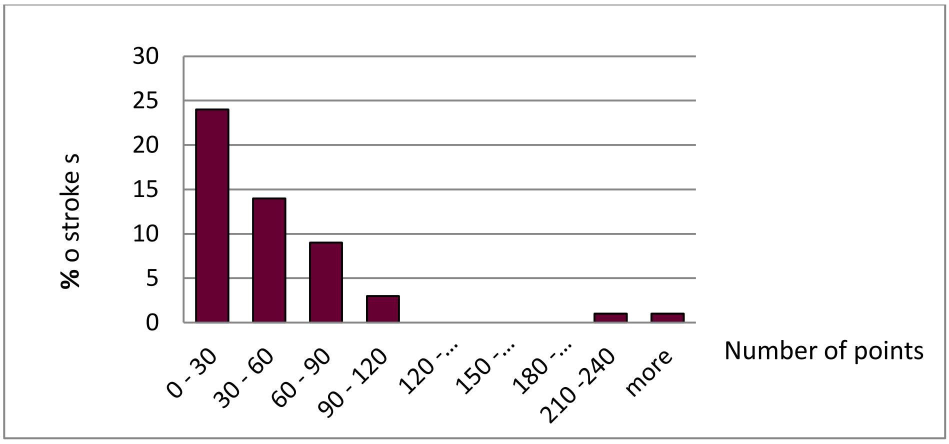
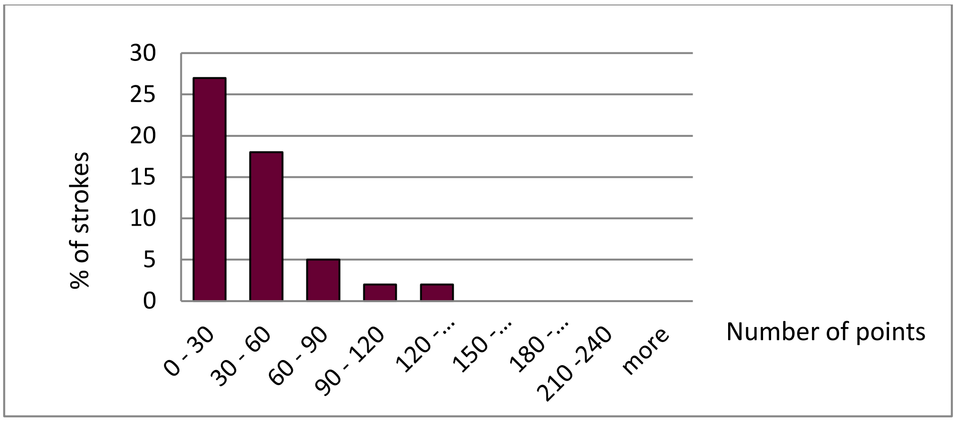


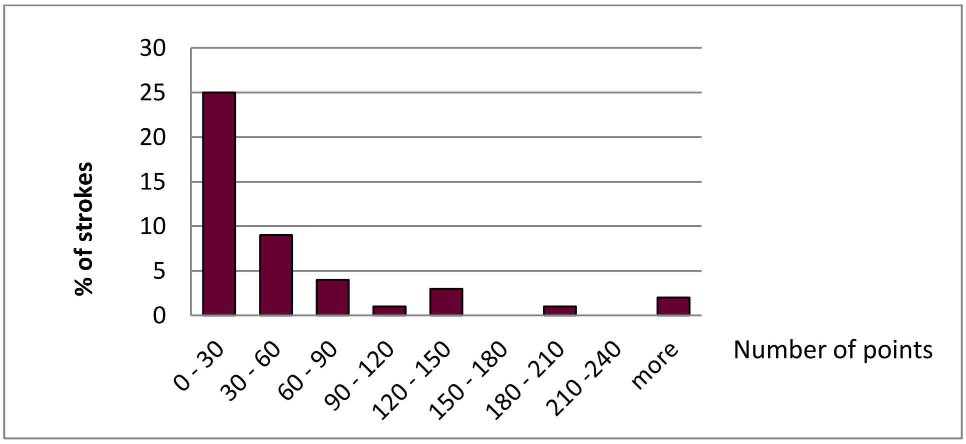
Figure 24 shows the number of strokes in the drawings used in my formal experiment



(a) stylus (draw 1#)

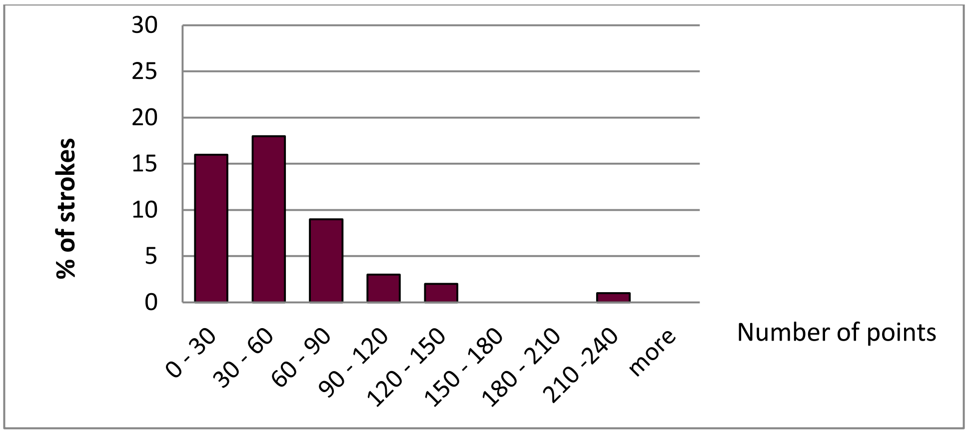


(b) stylus (draw 2#)

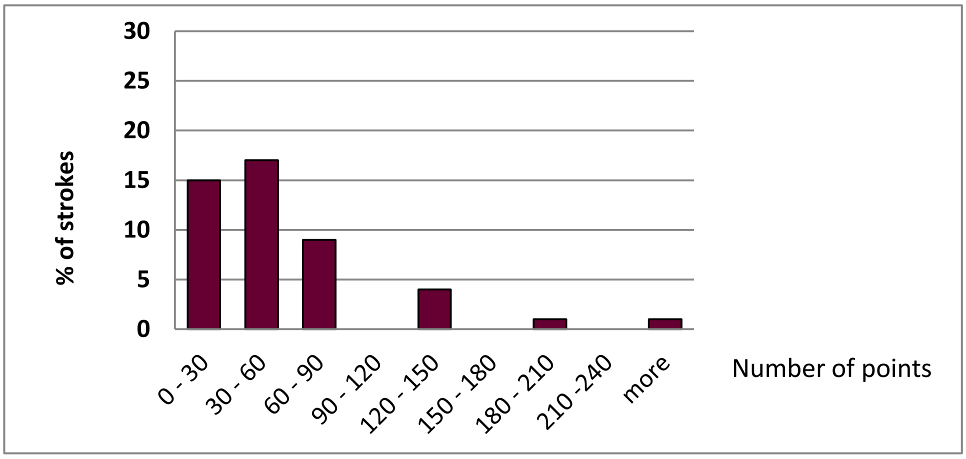


(c) stylus (draw 3#)

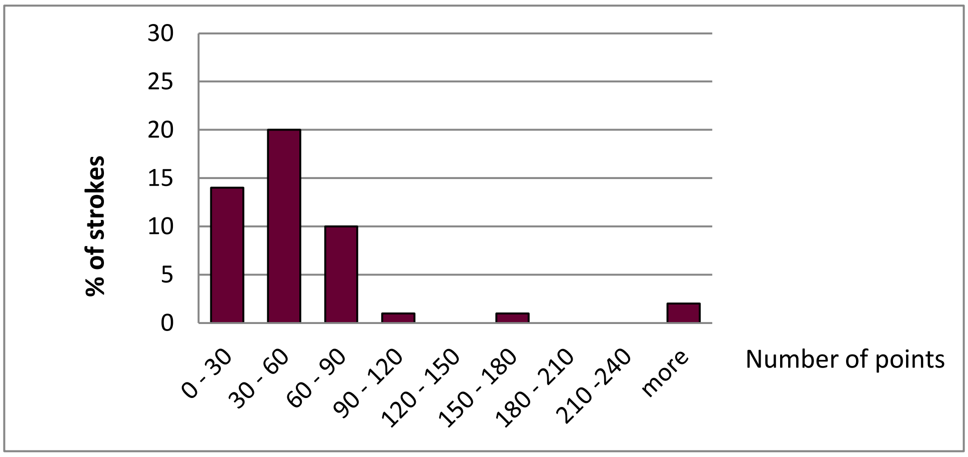
Figure 25 show the histograms of number of points in stroke for each images used in stylus condition



(d) finger (draw 1#)



(e) finger (draw 2#)



(f) finger (draw 3#)

Figure 26 shows the histograms of number of points in stroke for the images used in finger condition

After completing the entire experiment, participants were requested (see figure 27) to give their feedbacks in a survey.

Participant ID: ______   *Female/Male*   *Age ________*

1. How much do like the PLAIN technique?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

2. How much do like the NOTE S technique?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

3. How much do like the ISA technique?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

4. Please rank your preference of PLAIN, NOTE S and ISA technique. *(1 is least preferred and 3 is most preferred)*

______ PLAIN   ______ NOTE S   ______ ISA

5. When you use a pen, would you like using ISA for writing?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

6. When you use a pen, would you like using ISA for drawing?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

7. When you use your finger, would you like using ISA for writing?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

8. When you use your finger, would you like using ISA for drawing?

A. dislike it at all   B. dislike   C. neutral   D. like it   E. like it very much

9. What do you like about ISA?

10. What do you not like about ISA

11. Do you have any suggestion or comment to ISA?

Figure 27 shows the survey used after experiment

5.1.6 Participants

12 people (3 female, 9 male) with an average age of 24.3 (SD 2.3) participated. Participants were pre-screened for color blindness, in case it would prevent them from seeing any colored highlighted on the screen. Since our current bezel-focus rejection technique is developed for right-handed users only, all the participants are pre-screen for their handedness.

5.2 Experimental Results

In the section, I analyze the experiment results with respect to the rejection rate of errant touches, the frequency of errant touches, task completion time, and users' preferred interface. The rejection rate of errant touches shows effectiveness of the bezel-focus rejection technique. The frequency of errant touches reveals the users' inclination to place their hands on tablet while writing or drawing. Task completion time shows how significantly their errant-touch-rejection techniques affect users' writing or drawing speed. Users' preference reveals their acceptance of each technique at the end of the study.

5.2.1 Errant-touch Rejection Rate

I defined the rejection rate of errant touches to be:

$$\text{Rejection rate of errant touches} = \frac{the\ number\ of\ errant\ touches\ that\ are\ rejected}{the\ total\ number\ of\ errant\ touches}$$

The reject rate represents the performance of rejecting errant touches in each technique. In the experiment, I counted errant touches by instrumenting my system to count rejected strokes, and I noted why each stroke was rejected. In order to avoid false positives (i.e., drawing strokes that were rejected as errant strokes), I watched the entire experiments and encouraged participants to speak up if anything goes oddly. The rejection rates of each technique are presented in table 1.

	Finger			Stylus		
	PLAIN	*Note S*	*Bezel*	*PLAIN*	*Note S*	*Bezel*
Write	1.00 (SD 0.00)	1.00 (SD 0.00)	1.00 (SD 0.00)	0.83 (SD0.41)	0.92 (SD 0.16)	1.00* (SD 0.00)
Draw	1.00 (SD 0.00)	0.75 (SD 0.50)	0.875 (SD 0.25)	0.83 (SD 0.29)	0.92 (SD 0.14)	0.96 (SD 0.06)

Table 1 shows the mean values of errant touch rejection rate for each technique in writing and draw tasks. The value with "*" presents a round-up result.

The results from table 1 are somewhat misleading since the data is very sparse. To put this data in context, Table 2 shows the mean number of touches per task in each category. In this table, *draw rejected* presents the number of intended touches that are rejected. The *errant rejected* row presents the number of errant touches that are rejected. The *errant accepted as draw* row presents the number of errant touches that are not rejected. The *ISA-move accepted as draw* row presents the number of time that users intended to move ISA but left undesired ink instead. The *draw accepted as ISA-move* row presents the number of time that users intended to draw but moved ISA instead. The *ISA-move accepted as draw* row and the *draw accepted as ISA-move* row are only present for bezel-focus rejection. Based on table 4, the rejection rate of errant touches can be measured as:

$$Rejection\ rate = \frac{The\ number\ of\ errant\ accepted\ as\ draw}{The\ number\ of\ errant\ rejected +\ errant\ accepted\ as\ draw}$$

In calculating the rejection rate, I did not include the *ISA-move accepted as draw* and the *draw accepted as ISA-move.* Alternatively, I considered them as specific events in bezel-focus rejection, and I will analyze in the later section.

Some of the values in table 2 (those with an asterisk) were estimated because exact values were not available. I did not collect exact values for *draw rejected* and *errant rejected* for PLAIN and Note S techniques, but I did count the number of times that a second touch cancels ink made by the first touch (case 4 in section 5.1.2), which accounted for all errant touches rejected for PLAIN and Note S techniques. Table 2 assumes that in each of these cases, one touch was intended as a draw and one was errant. As for the draw rejected row in bezel-focus rejection, I entered zeros here, because I did not detect any occurrences, but these values were not counted automatically, and I may have missed some.

Table 2 shows that errant touches are rare in PLAIN and Note S. In PLAIN and Note S, errant touches occurred 1 to 5 times per task on average. While for bezel-focus rejection, errant touches occurred 5 to 10 times per tasks for finger and 56 to 138 times for stylus. When using a finger, errant touches are approximately twice more frequent with bezel-focus rejection than with PLAIN or Note S. When using a stylus, errant touches are about 30 times more frequent with bezel-focus rejection than with PLAIN or Note S. These results reflect that participants are more inclined to rest their hands on table when using bezel-focus rejection than PLAIN and Note S. The results are also consistent with the feedback in after-experiment survey which will be discussed later. The high standard deviations in bezel-focus rejection are probably caused by the variety of hand-resting preference by participants

Even though errant touches were relatively rare in the *PLAIN* and *Note S* conditions, I ran a statistical analysis to look for significant differences in rejection rate. Since it is meaningless to measure "rejection rate" when there are no errant touches, I first removed data for those participants that produced no errant touches in one or more conditions. For those cases, participants did not generate any errant touches on tablet because they always hovered their hands above the tablet. Table 2 shows the number of participants who produced one or more errant touches with each interface in each condition (finger-write, finger-draw, stylus-write, and stylus-draw) combined between 2nd and 3rd block. In order to conduct statistical analysis on reject rate, I selected the participants with errant touches in all of three techniques. In the writing task, 2 and 6 out of 12 participants are selected in finger and stylus condition. In the drawing task, 4 and 3 out of 12 participants are selected in finger and stylus condition (see table 2).

	Finger			
	PLAIN	*Note S*	*Bezel*	All
Write	4	4	11	2
Draw	5	7	12	4
	Stylus			
	PLAIN	*Note S*	*Bezel*	All
Write	7	6	11	6
Draw	6	7	12	3

Table 2. The number of participants out of 12 with one or more errant touches in each condition and in all conditions. The "All" column shows the number of participants available for statistical analysis

		PLAIN	Note S	Bezel
Finger - Write	**Draw rejected**	1.17* (SD 2.04)	0.83* (SD 1.75)	0.00* (SD 0.00)
	Errant rejected	1.17* (SD 2.04)	0.83* (SD 1.75)	10.58 (SD 15.10)
	Errant accepted as draw	0.08 (SD 0.29)	0.00 (SD 0.00)	0.00 (SD 0.00)
	ISA-move accepted as draw			0.33 (SD 0.49)
	Draw accepted as ISA-move			0.33 (SD 0.89)
Finger - Draw	**Draw rejected**	3.33* (SD 8.54)	1.92* (SD 3.32)	0.00* (SD 0.00)
	Errant rejected	3.33* (SD 8.54)	1.92* (SD 3.32)	4.08 (SD 3.70)
	Errant accepted as draw	0.25 (SD 0.87)	0.08 (SD 0.29)	0.17 (SD 0.58)
	ISA-move accepted as draw			0.67 (SD 0.78)
	Draw accepted as ISA-move			0.17 (SD 0.39)
Stylus - Write	**Draws rejected***	4.00* (SD 6.92)	5.00* (SD 9.37)	0.00* (SD 0.00)
	Errant rejected*	4.00* (SD 6.92)	5.00* (SD 9.37)	137.83 (SD 170.30)
	Errant accepted as draw	0.08 (SD 0.29)	0.25 (SD 0.62)	0.58 (SD 1.73)
	ISA-move accepted as draw			0.58 (SD 1.24)
	Draw accepted as ISA-move			0.25 (SD 0.45)
Stylus - Draw	**Draw rejected**	2.00* (SD 4.53)	2.00* (SD 3.38)	0.00* (SD 0.00)
	Errant rejected	2.00* (SD 4.53)	2.00* (SD 3.38)	56.25 (SD 87.48)
	Errant accepted as draw	0.50 (SD 1.45)	0.08 (SD 0.29)	0.33 (SD 0.89)
	ISA-move accepted as draw			0.50 (SD 0.90)
	Draw accepted as ISA-move			0.00 (SD 0.00)

Table 3 shows the mean values of the number of times each event happened in the each task. An asterisk (*) means the value is estimated

From table 3, we can see that the data is sparse. Very few of data are selected to measure the rejection rate of errant touches. For the finger condition, 2 samples in writing task and 4 samples in drawing tasks are selected; for the stylus condition, 6 samples in writing task and 3 samples in drawing task are selected. In that case, statistical tests are not useful, but I ran them for completeness.

I conducted a non-parametric Friedman test on the rejection rate across each techniques. This test found no significant effect of technique on rejection rate in the drawing condition with finger ($N= 4, \chi^2 = 1.00, df = 2$ *and* $p > 0.5$) or stylus ($N = 6, \chi^2 = 1.40, df = 2$ *and* $p > 0.1$). Similarly, this test found no significant effect of technique on rejection rate in the writing condition with finger ($N= 6, \chi^2 = 1.40, df = 2$ *and* $p > 0.1$) or stylus ($N = 3, \chi^2 = 0.29, df = 2$ *and* $p > 0.5$).

These results show that participants generated many more errant touches when using bezel-focus rejection interface than PLAIN and Note S. This indicates that participants are more inclined to rest their hands on the tablet when using bezel-focus rejection than PLAIN and Note S rejection. Survey responses were consistent with this finding. Many participants reported feeling much more comfortable resting hands on tablets with bezel-focus rejection. In the survey, 8 out of 12 participants gave the same rate in the likert-scale questions of “how much do like the PLAIN technique?” and “how much do like the NOTE S technique?” One participant commented, “I don’t found differences between Plain canvas and Note S technique”. Those participants are inclined to apply the same hand posture when they are using Note S rejection as Plain canvas to avoid contacts on tablet. Furthermore, bezel-focus rejection has high rejection rate so that it allows users to rest their hands safely on the surface of tablet.

5.2.2 Completion Time

I conducted repeated measured ANOVA test to evaluate the effect of technique, block, task and input on completion time. The full results appear in table 4, including interaction effects among independent variables. Table 4 shows a significant main effect for technique on completion time and no significant interactions for anything involving technique (*block * technique, input * technique, task * technique, block * input * technique, block * task * technique, input * task * technique, or block * input * task * technique*).

FACTORS	STATISTICAL RESULTS	FACTORS	STATISTICAL RESULTS
Block	$F_{1, 11} = 40.67$, $p < 0.001$	*Input * Technique*	$F_{2, 22} = 0.22$, $p > 0.5$
Input	$F_{1, 11} = 50.07$, $p < 0.001$	*Task * Technique*	$F_{2, 22} = 2.54$, $p > 0.1$
Task	$F_{1, 11} = 152.00$, $p < 0.001$	*Block * Input * Task*	$F_{1, 11} = 40.64$, $p < 0.001$
Technique	$F_{2, 22} = 5.28$, $p < 0.001$	*Block * Input * Technique*	$F_{2, 22} = 0.46$, $p > 0.5$
Block Input*	$F_{1, 11} = 40.67$, $p < 0.01$	*Block * Task * Technique*	$F_{2, 22} = 0.77$, $p > 0.1$
*Block * Task*	$F_{1, 11} = 6.88$, $p < 0.05$	*Input * Task * Technique*	$F_{2, 22} = 0.07$, $p > 0.5$
*Block * Technique*	$F_{2, 22} = 1.66$, $p > 0.1$	*Block * Input * Task * Technique*	$F_{2, 22} = 2.91$, $p > 0.05$
*Input * Task*	$F_{1, 11} = 1.39$ $p > 0.1$		

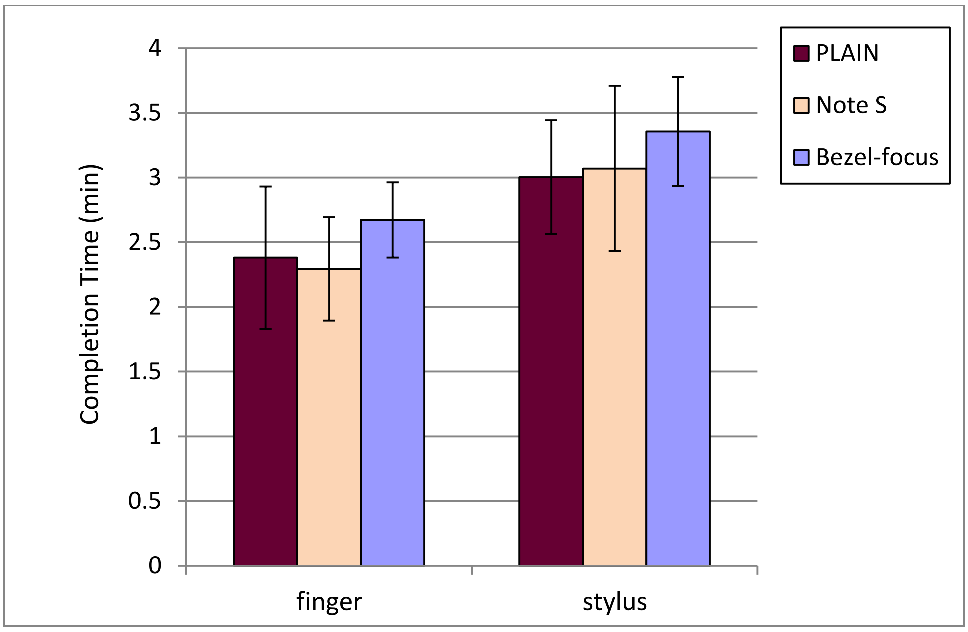
Table 4 shows the statistical results on completion time

Since there were no significant interactions between technique and other variables, I used paired-sample t-tests to make pairwise comparisons of the techniques while treating block, input, and task as between-subjects variables. I used the Bonferroni method to correct for Type I error on the pairwise tests ($\alpha = .05/3 = .017$). The difference between Bezel and Note S is significant ($t_{95} = -4.98, p < 0.01$), the difference between Bezel and PLAIN is significant ($t_{95} = -4.04, p < 0.01$), and the difference between PLAIN and Note S is not significant ($t_{95} = 0.65, p > 0.1$). The mean values of completion time for PLAIN, Note S and bezel-focus rejection are presented in table 5.

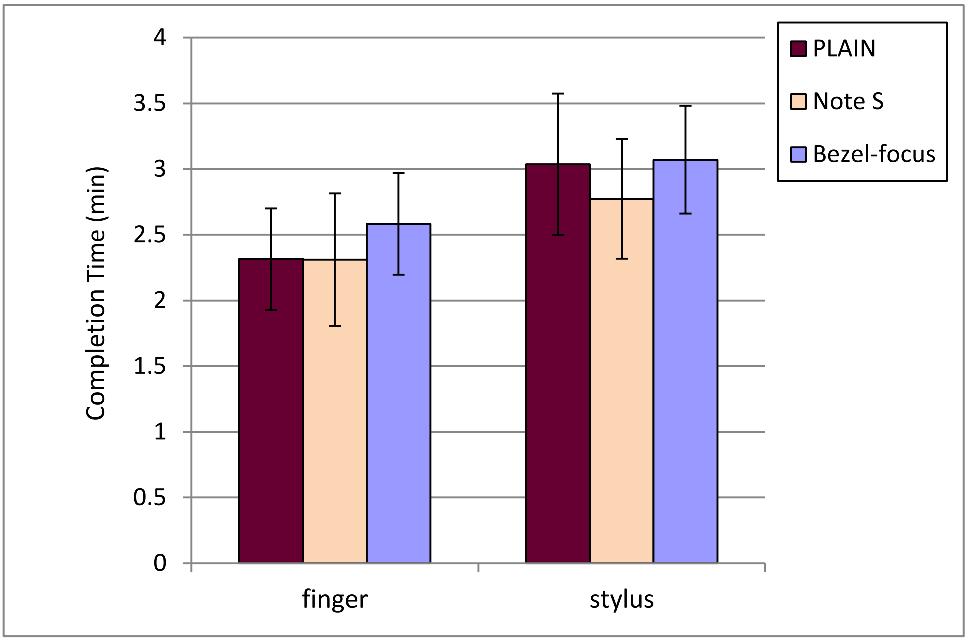
	PLAN	Note S	Bezel-focus
Completion Time	*2.09 (SD 0.81)*	*2.06 (SD = 0.78)*	*2.27 (SD 0.83)*

Table 5 shows the mean values of completion time for each technique

Table 4 also shows significant main effects for input, task, and block on completion time, as well as significant interaction effects for input * block, block * task, and block * input * task. This is not surprising, since different tasks were used for each block and input type. Because of this, I did not draw any meaningful conclusions from the significant differences between finger and stylus. I present the means for writing task in figure 28 and drawing task in figure 29 and leave further analysis for future work.

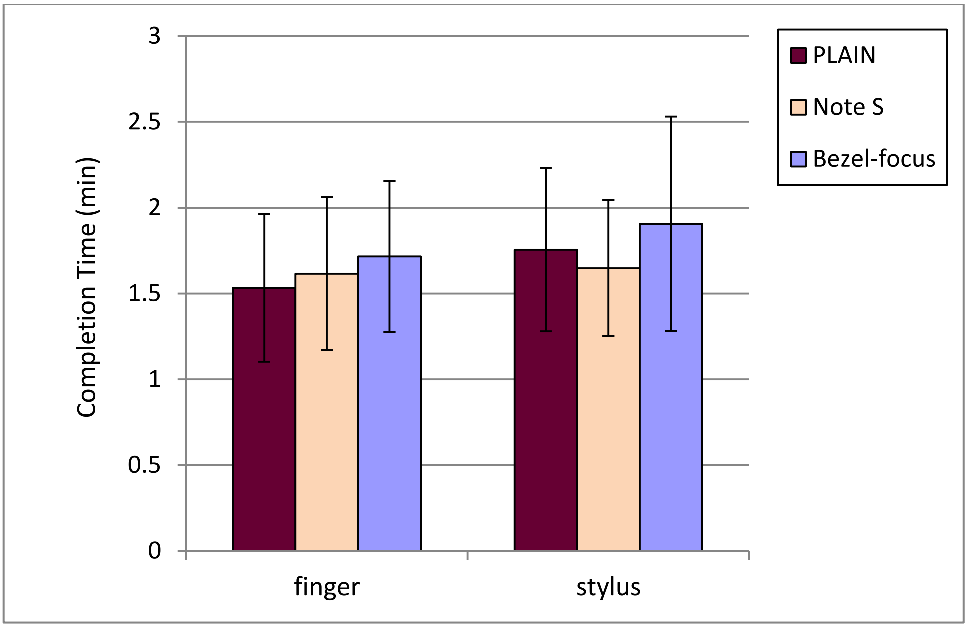


(a). write (block 2)

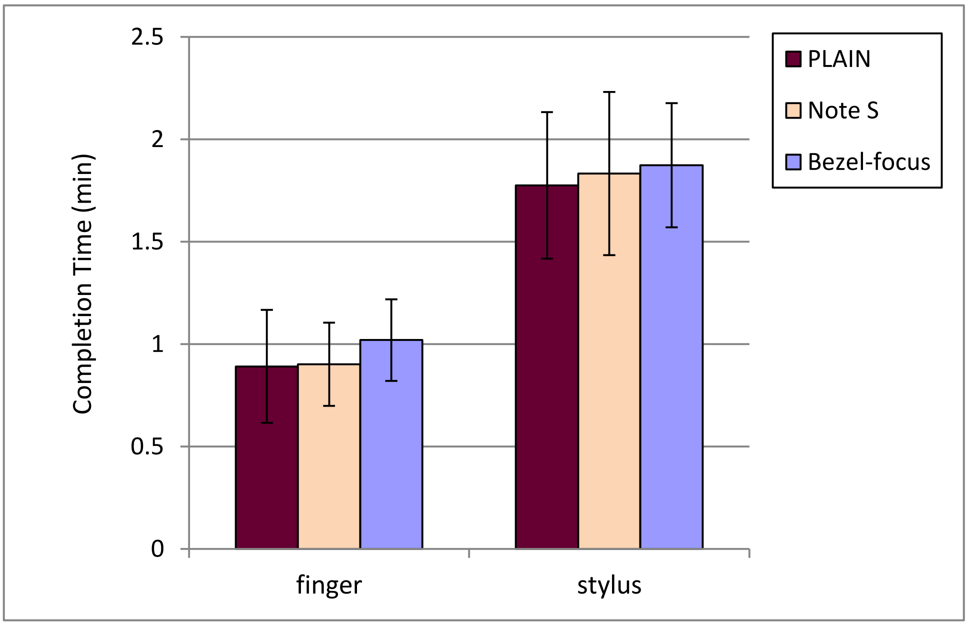


(b). write (block 3)

Figure 28 show the mean value of completion time in block 2# and block 3# in writing task



(c). draw (block 2)



(d). draw (block 3)

Figure 29 show the mean value of completion time in block 2# and block 3# in drawing task

5.2.3 The Frequency of Errant Touches

In the experiment, I defined the frequency of errant touches as the number of errant touches per minute. The frequency of errant touches reveals users' inclination of resting their hands on tablet. In general, users will rest their hands more frequently on tablet if the interface can reject errant touches better than others. On the contrary, users are inclined not to contact with the tablet if the current interface is not able to reject errant touches securely since they have to put extra effort on clicking UNDO or CLEAR ALL button and redrawing it. The mean values of frequency of errant touches are presented in table 6. I conducted a Friedman test on the frequency of errant touches since it is seldom normally distributed (see figure 30)

	Finger			Stylus		
	PLAIN	*Note S*	*Bezel*	*PLAIN*	*Note S*	*Bezel*
Write	0.29 (SD 0.50)	0.20 (SD 0.44)	2.13 (SD 2.92)	0.70 (SD 1.21)	0.88 (SD 1.51)	20.86 (SD 23.26)
Draw	1.64 (SD 4.27)	0.88 (SD 1.57)	1.82 (SD 1.06)	0.63 (SD 1.48)	0.66 (SD 1.10)	14.97 (SD 19.52)

Table 6 shows the mean values of frequency of errant touches in each condition

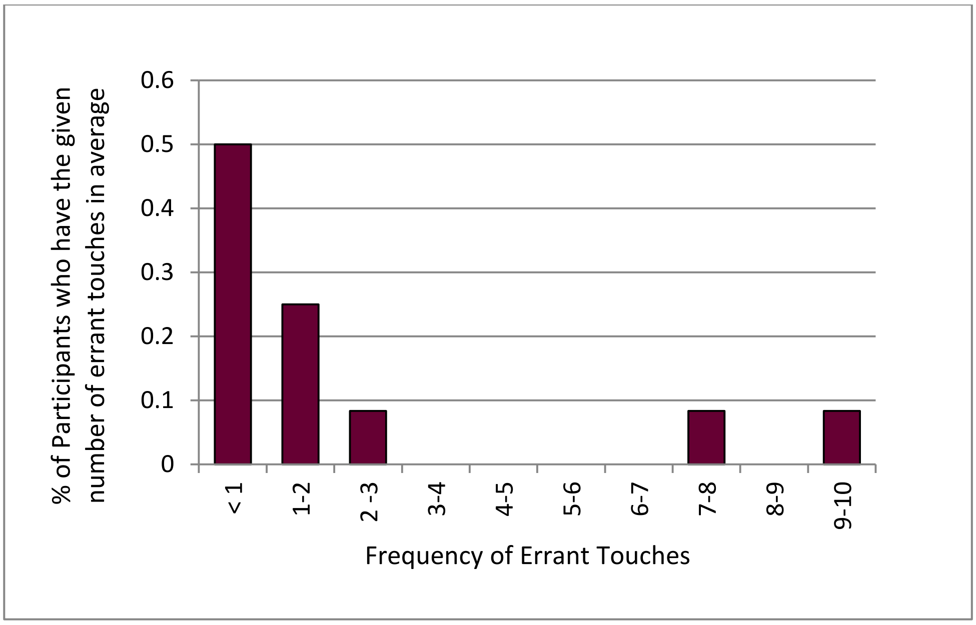
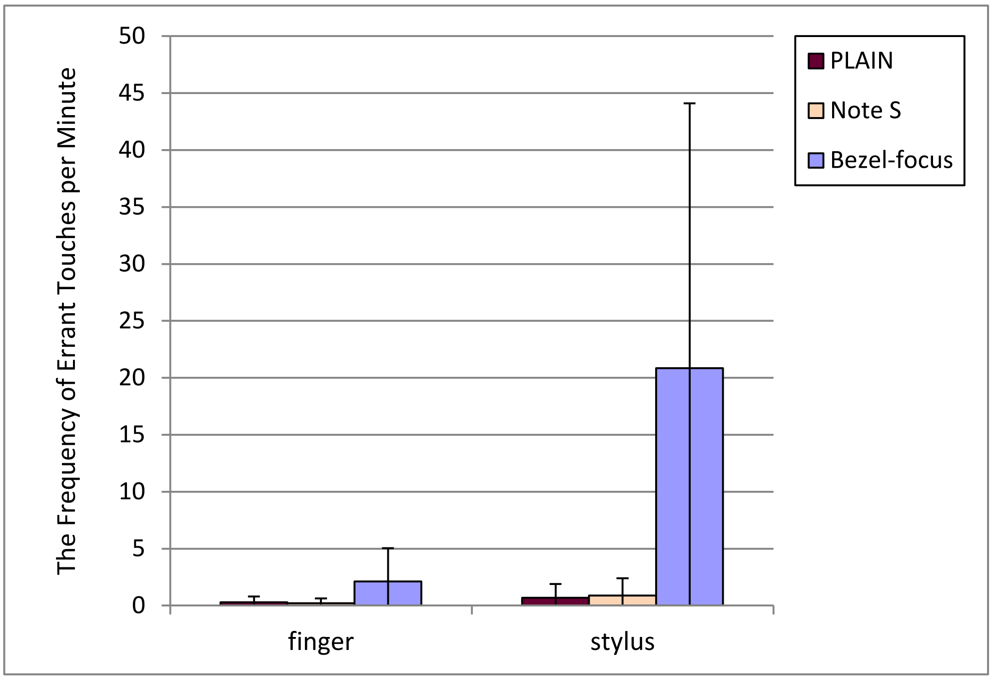
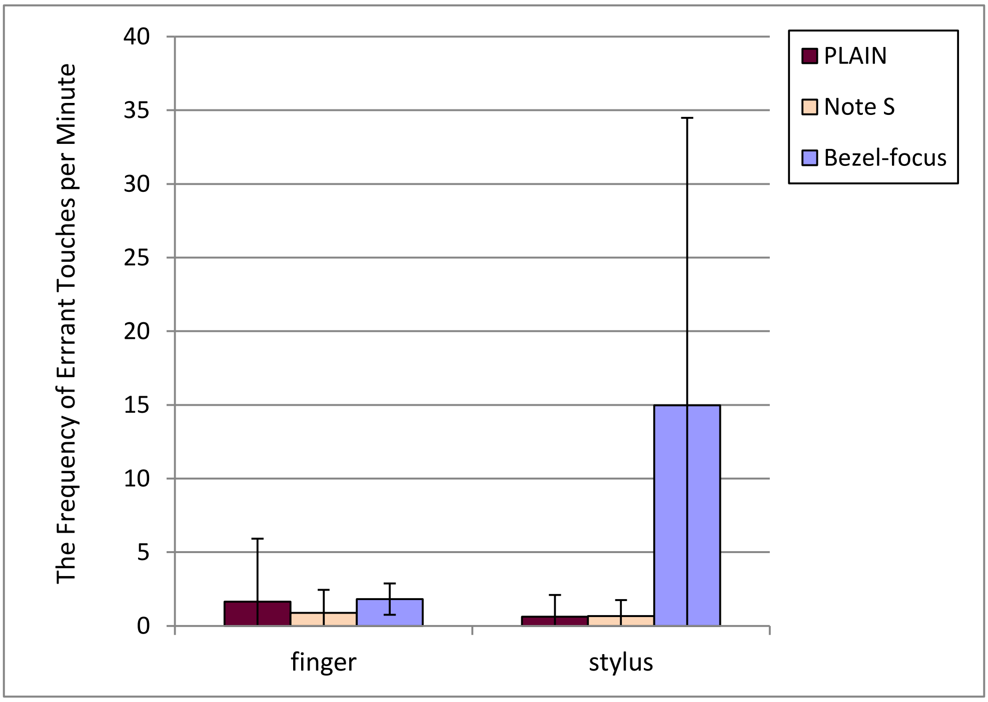


Figure 30 shows histogram of the frequency of errant touches across tasks in average

The Friedman-test results show that the frequency of errant touches is significantly different across PLAIN, Note S and bezel-focus rejection in writing ($\chi^2 = 12.6667, df = 2, p < 0.01$) and drawing tasks ($\chi^2 = 8.9767, df = 2, p < 0.05$) by finger (see figure 30). Similar to the finger condition, the results (see figure 31) show that the frequency of errant touches is also significantly different from bezel-focus rejection to PLAIN and Note S in writing ($\chi^2 = 17.9024, df = 2, p < 0.001$) and drawing tasks ($\chi^2 = 16.3111, df = 2, p < 0.001$). The mean values of the frequency of errant touches are presented in figure 31. I further conducted Wilcoxon test on the frequency of errant touches pair-wisely (see table 7). The results show significant differences between both Bezel and PLAIN and Bezel and NoteS in many conditions, but some fall short of significance when correcting for Type I error by the Bonferroni method, and NoteS vs. Bezel falls far short in the finger-draw condition. The large standard deviation in bezel-focus rejection probably is caused by outliers but it is not certain since the current sample is small.



(a). write



(b). draw

Figure 31. The box plot show the mean frequency of errant touches in PLAIN, Note S and bezel-focus rejection in (a) writing and (b) drawing tasks

	Write		
	PLAIN vs. Note S	*Note S vs. Bezel*	*Bezel vs. PLAIN*
Finger	z = -.1.05, p > 0.5	z = -2.31, p < 0.05	z = -2.49, p < 0.05
Stylus	z = -.98, p > 0.05	z = -2.93, p < 0.01	z = -2.93, p < 0.01
	Draw		
	PLAIN vs. Note S	*Note S vs. Bezel*	*Bezel vs. PLAIN*
Finger	z = -.34, p > 0.5	z = -2.12, p < 0.05	z = -1.88, p > 0.05
Stylus	z = -.65, p > 0.5	z = -2.98, p < 0.01	z = -3.06, p < 0.01

Table 7 shows the Wilcoxon-test results between two techniques. The comparison results with significant difference are highlighted in grey

5.2.4 User Preference

The results of user preference are based on the after-experiment survey. In the survey, 10 out of 12 participants rater the bezel-focus rejection as the most preferred. I conducted Freidman test on participants' subjective ratings of each technique, and found a significant effect of technique on rating ($\chi^2 = 8.67, N=12, df = 2, \text{and } p < 0.05$). Furthermore, I conducted pairwise Wilcoxon tests on user preference, using the Bonferroni method to correct for Type I error (α = .05/3 = .017). There was no significant difference in user preference between the PLAIN and NoteS conditions (z = -1.63, $p > 0.05$), and the difference in preference fell short of significance between Note S and Bezel (z = -2.18, $p < 0.05$) and PLAIN and Bezel (z = -2.29, $p < 0.05$). I expect the reason of no statistical difference between Note S and bezel-focus rejection is due to the small sample size. In figure 32, we can find that 8 out 12 *like* bezel-focus rejection exclusively.

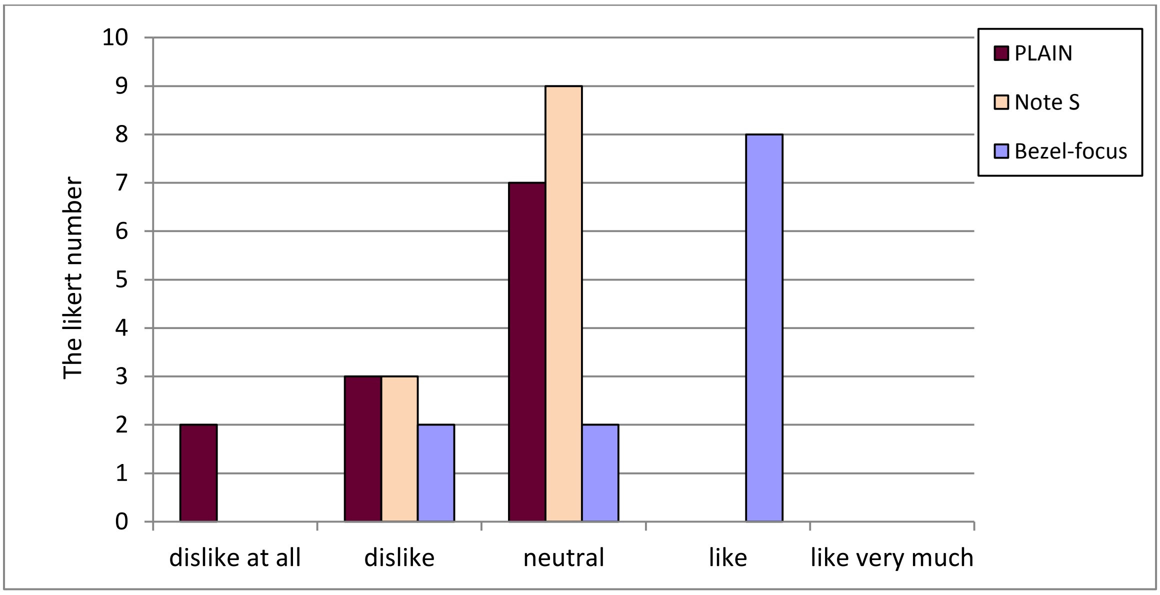


Figure 32 shows the number of 5-point Likert scores

Participants gave the following reason for preferring bezel-focus rejection:

- *The bezel-focus rejection allows (me) to rest hand on tablet securely.*
- *The gestures (e.g. tap, drag and pinch) that are designed for controlling ISA (e.g. resize and reposition) is very intuitive and flexible*
- *The ISA is very suitable for left-to-right writing tasks.*
- *The implicit approach of rejecting errant touches inside of ISA is fairly foolproof.*

Participants 8 and 10 rate the bezel-focus rejection as the least preferred technique overall because they prefer not touching tablet in any cases. Compared to PLAIN and Note S, bezel-focus rejection requires extra manipulation on ISA and changes their existing writing behavior.

In the survey, 7 out of 12 participants selected "like" bezel-focus rejection when using a stylus for writing. 8 out of 12 participants selected "like" and 1 participant selected "like it very much" for bezel-focus rejection in drawing by a stylus. 6 out of participants "like" bezel-focus rejection in writing by both stylus and finger.

However, participants' preference on bezel-focus rejection drops when they are using their bare fingers: 4 out of 12 participants and 1 participant selected "like" and "like it very much" respectively for bezel-focus rejection for writing by finger. Similarly, 5 out of 12 participants and 1 participant selected "like" and "like it very much" respectively for bezel-focus rejection when using finger in drawing tasks.

The drop of user preference to bezel-focus rejection may be caused by the variety of writing posture of using finger from stylus. By using a finger, participants generally hover their hands above tablet to adjust their index fingers (all the participants performed ink tasks by index finger in the experiment) to a comfortable angle. In doing so, their palms leave the surface of tablet and avoid contacts with tablet naturally. In this regard, bezel-focus rejection is less preferred by participants in the finger condition than the stylus condition since they did not intend to place their hands on tablet when using a finger.

However, problems are still remained. Our participants said:

1) *I sometimes made undesired inks at the very left of the ISA when I intended to drag ISA because the size of bezel is too small*
2) *I sometimes accidentally dragged the ISA when I intended to make inks at very left of the ISA because the size of bezel is too large*
3) *It requires extra learning effort since bi-manual interaction is less intuitive than free-hand writing.*
4) *It is not suitable for writing or drawing in standing posture.*

Problem (1) and (2) are regarding to the optimization of the (width) size of bezel. The occurrence of time that participants complained the size of bezel can be referred in table 8.

	(1)	**(2)**	**(1) and (2)**
Count	7	1	1

Table 8 shows the occurrence that participants complained either (1) or (2) or both.

According to participants' feedback, the size of bezel should be large enough to ease ISA interaction on the one hand. On the other hand, the size of bezel should be small enough because users are likely to write or draw fairly closed to the edge of tablet. In this regards, an optimal value of the bezel size is one of important factors on the user experience of bezel-focus rejection. The same is true for Problem (3) and (4), and they remain to be solved in our future study.

5.3 Discussion

The results of this experiment show that bezel-focus rejection has a high errant-touch rejection rate and is most-preferred by participants. It makes participants more inclined to put their hands on tablet when writing/drawing than PLAIN and Note S, tough it slows down participants' writing/drawing speed slightly.

The reason that I proposed a mixed explicit and implicit approach, instead of either a purely explicit or implicit approach, is that it balances the reliability and intuitiveness of rejection technique. On the one hand, explicit approaches are generally more reliable that implicit ones in terms of rejection accuracy; on the other hand, implicit approaches are more intuitive than explicit approaches because they do not require users to change their existing writing behaviors.

Bezel-focus rejection is mainly an explicit rejection technique so that it achieves high errant-touch rejection rate and frequency of errant touches. On the contrary, it is less intuitive than PLAIN and Note S so that the completion time of bezel-focus rejection is larger than PLAIN and Note S

Currently, bezel-focus rejection technique rejects errant touches by ISA, a rectangle-shaped cover sheet that does not match the pattern of errant touches identified in my exploratory study. It is possible to design an explicit errant touch rejection technique with a cover sheet that matches the observed pattern of errant touches more closely. In the future study, I consider designing a mixed explicit and implicit approach, *writing-first rejection*, which rejects errant touches by the geometric model of errant touch pattern. Writing-first rejection requires users to write before their hands touch on tablet. Given the first touch, rest-focus rejection generates a cover sheet that matches the geometric model of errant touch patterns.

The cover sheet is capable of relocating implicitly if all touches move out of the cover sheet. It also supports to implicitly resize the cover sheet if some touches move out of the cover sheet but at least one stays.

In the future study, I also expect to compare the performance of writing-first rejection to bezel-focus rejection in terms of errant-touch rejection rate, completion time, frequency of errant touches and user preferences in a similar way as I did in this thesis. Furthermore, I will investigate the ink quality using by writing-first rejection and bezel-focus rejection.

Chapter 6: Conclusions

In conclusion, this research addressed two major problems: (1) understanding the property of errant touches when people are performing ink tasks on a multi-touch tablet and (2) developing errant touch rejection technique which can be applied to current ink applications.

To understand the property of errant touches, I conducted an exploratory study to investigate errant touches in either capacitive stylus or bare finger condition. In the capacitive stylus condition, participants are requested to complete tasks by a capacitive pen. On other hand, participants are requested to complete tasks by their fingers in the bare finger condition. In each condition, we investigate errant touch according to four types of task that is, tapping, dragging, writing and drawing. The study results shows:

- People are more possible to have errant touch problem when using stylus than finger. No matter using stylus or finger, errant touch problem is more severe when people are performing writing and drawing task than tapping and dragging task.
- Errant touches occur rarely at the top and left area of tablet for right-handed users.
- Contact size is a useful parameter in errant-touch rejection design for the users who perform ink tasks by stylus.

- Errant touches do not necessarily occur either before or after the intended touch.
- 80% of errant touches are invoked within 0.5 second of the intended touch.
- The patterns of errant touches present the position of errant touches related to the intended touch, and could serve as a useful guide for designing a geometric model of cover sheet.

To reject errant touches, I proposed a mixed explicit and implicit approach, *bezel-focus rejection*. Bezel-focus rejection creates an *Ink Start Area (ISA)*, which is the unique area allowed inks on tablet when users are interacting the bezel of their non-dominant hand side. By manipulating ISA, bezel-focus rejection technique explicit rejects errant touches that are invoked outside of ISA and hence allows users to safely rest their hand on the tablet when writing or drawing. Inside of ISA, bezel-focus rejection technique implicitly rejects simultaneous multi-touches by their relative positions. Bezel- focus rejection also Bezel-focus rejection supports *tap*, *drag* and *pinch* gestures to invoke, relocate and resize ISA so that uses can choose an appropriate ISA in different ink scenarios. Bezel-focus rejection is applied an implicit strategy to reject errant touches occurred within ISA based on users' handedness.

To evaluate the performance of bezel-focus rejection, I conducted a within-subject experiment to compare its performance with two existing ink interfaces (i.e. plain canvas and Note S canvas) in writing and drawing tasks by both finger and stylus. The experiment results show that our proposed technique can reject errant touches securely though it slight slows down users' writing speed. The results also show that users are more inclined to put their hand on tablet when using the proposed technique and it is most preferred by users.

Bibliography

1. Grosky, W.I., et al., *Applications and Issues in Pen-Centric Computing.* MultiMedia, IEEE, 2008. **15**(4): p. 14-21.
2. Hinckley, K., et al. *Pen + touch = new tools*. in *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. 2010. New York, New York, USA: ACM.
3. Schmidt, D., F. Block, and H. Gellersen, *A Comparison of Direct and Indirect Multi-touch Input for Large Surfaces*, in *Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part I*. 2009, Springer-Verlag: Uppsala, Sweden. p. 582-594.
4. Brandl, P., et al., *Occlusion-aware menu design for digital tabletops*, in *CHI '09 Extended Abstracts on Human Factors in Computing Systems*. 2009, ACM: Boston, MA, USA. p. 3223-3228.
5. Hancock, M.S. and K.S. Booth, *Improving menu placement strategies for pen input*, in *Proceedings of Graphics Interface 2004*. 2004, Canadian Human-Computer Communications Society: London, Ontario, Canada. p. 221-230.
6. Siio, I. and H. Tsujita, *Mobile interaction using paperweight metaphor*, in *Proceedings of the 19th annual ACM symposium on User interface software and technology*. 2006, ACM: Montreux, Switzerland. p. 111-114.
7. Matulic, F. and M. Norrie, *Empirical evaluation of uni- and bimodal pen and touch interaction properties on digital tabletops*, in *Proceedings of the 2012*

ACM international conference on Interactive tabletops and surfaces. 2012, ACM: Cambridge, Massachusetts, USA. p. 143-152.

8. Kim, H., et al., *Tablaction: collaborative brainstorming system with stylus-fingertip interactions on tablet PCs*, in *Proceedings of the 9th ACM SIGGRAPH Conference on Virtual-Reality Continuum and its Applications in Industry*. 2010, ACM: Seoul, South Korea. p. 81-84.
9. Rosenberg, I. and K. Perlin. *The UnMousePad: an interpolating multi-touch force-sensing input pad*. in *ACM SIGGRAPH 2009 papers*. 2009. New Orleans, Louisiana: ACM.
10. Lopes, P., R. Jota, and J.A. Jorge, *Augmenting touch interaction through acoustic sensing*, in *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. 2011, ACM: Kobe, Japan. p. 53-56.
11. Murugappan, S., et al., *Extended multitouch: recovering touch posture and differentiating users using a depth camera*, in *Proceedings of the 25th annual ACM symposium on User interface software and technology*. 2012, ACM: Cambridge, Massachusetts, USA. p. 487-496.
12. Vogel, D., et al. *Hand occlusion with tablet-sized direct pen input*. in *Proceedings of the 27th international conference on Human factors in computing systems*. 2009. Boston, MA, USA: ACM.
13. Zeleznik, R., et al. *Hands-on math: a page-based multi-touch and pen desktop for technical work and problem solving*. in *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. 2010. New York, New York, USA: ACM.

14. Wagner, J., et al., *BiTouch and BiPad: designing bimanual interaction for hand-held tablets*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2012, ACM: Austin, Texas, USA. p. 2317-2326.

Curriculum Vitae

SHU Ke is a Master of Science Candidate from School of Information Systems at Singapore Management University, under the supervision of Assistant Professor Richard Davis and co-advising from Assistant Professor Jason Woodard. Before studying at Singapore Management University, he received Bachelor of Science degree in the School of Information Management from Sun Yat-sen University in China. His current research areas are Human Computer Interaction and Pen-based Computing.