APPROVAL SHEET

Title of Dissertation: Thumb-Based Approaches to Target Acquisition, Zooming, and Text Entry in Single-Handed Interaction with Mobile Phones

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ABSTRACT

Title of Document:	THUMB-BASED APPROACHES TO TARGET ACQUISITION, ZOOMING, AND TEXT ENTRY IN SINGLE-HANDED INTERACTION WITH MOBILE PHONES
	Jianwei Lai, Ph.D., 2016
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Single-handed interaction with mobile handheld devices is often desired yet challenging and problematic, especially for users with situational impairments or upper limb disabilities. In this dissertation, three novel thumb-based techniques were designed, developed, and evaluated to address three challenges in single-handed interaction with touch-screen mobile phones, including target acquisition, zooming, and text entry.

First, we proposed and developed ExtendedThumb to address the target acquisition problem caused by limited thumb accessibility in single-handed interaction with mobile phones. An empirical user evaluation of ExtendedThumb and two baseline target acquisition techniques, including direct touch and MagStick, was conducted. ExtendedThumb significantly outperforms MagStick in target acquisition speed, perceived ease of use, perceived effectiveness, and overall satisfaction, while achieving a similar level of accuracy. ExtendedThumb also achieves significantly higher performance in user perception than direct touch.

Second, ContextZoom was proposed and implemented for single-handed zooming on touch-screen mobile devices. It works as an add-on feature for other existing zooming techniques by supporting zooming in/out a portion of a viewport. The results of an empirical evaluation show that equipped with ContextZoom, users' performances with the Google Maps' single-handed zooming technique and the button-based zooming technique in partial viewport zooming were improved significantly in terms of task completion time and number of discrete actions. Participants also reported higher levels of perceived effectiveness and overall satisfaction with ContextZoom than without ContextZoom while using the Google Maps' single-handed zooming technique, and reported a similar level of perceived ease of use.

Third, ThumbStroke was developed to support both single-handed and sight-free text entry. The keyboard allows users to enter text by making strokes with a thumb in any area on a touch screen where they feel comfortable. We evaluated ThumbStroke through a longitudinal lab experiment including 20 sessions with 13 participants, in which participants typed phrases with the ThumbStroke, Escape and QWERTY keyboards. ThumbStroke shows advantages in typing accuracy and user perception in comparison to the other two keyboards and results in faster typing speed than QWRTY in the sight-free condition.

The findings of this dissertation provide both research and practical insights for single-handed and sight-free interaction with mobile devices.

THUMB-BASED APPROACHES TO TARGET ACQUISITION, ZOOMING, AND TEXT ENTRY IN SINGLE-HANDED INTERACTION WITH MOBILE PHONES

By

Jianwei Lai

Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

To my parents, Yinsi Lai and Weihong Li, my husband, Sen Wang, and my son Ian Wang

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Chapter 1 : Introduction

1.1 Research Motivations

According to the International Telecommunication Union, there were more than seven billion mobile subscriptions worldwide at the end of 2015. The rapid advances of mobile handheld devices (e.g., mobile phones) and wireless communication technologies offer an unprecedented level of flexibility, accessibility, and convenience to users, particularly for ubiquitous information access (Zhang & Lai, 2011). Mobile phones become portable tools for not only communication and personal information management, but also Internet access, entertainment (e.g., gaming), social networking, mobile commerce, etc. They have become an integral part of people's daily life (Froehlich, Chen, Consolvo, Harrison, & Landay, 2007).

Field usability studies have demonstrated the importance of supporting single-handed use of mobile phones (Hirotaka, 2003). Research has revealed that users prefer to use mobile phones with one hand (Karlson & Bederson, 2007; Karlson, Bederson, & Contreras-Vidal, 2006), so that the other hand can be freed for other physical or attentional demands (Oulasvirta, Tamminen, Roto, & Kuorelahti, 2005). There are also numerous situations, in which only one hand is available for both holding and interacting with a mobile device. First, according to Amputee Coalition (2016), 2 million Americans lived with limb loss in 2015. It is estimated that this number will be more than 3.6 million by the year 2050 (Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008). Many people suffer from hand or arm losses. Second, people often come across situational impairments (Sears, Lin, Jacko, & Xiao, 2003), which refer to difficulties in accessing or interacting with mobile devices due to the context or situation that one is in, as opposed to physical impairments. Situational impairments can be caused by an environment, task, or social context (Korhonen, Holm, & Heikkinen, 2007). For example, a user may have a cup of coffee in one hand, or hold a handle bar on a moving bus, leaving just one hand for holding and interacting with a mobile device. Third, user mobility further exacerbates the problem – users may not be able to put their devices on a supporting surface, such as a table, while interacting with them. Therefore, mobile device interfaces that accommodate single-handed interaction can offer significant benefits.

Single-handed thumb interaction has been widely used (Park & Han, 2010a). Current mobile devices with touch screens, however, are poorly suited for single-handed interaction. First, mobile device interfaces typically feature targets that are too small for fingertip actuation. Thus, single-handed interaction is often error-prone due to the "fat thumb" problem and small buttons and icons. Second, the entire touch screen is valid for users' input. When a device is held by a hand, some places on the screen may be out of reach for a thumb, which cause the limited thumb accessibility problem (Karlson, Bederson, & SanGiovanni, 2005). The trend of screen size increase aggravates this problem by further decreasing thumb mobility. There are more and more phones with a 5" or larger touch screen, such as iPhone 7 plus (5.5"), Galaxy Note 7 (5.5"), Galaxy S7 (5.1"), LG g5 (5.3"), HTC Butterfly (5.0") and Sony Xperia Z (5.0"). Users usually have to interact with large-screen mobile phones using both hands, with one hand holding a phone and the other interacting with it (Boring et al., 2012). Third, when using a finger to interact with a mobile device directly, it will cover a part of the screen, causing the visual occlusion problem. Sometimes a finger may accidentally select unintended targets while moving on a touch screen. These problems pose significant challenges for target selection.

Although large screens of mobile phones can improve some aspects of user experience by allowing users to see more content in a viewport and reduce scrolling, they also bring new usability challenges, especially for single-handed interaction. The larger the screen size, the more areas on the screen that users will have difficulty in reaching. Therefore, it is necessary to develop effective mechanisms for single-handed interaction with touch-screen mobile phones to improve the accessibility and usability of mobile phones.

In addition, a previous study (Nicolau & Jorge, 2012) found that two-handed interaction does not provide additional stability or input accuracy. Single-handed phone use is common, and should be an essential consideration in design (Karlson et al., 2006). However, current design of mobile phones does not support single-handed interaction well. Small and light phones are easy to control with one hand, but they usually have tiny buttons and crowded keypads, which are unfriendly and difficult for a thumb to interact with. Stylus-based touch screens maximize information content with rich interface designs, but targets are too small and/or too distant for effective thumb interaction (Karlson et al., 2006).

1.2 Research Questions

Thumb interaction with mobile devices is a relatively recent field (Roudaut, Huot, & Lecolinet, 2008). The overarching research question that this research strives to address is: **How to design and develop effective, device-independent thumb-based techniques to improve single-handed interaction with touch-screen mobile devices?** Aiming to advance the state-of-the-art mobile technology, this research proposes, designs, implements, and evaluates three novel thumb-based approaches that improve the most common activities in single-handed interaction with mobile devices, including target acquisition, zooming, and text entry.

One common practice performed on a mobile phone is selecting a target on the screen. There are several issues with single-handed target selection on touch-screen mobile phones. For example, some places on the screen are difficult to reach, e.g., the left-top corner for a right-handed user. Aiming at small targets is inaccurate for users with a fat thumb. Therefore, the first research question of this dissertation is: **How to improve single-handed target acquisition with a touch-screen mobile device?**

Zooming is another common operation on mobile phones. A zooming function enables users to view more content at small zooming levels and less content at large zooming levels. Thus, an intuitive and smooth manipulation method for changing the scale parameter is vital for mobile phone interaction (Miyaki & Rekimoto, 2009). "Pinch" is widely used for zooming on current touch screen smart phones. The user moves two fingers apart/towards each other to zoom in/out. It requires two hands, with one holding the phone and the other interacting with the phone. Furthermore, existing zooming techniques for single-handed interaction mainly focus on developing methods for zooming the content in the whole viewport. Because of the smaller screen size comparing to desktops and laptops, users often lose context or get lost completely in the navigation space after changing the whole viewport scale on mobile phones. Hence, the second research question is: **How to better support single-handed zooming operation with a touch-screen mobile device?**

Texting is an essential function of mobile communication. About 83% of American adults own cell phones, and three-quarters of them (73%) send and receive text messages. Especially users between the ages of 18 and 24 exchange an average of 109.5 messages per day (Smith, 2011). Thus, it is important and necessary to design an effective keypad to increase the accuracy and efficiency of text entry (Hirotaka, 2003). Nevertheless, mobile text input is not well supported by today's keyboards (Romero, Frey, Southern, & Abowd, 2011). The standard QWERTY keyboard layout is adopted by the majority of mobile devices, although its size is imposing and ill-suited to the mobile paradigm (MacKenzie & Soukoreff, 2002). A common use of soft keyboards on mobile devices forces the user to constantly look at the screen and hunt and peck for keys, which significantly lowers the potential texting throughput (Romero et al., 2011). Typing with one-hand is even more challenging because users need to secure a device with his/her palm and four fingers and at the same time to reach keys with the thumb, which has limited flexion and extension. In addition, some of the keys on the sides of a device screen can be difficult for a thumb to reach. Thus, the third research question in this dissertation research is: **How to improve single-handed text entry with a touch-screen mobile device?**

1.3 Research Outline

The specific research questions and corresponding techniques and chapters are shown in Table 1.

Table 1 Research Questions and the Related Techniques

Research questions	Techniques	Chapter
How to improve single-handed target acquisition?	ExtendedThumb	Chapter 2
How to improve single-handed zooming?	ContextZoom	Chapter 3
How to improve single-handed text entry?	ThumbStroke	Chapter 4

The dissertation has achieved the following specific goals:

- Design and develop ExtendedThumb, a virtual thumb controlled by the movement of a real thumb on the screen of a mobile device, for accessing difficult-to-reach targets. The novelty of ExtendedThumb is that it enables users to reach distant targets with a proxy of a real thumb.
- Design and develop a context-oriented zooming technique that allows a thumb to zoom in or out a portion of a viewport at desired levels with any specified target on the screen as the zooming center. Its uniqueness is that users can determine the zooming center so that a target will stay in the viewport during zooming operation, and it provides context information to users to prevent them from getting lost during zooming operation.
- Design and develop a unique thumb-based keyboard that enables text entry by a thumb in single-handed interaction. Its novelty lies in that a user can select and enter any character by moving his/her thumb anywhere on a device screen, without the necessity to physically press the corresponding keys as almost every existing soft keyboard requires, which could be beneficial in both single-handed and sight-free text entry.
- Empirically evaluate the effectiveness, efficiency, and usability of the proposed thumb-based techniques, and develop theoretical guidelines for the design of single-handed interaction techniques for researchers of mobile interaction, designers of mobile interfaces, and manufacturers of mobile devices.

The remainder of this dissertation is organized as follows. In Chapter 2, the proposed ExtendedThumb for single-handed target acquisition is introduced, including the related work, the design of ExtendedThumb, empirical evaluation, results, discussion, and future work. In Chapter 3, ContextZoom, the proposed single-handed partial viewport zooming technique, is discussed, including the related work, the design of ContextZoom, empirical evaluation, results, discussion, and future work. In Chapter 4, ThumbStroke, the proposed single-handed keyboard, is presented, including the related work, the design of ThumbStroke empirical evaluation, results, discussion, and future work. The dissertation is concluded with summarizing the research contributions and implications in Chapter 5.

Chapter 2 : ExtendedThumb — A Target Acquisition Approach for Single-Handed Interaction with Touch-Screen Mobile Phones

2.1 Research Background

Users prefer to use mobile phones with one hand (Karlson & Bederson, 2007; Karlson et al., 2006), so that the other hand can be used for other physical or attentional demands (Oulasvirta et al., 2005). In addition, millions of people with upper limb loss or hand disabilities have to interact with mobile phones using one hand only. Field usability studies have demonstrated the importance of making mobile phones support single-handed use (Hirotaka, 2003). Current mobile devices with touch screens, however, are poorly suited for single-handed interaction (Park & Han, 2010a). First, targets displayed on mobile device screens are typically too small for fingertip actuation. Thus, single-handed interaction is often error-prone due to the "fat thumb" problem (Boring et al., 2012). Second, the entire touch screen is valid for user input. When a device is held in a hand, some places on its screen may be out of reach for a thumb (Karlson et al., 2005). Third, when using a thumb to interact with a mobile device directly, the thumb will cover a part of the screen, causing the visual occlusion problem (Scheibel et al., 2013).

Usability is one of the major concerns with mobile devices (Gündüz & Pathan, 2013). These above-mentioned problems pose significant challenges to target selection. Users usually have to interact with large-screen mobile phones using both hands, with one hand holding a phone and the other interacting with it (Boring et al., 2012). Although large screens of mobile phones improve some aspects of user experience by enabling users to see more content in a viewport and reduce scrolling, they also bring new usability challenges, especially for single-handed interaction. The larger the screen size, the more areas on the screen that users will have difficulty in reaching. Therefore, it is necessary to develop effective techniques for single-handed interaction to improve the usability of touch-screen mobile phones. Researchers have been studying single-handed interaction with mobile devices, including thumb motor performance (Trudeau, Udtamadilok, Karlson, & Dennerlein, 2012a), touch key design (Park & Han, 2010b), and usability of single-handed interaction methods (Choi & Kim, 2013).

Selecting targets on the screen of a mobile handheld device is one of the most basic operations. This operation involves a process by which a user uses his/her neuromuscular system and coordinates his/her fingers and hands involved in performing this motor skill. Such a process is often referred to as human motor control (Rosenbaum, 1991; Wise & Shadmehr, 2001). Although selecting an item through direct touch is the most intuitive way, thumb mobility and advantages of direct touch tend to decrease as device size increases (Karlson et al., 2006). So mobile devices should support single-handed interaction, with a thumb being used for selecting objects (Roudaut et al., 2008).

One problem of using a thumb on tactile screens of mobile phones is thumb accessibility: hand and thumb morphology makes it difficult for a thumb to reach some regions of a screen, such as corners and places near screen borders. Human motor control capabilities are bounded (Bérard, Wang, & Cooperstock, 2011). A previous study on thumb motor performance (Trudeau, Young, Jindrich, & Dennerlein, 2012b) found that a thumb's motor performance was significantly higher for adduction movement orientations compared to extension, and performance was generally higher for smaller phones than for larger ones. Therefore, when the location of a target on a device screen is further away from the current position of an operating thumb, the user's motor control capability and performance will decrease, especially when he/she tries to extend his/her thumb to reach targets. Another problem is visual occlusion: a thumb occludes part of the screen and blocks content underneath. The contact area between a thumb and a tactile screen is relatively large, which causes ambiguity about which part of the fingertip defines a selection point (Roudaut et al., 2008). The lack of tactile feedback further worsens this problem. The third problem is low accuracy. Target selection is error-prone, especially when a target is tiny and/or close to other items.

Some techniques have been proposed to solve each problem separately, but not all three problems simultaneously. Hence, the first research question of this dissertation is how to improve single-handed target acquisition with a touch-screen handheld device. To address the challenges described above, we propose and empirically evaluate a new approach, called ExtendedThumb, for target acquisition in single-handed interaction with touch-screen mobile phones. ExtendedThumb works as a proxy of a real thumb. It reaches out to a distant target on a device screen in the same dragging direction of the real thumb but with a longer moving distance than the latter. Users can adjust the moving direction and of ExtendedThumb by moving the real thumb on a device screen. The object that is currently focused by the ExtendedThumb will be selected when the real thumb lifts up from the screen. We have developed a prototype of ExtendedThumb for Android phones and conducted a usability evaluation of ExtendedThumb through a controlled lab experiment.

This study provides multifold contributions. First, ExtendedThumb addresses the thumb accessibility problem by enabling easy access to any screen area that is difficult to reach via direct touch. Second, to address the visual occlusion and low target selection accuracy problems, ExtendedThumb uses a clear virtual thumb and provides explicit aiming markers. Third, the results of the empirical evaluation reveal a number of areas on a device screen that are generally perceived as difficult to reach, which provide practical insights for future designs of mobile user interfaces and effective single-handed interaction techniques.

2.2 Related Work

We categorize existing approaches to target acquisition into three categories based on the problems that they attempt to address, including thumb accessibility, visual occlusion, and low accuracy.

2.2.1 Approaches to Improving Accessibility

According to Fitts' law (MacKenzie, 1992), there are two ways to reduce difficulty in target acquisition: enlarging a target or bringing it closer (Blanch, Guiard, & Beaudouin-Lafon, 2004). Proxy-based navigation techniques, such as drag-and-pop, drag-and-pick (Baudisch et al., 2003), and vacuum filter (Bezerianos & Balakrishnan, 2005), attempt to bring distant objects closer to a user's interaction space by creating local copies of them. These techniques support interaction with distant objects by reducing navigation movement. The downside of the drag-and-pop and drag-and-pick methods is that users need to drag distant targets one by one towards the current viewport manually, which makes the original difficult-to-reach target acquisition problem remain unsolved. The vacuum filter is a circular widget with a user controllable arc of influence centered at the widget's point of invocation spanning out to the edges of a display. Distant objects located inside this influence arc will be brought closer to the widget's center in the form of proxies that can be manipulated in lieu of original objects (Bezerianos & Balakrishnan, 2005). The problem with these techniques is that they are developed for large screens (e.g., wall-sized displays), not for thumb interaction. They are not practical for mobile phones because bringing distant objects to a closer area within easy reach can be challenging in the first place.

Instead of bringing a target closer, other techniques attempt to enable users to interact with distant objects through a representation of the display. For example, ThumbSpace (Karlson & Bederson, 2007) works like an absolute-position touch pad superimposed on a portion of a standard touch screen interface. It represents a linear scaling of an original display. Interacting with only a sub-region of a device screen, users can access all locations on the screen. ThumbSpace addresses the thumb accessibility problem by allowing users to personalize the size and placement of the touch pad. Its limitation, however, is that users need to make an initial guess about the location in a sub-region of ThumbSpace that corresponds to an intended target, which requires extra mental efforts. Radar View (Nacenta, Aliakseyeu, Subramanian, & Gutwin, 2005) and Bubble Radar (Aliakseyeu, Nacenta, Subramanian, & Gutwin, 2006) use a miniature representation of a display to enable easy access to distant objects. Given the fact that screens of mobile phones are smaller than those of desktops and tablets, a reduced representation of a mobile phone display would be too small for effective interaction.

2.2.2 Approaches to Avoiding Visual Occlusion

Vision clues play an important role in controlling reaching and pointing movements by a hand (Shadmehr & Wise, 2004). Visual occlusion can reduce such benefits.

Some techniques try to avoid visual occlusion by manipulating the position of a selection point or the location of objects displayed on a screen. For example, the offset cursor (Sears & Shneiderman, 1991) integrates a selection cursor positioned off the tip of a user's finger with a stabilization algorithm to achieve character-level selection. One problem with the offset cursor is that users have to aim below an intended target (Karlson & Bederson, 2007). Brandl et al. (2009) present an adaptive menu with a blank area, in which no menu items are placed. In other words, no items would be placed in the area that may be blocked by a user's hand. Unfortunately, this method is designed only for selecting menu items. It is inappropriate for target selection in other situations, such as clicking a hyperlink on a Website. MagStick (Roudaut et al., 2008) reaches a target with a stick moving in the opposite direction of a real thumb's moving direction. Although this strategy could be effective for avoiding visual occlusion because a real thumb must be moved away from a target in order to move the stick toward it, such an opposite moving direction is counter intuitive. Meanwhile, there may not be enough space for a real thumb to move away from a target if the starting point is close to the border of a screen.

Some other techniques focus on supporting target aiming to reduce the impact of visual occlusion. Kwon et al. (2009) propose a regional error correction method that works for text input only. Shift (Vogel & Baudisch, 2007) presents a callout showing a copy of the occluded screen area and places it at a non-occluded location with a pointer representing the selection point of a finger. Users can move the pointer towards a target by adjusting their finger on the screen and acquire the target by lifting the finger up. RegionalSliding (Xu, Yu, Liu, & Shi, 2014) renders a selected target and its surrounding objects as a marking menu when users press down on the screen, and enables users to complete a selection with sliding gestures based on the visual feedback from the rendered area. This group of methods, however, fails to address the thumb accessibility problem.

2.2.3 Approaches to Improving Accuracy

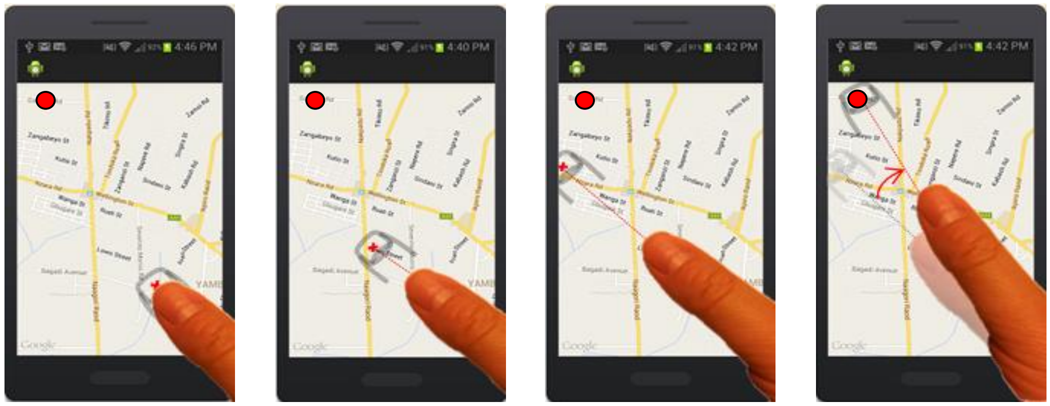
A variety of techniques have been developed to improve the accuracy of target selection. An area cursor (Worden, Walker, Bharat, & Hudson, 1997) has a larger activation area than a conventional cursor. Unlike most cursors that have a single point or "hot spot" as the point of activation, area cursors have larger hot spots. By extending the notion of an area cursor, a bubble cursor (Grossman & Balakrishnan, 2005) dynamically resizes its activation area based on the proximity of surrounding targets so that only one target is selectable at any time. DynaSpot (Chapuis, Labrune, & Pietriga, 2009) is an area cursor that couples its activation area with speed. Escape (Yatani, Partridge, Bern, & Newman, 2008) uses gesture directions with icon cues to improve target selection accuracy. Those methods are useful when there are multiple pre-defined targets. However, in many cases, such pre-defined targets may not exist. For example, when a user browses a website on a mobile phone, it is difficult to predict his/her targets in advance. TapTap (Roudaut et al., 2008) is a technique based on a temporal multiplexing strategy. The first tap serves to specify a focus area in the original view, and the second tap magnifies the focus area and displays it at a larger scale in order to make target selection easier. That method requires pre-defined targets and extra actions from a user.

Despite prior studies and innovations, the problems of thumb accessibility, visual occlusion, and low accuracy in single-handed interaction have not been well solved (Roudaut et al., 2008). Many existing techniques focus on addressing one problem only. This study aims to provide a novel method that can address all three problems simultaneously.

2.3 Design of ExtendedThumb

The design of ExtendedThumb considers the following issues:

- Thumb accessibility decreases as device size increases. Users are comfortable when interacting with a mobile device within a sub-region of a device screen (Karlson et al., 2006). Therefore, an effective interaction technique should make a real thumb only need to move within its comfort area;
- Visual occlusion should be avoided in a way that makes a target always visible during the entire selection process;
- The design should reduce the impact of target size and thumb size on the performance of target selection to alleviate the low accuracy problem.



(a) (b) (c) (d)

Figure 2.1 ExtendedThumb

(a) A red cross located at the tip of the virtual thumb shows the current selection position; (b) when a real thumb moves towards a target (e.g., the red dot on the map), the virtual thumb extends along the same direction with a longer moving distance; (c) the virtual thumb misses the target; and (d) the user adjusts the selection position of the virtual thumb by turning the real thumb and moving it towards the target. When the red cross of the virtual thumb is on the target, the user lifts his/her thumb up from the screen to select it.

A user can initiate ExtendedThumb with a double tap on the screen. A target selection scenario with ExtendedThumb is presented in Figure 2.1. There are four steps to choose a target on the screen with ExtendedThumb: 1) aim at a target; 2) move the real thumb toward the target. The virtual thumb moves in the exactly same direction as the real thumb but with a longer moving distance based on a user defined ratio; 3) adjust the selection position of the virtual thumb by changing the moving distance and direction of the real thumb; and 4) lift the real thumb up from the screen to select the target when the red cross sign located at the tip of the virtual thumb is on the target. Such a take-off strategy for target selection has been commonly used (Sears & Shneiderman, 1991) and proven to have high accuracy. As long as the virtual thumb appears on the screen, a real thumb cannot interact directly with items on the screen. After a user selects a target, the virtual thumb will automatically disappear.

ExtendedThumb is not intended to completely replace target selection with direct touch. Instead, it should be mainly used for acquisition of difficult-to-reach targets on a device screen when direct touch is ineffective or even impossible. ExtendedThumb has the following unique advantages: 1) a user can reach difficult targets by moving a thumb within a sub-region of the device screen, in which the user can move his/her thumb easily and comfortably; 2) because the designed virtual thumb is transparent (Figure 2.1), it does not block any content on a device screen and visual occlusion is avoided; 3) there is a red cross at the tip of the virtual thumb and a dotted line showing its moving direction, which can be used as explicit markers to aim at a target to improve target selection accuracy; 4) compared with moving a real thumb further away from a target in order to move a virtual thumb towards it, e.g., MagStick (Roudaut et al., 2008), ExtendedThumb is more intuitive by aligning the moving directions of a real thumb and the virtual thumb; and 5) the direct touch method typically has a control-display (c-d) ratio of 1, in which a pointer's movement matches a finger's movement completely (Vogel & Baudisch, 2007). With

ExtendedThumb, movements of a real thumb and the virtual thumb can either follow a user-defined ratio or be thumb speed-dependent.

2.4 Implementation

A prototype of ExtendedThumb was implemented in Java using Android APIs in Eclipse. The prototype system was installed on a Samsung Galaxy Note 2 phone with 2GB RAM, a 1.6GHz dual-core processor, a 5.5" HD Super AMOLED (1,280 * 720 pixels) display, and an Android 4.1.2 operating system. When a user interacts with its touch screen, a system log in the mobile phone records the time and pixel coordinates of that interaction.

2.5 Empirical Evaluation

A controlled laboratory experiment with a 3*2 (target acquisition methods * target size) within-subjects design was conducted to evaluate the effect of ExtendedThumb on completion time, error rate, and user perceptions of target acquisition while using direct touch (i.e., selecting a target through direct tapping by a thumb) and MagStick (Roudaut et al., 2008) as baseline methods.

2.5.1 Participants

We recruited 36 participants (23 male and 13 female; 3 left-handed and 33 right-handed) from an east-coast university in the United States. They were undergraduate and graduate students with a major in information systems. Among them, 17 were between 21 and 25 years old; 12 were between 26 and 30 years old, and 7 were over 30 years old. They all had used touch-screen mobile phones. Participants received extra course credits for participating in the experiment. To further motivate participants to try their best in the tasks, the top three participants who finished the tasks with the shortest time and the fewest errors were provided with an extra monetary bonus ($25, $15, and $10, respectively).

2.5.2 Apparatus

MagStick (Roudaut et al., 2008) is a target selection method based on thumb movement. It uses a telescopic stick to control a "magnetized" cursor. It reaches a target with the stick moving in the opposite direction of a real thumb's moving direction. The magnetization of the cursor moves the stick tip to a target while the cursor goes in an offset area around the target (Figure 2.2). The length ratio between the part of the stick controlled by a real thumb and the part of the stick that controls the cursor is 1:1.

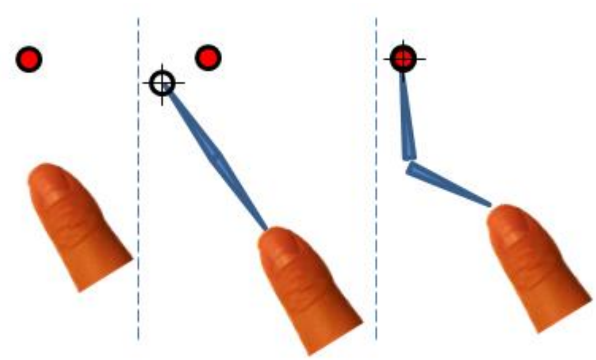


Figure 2.2 MagStick

Although different speed ratios can be used in ExtendedThumb for controlling its extending speed, in order to control the complexity of the experiment and minimize confounding effect, a fixed 1:2 ratio between moving distances of a real thumb and ExtendedThumb was used in the experiment. This ratio was determined through a pilot study that tested ExtendedThumb with several different ratio values. The 1:2 ratio was more effective and preferred by participants. In addition, some previous studies, e.g., (Yu, Huang, Hsu, & Hung, 2013), also used the same fix ratio of 1:2.

2.5.3 Independent and Dependent Measures

Independent variables include target acquisition methods and target size. Target acquisition methods include direct touch, MagStick, and ExtendedThumb. A previous study (Parhi, Karlson, & Bederson, 2006) found that 9.6 mm was sufficiently large for single-handed thumb interaction with touch-screen mobile phones. Therefore, we used target sizes of 7 mm and 10 mm. The three target acquisition methods and two target sizes create six experimental conditions.

Dependent variables include participants' performance and perception. Participants' performance of target selection tasks was assessed by task completion time and error rate:

- Task completion time was measured as the duration between the time when a target appeared on a device screen and the time when a participant's thumb left the screen to select the target.

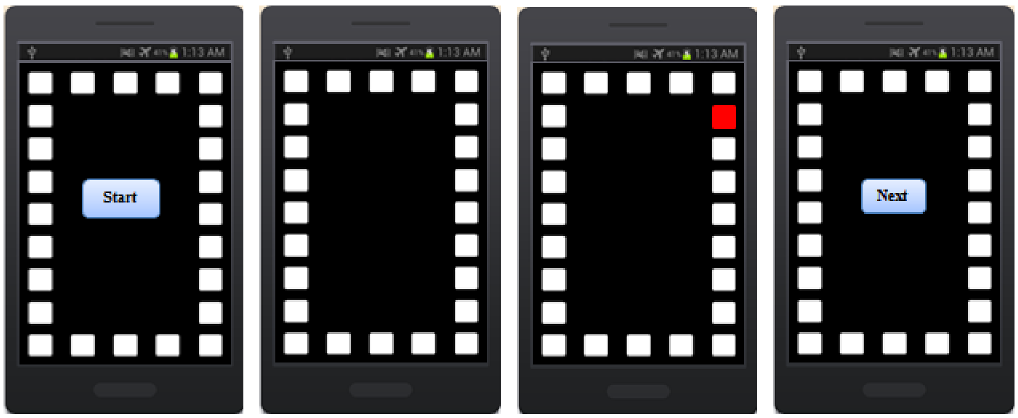
- Error rate was measured by the percentage of incorrect selections. If the touch point (i.e., the cross) of the virtual thumb, or the touch point of a real thumb with direct touch, or the stick tip of MagStick, was not on a target square when a selection was made, the system recorded it as an error. An error rate was calculated for each participant under each experiment condition.

Table 2.1 Questions Measuring User Perceptions

Factors	**Items** (1 representing "Totally Disagree", 4 representing "Neutral", and 7 representing "Totally Agree")
Perceived ease of use	Overall, I am satisfied with how easy it is to use this method. It was simple to use this method. It was easy to learn to use this method.
Perceived effectiveness	I could effectively complete the tasks using this method. I was able to complete the tasks quickly using this method. I was able to efficiently complete the tasks using this method.
Overall satisfaction	Overall, I am satisfied with this method for target selection.

Participants' perceptions of target acquisition methods were assessed through post-study questionnaires. Specifically, perceived ease of use, perceived effectiveness, and overall satisfaction of participants with regard to target acquisition methods were assessed through seven 7-point Likert scale questions (Table 2.1). Those questions were adapted from the IBM Post-Study System Usability Questionnaire (Lewis, 1995) and were grouped into three factors.

2.5.4 Procedure



(a) (b) (c) (d)

Figure 2.3 The Interface of the Target Selection Game

After signing a consent form, participants went through a 15-minute training session prior to the experiment. After participants were comfortable with the three target acquisition methods and experiment tasks, the experiment would start. Participants were first asked to click on each of the twenty-four 10mm squares located at the border of the screen of a Samsung Galaxy Note 2 phone (Figure 2.3) with the thumb of the same hand that held the phone. Those targets appeared in the red color one by one in a randomized order for at least three times. Each participant was asked to rate every target as “difficult to reach” or “easy to reach”. The selection of difficult-to-reach areas was carried out with the direct touch method only. Those squares rated as “difficult to reach” by a participant became targets that would be presented one by one in a random sequence for that participant under six experiment conditions.

After potential target positions were identified for individual participants, participants then played the same target selection game using their own set of identified difficult-to-reach targets on a Samsung Galaxy Note 2 phone. As shown in Figure 2.3, in this game, 24 equal-size squares were located along the borders of the mobile phone screen. The game began when a participant clicked a “START” button (Figure 2.3(a)). Three seconds later, one of those squares previously categorized as difficult to reach by that participant would be randomly chosen and highlighted in red as the current target (Figure 2.3(b) and 2.3(c)) and the system timer started. The participant was instructed to click the target as quickly and precisely as possible with the thumb of the same hand that held the phone. He/she only had one chance to select a target. When a selection action was made, the system automatically recorded the time as the ending time of the current target selection, and a “NEXT” button would appear at the center of the screen (Figure 2.3(d)). Three seconds after the participant clicked the “NEXT” button, the second target would appear. Such a procedure would be repeated until each candidate target had appeared as the current target once under each of the six experiment conditions. The sequence of six conditions was balanced with a Latin square design (Maxwell & Delaney, 2004) among all participants to minimize learning effects.

During the experiment, participants were asked to sit in a chair to avoid potential impact of participants' mobility on target selection performance, and only the dominant hand was allowed to hold and interact with the phone simultaneously.

2.5.5 Data Analysis

Task completion time and error rates were analyzed using a 3 * 2 repeated measures analysis of variance with within-subjects factors of target acquisition methods (direct touch, ExtendedThumb, and MagStick) and target size (7mm and 10mm). Mauchly's test of sphericity showed no sphericity violations. Bonferroni Post-hoc test was carried out for multiple comparisons. By following many prior studies, e.g., (Barnhart & Goldinger, 2013; Koten, Langner, Wood, & Willmes, 2013; Lemhöfer, Koester, & Schreuder, 2011; Mizuno & Matsui, 2013), error rates were arcsine transformed to correct for non-normality in their distributions prior to the analysis. Two-tailed paired samples t-test was performed to further examine the effect of target size on each target acquisition method when the interaction effect between target acquisition methods and target size was significant. Normality tests of perceived ease of use, perceived effectiveness, and overall satisfaction showed no evidence that those data were not normally distributed based on the rules of thumb for determining normality (West, Finch, & Curran, 1995). Hence, repeated measures analysis of variance with Bonferroni post hoc tests was performed to compare the perceived ease of use, perceived effectiveness, and overall satisfaction with three target acquisition methods.

2.6 Results

2.6.1 Identification of Difficult-to-Reach Targets

The average number of candidate targets identified by participants as difficult to reach was 9.7. Figure 2.4 shows the difficult-to-reach locations reported by participants. More than half of the participants reported that the squares 1, 2, 13, 17, 18, 23, and 24 were difficult to reach. More than 30% but less than 50% of participants reported that the squares 3, 4, 5, 6, 12, 14, 16, 19 and 22 were difficult to reach, and less than 30% rated the remaining squares as difficult to reach.

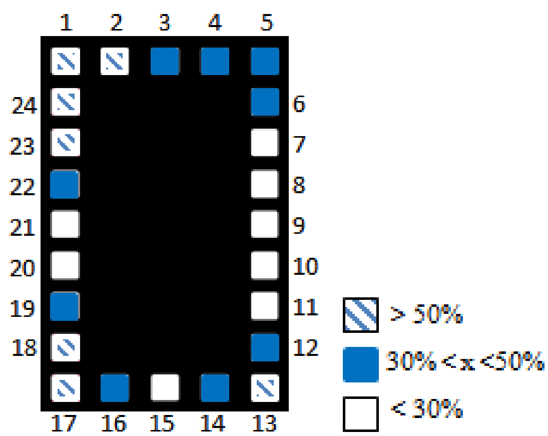


Figure 2.4 Reported Difficult-to-Reach Targets

2.6.2 Task Completion Time

The means of task completion time under six experiment conditions are shown in Figure 2.5. There are significant main effects of target size ($F(1, 35) = 25.25$, $p < 0.001$) and target acquisition method ($F(2, 70) = 64.94$, $p < 0.001$) on task completion time, but no significant interaction effect. Participants using direct touch with a thumb for target acquisition were significantly faster than those using ExtendedThumb and MagStick ($p < 0.001$). In addition, participants performed tasks significantly faster when using ExtendedThumb than when using MagStick ($p < 0.001$). Participants finished tasks with 10mm targets significantly faster than with 7mm targets ($p < 0.001$).

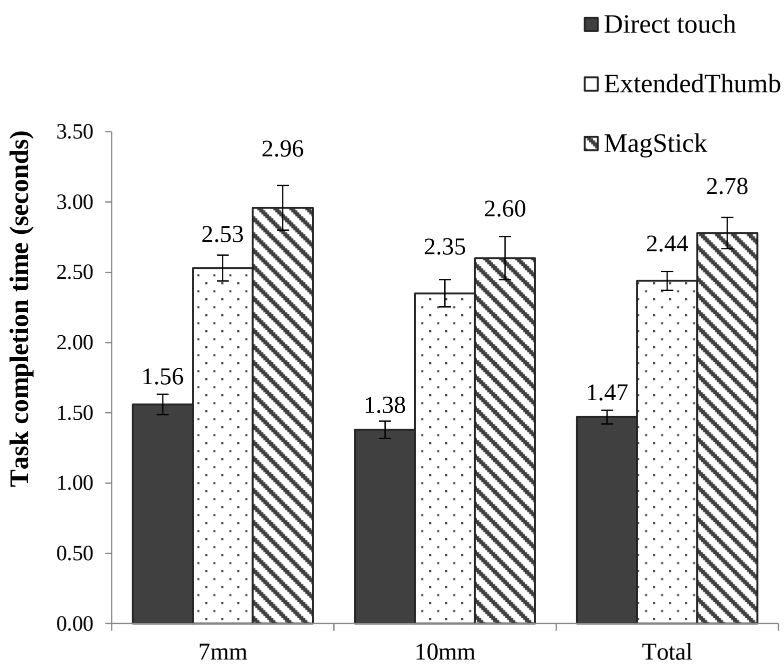


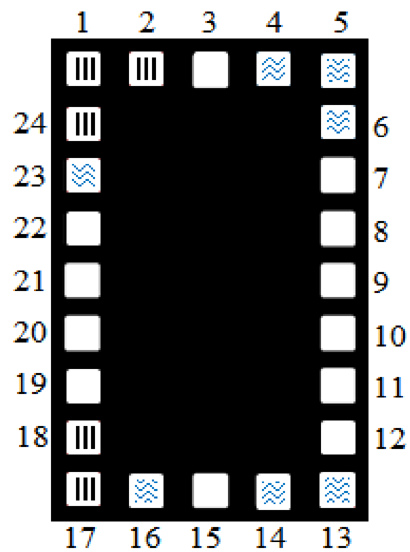
Figure 2.5 Task Completion Time with Different Target Sizes

(Unit: seconds; error bars represent standard errors)

2.6.3 Error Distribution and Error Rates

The distribution of selection errors of 33 right-handed participants is shown in Figure 2.6. 53.1% of total errors occurred on squares 1, 2, 17, 18 and 24; and 28.6% of errors occurred on squares 4, 5, 6, 13, 14, 16, and 23. The remaining squares accounted for

18.3% of errors. Given the small number of left-handed participants, the distribution of selection errors of left-handed participants is not analyzed. As presented in Figure 2.4 and 2.6, those areas located at the top-left and bottom-left corners are most difficult for target acquisition, followed by those located at the top-right and the bottom-right corners of the device screen



53.1% of errors occurred when selecting targets

28.6% of errors occurred when selecting targets

18.3% of errors occurred when selecting targets

Figure 2.6 Error Distributions

The error rates in six conditions are shown in Figure 2.7. The main effects of target size ($F (1, 35) = 9.79$, $p < 0.01$) and target acquisition method ($F (2, 70) = 36.34$, $p < 0.001$), as well as the effect of interaction between target acquisition method and target size ($F (2, 70) = 11.92$, $p < 0.001$), on selection error rates are all significant.

Direct touch caused a significantly higher error rate than the other two methods ($p < 0.001$). Participants generated a lower error rate while using ExtendedThumb than using MagStick, although the difference was not statistically significant.

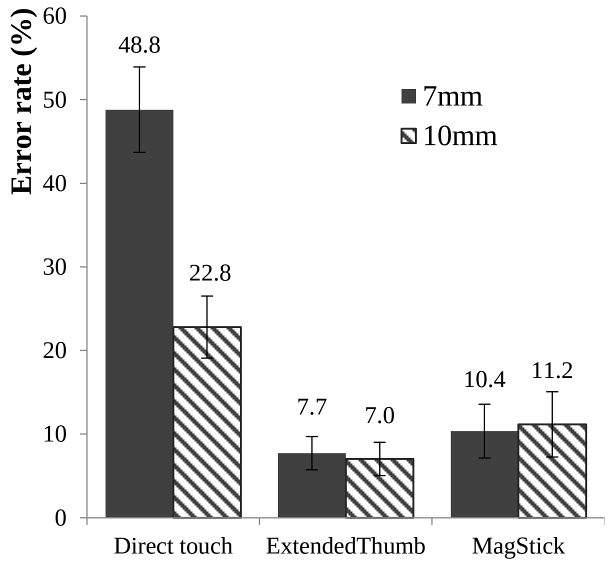


Figure 2.7 Means of Error Rates of the Three Target Acquisition Methods (%) (error bars represent standard errors)

Results also reveal that participants produced significantly lower error rates when finishing tasks with 10mm targets through direct touch than with 7mm targets ($t = 4.61$, $p < 0.001$). There was no significant difference between 10mm and 7mm targets for ExtendedThumb and MagStick. Furthermore, the overall error rate of selecting 7mm targets (22.3%) was significantly higher than that of selecting 10mm targets (13.7%) ($p < 0.05$).

2.6.4 User Perceptions

The Cronbach's Alphas for perceived ease of use and perceived effectiveness constructs were .84, and .93 respectively, both well above the recommended minimum level (Peterson, 1994). Results of analysis on perceived ease of use (Table 2.2) reveal significant differences among target acquisition methods ($F(2, 68) = 5.34$, $p < 0.01$). The mean of perceived ease of use of ExtendedThumb was significantly higher than those of MagStick (mean difference = 0.92, $p < 0.01$) and direct touch (mean difference = 0.69, $p < 0.05$). There was no significant difference between direct touch and MagStick.

There were significant differences among the three target acquisition methods in perceived effectiveness ($F(2, 68) = 7.62$, $p < 0.01$). The mean of perceived effectiveness of ExtendedThumb was significantly higher than those of MagStick (mean difference = 0.80, $p < 0.01$) and direct touch (mean difference = 1.33, $p < 0.001$). There was no significant difference in perceived effectiveness between direct touch and MagStick either.

There were also significant differences among the three target acquisition methods in overall satisfaction ($F(2, 68) = 5.56$, $p < 0.01$). The mean of satisfaction with ExtendedThumb was significantly higher than those of MagStick (mean difference =

0.86, $p < 0.05$) and direct touch (mean difference = 1.26, $p < 0.01$). There was no significant difference between direct touch and MagStick.

Table 2.2 Means of Perceived Ease of Use, Perceived Effectiveness, and Overall Satisfaction of Three Target Acquisition Methods

Factor	**Method**	**Median**	**Mean**	**SD**
Perceived ease of use	ExtendedThumb	6.00	6.06	0.97
	MagStick	5.00	5.13	1.38
	Direct touch	5.67	5.36	1.52
Perceived effectiveness	ExtendedThumb	5.67	5.61	1.15
	MagStick	5.00	4.81	1.36
	Direct touch	4.33	4.28	1.88
Overall satisfaction	ExtendedThumb	6.00	5.80	1.28
	MagStick	5.00	4.94	1.59
	Direct touch	4.00	4.54	1.98

Participants also provided their personal preference between ExtendedThumb and MagStick in the post-experiment questionnaire. Among 36 participants, 25 preferred ExtendedThumb and 11 preferred MagStick (Chi-Square value = 5.44, $df = 1$, $p < 0.05$). The reported reasons for preferring ExtendedThumb over MagStick included "When I try to reach something, I always go towards it, not in opposite direction"; "Dragging away seemed counter intuitive"; "It (ExtendedThumb) seems more natural and responsive"; and "Because I am still able to see my target, plus it is easier", etc.

Participants who preferred MagStick provided the following reasons: “I am familiar with it due to a mobile game, Angry Birds”; “It felt like an arch game, in which you pull back to aim”; and “It is a personal habit”. In sum, the main reason that the majority of the participants prefer ExtendedThumb over MagStick is because they feel that the former is more natural, while the main reason that some participants prefer MagStick is attributable to their prior experience of playing games.

2.7 Discussion

ExtendedThumb is aimed to assist users with selecting difficult-to-reach objects on a touch-screen mobile device, which is intended to be used as a supplement tool for direct touch. Previous studies on target acquisition in single-handed interaction, such as (Karlson & Bederson, 2007), placed targets on the whole display of mobile devices. Those methods were aimed to serve as alternative or replacement tools for target acquisition instead of supplement tools for direct touch. In contrast, our study only used difficult-to-reach targets reported by participants themselves. The reported difficult-to-reach target locations provide unique insights for future mobile interface design. The findings of this study demonstrate superior effectiveness and user perception of the proposed ExtendedThumb method in comparison to baseline methods.

ExtendedThumb allows users to use a virtual thumb, which works like a cursor and is controlled by a real thumb, to select difficult-to-reach targets. We have found that

ExtendedThumb and MagStick led to significantly lower error rates than direct touch. It may be because the red-cross mark of ExtendedThumb and the tip of MagStick are much smaller than a real thumb, making targeting and positioning more easily and accurately. Both ExtendedThumb and MagStick are controlled by a real thumb, which is far from a target, and the content around the target will not be blocked. As a result, the visual occlusion problem and the ambiguity about which part of the thumb defines a selection point no longer exist.

We also found that target size has significant impact on the error rate of direct touch but not on those of ExtendedThumb and MagStick. This is because the contact area between a thumb and the tactile screen is relatively large, and the thumb occludes the content below it. As a result, it is difficult to land a thumb on a target accurately. However, for target acquisition tools equipped with a 'cursor' (e.g., a cross mark), such as ExtendedThumb, target selection accuracy is unlikely influenced by target size because the location of the cursor is obvious and visual occlusion problem is avoided. The use of a cursor decouples target size from thumb size. The results indicate that incorporating a cursor into single-handed interaction tools for target acquisition can be very beneficial, especially when targets are small and high selection accuracy is required.

This study offers empirical evidence and practical insights for the design of single-handed interaction techniques. Our results show that ExtendedThumb is superior to

MagStick in terms of target acquisition speed, perceived ease of use, perceived effectiveness, and overall satisfaction, while achieving a similar level of accuracy. This may be largely attributable to aligning the moving directions of a real thumb and the virtual thumb, which is more natural. It is consistent with the way that people use a mouse with a desktop computer to control the cursor on a display. Therefore, we suggest that designers of future single-handed interaction techniques should align the movements of a real thumb and a virtual thumb proxy in the same direction. Previous studies have shown that human motor performance in device control depends on the muscle groups being activated. As such, the precision of motor activities varies with the choice of device and mode of operation (Bérard et al., 2011). Therefore, for target acquisition in single-handed interaction with mobile devices, it is necessary to avoid physical actions of a real thumb that requires fine motor skills that exceed the thumb's motor control capability.

The major motivation of designing ExtendedThumb is to help users overcome the difficulty in a user's motor control when selecting difficult-to-reach targets on a device screen using a thumb by providing a more effective mode of operation. Because the ExtendedThumb's movement is controlled by a real thumb's movement within its comfort zone, the degree of motor control of that real thumb is higher than the counterpart without an ExtendedThumb. As a result, the precision of target acquisition with ExtendedThumb is higher than the precision of the direct touch method.

Although it is the fastest among the three examined techniques, direct touch is not always practical and effective for target selection, especially when targets are difficult to reach. This problem worsens as the size of mobile device screen increases. Similarly, direct touch was found fast but error prone in (Karlson & Bederson, 2007) and (Roudaut et al., 2008). There are several possible reasons for this phenomenon. First, it is much easier and faster for a person to move his/her thumb in the air than dragging it on a screen surface. Second, it is more difficult to control the direction and distance of thumb movement on the screen than in the air. Third, participants in our study had never used ExtendedThumb and MagStick before the experiment. Therefore, they were much more familiar with direct touch than with other two methods, which may contribute to the difference in task completion time. In addition, when users reach distant objects with direct touch, they usually have to change the way that they grab mobile phones (Yu et al., 2013). After target selection, they have to adjust their hands back to the normal position. In the experiment, we did not take the time of adjusting hands back to the normal position into consideration. Therefore, in real world usage, using direct touch may take longer time than what was measured in this experiment.

Chapter 3 : ContextZoom — A Single-Handed Partial Zooming Technique for Touch-Screen Mobile Devices

3.1 Research Background

Zooming is one of the most commonly performed operations on touch-screen mobile devices. An intuitive and smooth method of changing zooming levels is vital (Miyaki & Rekimoto, 2009). Most of current touch-screen mobile devices allow users to zoom by finger pinch, which often requires both hands to operate, with one hand holding a device and the other performing the pinch gesture. As a result, such a pinch-based zooming technique does not work well for single-handed interaction(Boring et al., 2012), which is referred to as a user holding and interacting with a mobile device with the same hand simultaneously.

It is suggested that most users prefer single-handed interaction with mobile handheld devices, even when both hands are available (Karlson & Bederson, 2007; Karlson et al., 2006), especially when they have situational impairments (Korhonen et al., 2007) or upper limb/hand disabilities (Lai & Zhang, 2014). As opposed to physical impairments, situational or situationally-induced impairments (Sears et al., 2003) refer to impairments in which a user temporarily has difficulty in accessing or interacting with mobile devices due to the context or situation he/she is in, such as environment context (e.g., bright sunlight), specific task context (e.g., holding a cup of coffee with one hand), or social context (disturbance caused to other people) (Korhonen et al., 2007). Situational impairments often occur when people use mobile phones on the go (Wobbrock, 2006). In single-handed interaction, a hand holds a phone when its thumb performs other actions (Trudeau et al., 2012a). Current touch-screen mobile devices do not support single-handed interaction well (Park & Han, 2010a), although thumb-based single-handed interaction is often preferred by users in their daily life (Kim & Jo, 2015).

Due to the small screen size of mobile phones, users often lose context or get lost completely in the navigation space (Zhang & Lai, 2011). Zooming, especially zooming in, makes it difficult for a user to retain a sense of context and maintain a mental model of the navigation space (Qu, Wang, Cui, Wu, & Chan, 2009; Robbins, Cutrell, Sarin, & Horvitz, 2004). Users often have a difficult time figuring out where they are on a webpage or map after zooming in. Hence, the second research question of this dissertation is how to improve single-handed zooming with a touch-screen handheld device?

To address the above problem, in this study, we design, develop, and evaluate a thumb-based zooming technique called ContextZoom for single-handed interaction with touch-screen mobile devices. ContextZoom, which enables zooming a portion of a viewport, is mainly designed to be an add-on feature for current zooming methods that only focus on zooming the whole viewport, such as the Google Maps' single-handed zooming technique and the button-based zooming technique. ContextZoom can provide context information to users when they perform single-handed zooming to avoid navigation loss. Here context includes user context (i.e., users' points of interest) and content context (i.e., the content on the screen before zooming). ContextZoom is designed particularly for single-handed thumb use. It enables users to specify any target on a device screen as the center of zooming, which will always remain at the same location in the viewport after zooming. The zooming level is controlled by the moving distance of a thumb on the device screen. ContextZoom mainly supports partial viewport zooming. Users will see a portion of a screen in detail and will be able to go back to the previous screen before zooming quickly so that users will not get lost during navigation.

The rest of section will be organized as follows. We will start with reviewing existing zooming methods first. Then, we will present the design of ContextZoom, followed by the description of our empirical evaluation methodology. Next, we will present results. Finally, the session will be concluded with the discussion on major findings and limitations of ContextZoom.

3.2 Related Work

In this section, we first focused on two categories of zooming techniques, including multi-touch zooming techniques and single-handed zooming techniques. Then Focus

& Context techniques that support both whole and partial viewport navigation will be introduced.

3.2.1 Multi-Touch Zooming Techniques

The two-finger pinch zooming technique (Jordà, Julià, & Gallardo, 2010; Westerman, 1999), the most popular zooming technique used on touch-screen mobile devices, often requires users to hold a device with one hand and perform pinch operations using the other by moving two fingers apart from or towards each other. Pinch-to-zoom is awkward and ineffective for single-handed interaction (Ti & Tjondronegoro, 2012). Double tap (Hinckley & Song, 2011) is a commonly used method for single-handed zooming, with the first double-tap to zoom in and the second to zoom out. Its limitation lies in that the zooming level is fixed. As a result, the double-tap method is not effective for tasks that require different zooming levels, such as browsing maps and photos. To address this problem, Google Maps uses double-tap as a zooming gesture only, so that users can double tap multiple times to achieve specific zooming levels. However, its zooming-out operation requires users to tap with two fingers on the screen, which is challenging in single-handed interaction with mobile devices. In sum, existing multi-finger zooming techniques are not effective for single-handed interaction because they usually require two hands.

3.2.2 Single-Handed Zooming Techniques

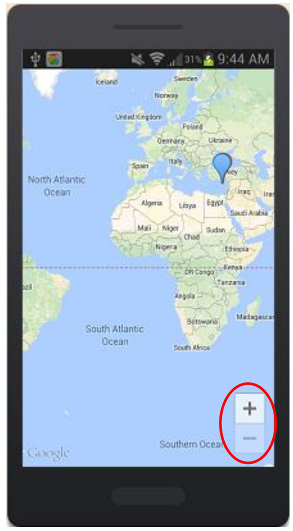


Figure 3.1 The Button-based Zooming Technique

With Google Maps' single-handed zooming technique, a user first double taps on a device screen. Then instead of lifting the finger away from the screen, he/she drags his/her finger down/up on the screen to zoom in/out. Because this technique always zooms in/out with the current viewport center as the zooming center, when zooming in a map, a point of interest may go off the screen, causing potential confusion to users and requiring their extra effort to bring the interested point back to the viewport. Google Maps uses a pair of buttons ('+' for zooming in and '-' for zooming out, as shown in Figure 3.1) to change the zooming level, which also uses the viewport center as the zooming center. Thus, it suffers from the same problem as mentioned above.

GraspZoom (Miyaki & Rekimoto, 2009) enables users to magnify content with one hand using an external pressure sensor attached to the back of a mobile phone, which limits its practicality and adoption (Ti & Tjondronegoro, 2012). A rubbing gesture, a small repetitive diagonal motion of a finger, is used by (Olwal, Feiner, & Heyman, 2008) for zooming on touch-screen devices. This technique takes into account the orientation of the rubbing gesture - a right-handed user zooms in by rubbing back and forth along the lower-left-to-upper-right diagonal, and zooms out by rubbing along the lower-right-to-upper-left diagonal. The motion directions for left-handed users are opposite. CycloStar (Malacria, Lecolinet, & Guiard, 2010) is another gesture-based technique, in which a user performs a circular gesture to zoom in (clockwise) or out (counter-clockwise). Fat Thumb (Boring et al., 2012) uses contact area size of a thumb tip to activate the zooming mode. A user moves a thumb with a small contact size to pan the content. By increasing the contact size, the user activates the zooming mode, with moving the thumb around its joint to the right/left for zooming in/out. The limitation of Fat Thumb is that users may accidently switch to the zooming mode when panning. Using Fat Thumb also requires some cognitive efforts of users in order to control the contact size when moving a thumb on the screen. All those existing methods are challenging for single-handed zooming because some locations on a mobile screen, such as corners, are difficult to reach by a thumb in single-handed interaction. Even with extra panning, some places are still difficult to reach, such as the address bar of an Internet browser.

Different from thumb gestures performed on device screens, tilting gesture-based zooming methods rely on tilting mobile devices in different ways for zooming, such as Tilt-to-zoom (Hinckley & Song, 2011) and TiltZoom (Ti & Tjondronegoro, 2012). Tilting a device towards (or away from) a user will zoom in (or out). Because a tilting gesture changes the angle of a device, it may prohibit a user from seeing the content displayed on the screen clearly during the motion.

3.2.3 Focus & Context Techniques

While zooming, users either magnify (zoom in for a focus) or de-magnify (zoom out for context) an interface, but not both simultaneously (Cockburn, Karlson, & Bederson, 2009). Focus & Context techniques are aimed to provide views of both a focus and context. For example, ZoneZoom (Robbins et al., 2004) divides a viewport into nine segments, with each mapping to a key on a number keypad of mobile phones. Users can zoom in any particular segment by selecting the corresponding key, and zoom out to the previous whole viewport by selecting the same key again or a dedicated “zoom-out” key on the keypad. Although ZoneZoom enables users to switch between focus and context views, it is not convenient for touch-screen mobile devices without a physical keyboard, because bringing up the virtual keyboard and then selecting keys require additional efforts from users. In addition, each key selection can only make the view be zoomed in/out by a fixed level, which makes it impossible to reach any arbitrary zooming level.

Focus & Context visualization techniques, such as Fisheye (Bederson, Clamage, Czerwinski, & Robertson, 2004), Flip zooming (Björk, 2000) and AppLens (Karlson et al., 2005) display a focused area with a larger zooming level embedded in a surrounding context area with a smaller zooming level, thus allowing the focal information to be displayed in a more salient way without losing context (Zhang & Lai, 2011). However, because an overview or a surrounding area (i.e., context) is typically displayed in a much smaller zooming level or font size in comparison to the focused area, such context could be illegible on the screen of mobile devices and thus becomes useless while wasting valuable display space (Zhang & Lai, 2011). In addition, although context information can help prevent users from getting lost during zooming, existing Focus & Context visualization techniques do not work for zooming on mobile phones because they usually magnify a focused area with a fixed zooming level.

In sum, although there exist a number of different single-handed zooming techniques, they have various limitations that affect their effectiveness, including 1) by using the screen center as the zooming center, a target may go off the screen after zooming in; 2) due to zooming with fixed zooming levels, users cannot reach any desired zooming level; and 3) there is a lack of context information provided to users during zooming.

3.3 Design of ContextZoom

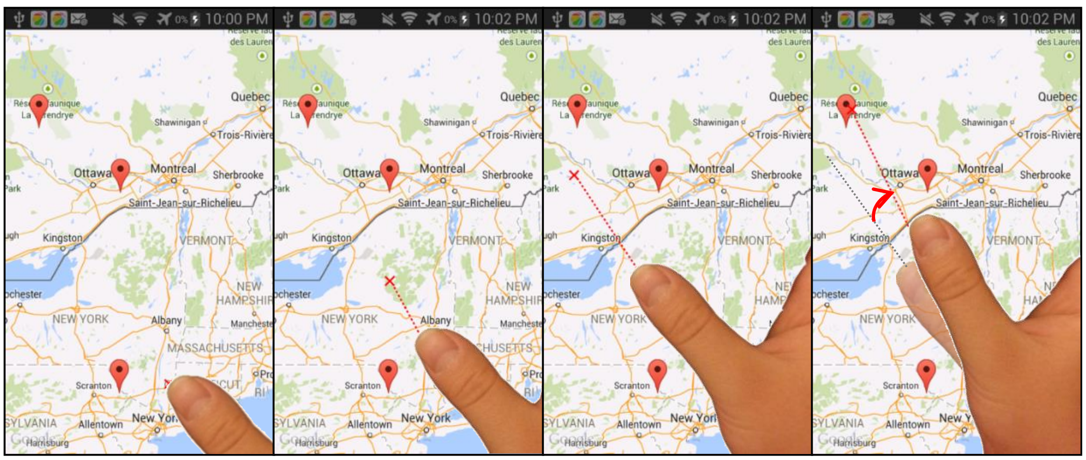
In this research, we have designed ContextZoom, a novel single-handed zooming technique for touch-screen mobile handheld devices to address the limitations of existing methods described above. The design of ContextZoom takes several factors into consideration. Specifically, ContextZoom is designed to

- support single-handed partial viewport zooming by developing a thumb-based zooming approach;
- allow a user to specify any point of his/her interest on a mobile device screen as the zooming center, which will stay at the original location after zooming in; and
- present context of a navigation space to help users maintain a mental model of the navigation space to prevent them from getting lost.

Google Maps uses a long finger press on a touch screen to select a point on the screen as the point of interest and insert a pin at that location. ContextZoom adopts this idea and presents all targets as pins. With ContextZoom, a long press on an existing pin will select that pinned location as the zooming center.

We adopt ExtendedThumb (Lai & Zhang, 2014), as introduced in the preceding chapter, to enable a user to reach and select difficult-to-reach objects as a zooming center with one hand without any panning (Figure 3.2).

After a zooming center is selected (Figure 3.3 (a)), a user can move his/her thumb at anywhere on the screen to perform zooming or do a long press on another location to re-select a different zooming center. As long as the red cross appears on the screen, the panning function is temporarily disabled. After zooming is performed, the red cross will disappear, the selected zooming center will be at the center of the partial viewport, and the panning function will be automatically resumed.

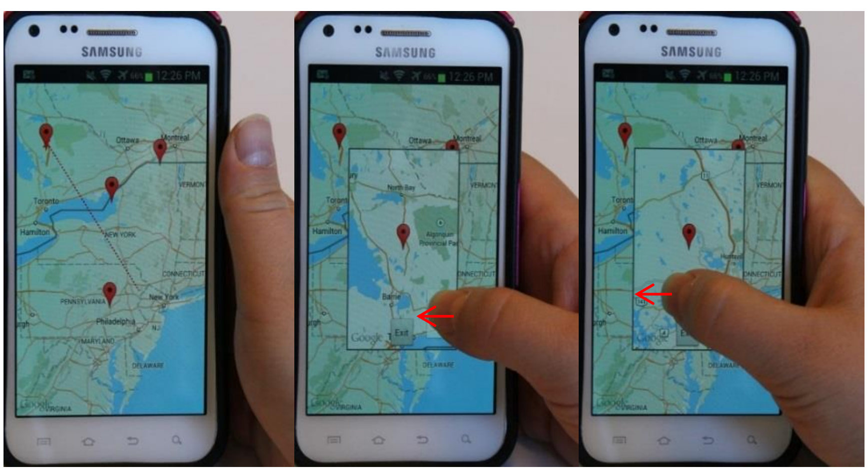


(a) (b) (c) (d)

Figure 3.2 Zooming Center Selection

(a) a red cross appears initially at the point underneath the real thumb after a long press; if the thumb leaves the screen, the current location of the red cross will be selected as the zooming center. Otherwise, (b) when the thumb moves towards a target, the red cross goes in the same direction, but with doubled traveling distance; (c) the red cross misses the target; and (d) the user adjusts the position of the red cross by turning the thumb and moving it towards the target. When the red cross is on the target, the user can select it as the zooming center by lifting the thumb up from the screen.

Different from the Google Maps' single-handed zooming technique, which only supports whole viewport zooming, ContextZoom provides a partial zooming function to enable users to just zoom a portion of the whole viewport. A user can move his/her thumb from anywhere on the screen to the left to zoom in a partial viewport (Figure 3.3 (b)), with the selected zooming center being at its center and the default size of the partial viewport being 1/3 of the whole viewport. A user can reset the size of the partial viewport. The longer the user drags his/her finger to the left, the larger the zoom-in level (Figure 3.3(c)). We adopted this horizontal swiping gesture because it was found to be useful for mobile Websites (Dou & Sundar, 2016). When the thumb leaves the screen, partial zooming will automatically stop.



(a) (b) (c)

Figure 3.3 Partial Zooming with ContextZoom

The user can interact with a map in a partial viewport in the same way as interacting with a regular map. For example, he/she can perform the Google Maps' single-handed zooming in a partial viewport to adjust the zooming level, and exit the partial viewport and go back to the original whole viewport (as shown in Figure 3.3(a)) by selecting the "Exit" button at the bottom of the partial viewport (Figure 3.3(b)). Similarly, he/she can drag his/her thumb to the right on a device screen to zoom out a portion of displayed content after selecting a zooming center. When the current focus is in the whole viewport of a mobile phone screen, he/she can click on the "Back" button of the phone to go back to the previous partial viewport, just like users can click the "Back" button to go back to the previous webpage they have visited while browsing the Web.

3.4 Implementation

We have implemented a prototype of ContextZoom in Java using the Android SDK and the Google Maps' APIs in Eclipse for user evaluation. The prototype system was installed on a Samsung Galaxy S2 phone featuring a 1.2GHz dual-core processor, a 4.52" Super AMOLED Plus (480*800 pixels) display, 1GB RAM, and the Android 4.1.2 operating system. A system log on this phone automatically recorded the time of interactions when a participant used ContextZoom.

3.5 Evaluation of Partial Zooming with ContextZoom

Although a number of zooming techniques for mobile devices have been proposed, few studies have compared them (Garcia-Lopez, de-Marcos, Garcia-Cabot, & Martinez-Herraiz, 2015). In order to evaluate ContextZoom, a controlled laboratory experiment was conducted, with the Google Maps' single-handed zooming method (referred to as GMS hereafter) and the button-based zooming method (shown in Figure 3.4, referred to as BB hereafter) as two baseline methods. ContextZoom was incorporated into both methods as an add-on feature. With GMS, a user first double taps a device screen. Then without lifting the finger away from the screen, he/she drags his/her finger down/up on the screen to zoom in/out. With BB, a user presses the '+' button for zooming in and '-' for zooming out. We did not include more zooming methods for mobile devices as baselines in the experiment because of the cost of implementing them, as well as the scope and complexity of this study. As a matter of fact, some other prior studies on zooming only involved one or two baseline zooming methods in their evaluation, e.g., (Malacria et al., 2010; Olwal et al., 2008). We choose GMS because Google Maps is commonly used by users. The BB method is available in some mobile versions of Google Maps (such as version 6.14.5) and is also popular in the desktop version of Google Maps. Although double-tap is used by Google Maps as a zoom-in gesture, the corresponding zoom-out operation requires a two-finger-tap, which is challenging in single-handed interaction. Thus, we did not include the double-tap zooming technique in the evaluation.

3.5.1 Participants

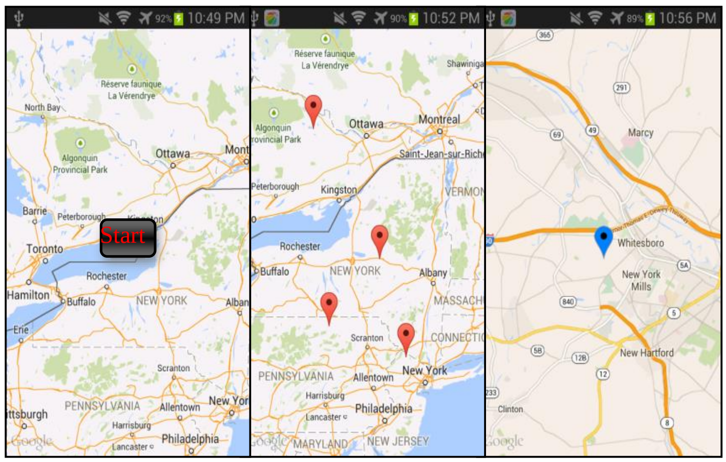
43 (24 male, 19 female) undergraduate and graduate students with a major in information systems at an east-coast university in the United States participated in the study. Among them, 28 were between 18 and 25 years old; 14 were between 26 and 30 years old; and 1 was over 30 years old. They were all right-handed and had prior experience with zooming on touch-screen mobile phones. Participants received extra course credits for participating in the experiment.

To minimize the confounding effect of using different zooming techniques within the partial viewport, we divided participants into two groups randomly. Group 1 participants (23) performed zooming tasks with GMS and with GMS enhanced by ContextZoom as an add-on feature (referred to as ContextZoom+GMS hereafter), and group 2 participants (20) used BB and BB enhanced by ContextZoom (referred to as ContextZoom+BB), respectively.

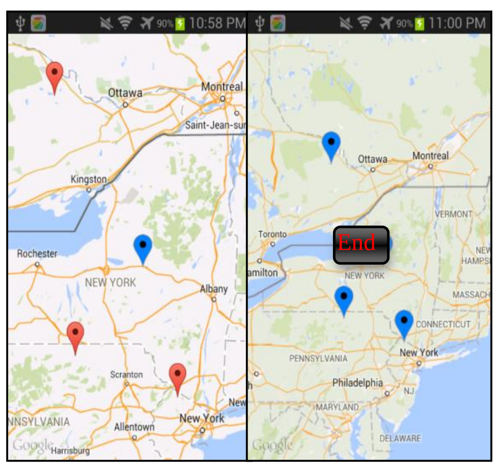
3.5.2 Experimental Tasks

Zooming tasks were designed to evaluate the proposed zooming technique. Once a participant clicked the start button on the system interface (Figure 3.4(a)), there would be two, four, or eight targets appearing on a map displayed on the screen as red pins (Figure 3.4(b)). The system recorded this time as the task starting time. Participants were instructed to zoom in a map until reaching a certain level that was equal to or higher than a predefined level (referred to as the aimed zooming level), when a red pin in the viewport would turn into blue (Figure 3.4(c)). Pins would not turn into blue if they were off the viewport. This design required the participants to not only zoom in the map to the aimed zooming level, but also to keep a target/pin within the viewport. The locations of the pins on the device screen were randomly determined. Because if two targets were too close to each other, when a participant zoomed in the viewport to the aimed zooming level, both targets could be shown in the viewport and turn into blue. That means the participant finished two targets with only one zooming action, which literally makes finding two targets become finding one. To prevent this from happening, we made the targets at least 100 pixels away from each other to guarantee that only one pin would appear in the viewport when the aimed zooming level was reached or exceeded. Participants needed to zoom out (or go back to the whole viewport by clicking the “Exit” button at the bottom of the partial viewport with ContextZoom (Figure 3.3(b)) to find another target (Figure 3.4(d)), and then zoomed in to reach the aimed zooming level as quickly as possible and meanwhile kept the target/pin within the viewport. After all designated targets turned into blue, participants needed to zoom out or go back to the whole viewport. When a map’s zooming level was equal to or lower than the initial zooming level, an “End” button would appear on the screen (Figure 3.4(e)). The system recorded the time when the “End” button appeared as the ending time of the current zooming task. Then participants could start the next zooming task.

Participants were instructed to complete the zooming tasks as fast as possible. The initial zooming level and aimed zooming level were the same across all tasks. The tasks were designed to be equivalent to zooming a map into a particular region of interest. Similar tasks were also used in (Ti & Tjondronegoro, 2012).



(a) (b) (c)



(d) (e)

Figure 3.4 A Zooming Task

3.5.3 Independent and Dependent Measures

The independent variables were the zooming method and target density. There were two pairs of zooming methods in this study, including ContextZoom+GMS vs. GMS (Group 1), and ContextZoom+BB vs. BB (Group 2). Participants of group 1 used ContextZoom+GMS and GMS; and those of group 2 used ContextZoom+BB and BB. When users browse maps to search for nearby points of interest, such as restaurants or banks, they usually identify multiple targets. Thus, we used three different target numbers, including two, four, and eight, to represent low, medium, and high target density. For each group, participants were required to finish three map zooming tasks with the three different levels of target density and a pair of designated zooming techniques. As a result, there were six zooming tasks for each participant.

Dependent variables included participants' zooming task performance and perception. Participants' performance of zooming tasks was assessed by task completion time and the number of discrete actions performed while accomplishing a task.

- Task completion time: it is measured by the duration between the time when targets appeared on a device screen and the time when a participant went back to the initial zooming level after all targets turned into blue. Since three tasks involved different numbers of targets, we divided task completion time by the number of targets involved in that task to get the average task completion time.

- Number of discrete actions: the experimental system recorded each discrete action performed on the device screen by individual participant during each task, including tap and thumb moving actions. The aggregated number of tap and moving actions of each participant was counted as his/her discrete action number for each task. Similarly, we divided the number of discrete actions performed in each task by the number of targets to get the average number of discrete actions per task.

Table 3.1 Questionnaire Items Measuring User Perceptions

Factors	**Items** (1 representing "Totally Disagree" and 7 representing "Totally Agree", with 4 being "Neutral")
Perceived ease of use	Overall, I am satisfied with how easy it is to use this zooming method. It was simple to use this zooming method. It was easy to learn to use this zooming method.
Perceived effectiveness	I could effectively complete the tasks using this zooming method. I was able to complete the tasks quickly using this zooming method. I was able to efficiently complete the tasks using this zooming method.
Overall satisfaction	Overall, I am satisfied with this method for zooming.

Perceived ease of use, perceived effectiveness, and overall satisfaction of participants with regard to zooming methods were assessed through a post-experiment survey consisting of seven 7-point Likert scale questions (Table 3.1). The questions, grouped by those three factors, were adapted from the IBM Post-Study System Usability Questionnaire (Lewis, 1995), which was originally developed by applying psychometric methods to measure user satisfaction and subjective assessment with system usability (Lewis, 1995).

3.5.4 Procedure

In this study, the participants carried out six zooming tasks while walking on a treadmill. Participants were required to hold a Samsung Galaxy S2 phone and interact with it with their dominant hand only while holding an empty water bottle in the other hand to simulate a situational impairment condition. By following a previous study (Bergstrom-Lehtovirta, Oulasvirta, & Brewster, 2011), the moving speed of the treadmill was set by participants themselves according to their normal walking speeds while interacting with a touch-screen device. The mean of participants' selected walking speeds was 2.1 km/h (SD = 0.7 km/h). There was no significant difference in the walking speeds of two groups ($p > 0.05$).

After signing a consent form, participants went through a 15-minute training session prior to the experiment to get familiar with the experimental zooming techniques and tasks. The participants were explained how ContextZoom and the other two zooming methods worked, and practiced with several sample tasks similar to the formal experimental tasks using those experimental zooming methods. After participants were comfortable with them, the experiment would start. During the experiments, no participant ever reported any problems with the zooming methods, including ContextZoom.

Participants finished three tasks (one with each different target density) using ContextZoom+GMS and GMS or ContextZoom+BB and BB. The sequences of the six zooming techniques and the target density levels were balanced among individual participants in order to minimize learning effects.

3.5.5 Results

1) Task Completion Time

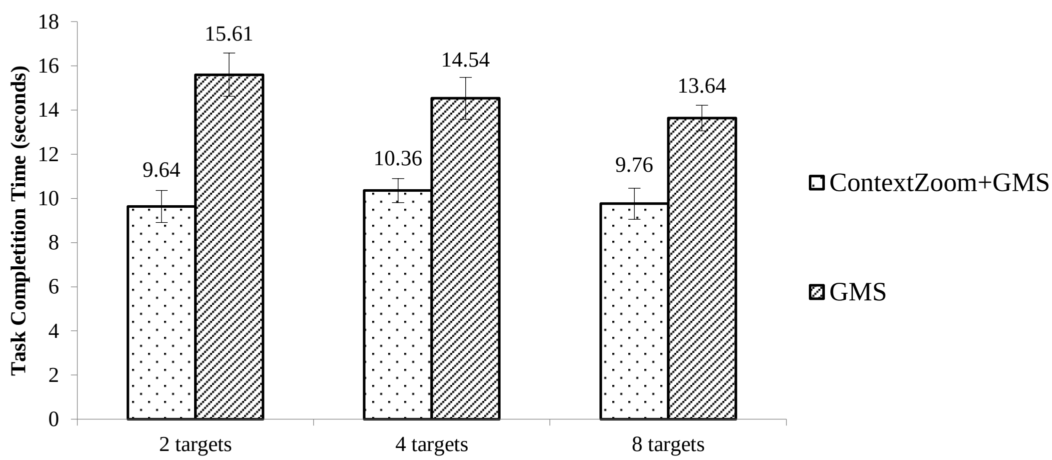


Figure 3.5 Means of Task Completion Time of Group 1

(error bars representing standard errors)

Task completion time was analyzed using 2*3 repeated measures analysis of variance with within-subjects factors of zooming method (ContextZoom+GMS vs. GMS or ContextZoom+BB vs. BB) and target density (two, four and eight targets). The means of task completion time of groups 1 and 2 are shown in Figures 3.5 and 3.6, respectively.

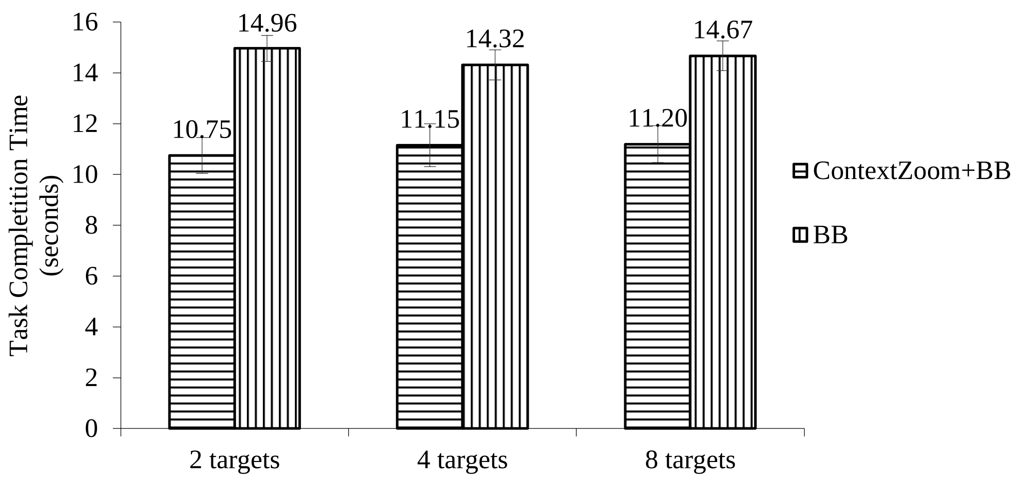


Figure 3.6 Means of Task Completion Time of Group 2

(error bars representing standard errors)

For group 1, Mauchly's test of sphericity shows no violations. The main effect of zooming method on task completion time ($F(1, 22) = 96.15$, $p < 0.001$) is significant, but the main effect of target density ($F(2, 44) = 2.34$, $p > 0.05$) and the interaction effect between zooming method and target density ($F(2, 44) = 3.21$, $p > 0.05$) are insignificant. Bonferroni Post-hoc test results show that the task completion time of ContextZoom+GMS is significantly less than that of GMS (mean difference = -4.68, $p < 0.001$). Participants using ContextZoom+GMS took significantly and consistently less time to complete experimental tasks than their counterparts when using GMS only across all three levels of target density. Results of paired samples t-tests on task completion time of three target densities are 8.90 (two targets), 5.70 (four targets), and 5.54 (eight targets), respectively, which are all significant ($p < 0.001$).

For group 2, Mauchly's test of sphericity shows no violations. The main effect of zooming method ($F (1, 19) = 43.67$, $p < 0.001$) is significant, but the main effect of target density ($F (2, 38) = 0.10$, $p > 0.05$) and the interaction effect between zooming method and target density ($F (2, 38) = 1.11$, $p > 0.05$) are insignificant. Bonferroni Post-hoc test results show that task completion time of ContextZoom+BB is significantly less than that of BB (mean difference = -3.62, $p < 0.001$). Participants using ContextZoom+BB took significantly and consistently less time to complete experimental tasks than their counterparts when using BB only across all three levels of target density. Results of paired samples t-tests on task completion time of three target densities are 6.50 (two targets), 4.17 (four targets), and 5.29 (eight targets), respectively, which are all significant ($p < 0.001$).

2) Number of Discrete Actions

The number of discrete actions is analyzed using 2*3 repeated measures analysis of variance with within-subjects factors of zooming method (ContextZoom+GMS vs. GMS or ContextZoom+BB vs. BB) and target density (two, four and eight targets).

The means of the numbers of discrete actions of groups 1 and 2 are shown in Figures 3.7 and 3.8, respectively.

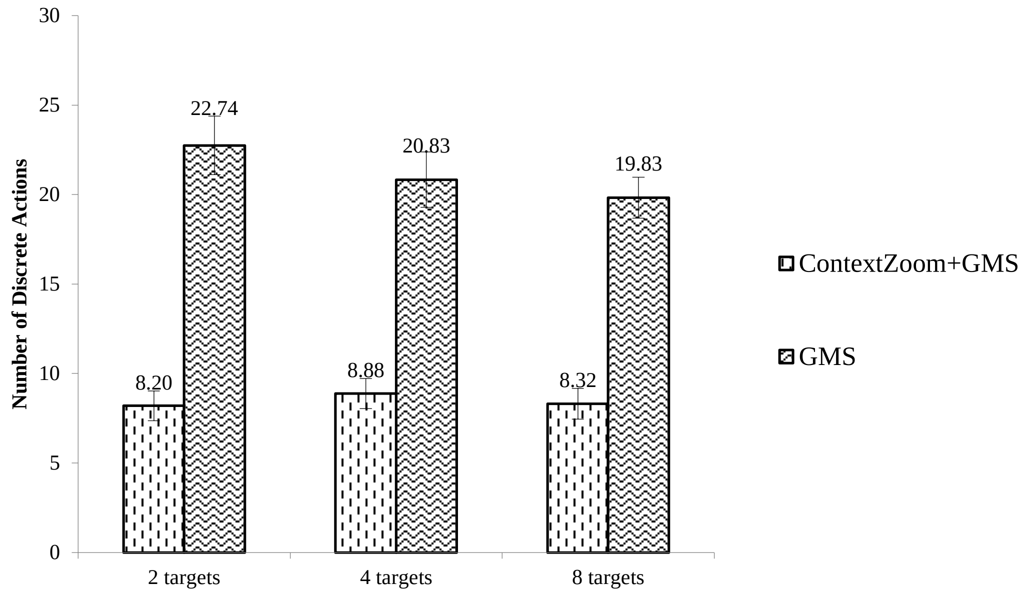


Figure 3.7 Discrete Action Numbers of Group 1

(error bars representing standard errors)

For group 1, Mauchly's test of sphericity shows no violations. The main effects of zooming method ($F(1, 22) = 151.95$, $p < 0.001$) and the interaction effect between zooming method and target density ($F(2, 44) = 3.92$, $p < 0.05$) are significant, but the main effect of target density is not ($F(2, 44) = 2.81$, $p > 0.05$). Bonferroni Post-hoc test results indicate that the number of discrete actions taken by the participants when using ContextZoom+GMS is significantly smaller than that when using GMS only (mean difference = -12.67, $p < 0.001$). Specifically, participants took significantly fewer discrete actions with ContextZoom+GMS than with GMS only across all three levels of target density. Paired samples t-test results are 11.00 (two targets), 10.01 (four targets), and 9.77 (eight targets), respectively ($p < 0.001$).

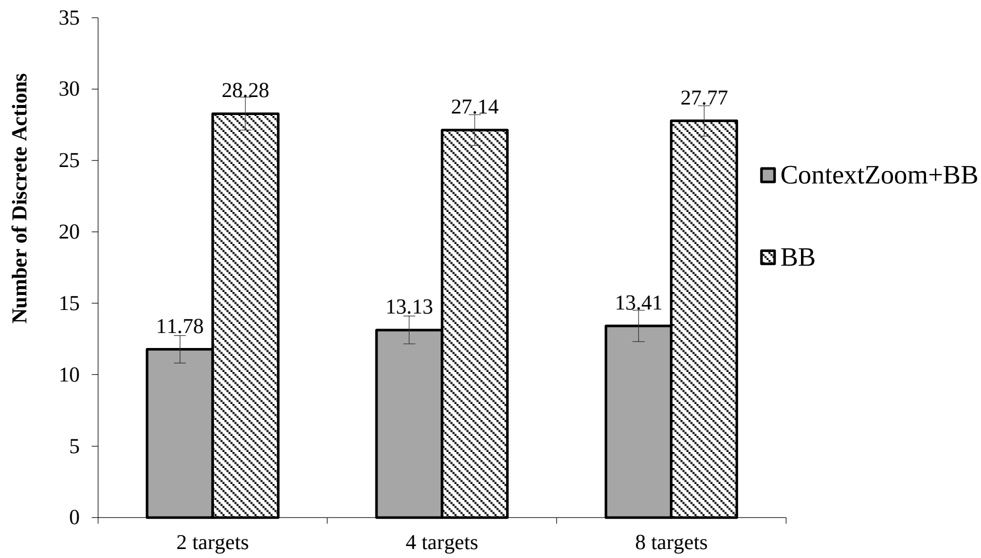


Figure 3.8 Discrete Action Numbers of Group 2

(error bars representing standard errors)

For group 2, Mauchly's test of sphericity shows no violations. The main effect of zooming method is significant ($F(1, 19) = 484.29$, $p < 0.001$), but the main effect of target density ($F(2, 38) = 0.31$, $p > 0.05$) and the interaction effect between zooming method and target density ($F(2, 38) = 5.14$, $p > 0.05$) are not. Bonferroni Post-hoc test results suggest that the number of discrete actions taken by the participants when using ContextZoom+BB is significantly smaller than that when using BB only (mean difference = -14.95, $p < 0.001$). Specifically, participants took significantly fewer discrete actions with ContextZoom+BB than with BB only across all three levels of target density. Paired samples t-test results are 18.54 (two targets), 17.71 (four targets), and 17.49 (eight targets), respectively ($p < 0.001$).

3) User Perceptions

Table 3.2 Means of Perceived Ease of Use, Perceived Effectiveness, and Overall Satisfaction for Evaluation of Partial Viewport Zooming

Group	**Factor**	**Method**	**Mean**	**SD**	***t***
Group 1	perceived ease of use	ContextZoom+GMS	5.67	1.19	1.49
		GMS	5.09	1.61	
	perceived effectiveness	ContextZoom+GMS	5.81	1.45	2.33*
		GMS	4.70	1.64	
	overall satisfaction	ContextZoom+GMS	5.96	1.61	2.88**
		GMS	4.52	1.65	
Group 2	perceived ease of use	ContextZoom+BB	6.15	1.07	.73
		BB	5.85	1.06	
	perceived effectiveness	ContextZoom+BB	6.12	1.17	1.46
		BB	5.45	1.22	
	overall satisfaction	ContextZoom+BB	6.25	1.12	1.73
		BB	5.45	1.35	

*$p < 0.05$; ** $p < 0.01$

The Cronbach's Alphas for perceived ease of use and perceived effectiveness constructs are 0.87 and 0.96, respectively, all above the recommended minimum level of 0.7 (Peterson, 1994).

Results in Table 3.2 demonstrate that the participants reported higher levels of perceived effectiveness ($p < 0.05$) and overall satisfaction ($p < 0.01$) with ContextZoom+GMS than with GMS only while achieving a similar level of perceived ease of use. There is no significant difference between ContextZoom+BB and BB in those three measures of user perception.

3.6 Evaluation of Whole Viewport Zooming with ContextZoom

Although ContextZoom is mainly intended to support partial zooming on mobile devices, we also evaluated its effectiveness for zooming the whole viewport as a standalone tool. To be consistent with GMS, after determining the zooming center for ContextZoom, a participant could move his/her finger downward (or upward) to zoom the whole viewport in (or out). Since the goal of this part of the evaluation was to assess the effectiveness of ContextZoom in whole viewport zooming, the partial zooming feature was disabled.

3.6.1 Experiment Design

We used the same experimental tasks, independent and dependent measures, and experimental procedure for evaluating partial zooming with ContextZoom. 20

participants (12 male, 8 female) were recruited form the same department. Among them, 13 were between 18 and 25 years old; and 7 were between 26-30 years old. Each participant was required to complete three zooming tasks that involved two, four, and eight targets using ContextZoom, GMS, and BB. Therefore, each participant would complete a total of nine zooming tasks in the experiment. The sequence of tasks in the experiment was balanced to minimize any learning effect.

3.6.2 Results

1) Task Completion Time

Task completion time was analyzed using 3*3 repeated measures analysis of variance with within-subjects factors of zooming method (ContextZoom, GMS and BB) and target density (two, four and eight targets). Greenhouse-Geisser correction was used for sphericity violation.

The results show a significant main effect of zooming method ($F(1.18, 22.47) = 31.01$, $p < 0.01$) on task completion time, but the main effect of target density ($F(2, 38) = 2.64$, $p > 0.05$) is insignificant, nor is the interaction effect between zooming method and target density ($F(2.73, 51.81) = 0.34$, $p > 0.05$). The means of task completion time for ContextZoom, GMS, and BB are 21.66 (SD = 7.19), 13.64 (SD = 2.79), and 13.19 (SD = 2.41) seconds respectively. Participants spent significantly more time with ContextZoom than with the other two methods ($p < 0.001$).

2) Number of Discrete Actions

The number of discrete actions taken to complete tasks is also analyzed using 3*3 repeated measures analysis of variance with within-subjects factors of zooming method (ContextZoom, GMS and BB) and target density (two, four and eight targets). Mauchly's test of sphericity shows no violations. The main effects of zooming method ($F(2, 38) = 28.33$, $p < 0.01$) and target density ($F(2, 38) = 5.12$, $p < 0.01$) are significant, but the interaction effect between the two ($F(4, 76) = 0.29$, $p > 0.05$) is insignificant. The means of numbers of discrete actions taken by the participants when using ContextZoom, GMS, and BB are 16.55 (SD = 5.64), 18.67 (SD = 5.03), and 25.40 (SD = 3.88) respectively. The numbers of discrete actions with ContextZoom and GMS are significantly fewer than that of BB. Although ContextZoom leads to the fewest number of discrete actions, there is no significant difference between ContextZoom and GMS. The task with eight targets yields less number of discrete actions than tasks involving two and four targets ($p < 0.05$). There is no significant difference between tasks involving two and four targets.

3) User Perceptions

The Cronbach's Alphas for perceived ease of use and perceived effectiveness are 0.91 and 0.93, respectively, all above the recommended minimum level of 0.7 (Peterson, 1994). Results in Table 3.3 demonstrate that the participants reported higher levels of perceived ease of use with BB than with ContextZoom ($p < 0.01$). There is no statistically significant difference between the ContextZoom and GMS or GMS and

BB. Participants reported higher perceived effectiveness with both GMS ($p < 0.05$) and BB ($p < 0.01$) than with ContextZoom. There is no significant difference between GMS and BB. BB received higher overall satisfaction than GMS ($p < 0.05$), and GMS resulted in higher satisfaction than ContextZoom ($p < 0.05$).

Table 3.3 Means of Perceived Ease of Use, Perceived Effectiveness, and Overall Satisfaction for Evaluation of Whole Viewport Zooming

Factor	Method	Mean	SD	F
perceived ease of use	ContextZoom	4.65	0.88	8.85**
	GMS	5.43	1.22	
	BB	5.92	0.65	
perceived effectiveness	ContextZoom	4.67	0.85	8.94**
	GMS	5.51	1.14	
	BB	5.82	0.76	
overall satisfaction	ContextZoom	4.65	0.93	9.06**
	GMS	5.25	1.41	
	BB	6.00	0.79	

**p < 0.01

3.7 Discussion

ContextZoom makes several contributions to the research on single-handed zooming on mobile handheld devices. First, ContextZoom improves users' performance of single-handed partial viewport zooming with GMS and BB by reducing task completion time and the number of discrete actions taken to complete zooming tasks. Second, when a point of interest is selected as the zooming center for ContextZoom, it will be guaranteed to stay in the viewport during and after zooming, so that the user will not miss it. This design can reduce users' interactions with the screen, which is manifested by the fewer number of discrete actions taken by the participants of this study and lower task completion time. Third, by incorporating the ExtendedThumb technique, ContextZoom enables users to select any target point on a mobile device screen by a thumb as the zooming center without panning. Fourth, the partial viewport zooming enabled by ContextZoom allows zooming a portion of the content on the device screen without losing context, such as the locations of other targets.

The results of our empirical study show that ContextZoom+GMS and ContextZoom+BB outperformed GMS and BB in both task completion time and number of discrete actions for partial viewport zooming. It may be because the baseline techniques always use the viewport center as the default zooming center, in which some targets may go off the screen after zooming. Therefore, participants had to find and bring those targets back to the viewport. With ContextZoom, users can make a target as the zooming center to make sure it stays in the viewport after zooming. Even if the user accidently moves a target originally at the center out of the partial viewport, he/she can easily go back to the initial screen in the whole viewport to start over quickly by clicking the "Exit" button in the partial viewport. However, with GSM and BB, it could be challenging for users to go back to the initial screen, which requires a lot of zooming and navigation actions. Furthermore, participants had to zoom out to find other targets after finding one.

With regard to the number of discrete actions taken to accomplish experimental tasks, the interaction effect between zooming method and target density of group 1 in the partial zooming experiment is significant. As the target density increased, the average number of discrete actions taken for getting each target while only using GMS decreased. It could be because when a task involved more targets, participants needed to zoom in/out for more times, providing them more opportunities to learn the locations of targets. As a result, it became easier for them to find the targets, which saved some navigation and led to the fewer average number of discrete actions while using GMS only. Different from GMS, we do not see a similar pattern for ContextZoom+GMS, which indicates ContextZoom+GMS has stable performance in number of discrete actions with different target densities.

Participants also achieved significantly higher levels of perceived effectiveness and overall satisfaction when they used ContextZoom+GMS than when they used GMS only, while achieving a similar level of perceived ease of use. It may be because the double-tap-hold gesture used in GMS was relatively unfamiliar to the participants. Participants tended to lift their thumb up from the screen after the second tap, rather than to hold it on the screen. In fact, this double-tap-and-lifting gesture is not unusual.

Participants’ previous experience with it may hinder them from learning the Google Maps’ single-handed zooming technique, which was indicated by participants’ comments after the study, such as “double tap and hold is confusing”; “it was awkward at first”; and “it took time to get used to it”. For group 2, the clicking interaction of BB was very simple and effective, which may lead to the insignificant difference between ContextZoom+BB and BB only in user perceptions, although ContextZoom+BB was significantly better than BB in both task completion time and number of discrete actions.

Based on our observation during the experiment, all the participants used one strategy when they used GMS and BB: they first dragged a target to the screen center, and then performed the zooming operation. However, the problem is that it was very difficult for a participant to put the target exactly at the center of the screen. Even if it was just a few millimeters away from the center, the target could go off the screen very quickly when zooming in. It is why with GMS and BB, participants always needed to scroll the viewport to look for the targets after zooming in, even after they brought a target to the screen center before they performed the zooming gesture. ContextZoom is designed as an add-on feature for current existing methods to enable partial zooming. Therefore, it is not hugely surprising that the participants took more time to complete the experimental tasks when using ContextZoom for the whole viewport zooming than using GMS and BB. It could be because when a participant reached the farthest place he/she can reach on the screen, he/she had to first bring his/her thumb back and then choose a zooming center with a long press before he/she could do the zooming gesture again. With an Android smartphone, the default time for a long press gesture is 500ms. That means a user has to press on the screen for at least 500ms to trigger the long press gesture to specify a zooming center. Since a participant had to repeat the procedure of choosing a zooming center with a long press gesture, it may slow down the whole viewport zooming with ContextZoom. We did not find the same issue in the partial zooming evaluation. It is because when ContextZoom is used for partial zooming, users could do zooming gestures in the partial viewport with the selected target as the zooming center. There was no need for them to select the zooming center again. There are many different types of interaction gestures that can be performed on touch-screen devices (Park & Han, 2014). In the future, we will look for a more efficient way to define a zooming center and to initiate ContextZoom. Another possible reason for the relatively poor performance and lower perceptions of ContextZoom in whole viewport zooming than those of GMS and BB is that participants were much more familiar with using the latter two existing methods for whole viewport zooming than ContextZoom, which does not offer ContextZoom any advantages over the two baselines in this task.

Unlike traditional Focus & Context techniques, we did not put the context and the focal area in the same viewport because due to the small screen size of mobile phones, the context could be illegible on the screen of mobile devices and becomes useless while wasting valuable display space (Zhang & Lai, 2011). Thus, we put the focal area and the context in two viewports with a quick switch method. In addition, the partial viewport is overlaid on the whole viewport, and the size of the partial viewport can be adjusted by the user.

Chapter 4 : ThumbStroke — A Thumb-Based Single-Handed and Sight-Free Virtual Keyboard for Touch-Screen Mobile Devices

4.1 Research Background

Ideally, mobile interaction should just require one hand (Roudaut et al., 2008). Current design of mobile devices, however, does not support single-handed interaction well (Park & Han, 2010a). Mobile phones have tiny buttons and crowded keypads, which are difficult to press accurately with a thumb, especially with a big thumb (Boring et al., 2012). There are also more areas on a large touch screen that are difficult to reach in single-handed interaction (Karlson et al., 2006).

Texting is an essential function of mobile communication and connectivity. Nevertheless, text input on mobile handheld devices is not well supported (Romero et al., 2011). The standard QWERTY keyboard layout has been adopted by the majority of mobile devices, although its size ill-suited to the mobile paradigm (MacKenzie & Soukoreff, 2002). Typing with the same hand that holds a phone is even more problematic because the user need to secure the device with his/her palm and four fingers while reaching keys with the thumb, which has limited flexion and extension. Some of the keys can be difficult to reach by a thumb. Hence, the third research question is how to improve single-handed text entry with a touch-screen handheld device?

To address the above challenges, we propose a direction-based stroke keyboard called ThumbStroke to support single-handed text entry on touch-screen mobile devices. This keyboard has several distinct features: 1) users can interact with the ThumbStroke keyboard indirectly at any place on a touch screen where they feel comfortable, which solves the problem of limited thumb accessibility; 2) instead of tapping on specific keys to enter characters as with traditional virtual keyboards, users using ThumbStroke can make a stroke at any place on a device screen to select and enter a character. Hence, the keyboard position on the device screen is not constrained by the mobility of a thumb; 3) direct press on keys is not required by ThumbStroke. When users press on keys in a traditional keyboard, the thumb will cover the content underneath, causing the visual occlusion problem (Scheibel et al., 2013); and 4) ThumbStroke does not require precise pressing on keypads, which can be used to support sight-free text entry. Here sight-free refers to tying without looking at the screen. With ThumbStroke, the negative effect of visual occlusion and small key size on text entry can be eliminated.

The rest of the session will be organized as follows. We will first introduce the literature on existing methods for text entry on mobile devices. Then, we will present the design of ThumbStroke, followed by the description of our empirical evaluation methodology. Next, we will present and discuss results. Finally, the session will conclude with future research directions.

4.2 Related Work

Low thumb accessibility, visual occlusion, and low accuracy (Lai & Zhang, 2014; Roudaut et al., 2008) are common problems in single-handed interaction with touch-screen mobile phones. Some keys on a traditional soft keyboard such as QWERTY are difficult to reach due to the limited thumb accessibility. When users tap on keys on a touch screen, the thumb will occlude the content underneath. In addition, the tiny keys of the QWERTY keyboard on mobile phones make it even worse. As a result, the accuracy and speed of text entry with such a keyboard are severely affected.

Some text entry techniques for mobile devices have been proposed based on menu selection. No-look notes (Bonner, Brudvik, Abowd, & Edwards, 2010) is a pie-menu-based technique to support text entry for blind users. It offers two-step access to characters with finger gestures instead of precise tapping required by the regular QWERTY keyboard. Popie (Sato, Shizuki, Miura, & Tanaka, 2004) is a menu-selection-based Japanese input method, which requires users to select words by interacting with two menus. With T-cube (Venolia & Neiberg, 1994), after users press an area of the pie-menu, another pie menu will appear and users need to make another selection in the new pie menu. Those techniques require at least two steps: first, users need to find a segment of a menu; second, making another interaction to enter a character in the selected segment. Nevertheless, they did not fundamentally solve the problems of low thumb accessibility and visual occlusion. In addition, an extra step could also increase users' cognitive effort.

There exist some stroke-based text entry methods. For example, with ShapeWriter (Zhai et al., 2009), instead of tapping on individual keys, a user can enter a word by sliding a finger through all the letters in the word consecutively. The keyboard approximately traces all letters in the intended word, regardless of their locations, and analyzes them using a statistical model. The statistically most likely word will then be selected (Zhai & Kristensson, 2012; Zhai et al., 2009). Escape-Keyboard (Banovic, Yatani, & Truong, 2013) enables a user to enter letters by pressing the thumb on different areas on the screen and flicking into different directions. One limit of the keyboard is that the user needs to reach to a region to select a character, which could be challenging with large phones in the first place. KeyScretch (Costagliola, Fuccella, & Di Capua, 2011) allows users to type with both taps and strokes. Whenever a key is pressed, a radial menu with frequently used characters will appear around it, which can be selected through a stroke. Still this method did not address the limited thumb accessibility and visual occlusion problems. With EdgeWrite (Wobbrock, Myers, & Kembel, 2003), users enter text by traversing the edges and diagonals of a square hole, and gesture recognition is accomplished through the sequence of corners that are hit. Characters are represented with different patterns. To enter a character, users need to draw a corresponding pattern within the small hole. Given the large number of characters, this method may require a significant learning curve.

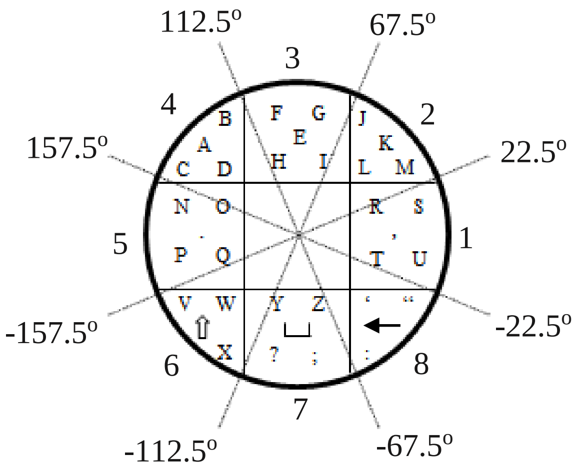
There are commercialized tools developed to support sight-free text entry. VoiceOver and TalkBack on iPhone and Android phones are used by visually impaired users. They read out the letter on a key when users press on it during text entry. Braille-based techniques, such as BrailleTouch (Southern, Clawson, Frey, Abowd, & Romero, 2012), TypeInBraille (Mascetti, Bernareggi, & Belotti, 2011), BrailleType (Oliveira, Guerreiro, Nicolau, Jorge, & Gonçalves, 2011), and BrailleKey (Subash, Nambiar, & Kumar, 2012), are also available for visually impaired users. They are usually designed for this group of users only. However, sight-free text entry is also useful for people without visual impairments. For example, when a user is in a rush to catch a bus and meanwhile he/she needs to send a message, it would be helpful if he/she does not need to look at the screen while typing.

None-braille based techniques are developed for sight-free text entry. With Escape (Banovic et al., 2013), users can flick their fingers to desired directions within a region on the screen to choose letters. However, flicking to different directions in a particular area can be challenging, especially with a large phone. No-Look Notes (Bonner et al., 2010) divides the screen into small segments, and presents characters within them. The user first needs to put a finger to the segment that contains the character he/she intent to enter. Then he/she can select a segment by keeping one finger on a segment and then tapping a second finger on the screen. Selecting a segment brings the user to another screen with that segment's characters presented on it. Users then select the desired character by putting a finger in the area contains it and tapping on the screen with a second finger. This two-step way of selecting characters can be tedious and time-consuming. A graffiti-based keyboard (Tinwala & MacKenzie, 2009) is developed for sight-free text entry. The challenge is to recognize users' handwriting input strokes accurately, and it also requires users to remember all the Graffiti characters.

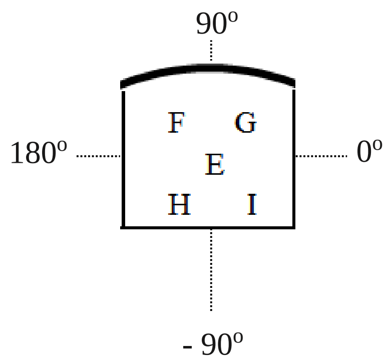
In order to solve the above-mentioned issues of existing techniques for single-handed and sight-free text entry, we developed ThumbStroke to support both single-handed and sight-free text entry.

4.3 Design of ThumbStroke

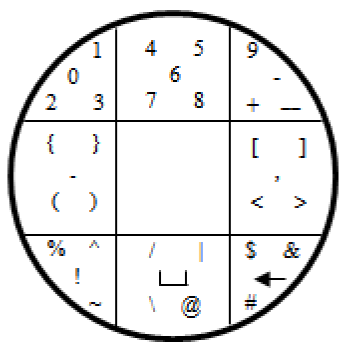
The objective of this research is to design, develop, and evaluate a thumb-stroke-direction based keyboard to address the common problems of single-handed text entry on mobile devices, including low thumb accessibility, visual occlusion, and low accuracy simultaneously and meanwhile to support sight-free text entry.



(a) Direction Range of Eight Small Areas



(b) Direction Range in a Small Area



(c) The Keypad of Numbers and Symbols

Figure 4.1 Keypads of ThumbStroke

ThumbStroke is a virtual keyboard with a single round key. The key is divided into eight small areas around its center, as shown in Figure 4.1(a) and Figure 4.2. With the center of the key as the reference point, each of the eight small areas is located within a certain direction range (between two adjacent dotted lines in Figure 4.1 (a)). With the center of each small area as the reference point, a character is located in the center or in a certain direction range. For example, as shown in Figures 4.1(a) and 4.1(b), ‘A’ is located in the center of the small area 4, and ‘G’ is located in the direction of 0~90^{o} from the center ‘E’. According to (Lai & Zhang, 2014), angle intervals of thumb moving directions (i.e., the angle between two adjacent but different moving directions) influences thumb movement speed and accuracy in single-handed interaction. It is suggested that the angle interval between any two adjacent areas or keys should be no less than 45^{o}. Therefore, we adopt this guideline in the design of the proposed ThumbStroke. In addition, when ThumbStroke appears on a device screen, if a user double taps anywhere on the screen, the keyboard will switch between a letter keypad (i.e., Figure 4.1(a)) and a symbol/number keypad (i.e., Figure 4.1(c)).

(a) (b) (c)

Figure 4.2 Text Entry via ThumbStroke

The fundamental unique feature of the ThumbStroke keyboard lies in that individual characters can be selected for text entry completely based on thumb strokes at any location on the touch screen without physically pressing any keys on the keyboard.

Figure 4.2 illustrates how to type with ThumbStroke:

- When a user touches the text field, ThumbStroke will automatically appear on the screen (Figure 4.2(a)). A long press in the center enables users to move the keyboard to any location that they prefer. The center of the keyboard will be activated automatically as the reference point whenever the user touches the screen.
- A user moves his/her thumb on the screen in the direction toward an intended small area. The moving direction is calculated and one of the eight surrounding small areas in that direction will be identified and chosen as the current focus area. The character located in the center of that focus small area is automatically selected as the current reference point, which is highlighted in bold and changed to the red color from the original white color (i.e., the letter 'E' in Figure 4.2(b)). If the user lifts his/her finger away from the screen now, the currently activated letter (i.e., 'E') will be entered into the text field.
- If the user changes the moving direction towards the lower-right corner without lifting his/her thumb away from the screen, the letter 'I' will be activated (Figure 4.2(c)).
- The user lifts his/her thumb away from the screen, the activated letter 'I' will be entered, and the keyboard automatically goes back to its initial status.

The moving direction of the thumb is dynamically captured during the text entry process. As long as the direction change is larger than a threshold, a turning motion occurs. In addition, when ThumbStroke appears on a device screen, if a user double taps anywhere on the screen, the keyboard will switch between a letter keypad (i.e., Figure 4.1(a)) and a symbol/number keypad.

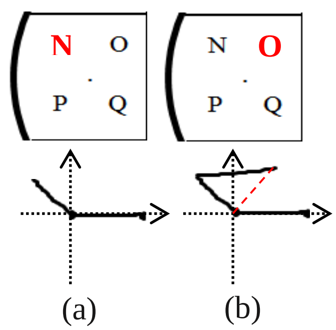


Figure 4.3 Error Correction

(a) The target character is 'O', but the user moves his/her thumb in the wrong direction, so that 'N' is chosen by mistake; and (b) instead of lifting the thumb away from the screen to enter 'N', the user moves it to the right. A new direction, which is represented by the red dotted line, is calculated, and 'O' will be selected.

Furthermore, ThumbStroke provides an error correction feature for users. If a user mistakenly selects a wrong character, he/she can change the selected/highlighted character by moving the thumb toward another direction to select the correct character (e.g., Figure 4.3). If a user has selected a wrong area, he/she can cancel the selection by continuing moving the thumb in the previous direction after a pause (e.g., Figure 4.4).

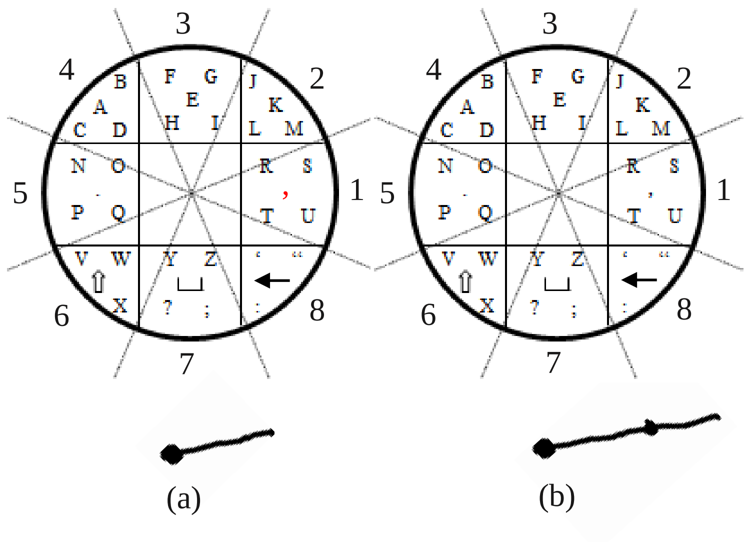


Figure 4.4 Area Cancelation

(a) the target character is ‘K’ in the small area 2, but the user moves the thumb in the wrong direction. The wrong small area 1 is chosen and ‘,’ is highlighted; and (b) instead of lifting the thumb up to enter ‘,’ or changing the stroke direction to select another character, the user moves the thumb in the previous moving direction after a pause. The attempt is canceled, and no character is entered into the text field.

The design of ThumbStroke is based on an assumption: users can move their thumb into eight directions accurately and quickly within an area that they feel comfortable on a touch-screen. In order to evaluate this assumption, we conducted the following study on direction’s impact on single-handed thumb interaction.

4.4 A Study of Direction's Impact on Single-Handed Thumb Interaction

When holding and using a touch-screen mobile phone with the same hand, users usually grasp the phone in the palm, with the thumb interacting with the touch screen and the other four fingers securing the phone. Due to morphological constraints, movements of the thumb are limited because the hand has to successfully complete the prehensile task of securing the phone while the thumb performs other actions (Trudeau et al., 2012a).

Movements of the thumb on touch screens are often direction-oriented. For example, the single-handed zooming function in Google maps enables users to drag the thumb upwards to zoom out and downwards to zoom in. Rubbing gestures are used in (Olwal et al., 2008) for zooming, in which the direction of gestures are taken into account. Scrolling/panning, the most frequent operations on touch-screen mobile phones, changes the content in the viewport to align with the thumb movement direction. In addition, many games on mobile phones, such as Angry Birds, also rely on fingers' moving directions. Meanwhile, it has been reported that movement directions of thumb have impact on movement performance (Trudeau et al., 2012a). However, thumb interaction with touch-screen mobile devices is a relatively new field (Roudaut et al., 2008). Research on users' direction-oriented interaction with touch-screen mobile phones is limited. It is unclear how movement directions of thumb may affect its interaction with a mobile device.

This study makes contributions by examining relationships between thumb movement directions and interaction performance. The rest of this sub-session is organized as follows. We will first introduce related work, followed by the description of our empirical study. Finally, we will present and discuss the findings of this study.

4.4.1 Related Work

Direction-oriented thumb movements play a prominent role in interaction with touch-screen mobile phones. Combining both commands and operands in single motions, thumb movements can help reduce the need for software buttons and menus (Karlson et al., 2005). A set of gestures have been used in AppLens and LaunchTile (Karlson et al., 2005) as directional commands. However, the efficiency and effectiveness of those gestures were not evaluated.

Using location-independent movements of thumb for interaction can provide tremendous benefits for blind users. For example, Apple's VoiceOver screen reader is controlled by a set of gestures. Users can touch or drag a finger on the screen and VoiceOver will tell them what is there. Flicking left or right can enable users to navigate from the current application to the next or the previous one. Given the common use of gestures in interacting with touch-screen devices by blind users and the lack of evaluation of the effectiveness of those gestures, a systematic study of direction-oriented movements is needed to gain insights for designing better gesture-based techniques.

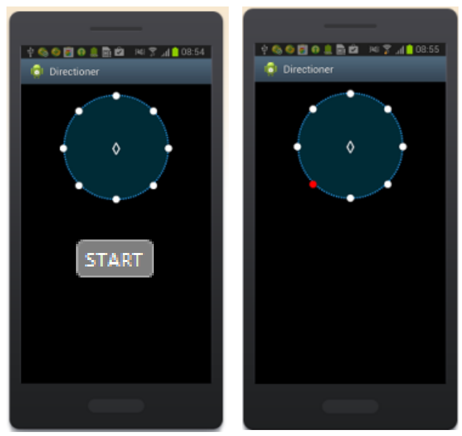
Direction-oriented thumb movements have also been used for text entry. The FlickKey Keyboard (http://www.flickkey.com) consists of six large keys, with nine characters on each key. To enter the character in the center of a large key, the user can tap anywhere on that key. To enter other characters on the same large key, the user first presses anywhere on the key, and then swipes in the direction toward the target character. FlickKey is designed based on the assumption that users can swipe accurately and efficiently in all eight directions, which has not been examined and validated. Trudeau et al. (2012a) have studied the impact of movement directions of thumb on its motor performance. They found that performance for "outward" directions was better than "inward" directions. However, they used mock-up phones instead of real touch-screen mobile phones in their study. Moreover, they only evaluated tap in eight directions but not the impact of directions on swipe.
Despite the increasingly common design and use of direction-oriented gestures on mobile phones, there have been relatively few systematic studies on direction-oriented interaction techniques. We believe understanding how moving directions may affect a thumb's movement performance can provide design guidelines for better interactive interfaces. Hence, we conduct this study to fill the void.

4.4.2 Participants

We recruited 32 participants (19 male, 13 female; all right-handed) from an east-coast university in the United States. 16 were between 18 and 25 years old; 11 were between 26 and 30 years old, and 5 were over 30 years old. They all had used touch-screen mobile phones. Each participant received $10 for participating in the experiment.

4.4.3 Experiment Design

Tap and swipe are two most frequently used thumb movements on touch-screen mobile phones. In this study, we used a target selection game (Figure 4.5) in a controlled lab experiment to evaluate users' performance of direction-oriented thumb movements, specifically tap and swipe, on touch-screen mobile phones in single-handed interaction. To select targets with tap (referred to as double tap hereafter), when a dot on the screen appears in red, as shown in Figure 4.5, a participant needs to estimate the direction from the center of the circle to the red dot (referred as target direction hereafter), and then taps twice on the screen. The first tapped place serves as the reference point. Right after the first tap, the user needs to finish the second tap in the same direction as the target direction. If the direction from the first tapped place to the second one aligns with the direction from the center of the circle to the target (Figure 4.6(b) and 4.6(c)), the participant selects the target successfully. To select a target with swipe, instead of tapping twice, the participant swipes in a similar direction as the target direction (Figure 4.6(a)). Participants could initiate a double tap or a swipe movement anywhere on the screen. Theoretically, thumb morphology makes it difficult for a user to reach some regions of a screen with one hand, such as corners and places near screen borders. Therefore, to minimize potential confounding effect of the difficulty in moving a thumb toward different areas on the screen, participants were instructed to move their thumb within the area that they felt comfortable.

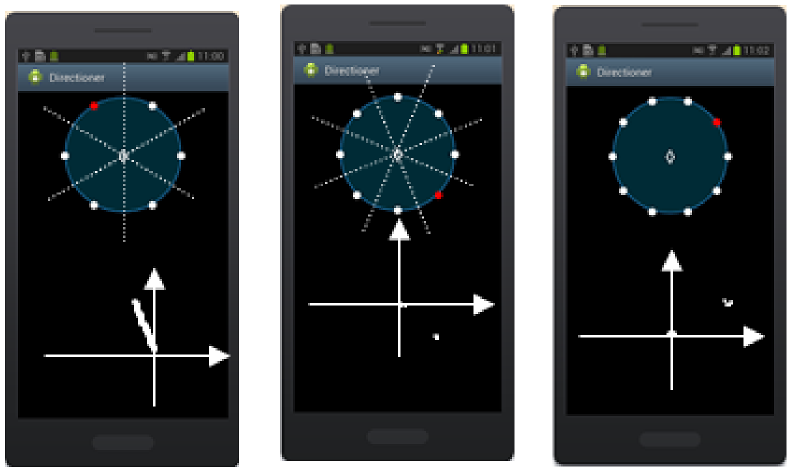


(a) (b)

Figure 4.5 Target Selection Game

(a) A participant clicks the "start" button to start the game; and (b) half a second later, a dot turning into red becomes a target.

This experiment was a 3*2 within-subjects factorial design (three angle intervals between adjacent dots: 60^{o}, 45^{o} and 36^{o} (Figure 4.6), and two target selection methods: double tap and swipe).



(a) (b) (c)

Figure 4.6 Interfaces of the Target Selection Game

(a) participant swiped on the screen to select a target. The angle interval between two adjacent dots was 60°. The direction range of each dot was indicated by the crossing dotted lines; (b) a participant selected a target with double tap. The interval was 45°; and (c) a participant selected a target with double tap. The interval was 36°.

4.4.4 Independent and Dependent Measures

Participants' performance was measured by target selection time and error rate. *Target selection time* refers to the time of a thumb movement taken by double tap or swipe for target selection. For double tap, timing started when a participant touched the screen with the first tap, and ended when the thumb left the screen after the second tap. For swipe, timing started when a participant touched the screen, and ended when the thumb left the screen. *Error rate* is computed as the percentage of incorrect selections. If the direction from a start point to an end point of swiping (or from the first tapped place to the second tapped place of double tap) was in the direction range toward a target, the target would be selected correctly. Otherwise, an error would occur. As shown in Figure 4.6(a) and Figure 4.6(b), with a 60^o angle interval, the direction range is target direction ± 30^o. With a 45^o angle interval, the direction range is target direction ± 22.5^o. Similarly, for a 36^o angle interval, the direction range is target direction ± 18^o.

4.4.5 Procedure

Participants played the target selection game on a Samsung Galaxy Note 2 phone (5.5" HD Super AMOLED (1,280 * 720 pixels) display) with their dominant hand only while sitting in a chair. After clicking the “Start” button (Figure 4.5(a)), one of the dots on the circle that have not been used as a target would be randomly chosen as the current target and become red (Figure 4.5(b)). Participants were required to select the target with double tap or swipe as quickly and accurately as possible. Once it is done, a “Next” button would appear in the position of the previous “Start” button and participants click it to start the next selection task. This procedure was repeated for 10 times under each of the six experimental conditions (three angle intervals * two interaction methods). The order of the six conditions was balanced with a Latin Square design to minimize the learning effect.

4.4.6 Results

1) Target selection time

The means of target selection time (ms) of six conditions are presented in Table 4.1. Repeated measures ANOVA results indicate that target selection time is significantly affected by interaction method ($F (1, 31) = 5.04$, $p < 0.05$), but not by angle interval ($F (2, 62) = 2.07$, $p > 0.05$). There is no significant interaction effect ($F (2, 62) = 0.64$, $p > 0.05$). More specifically, using double tap is significantly slower than using swipe ($p < 0.05$, Figure 4.7).

Table 4.1 Means of Target Selection Time (ms) and Error Rates (%)

Method	N	Interval	Selection time		Error rate	
			Mean	SD	Mean	SD
double tap	32	60º	285.03	69.15	2.81	4.57
double tap	32	45º	283.61	75.16	5.06	7.59
double tap	32	36º	291.56	69.96	19.06	14.45
swipe	32	60º	235.60	79.90	1.88	4.71
swipe	32	45º	248.67	91.64	2.88	5.20
swipe	32	36º	256.83	93.54	15.06	13.13

ANOVA was conducted to assess the difference in target selection time among different directions under each of the six conditions. The difference among all directions of six conditions is not significant ($p > 0.05$). In other words, under all conditions, movement direction does not influence target selection time.

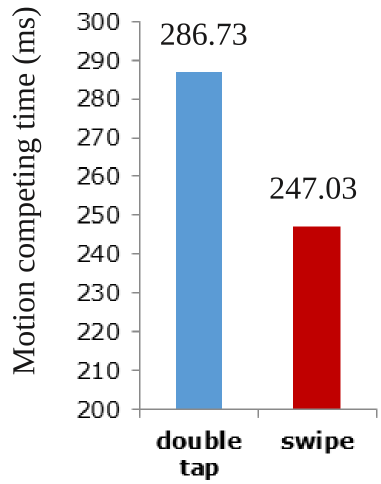


Figure 4.7 Means of Target Selection Time of Double Tap and Swipe

2) Selection Error Rates

The means of target selection error rates of six conditions are presented in Table 4.1. We have conducted repeated measures ANOVA on error rate after Arcsine transformation and found it to be significantly affected by interaction method ($F(1, 31) = 4.7$, $p < 0.05$) and angle interval ($F(2, 62) = 61.12$, $p < 0.001$). The interaction effect of method * angle interval is not significant ($F(2, 62) = 0.10$, $p > 0.05$). The error rate of double tap (Mean = 8.98%, SD = 12.08%) is significantly higher than that of swipe (Mean = 6.60%, SD = 10.42%, $p < 0.05$). The error rate of selecting targets with a 36^o angle interval (17.06%, SD=13.84%) is significantly higher than that with 45^o (Mean = 3.97%, SD = 6.55%) and 60^o (Mean = 2.34%, SD = 4.63%) intervals ($p < 0.001$), and there is also significant difference between targets with 45^o and 60^o intervals ($p < 0.05$).

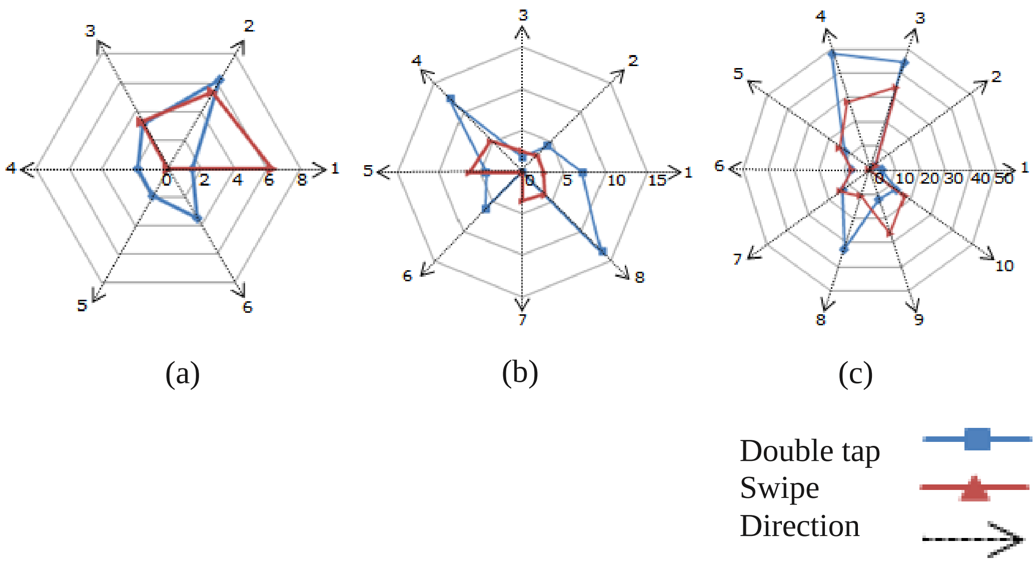


Figure 4.8 Error Rates in Different Directions

For targets separated with a 60° interval (Figure 4.8(a)), the error rates of double tap and swipe in all six directions are less than 6.30%, which means that users could perform both double tap and swipe relatively accurately in all six directions. For targets separated with a 45° interval (Figure 4.8(b)), the error rates of swipe in all eight directions are less than 6.30%. It indicates that users can still swipe relatively accurately in all eight directions. However, for double tap, the error rates of two directions, namely 4 and 8, are 12.24% and 13.51% respectively; and for targets separated with a 36° interval (Figure 4.8(c)), the error rates of seven directions (3, 4, 5, 7, 8, 9 and 10) are higher than 10% for both double tap and swipe, especially in directions 3 and 4. The error rates of both methods are less than 7.50% only in directions 1, 2 and 6.

4.4.7 Discussion

According to the results of the experiment, swipe is significantly faster and more accurate than double tap when using a thumb in single-handed interaction. It may be because swipe is a continuous and fluid motion, while double tap requires two touching and lifting actions, which causes an extra step and increases cognitive effort. The direction angle interval influences thumb movement accuracy, and directions with a 36^{o} interval are the most error-prone for swipe and double tap. Directions with a 45^{o} interval are more error-prone than directions with a 60^{o} interval.

The results of comparing target selection time and error rates under each of the six conditions indicate that although the movement direction is not a factor influencing how quickly users can perform double tap or swipe in the areas that are comfortable for a thumb, they have impact on the accuracy of double tap and swipe. Users perform double tap and swipe in six directions most accurately with a 60^{o} interval. The accuracies of eight directions with a 45^{o} interval for double tap and swipe are acceptable except two directions for double tap, namely "outward" (direction 4 in Figure 4.8(b)) and "inward" (direction 8 in Figure 4.8(b)) which have error rates higher than 10%. According to this finding, gesture-based interfaces based on swipe should be designed with no less than a 45^{o} interval for a direction range. In addition, double tap and swipe with less than or equal to a 36^{o} interval could be difficult and error prone, thus should be avoided.

The results of this study suggest the following guidelines to optimize the design of direction-based interaction methods for touch-screen mobile phones. First, single-handed swipe should be preferred over double tap for single-handed mobile interaction. Second, users can swipe well in directions with an angle interval no less than 45^{o}. For double tap, a 60^{o} interval is a safe choice, while 36^{o} will be challenging for both double tap and swipe. Practitioners, such as game designers, should take the angle interval factor into consideration. Third, the thumb movement direction influences the accuracy of target selection. Directions should be considered in the design of interaction methods and interactive interfaces.

4.5 Evaluation of ThumbStroke

A controlled laboratory experiment with a 3*2 (3 keyboards * 2 phones) within-subject design was conducted to evaluate ThumbStroke, with the Escape keyboard (Banovic et al., 2013), and the QWERTY keyboard used as the baseline methods. With Escape (figure 4.9(a)), users can enter the letter in the center of a flower by tapping on one of the areas. For the letters in the petals, users need to reach to the area and flip to the corresponding directions. The Escape keyboard was selected because it was also designed to support both single-handed and sight-free text entry, which was the same as ThumbStroke. The QWERTY keyboard was chosen because it was the most commonly used keyboard on mobile phones for users with or without visual impairments. Screen size may influence users' single-handed interaction with mobile phones. First, a big screen increases the difficulty to grasp the phone with one hand.

Second, a big screen provides more space for interaction; however, there are more areas that are out of reach for a thumb. Hence, to evaluate the potential moderating effect of mobile devices screen size on single-handed text entry, two phones with different screen sizes were used in this study.

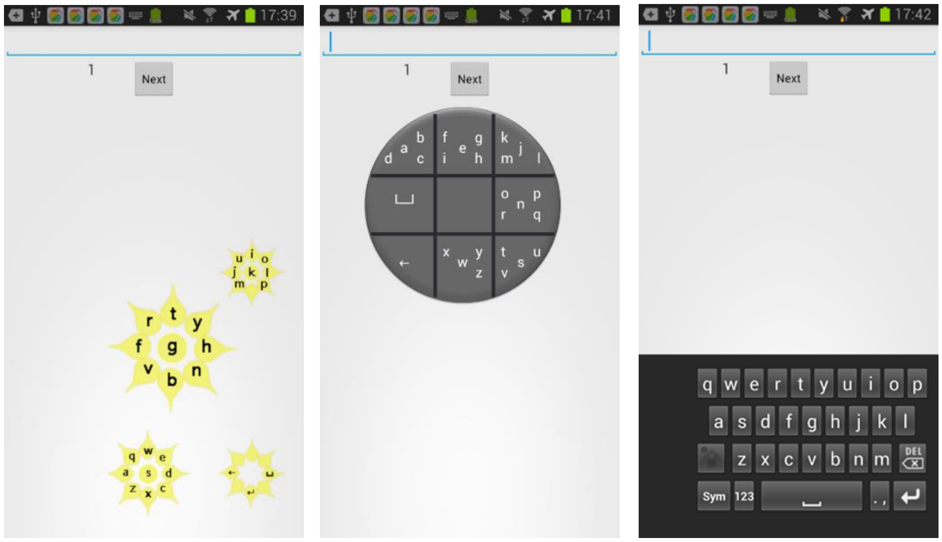
4.5.1 Participants

13 participants (5 male, 8 female) at an east-coast university in the United States participated in the study. They were undergraduate and graduate students with a major in information systems. Among them, 5 were between 18 and 25 years old; 7 were between 26 and 30 years old; and 1 were over 30 years old. They were all right-handed and had prior experience with touch-screen mobile phones. The participants had an average hand length of 17.2cm (SD = 0.9), thumb length of 6.5cm (SD = 0.6) and handbreadth of 9.5cm (SD = 0.7). Each participant received $200 for successfully completing all 20 sessions of experiments.

4.5.2 Apparatus

The ThumbStroke, Escape, and QWERTY keyboards were implemented in Java using the Android SDK in Eclipse for user evaluation. They were installed on two touch-screen phones. One was a Samsung Galaxy Note 2 phone with a 5.5” HD Super AMOLED display. The other one was a Kyocera Event phone with a 3.5" capacitive touch screen. When a participant interacted with those phones, system logs in the mobile phones recorded the time and pixel coordinates of the interactions.

By following the guideline provided by (Banovic et al., 2013), we anchored Escape in the bottom-right corner of the Galaxy Note 2 phone without scaling as shown in Figure 4.9 (a). With the Galaxy Note 2 phone, the single-handed operation mode can be enabled when necessary. In the single-handed operation mode, a keybard is placed align the left/right of the screen for left-handed/right-handed users to make it easier for them to use it with only one hand. We adoptted this single-handed operation mode by aligning QWERTY to the right side of the screen during the formal study (Figure 4.9 (c)), because all participants were right-handed. This arrangement was make because, in a pilot study with 31 participants, six of them reported it was extremly difficult for them to reach the keys that were far away from their thumb, and three participants were not able to finish the pilot study due to the fact that they could not reach the far keys with their thumbs using the Galaxy Note 2 phone. For the Kyocera Event phone, which had a small screen, Escape and QWERTY were aligned to both the left and the right sides of the screen. ThumbStroke was presented in the center of the screen by default for both phones (Figure 4.9 (b)), and users could adjust the position as they liked. The characters were arranged in alphabetical order to make it easier for participants to remember their locations.



(a) Escape **(b) ThumbStroke** **(c) QWERTY**

Figure 4.9 Keyboard Layouts

4.5.3 Independent and Dependent Measures

The independent variables are keyboard, phone and session.

Dependent variables include participants' text entry performance and perception.

Participants' performance of tasks was assessed by typing speed and error rates:

1) Words per Minute (WPM)

WPM measures typing speed. Here a "word" is defined as five characters, which is the average number of characters in a word, including spaces (Millet, 2009; Wobbrock, 2007). It is calculated as the following:

$$WPM = (|T|-1)/S *60/5$$

Where T is a final transcribed string entered by a participant, which may contain letters, numbers, punctuation marks, spaces, and other printable characters, but not backspaces. $|T|$ is the length of the string. S is the time measured in seconds between the entry of the first character and the entry of the last character of an text input. ‘60’ refers to 60 seconds per minute, and ‘5’ means each word contains 5 characters (Millet, 2009; Wobbrock, 2007).

2) Error Rate

Keystrokes are categorized into 4 groups based on Soukoeff and MacKenzis’ error metrics (Soukoreff & MacKenzie, 2003): Correct (C), Incorrect but Fixed (IF), Incorrect and Not Fixed (INF), and Fixed (F) keystrokes (e.g., backspace). IF means users enter wrong characters, but they delete them. INF means the errors are not fixed and appear in the final transcript. Corrected error rate (CER) and uncorrected error rate (UER) are calculated base on those four groups of keystrokes.

CER refers to the percentage of errors that users commit and then correct during a text entry process, which is calculated as IF/(C+INF+IF). Corrected errors are not reflected in the final text, yet this measure is still an important aspect of the accuracy of text entry (Soukoreff & MacKenzie, 2004). UER is the percentage of errors that are not corrected (Millet, 2009), which is calculated as INF/(C+INF+IF). Total Error Rate is the sum of CER and UER (Millet, 2009).

Table 4.2 Questions Related to User Perception Factors

Factors	Items (1 representing "Totally Disagree" and 7 representing "Totally Agree", with 4 being "Neutral")
Perceived Ease of Use	Overall, I am satisfied with how easy it is to use this keyboard. It was simple to use this keyboard. It was easy to learn to use this keyboard. I felt comfortable using this keyboard.
Perceived Effectiveness	I could effectively complete the tasks using this keyboard. I was able to complete the tasks quickly using this keyboard. I was able to efficiently complete the tasks using this keyboard. I believe I could become productive quickly using this keyboard.
Overall satisfaction	Overall, I am satisfied with this keyboard.

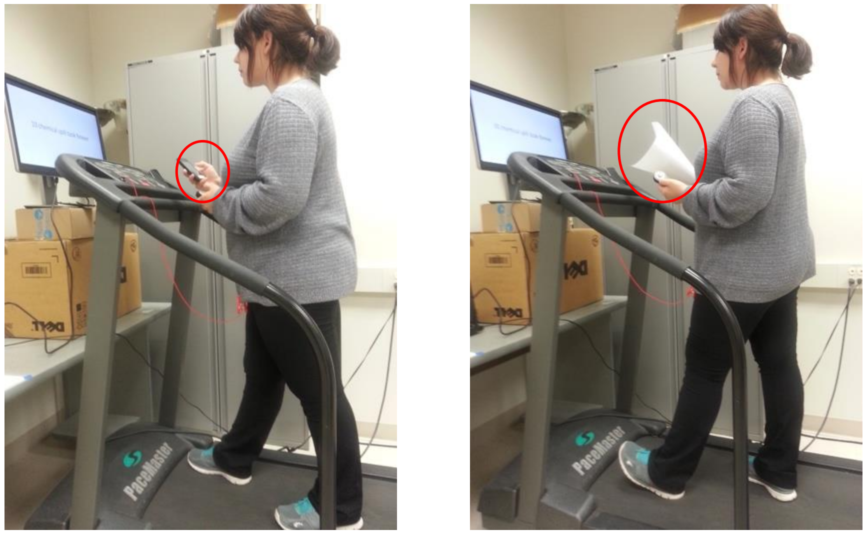
Participants' perceptions of two keyboards were assessed through post-study questionnaires at the end of the first and the last sessions in both the sighted and sight-free conditions. Perceived Ease of Use, Perceived Effectiveness, and Overall Satisfaction of participants were assessed through eight 7-point Likert scale questions (Table 4.2). Those questions were adapted from the IBM Post-Study System Usability Questionnaire (Lewis, 1995) and were modified and grouped into three factors.

4.5.4 Experiment Design

We asked participants to enter short phrases presented on a desktop monitor in front of the participant as fast and accurately as possible using ThumbStroke, Escape and QWERTY (Figure 4.10). The phrase set was adopted from (MacKenzie & Soukoreff, 2003), including 500 phrases (Appendix 8), which varied from 16 to 43 characters (mean = 28.61). Symbols and numbers were not included in the phrases.

Since there is learning curve for new keyboards, each participant completed 20 sessions in total in this study. During the first 10 sessions, participants were allowed to see the screen of the phones (Figure 4.10 (a), referred as sighted condition hereafter). In the last 10 sessions, the screens were blocked with a paper cone attached to participants' wrists with medical tapes (Figure 4.10 (b), referred as sight-free condition hereafter). In the sight-free condition, audio feedback is provided the same as VoiceOver and TalkBack do, which are the two most popular techniques on mobile phones for sight-free text entry of visually impaired people on iOS and Android products: whenever a character is selected, the character will be read out to provide feedback to participants. Similar audio feedback is also used by No-Look Notes (Bonner et al., 2010).

Depending on participants' availability, any two consecutive sessions were scheduled at a 2-72 hour interval, and participants were not allowed to complete more than three sessions within one day (Banovic et al., 2013).



(a) Sighted Condition **(b) Sight-Free Condition**

Figure 4.10 The Experiment Setup

Phrases were randomly picked and grouped into sets of 10 phrases, with no repeating phrases within an experiment session. During each session, participants entered one set of phrases with each keyboard and a total of 60 phrases for each session (2 phones * 3 keyboards * 10 phrases). The order of keyboards, mobile phones, and phrase sets were all balanced out. Since different keyboards usually apply different auto-correction and word prediction algorithms, auto-correction and word prediction were disabled for all conditions to minimize possible confounding effects.

It is quite common that users interact with phones with only one hand during situational impairment (Korhonen et al., 2007). To simulate situational impairment and the mobility of users in the real world, the participants entered phrases while walking on a treadmill (Figure 4.10). By following a previous study (Bergstrom-Lehtovirta et al., 2011), the moving speed of the treadmill was set by participants according to their normal walking speed when interacting with a touch-screen device. The mean of participants' walking speed was 2.0 km/h (SD = 0.7 km/h). In order to ensure single-handed interaction, participants were required to hold a phone and interact with it using their dominant hand only, while holding a remote controller in the other hand to click so that the next phrase would be presented on the screen after they finished the current phrase.

4.5.5 Procedure

After signing a consent form, participants went through a 15-minute training prior to the first session to get familiar with the ThumbStroke, Escape, and QWERTY keyboards. The participants were explained how the three keyboards worked, and practiced with several sample sentences similar to the sentences used in the formal experimental tasks using those keyboards. After participants were comfortable with them, the experiment would start. Participants finished session 1-10 in the sighted condition without audio feedback, and completed session 11-20 in the sight-free condition with audio feedback. Before the first session in the sight-free condition (session 11), participants had a 15-minute training with the audio feedback on the three keyboards. Participants practiced with several sample sentences similar to the sentences used in the formal experimental tasks using the three keyboards with audio feedback. At the end of the first and last sessions in both sighted and sight-free conditions, participants filled out questionnaires about user perceptions.

4.5.6 Results

StreamAnalyzer (Wobbrock & Myers, 2006) was used to analyze text entry data collected during the study. We modified the metrics of *NotCorrectedErroRate* and *CorrectedErrorRate* of StreamAnalyzer to calculate UER and CER. Repeated measures ANOVA was applied to evaluate the effects of keyboards, phones, and sessions on WPM, UER, CER, and user perceptions results. Greenhouse-Geisser correction was used when data failed the test for sphericity.

1) Typing Speed

The means of WPM of three keyboards and two phones across 10 sessions in the sighted condition are presented in Figure 4.11. The main effects of keyboard ($F(2, 24) = 188.77$, $p < 0.001$) and session ($F(2.98, 35.76) = 39.44$, $p < 0.001$) are significant. The main effect of phone ($F(1, 12) = 2.32$, $p > 0.05$) is not significant. There is no significant interaction effect between any two factors or among the three factors ($p > 0.05$). QWERTY is significantly faster than ThumbStroke (mean difference = 12.56, $p < 0.001$) and Escape (mean difference = 11.40, $p < 0.001$). There is no significant difference between ThumbStroke and Escape ($p > 0.05$). In the first sighted session (session 1), the average means of ThumbStroke, Escape, QWERTY are 4.95 (SD = 0.97), 6.00 (SD = 1.97) and 17.49 (SD = 3.51) respectively. In the last sighted session (session 10), the average means of ThumbStroke, Escape, QWERTY are 9.73 (SD = 1.47), 11.17 (SD = 2.34) and 21.00 (SD = 4.46) respectively.

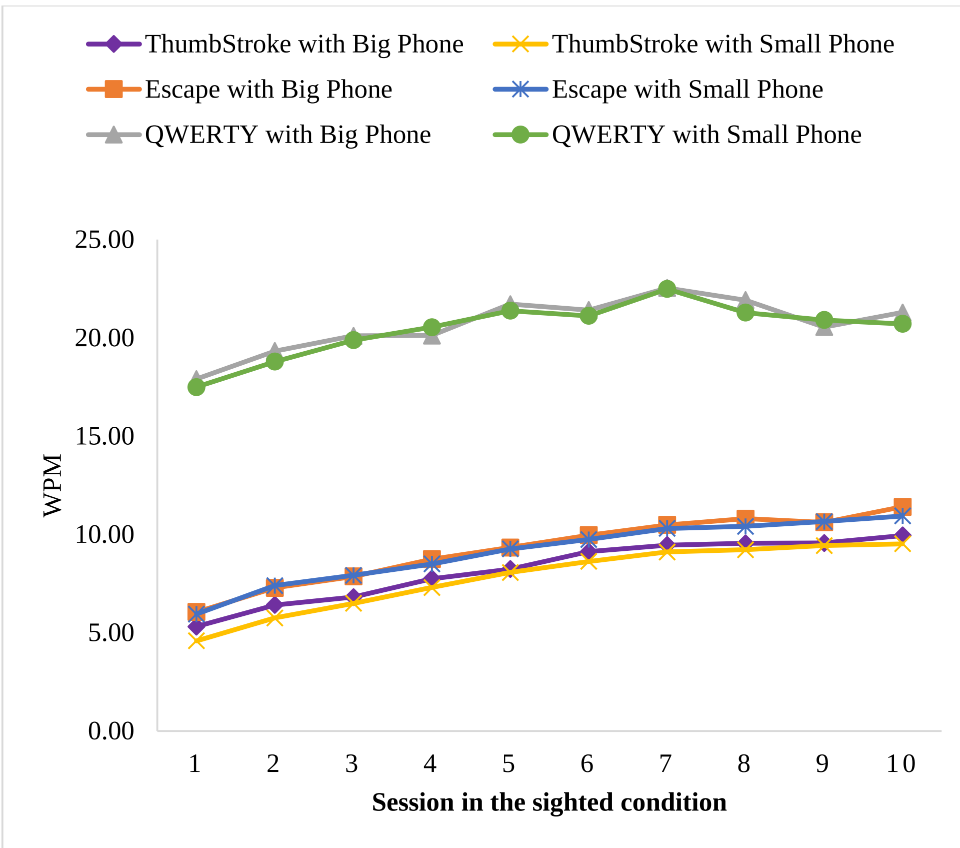


Figure 4.11 Means of WPM in the Sighted Condition

The means of WPM of three keyboards and two phones across 10 sessions in the sight-free condition are presented in Figure 4.12. The main effects of keyboard ($F(1.38, 16.59) = 7.07$, $p < 0.01$), session ($F(3.18, 38.15) = 40.90$, $p < 0.001$), and phone ($F(1, 12) = 7.48$, $p < 0.05$) are significant. The interaction effect between keyboard and phone is significant ($F(2, 24) = 5.00$, $p < 0.05$). There is no significant interaction effect between keyboard and session, phone and session, or among the three factors ($p > 0.05$). ThumbStroke (mean difference = 1.91, $p < 0.05$) and Escape (mean difference = 1.56, $p < 0.05$) are significantly faster than QWERTY. There is no significant difference between ThumbStroke and Escape ($p > 0.05$). The overall WPM of the big phone is also significantly larger than that of the small phone (mean difference = 0.31 $p < 0.05$).

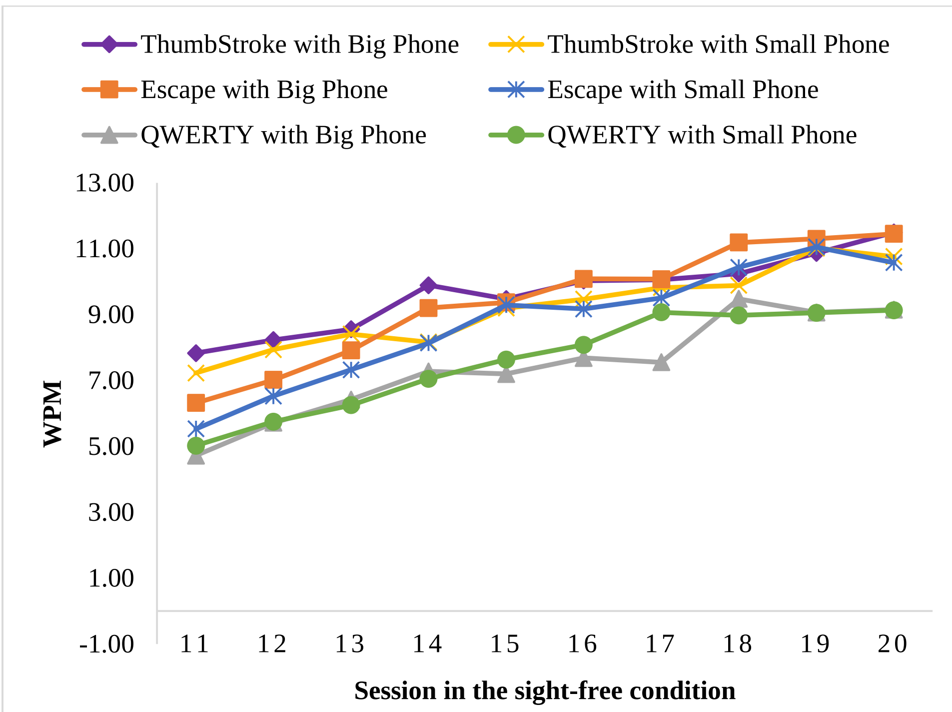


Figure 4.12 Means of WPM of in the Sight-Free Condition

In the first sight-free session (session 11), the average means of ThumbStroke, Escape, QWERTY with the big phones are 7.83 (SD = 2.04), 6.32 (SD = 1.57) and

4.72 (SD = 1.66) respectively, and those with the small phone are 7.23 (SD = 2.19), 5.53 (SD = 1.09) and 5.02 (SD = 1.97). In the last sight-free session (session 20), the average means of ThumbStroke, Escape, QWERTY are 10.50 (SD = 1.30), 11.45 (SD = 1.48), and 9.15 (SD = 3.13) with the big phone, and 10.76 (SD = 1.65), 10.57 (SD = 1.81), and 9.13 (SD = 2.66) with the small phone respectively.

2) Error Rate

UER

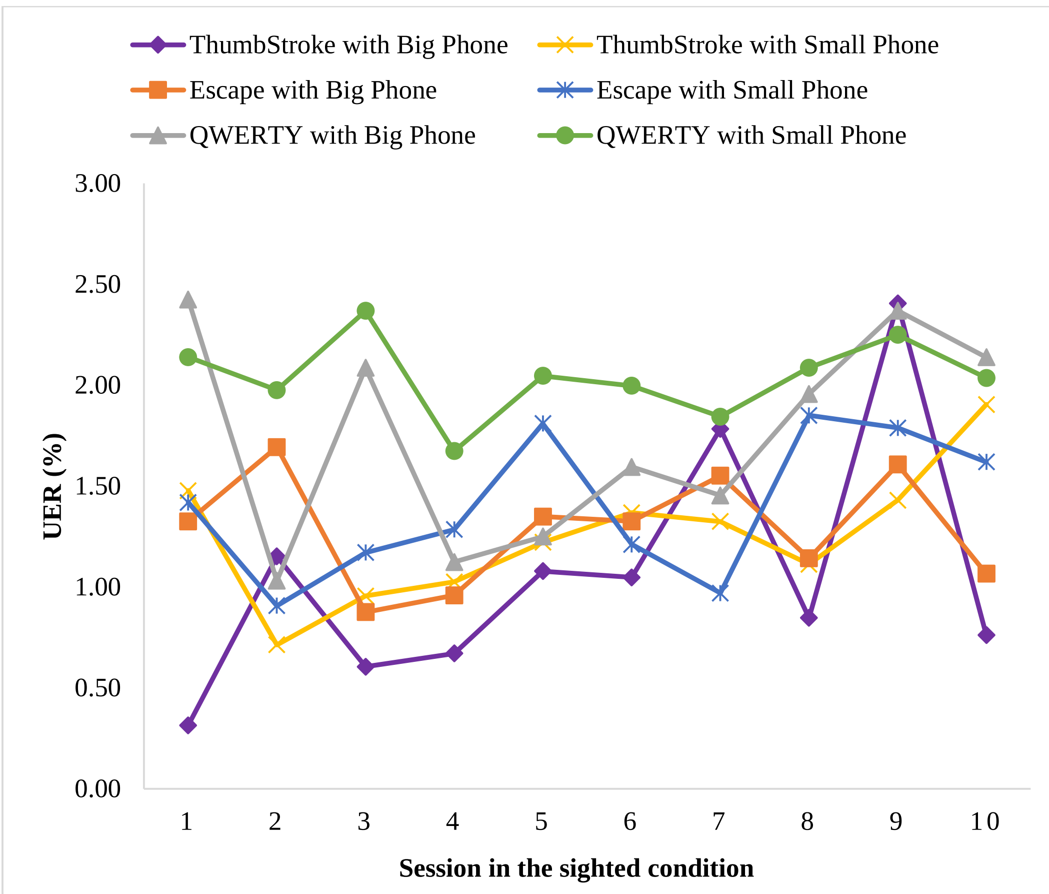


Figure 4.13 Means of UER in the Sighted Condition

For UER, the means of three keyboards and two phones across 10 sessions in the sighted condition are presented in Figure 4.13. The main effects of keyboard ($F(2, 24) = 4.57$, $p < 0.05$) and phone ($F(1, 12) = 8.30$, $p < 0.05$) are significant. The main effect of session is not significant ($F(3.02, 36.23) = 1.09$, $p > 0.05$). There is no significant interaction effect between or among independent factors ($p > 0.05$). ThumbStroke has significantly lower UER than QWERTY (mean difference = - 0.73, $p < 0.05$). There is no significant difference between ThumbStroke and Escape or QWERTY and Escape ($p > 0.05$). The UER while typing with the big phone is significantly lower than that of the small phone (mean difference = -2.00, $p < 0.05$).

For UER, the means of three keyboards and two phones across 10 sessions in the sight-free condition are presented in Figure 4.14. The main effects of keyboard ($F(2, 24) = 7.70$, $p < 0.05$) and session ($F(1.77, 21.18) = 4.88$, $p < 0.05$) are significant. The main effect of phone is insignificant ($F(1, 12) = 0.72$, $p > 0.05$). There is no significant interaction effect between or among independent factors ($p > 0.05$).

ThumbStroke has significantly lower UER than Escape (mean difference = - 3.17, $p < 0.05$) and QWERTY (mean difference = - 5.02, $p < 0.05$). There is no significant difference between QWERTY and Escape ($p > 0.05$). In the first session (session 11) of the sight-free condition, the UER of ThumbStroke, Escape, and QWERTY are 1.80 (1.88), 5.08 (SD = 4.56), and 8.43(SD = 8.34) respectively. In the last session

(session 20) of the sight-free condition, the UER of ThumbStroke, Escape, and QWERTY are 1.30 (1.06), 3.75 (SD = 4.28), 4.26(SD = 3.22) respectively.

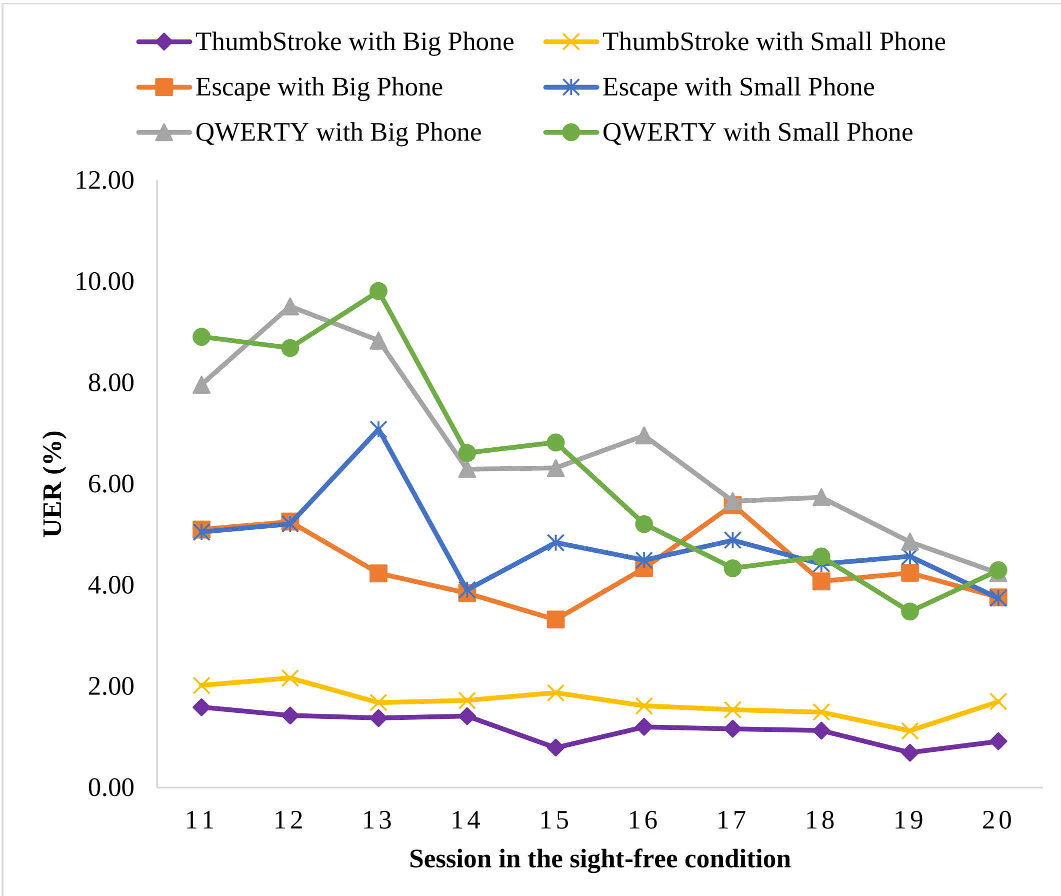


Figure 4.14 Means of UER in the Sight-Free Condition

CER

The means of CER of three keyboards and two phones across 10 sessions in the sighted condition are presented in Figure 4.15. The main effect of keyboard ($F (1.13, 13.55) = 9.15$, $p < 0.01$), and session ($F (2.93, 35.13) = 3.71$, $p < 0.05$) are significant.

The main effect of phone is not significant (F (1, 12) = 7.21, p > 0.05). There is no significant interaction effect between or among independent factors (p > 0.05).

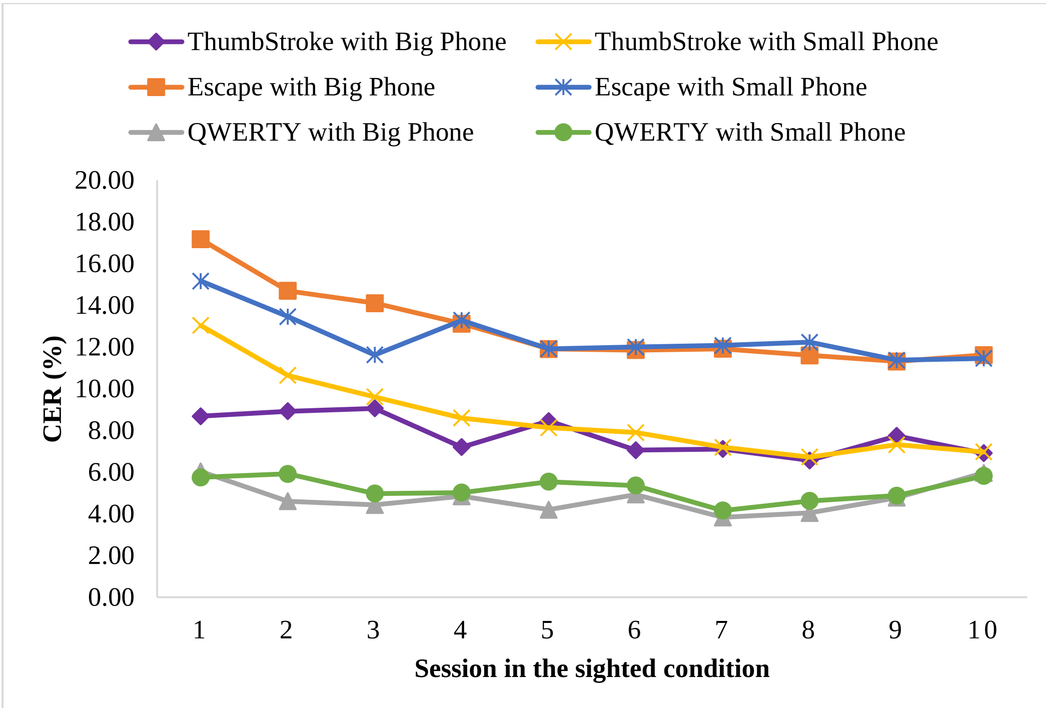


Figure 4.15 Means of CER in the Sighted Condition

ThumbStroke and QWERTY have significantly lower CER than Escape (ThumbStroke: mean difference = - 4.50, p < 0.05; QWERTY: mean difference = - 7.71, p < 0.05). There is no significant difference between ThumbStroke and QWERTY (p > 0.05). In the first session (session 1) of the sighted condition, the CER of ThumbStroke, Escape, and QWERTY are 10.87 (SD = 5.80), 16.17 (SD = 9.60), and 5.90 (SD = 2.62) respectively. In the last session (session 10) of the sighted condition, the CER of ThumbStroke, Escape, and QWERTY are 6.94 (SD = 2.96), 11.54 (SD = 9.22), and 5.89 (SD = 4.11) respectively.

The means of CER of three keyboards and two phones across 10 sessions in the sight-free condition are presented in Figure 4.16. The main effect of keyboard ($F(2, 22) = 3.69$, $p < 0.05$), and session ($F(2.58, 28.35) = 7.97$, $p < 0.01$) are significant. The main effect of phone is not significant ($F(1, 11) = 4.67$, $p > 0.05$). The interaction effect between keyboard and size is significant ($F(2, 22) = 5.25$, $p < 0.05$). There is no significant interaction effect between keyboard and session or phone and session or among all three factors ($p > 0.05$).

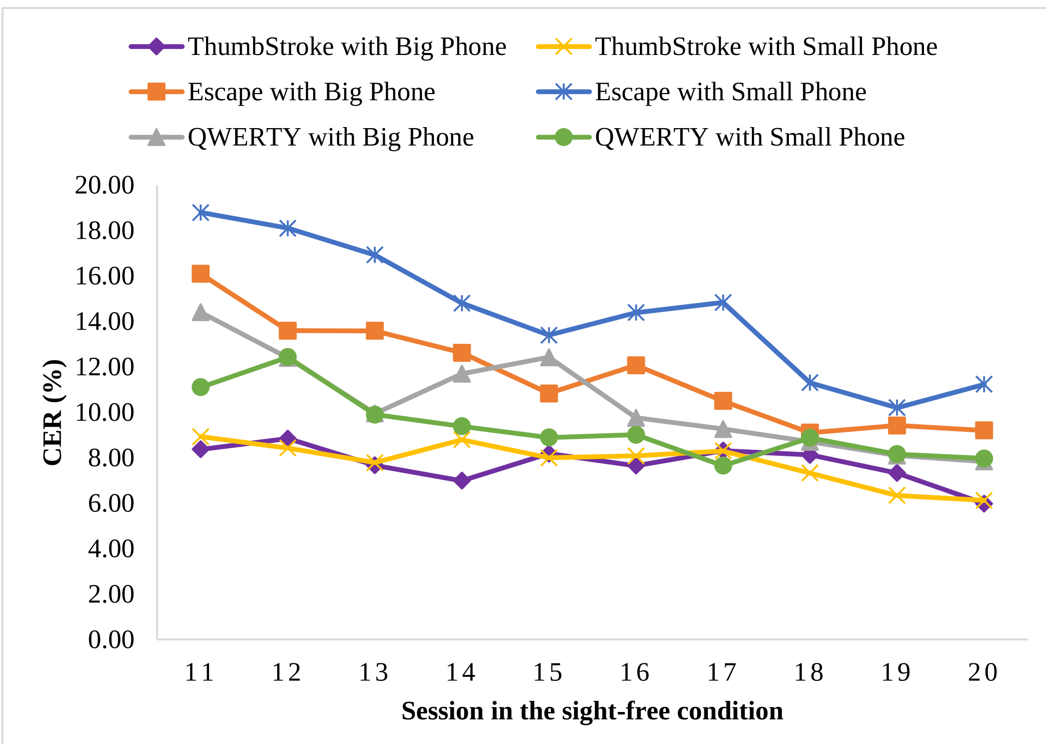


Figure 4.16 Means of CER in the Sight-Free Condition

ThumbStroke has significantly lower CER than Escape (mean difference = - 5.27, $p < 0.05$). There is no significant difference between ThumbStroke and QWERTY or Escape and QWERTY ($p > 0.05$).

In the first session (session 11) of the sight-free condition, the CER of ThumbStroke, Escape, and QWERTY are 8.65 (SD = 3.63), 17.44 (SD = 5.11), and 12.76 (SD = 8.48) respectively. In the last session (session 20) of the sight-free condition, the CER of ThumbStroke, Escape, and QWERTY are 6.05 (SD = 2.87), 10.22 (SD = 3.44), and 7.90 (SD = 10.18) respectively.

Total Error Rate

The means of Total Error Rate of three keyboards and two phones across 10 sessions in the sighted condition are presented in Figure 4.17. The main effects of keyboard ($F(1.19, 14.31) = 8.97$, $p < 0.01$) and session ($F(3.18, 38.21) = 3.14$, $p < 0.05$) are significant. The main effect of phone is not significant ($F(1, 12) = 2.57$, $p > 0.05$). The interaction effect between keyboard and phone is significant ($F(2, 22) = 5.92$, $p < 0.05$). There is no significant interaction effect between keyboard and session, phone and session, or among three independent variables ($p > 0.05$).

QWERTY has significantly lower Total Error Rate than the other two keyboards (ThumbStroke: mean difference = -2.48, $p < 0.05$; Escape: mean difference = -7.16, $p < 0.05$). There is no significant difference between ThumbStroke and Escape ($p >$

0.05). In the first session (session 1) of the sighted condition, the Total Error Rate of ThumbStroke, Escape, and QWERTY are 11.76 (SD = 5.76), 17.54 (SD = 8.46), and 8.18 (SD = 3.75) respectively. In the last session (session 10) of the sighted condition, the Total Error Rate of ThumbStroke, Escape, and QWERTY are 8.28 (SD = 3.65), 12.89 (SD = 9.69), and 7.98 (SD = 4.02) respectively.

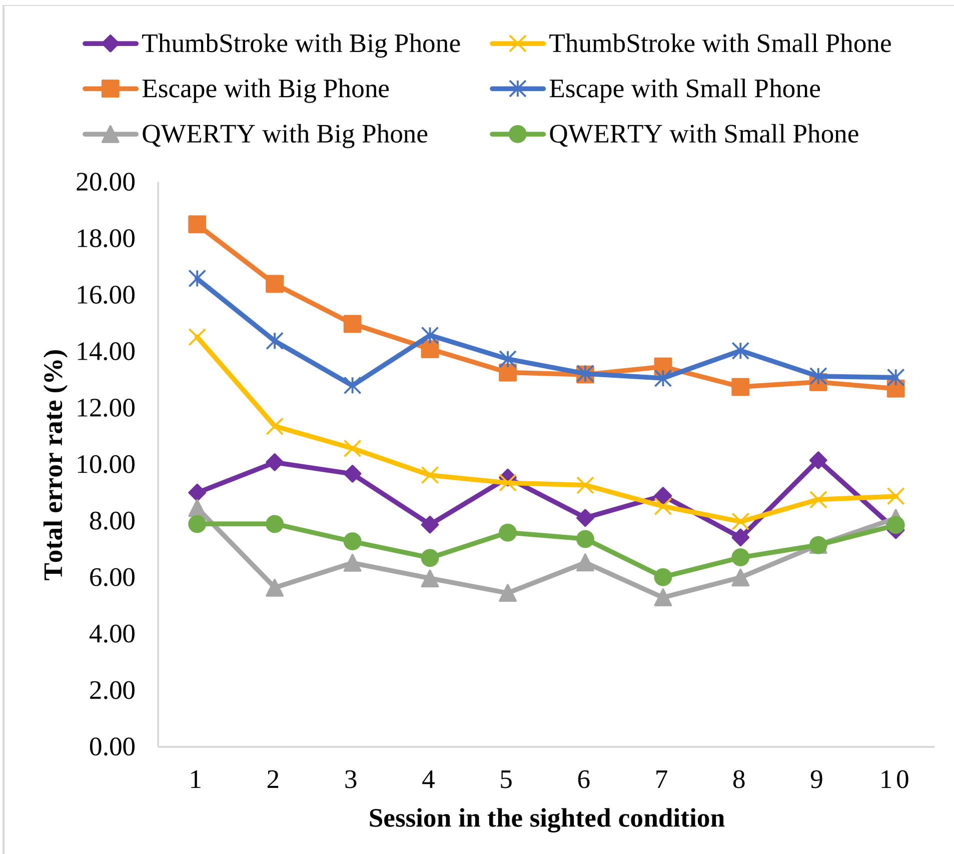


Figure 4.17 Means of Total Error Rate in the Sight-Free Condition

The means of Total Error Rate of three keyboards and two phones across 10 sessions in the sight-free condition are presented in Figure 4.18. The main effect of keyboard

(F (2, 22) = 8.70, $p < 0.05$), phone (F (1, 11) = 5.32, $p < 0.05$) and session (F (2.29, 25.17) = 13.21, $p < 0.001$) are significant. The interaction effect between keyboard and phone is significant (F (2, 22) = 5.92, $p < 0.05$). There is no significant interaction effect between keyboard and session or session and phone ($p > 0.05$).

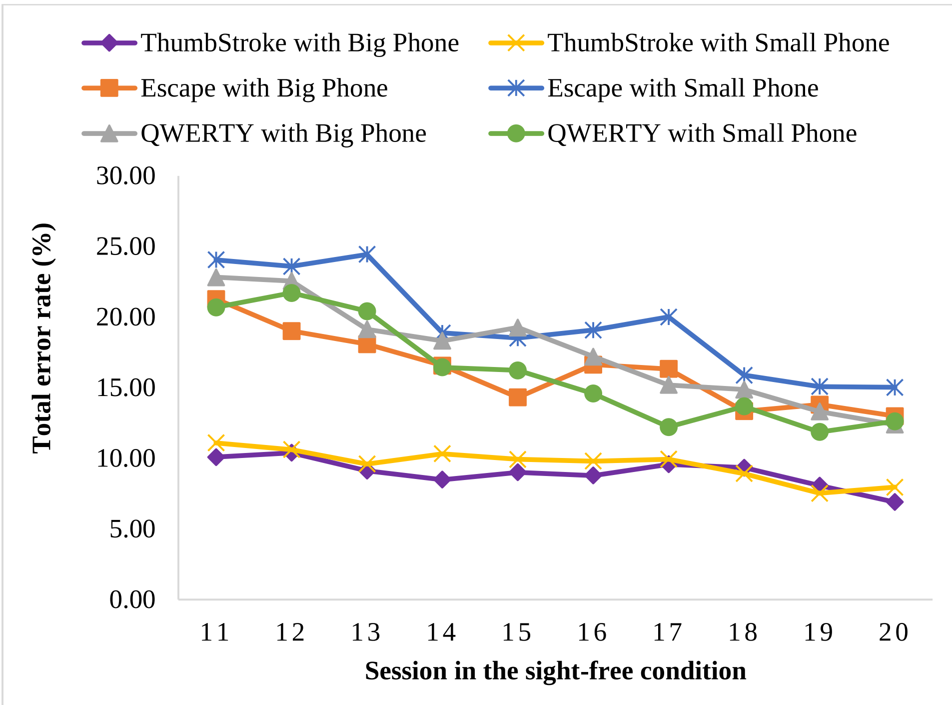


Figure 4.18 Means of Total Error Rate in the Sight-Free Condition

ThumbStroke has significantly lower Total Error Rate than the other two keyboards (QWERTY: mean difference = -8.57, $p < 0.05$; Escape: mean difference = -7.50, $p < 0.05$). There is no significant difference between QWERTY and Escape ($p > 0.05$). The Total Error Rate with the big phone is significantly lower than that with the small phone (mean difference: -0.78, $p < 0.05$).

In the first session (session 11) of the sight-free condition, the Total Error Rate of ThumbStroke, Escape, and QWERTY are 10.60 (SD = 4.00), 22.66 (SD = 7.67), and 21.75 (SD = 8.48) respectively. In the last session (session 20) of the sight-free condition, the Total Error Rate of ThumbStroke, Escape, and QWERTY are 7.44 (SD = 2.67), 14.01 (SD = 5.99), and 12.50 (SD = 9.27) respectively.

3) User Perception

The Cronbach's Alphas for Perceived Ease of Use and Perceived Effectiveness constructs are 0.92, and 0.96 respectively.

Table 4.3 Means of User Perception Factors in the Sighted Condition

Factors	**Session**	**Escape**		**ThumbStroke**		**QWERTY**	
		Mean	SD	Mean	SD	Mean	SD
Perceived Ease of Use	First Session	4.83	0.96	5.25	0.74	6.08	1.46
	Last Session	5.27	1.35	5.98	1.06	6.04	0.55
Perceived Effectiveness	First Session	4.54	1.15	5.04	1.18	6.13	1.58
	Last Session	5.15	1.37	5.73	1.10	6.02	0.65
Overall Satisfaction	First Session	4.62	1.39	5.38	1.39	6.08	1.61
	Last Session	5.15	1.21	6.00	1.15	6.08	0.64

The means of user perception factors in the sighted condition are presented in table 4.3. The main effect of keyboard on Perceived Ease of Use is significant ($F(2, 24) = 6.28$, $p < 0.05$), while that of session is not ($F(1, 12) = 2.30$, $p > 0.05$). The interaction effect between them is also insignificant ($F(2, 24) = 1.70$, $p > 0.05$). QWERTY receives significantly higher score on Perceived Ease of Use than Escape (mean difference = 1.01, $p < 0.05$). There is no significant difference between QWERTY and ThumbStroke or Escape and ThumbStroke.

The main effect of keyboard on Perceived Effectiveness in the sighted condition is significant ($F(2, 24) = 8.22$, $p < 0.05$), while that of session is not ($F(1, 12) = 1.92$, $p > 0.05$). The interaction effect between the two factors is not significant ($F(2, 24) = 1.57$, $p > 0.05$). The mean of QWERTY is significantly higher than that of Escape (mean difference = 1.23, $p < 0.05$). There is no significant difference between QWERTY and ThumbStroke or Escape and ThumbStroke ($p > 0.05$).

The main effect of keyboard on Overall Satisfaction in the sighted condition is significant ($F(2, 24) = 7.20$, $p < 0.05$), while that of session is not ($F(1, 12) = 1.55$, $p > 0.05$). The interaction effect between the two factors is not significant ($F(2, 24) = 0.74$, $p > 0.05$). The mean of QWERTY is significantly higher than that of Escape (mean difference = 1.20, $p < 0.01$). The mean of ThumbStroke is also significantly higher than that of Escape (mean difference = 0.81, $p < 0.05$). There is no significant difference between QWERTY and ThumbStroke ($p > 0.05$).

The means of user perception factors in the sight-free condition are presented in table 4.4. The main effects of keyboard and session on Perceived Ease of Use are significant (keyboard: $F(2, 24) = 24.59$, $p < 0.001$; session: $F(1, 12) = 7.50$, $p < 0.05$). The interaction effect between them is insignificant ($F(1.24, 14.82) = 3.78$, $p > 0.05$). ThumbStroke receives significantly higher score on Perceived Ease of Use than Escape (mean difference = 1.14, $p < 0.05$) and QWERTY (mean difference = 2.37, $p < 0.001$). Escape also has higher score than QWERTY (mean difference = 1.22, $p < 0.05$). During the last sight-free session (session 20), the score of Perceived Ease of Use is significantly higher than that in the first sight-free session (session 11) (mean difference = 0.82, $p < 0.05$).

Table 4.4 Means of User Perception Factors in the Sight-Free Condition

Factors	**Session**	**Escape**		**ThumbStroke**		**QWERTY**	
		Mean	SD	Mean	SD	Mean	SD
Perceived Ease of Use	First Session	4.62	1.37	6.00	0.75	3.08	1.37
	Last Session	5.38	1.09	6.29	0.74	4.48	1.70
Perceived Effectiveness	First Session	4.37	1.39	5.92	0.98	2.75	1.38
	Last Session	5.35	1.24	6.27	0.98	4.19	1.60
Overall Satisfaction	First Session	4.31	1.49	6.00	0.82	2.85	1.52
	Last Session	5.38	1.33	6.31	0.95	4.00	1.53

The main effects of keyboard and session on Perceived Effectiveness are significant (keyboard: $F(2, 24) = 23.25$, $p < 0.001$; session: $F(1, 12) = 6.74$, $p < 0.05$) in the sight-free condition. The interaction effect between the two factors is also significant ($F(2, 24) = 3.92$, $p < 0.05$). ThumbStroke receives significantly higher score on Perceived Ease of Effectiveness than Escape (mean difference = 1.24, $p < 0.05$) and QWERTY (mean difference = 2.63, $p < 0.001$). Escape also has higher score than QWERTY (mean difference = 1.39, $p < 0.05$). During the last sight-free session, the score of Perceived Effectiveness is significantly higher than that in the first sight-free session (mean difference = 0.92, $p < 0.05$).

The main effects of keyboard and session on Overall Satisfaction in the sight-free condition are significant (keyboard: $F(2, 24) = 23.13$, $p < 0.001$; session: $F(1, 12) = 6.01$, $p < 0.05$). The interaction effect between the two factors is not significant ($F(2, 24) = 2.47$, $p > 0.05$).

ThumbStroke receives significantly higher score on Overall Satisfaction than Escape (mean difference = 1.31, $p < 0.05$) and QWERTY (mean difference = 2.73, $p < 0.001$). Escape also has significantly higher score than QWERTY (mean difference = 1.42, $p < 0.05$). During the last sight-free session, the score of Overall Satisfaction is significantly higher than that in the first sight-free session (mean difference = 0.85, $p < 0.05$).

4.6 Discussion

We have designed and developed a stroke-based virtual keyboard called ThumbStroke for single-handed and sight-free text input on mobile handheld devices. Its design is aimed to address the limited thumb accessibility, visual occlusion, and low accuracy problems of single-handed text entry and meanwhile support sight-free text entry on touch-screen mobile devices. Its uniqueness, in comparison to existing studies and keyboards used on mobile devices, lies in the following aspects:

- It enables users to hold and interact with a touch-screen mobile phone with one hand only.
- ThumbStroke does not require precise tapping or clicking as traditional keyboards, such as QWERTY, do. It can be used to support sight-free text entry.
- Existing soft keyboards used on mobile phones may cause the thumb accessibility problem. Text input with ThumbStroke relies on thumb gestures performed anywhere on a device screen rather than physical press on keys. So the thumb accessibility problem is eliminated with ThumbStroke.
- Almost all of the existing soft keyboards are located at the bottom of a touch-screen mobile device. Research has shown that placing a keyboard at the top or middle of display can lead to lower error rates and higher user satisfaction than placing at the bottom of display (Nakagawa & Uwano, 2011). The location of ThumbStroke is flexible and can be moved by users as they like.

- Different from other menu-based keyboards, which often requires users to select a segment and then a character separately. ThumbStroke combines area selection and character selection within one single stroke, which can be more efficient.

4.6.1 Typing Speed

In the sighted condition, QWERTY is still the fastest method among the three, which is not out of our expectation. We think users' familiarity with QWERTY is one major reason that it achieved the highest typing speed. In fact, all the participants reported that they were familiar with the QWERTY keyboard, and used it on a daily base with their mobile phones. In order to make the QWERTY keyboard accessible to participants, we had to shift the keyboard to one side of the screen. Otherwise, some participants would not be able to type with the QWERTY keyboard using one hand because the far keys were out of their reach. As a result, the problem of limited thumb accessibility was not presented in the study. In addition, direct tap on keys are faster than making strokes, which is in line with our finding in the first project.

In the sight-free condition, the typing speed of QWERTY dropped dramatically and outperformed by ThumbStroke and Escape, this is also not out of our expectation since QWERTY requires users to press keys in the predefined area while the other two don't. In the sight-free condition, typing using the big phone was also faster than using the small phone. It could be because when participants typed with

ThumbStroke on the small phone, they had less space to move their thumbs on the screen, which reduced the flexibility of making strokes. The keys on the small phone are smaller than those on the big phone with QWERTY, which may be another reason for the lower typing speed with the small phone. ThumbStroke and Escape achieved similar level of typing speed in both sighted and sight-free condition.

4.6.2 Error Rate

In the sighted condition, ThumbStroke yielded significantly lower UER than QWERTY, we believe it is because QWERTY always required accurate key press, and the keys on a QWERTY keypad were crowded and error-prone. The big phone leaded to lower uncorrected error rate than the small phone. It could be because on the small phone the QWERTY had even smaller keys than on the big phone, which made text entry even more difficult. In the sight-free condition, ThumbStroke was significantly better than both Escape and QWERTY in UER. It may be because QWERTY required accurate press on keys and Escape required participants to reach a segment and then flicked toward a direction, which could be challenging. On the contrary, ThumbStroke does not have those limitations. Participants could do the strokes within the area they feel comfortable on the mobile phone screen. In addition, ThumbStroke provides the opportunities for a participant to cancel a selection of an area or a character immediately after realizing he/she made a mistake. Those features may contribute to the lower UER with ThumbStroke.

ThumbStroke is significantly better than Escape in CER in both the sighted condition and sight-free conditions. The possible reasons could be: 1) ThumbStroke provides error correction function. When a user chooses a wrong character with ThumbStroke, he/she can change the moving direction of the thumb to choose another character in the small area instead of entering the wrong character selected. However, when participants selected the wrong segment with Escape, they were not able to correct the error; 2) a user can cancel the selection if he/she has chosen a wrong small area with ThumbStroke; 3) ThumbStroke allows a user to perform the stroke gestures in the place where he/she feels comfortable; nevertheless, with Escape, a user has to reach to a small area first, and then perform gestures to different directions within the small area, which could increase the task difficulty, especially when participants were walking on a treadmill; and 4) users do not have to reach to the keyboard with ThumbStroke, so that there is no visual occlusion as with Escape. Another possible reason could be that we placed characters in alphabetical order on ThumbStroke, which was easy for participants to remember. Although Escape tried to match the layout of the QWERTY, when the letters were separated into different segments, it was difficult for participants to remember the locations in the sight-free conditions. ThumbStroke and QWERTY achieved similar level of CER in both sighted and sight-free conditions.

For Total Error Rate in the sighted condition, QWERTY had significantly lower number than the other two keyboards. It may be due to participants' familiarity with

QWERTY. However, in the sight-free condition, ThumbStroke has significantly lower Total Error Rate than the other two keyboards. The total error rate with the big phone was also lower than that with the small phone in the sight-free condition. One reason could be that even we shifted the QWERTY keyboard to the right side of the screen on the big phone (Galaxy Note 2), the size of the keys was still bigger than that on the small phone, which could result in lower error rate. The “Back”, “Home” and “Menu” buttons of the small phone are located along the lower border of the screen. Based on our observation during the experiments, those buttons were more likely to be clicked by accident in the sight-free condition, especially while using Escape, which had two segments right above the lower border of the screen. Furthermore, the big phone has more space for participants to drag their thumb with ThumbStroke, which could give them more flexibility.

We did not see significant main effect of phone on WPM, CER and Total Error Rate in the sighted condition, and on UER in the sight-free condition. It could be because we had to align the QWERTY to one side of the screen to make it possible for participants to enter characters, and we also anchored Escape in the bottom-right corner. In other words, the negative effect of phone size was already adjusted to make it possible to use QWERTY and Escape on the big phone.

4.6.3 User Perception

In the sighted condition, QWERTY yielded the highest score on Perceived Ease of Use among three keyboards, and higher score on Perceived Effectiveness and Overall Satisfaction than Escape. We believe it is because all participants were very familiar with QWERTY and used it on a daily base. Moreover, the click-based method to select a character is easier to perform than the stroke-based methods used with ThumbStroke and Escape. Nonetheless, in the sight-free condition, QWERTY was the worst among the three keyboards on Perceived Ease of Use, Perceived Effectiveness, and Overall Satisfaction, while ThumbStroke was the best on all these three aspects.

Chapter 5 : Conclusion and Future Work

In this dissertation, we presented the design, development and evaluation of three techniques, ExtendedThumb, ContextZoom, and ThumbStroke, to improve single-handed target acquisition, zooming and text entry on touch-screen mobile phones. The studies addressed fundamental challenges in single-handed interaction with mobile devices, particularly the limited thumb accessibility, visual occlusion, and fat thumb problems. We also conducted a study to evaluate direction's impact on single-handed thumb interaction. This dissertation makes contributions to not only research but also use of mobile devices.

5.1 Contribution

5.1.1 Contributions to Single-Handed Interaction with Mobile Phones

From a research perspective, this dissertation first, advances knowledge in the field of mobile HCI, particularly those pertinent to single-handed interaction; second, achieves a better understanding of user behaviors and obstacles while interacting with mobile devices with one hand; and third, gain new technical insights for developing better techniques for single-handed interaction through designing, developing, and evaluating the proposed approaches. The dissertation is particularly compelling because of the following intellectual merits:

- Proposing and developing a virtual thumb that can be controlled and manipulated flexibly by a real thumb's movements within an area where users feel comfortable on a touch screen for easy acquisition of otherwise difficult-to-reach targets. In the meantime, it also addresses both the visual occlusion and low precision problems that often perplex many existing methods for single-handed interaction.
- Designing and developing a thumb-based, context-oriented zooming technique that goes beyond the current zooming techniques. Using one thumb, the technique allows a user to specify any location on the screen as the center of zooming, instead of always zooming around the center of a device screen, and allows zooming a portion of the content on the device screen without losing context, such as the locations of other targets.
- Designing and implementing a novel soft keyboard with a round, single-button design that allows a user to select any character for text entry by moving a thumb at any location on the screen, unlike most existing keyboards that require users to physically press on a specific key in order to enter the corresponding character. This design not only supports single-handed text entry, but also sight-free text entry. It may also have the potential to be used on devices with tiny screens, such as smartwatches, since no accurate interaction is required.
- Empirically evaluating the proposed methods to gain a better understanding of users' behaviors and challenges in single-handed interaction and examine the impact of the three techniques on interaction performance, examining

relationships between thumb movement directions and interaction performance with one hand, and developing generic guidelines for the design of thumb-based interaction techniques for mobile devices based on observations and findings of empirical studies.

5.1.2 Practical Guidelines

This dissertation offers a variety of broad impacts. It provides practical guidelines and insights for designers of mobile interfaces (e.g., mobile games) and manufacturers of mobile devices to develop and/or incorporate better techniques to improve the support of mobile devices for single-handed interaction:

1) making direct touch on a target is faster than making strokes with a thumb. However, when a target is far away from the thumb, the accuracy of direct touch is questionable;
2) target size has impact on direct touch accuracy and speed, but it has less influence on indirect target acquisition methods, such as ExtendedThumb;
3) providing context, particularly a fast way to go back to the viewport before zooming, is helpful during zooming interaction;
4) the stroke-based target selection method could be beneficial in both speed and accuracy in sight-free interaction with mobile phones;
5) moving a thumb to left and right is easier than moving it inward or outward; and

6) when using direction-based strokes for single-handed interaction, the angle interval between any two directions should be no less than 45^{o}.

Furthermore, the techniques developed in this research can enable users to acquire difficult-to-reach targets, perform context-oriented partial viewport zooming, and enter text with a thumb, which improve single-handed interaction with mobile devices and helps free one hand for other demands. In addition, the techniques developed in this dissertation can also benefit people with upper-limb loss to interact with mobile devices. ThumbStroke may be also useful for people with visual impairments. According to (Ali, Kuber, & Hurst), it is challenging for a visually impaired user to walk with a cane for orientation and wayfinding, and meanwhile to use a phone. A keyboard that support both single-handed and sight-free text entry may be beneficial for this type of situation.

5.2 Limitations and Future Work

The initiation method of an interaction technique should not hinder users' task performance (Yu et al., 2013). Currently, a double-tap action is temporarily used to initiate ExtendedThumb. Double-tap is quick, but may conflict with other application-specific gestures. We plan to explore the use of bezel gestures in a future study to eliminate the conflict. With bezel gestures, a user first swipes through a bezel of the screen to set the gesture mode, then continues to draw a gesture, and finally releases contact to execute a command (Bragdon, Nelson, Li, & Hinckley, 2011). Bezel gestures, which are used in Bezel Swipe (Roth & Turner, 2009), can be used as a seamless mode switch between direct-touch interaction and a target acquisition technique (Yu et al., 2013).

One limitation of ExtendedThumb is that a fixed 1:2 c-d ratio of moving distance between a real thumb and the virtual thumb was used in this empirical evaluation to minimize confounding effect. In future work, we plan to explore speed-dependent ratios (Chapuis et al., 2009; Igarashi & Hinckley, 2000) for moving the virtual thumb. Another limitation is that in order to control the complexity of the study and minimize the influence of user mobility, we conducted evaluation in a laboratory environment. In the future, it is worth validating the effect of ExtendedThumb in a field study.

There are a few limitations with the ContextZoom study. Currently, a long press gesture is used to initiate the zooming center selection and to activate the zooming mode of ContextZoom. We choose this gesture to make it possible to incorporate it into Google Maps because the zooming center can be considered as a target and Google Maps enables users to choose a target with a long press to drop a pin. However, this initiation method may conflict with other mobile applications. We plan to explore other gestures, such as rubbing (Olwal et al., 2008) and bezel gestures (Bragdon et al., 2011), in a future study.

Second, when a user moves his/her thumb to zoom, he/she has to stop after reaching the furthest point on the screen that his/her thumb can reach. If he/she wants to change the zooming level further, he/she has to perform zooming in the partial viewport. The GMS technique shares a similar problem: after reaching the furthest location that one's thumb can reach, the user has to repeat the double-tap and hold gesture for further zooming, which could be tedious and time consuming. In other words, users cannot move their thumb along one-direction for too far due to the physical constraint of a finger or when it reaches the border of a device screen in single-handed interaction. This is a common problem of direction-based and thumb/finger-stroke based interactions, including panning. In the future, it is worth refining ContextZoom to overcome the limitations of thumb length and screen size.

Third, to simulate situational impairment, the participants in the ContextZoom study finished all the tasks while they were walking on a treadmill and holding a bottle in one hand. Nevertheless, mobile phones can be used in a large variety of contexts, including different motor activities and environmental elements, which may distract users' attention (Zhang & Adipat, 2005). In our future study, we would like to examine ContextZoom when involving participants in other motor activities, such as sitting and standing in different environments.

In addition, in order to control the scope and complexity of the ContextZoom study, we included two existing zooming methods as baselines and one type of zooming task. There are other zooming methods, such as TiltZoom (Ti & Tjondronegoro, 2012) and CycloZoom+ (Malacria et al., 2010), and potential experimental tasks, such as matching a red rectangular search target with a black reference frame in the middle of the screen used in (Spindler, Schuessler, Martsch, & Dachselt, 2014) and pointing tasks used in (Malacria et al., 2010). We plan to validate the findings of this study by deploying different zooming methods and tasks in future research. Although in our study, extending GMS and BB with ContextZoom for partial zooming resulted in reduced task completion time and fewer actions. It is possible that when integrating ContextZoom into another existing zooming method, it may negatively influence the performance of that method due to potential inconsistencies and conflicts. It underlines the importance to minimize the potential conflicts between the design of tools like ContextZoom and an original method that is aimed to be extended.

Sight-free text entry method could be beneficial to visually impaired users (Banovic et al., 2013). In the study of ThumbStroke, we adopted the method used by VoiceOver and TalkBack to provide audio feedback in the sight-free sessions, which were the popular methods on current iOS and Android mobile phones for visually impaired users. We believe ThumbStroke has the potential to be used by this group of people. We plan to evaluate ThumbStroke with visually impaired users in our future study.

Unlike traditional keyboards, such as QWERTY, ThumbStroke is based on stroke directions. As a result, it is key size independent. In addition, different from Escape, which have four segments, ThumbStroke has less restriction on its keypad size. This feature may be useful for devices with limited screen sizes, such as smartwatches. We also plan to evaluate ThumbStroke on a smartwatch in the future.

With ThumbStroke, users are able to drag their thumb wherever on the screen for a length as desired. In other words, users' interaction patterns can be very different even when they enter the same content. The interaction patterns of different users can be used for user authentication. We also plan to investigate into it in our future study.

One limitation of ThumbStroke is that the character arrangement on it does not map to that on a regular QWERTY keyboard. We used the alphabetical order, which was reported to be beneficial for participator to remember the locations. Some other arrangements, such as based on usage frequency, are worth further investigation. In addition, to simulate situational impairments, we asked participants to walk on a treadmill during the study. Due to the limit of the study scope, we were not able to test ThumbStroke in other motor conditions, such as sitting and standing. We would like to evaluate it in different conditions in the future.

Appendices

Appendix 1: Prior-Study Questionnaire of ExtendedThumb Evaluation

Pre-experiment questionnaire

1. Demographic information:

   Age: □ below 20 □ 21-25 □ 26-30 □ 31-35 □ 36-40 □ more than 40

   Gender: □ male □ female

   Education (status)

   □ Undergraduate student

   □ Master student

   □ Ph.D. student

   □ Other (Please specify)______________________

2. Familiarity with mobile handheld devices:

Do you currently own a handheld device (e.g., cell phone, Palm pilot, or Pocket PC)?

□ Yes □ No

Have you ever used a handheld device to perform the following activities within the past year?

a. Browsing Web pages □ Yes □ No

If the answer to the above question is yes, how often do you browse Web pages/sites on your handheld device?

□ Daily □ Weekly □ Monthly □ Once or twice a quarter □ Rarely

b. Browsing a map for finding a location □ Yes □ No

If the answer to above question is yes, how often do you browse maps on your handheld device?

□ Daily □ Weekly □ Monthly □ Once or twice a quarter □ Rarely

3. How often do you use a mobile handheld device for content browsing with two hands?

□ Frequently □ Occasionally □ Rarely □ Never

4. Please describe your experience of using a mobile handheld device to browse or search the Web with two hands. (Please circle only ONE answer for each statement)

Browsing and searching for information on the Web using a handheld device with TWO hands is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly find information I want from Web sites using a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly click an item on a Web page using a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly zoom in/out content on a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

5. How often do you use mobile handheld device with one hand?

□ Frequently □ Occasionally □ Rarely □ Never

6. Please describe your experience of using a mobile handheld device to browse or search the Web with one hand. (Please circle only ONE answer for each statement)

Browsing and searching for information on the Web using a handheld device with ONE hand is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly find information I want from Web sites using a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly click an item on a Web page using a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly zoom in/out content on a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

7. Comparing two-hand and one-hand interactions with mobile phones while browsing Web sites, which one do you prefer? Why?

Appendix 2: Prior-Study Question of ContextZoom Evaluation

1. Demographic information:

    - Age: □ below 20 □ 21-25 □ 26-30 □ 31-35 □ 36-40 □ more than 40
    - Gender: □ male □ female
    - Education (status)

      □ Undergraduate student

      □ Master student

      □ Ph.D. student

      □ Other (Please specify)______________________

2. Familiarity with mobile handheld devices:

- Do you currently own a handheld device (e.g., cell phone, Palm pilot, or Pocket PC)?

  □ Yes □ No

- Have you ever used a handheld device to perform the following activities within the past year?

a. Browsing Web pages □ Yes □ No

If the answer to the above question is yes, how often do you browse Web pages/sites on your handheld device?

□ Daily □ Weekly □ Monthly □ Once or twice a quarter □ Rarely

b. Browsing a map for finding a location □ Yes □ No

If the answer to above question is yes, how often do you browse maps on your handheld device?

□ Daily □ Weekly □ Monthly □ Once or twice a quarter □ Rarely

3. How often do you use a mobile handheld device for content browsing with <u>two hands</u>?

□ Frequently □ Occasionally □ Rarely □ Never

4. Please describe your experience of using a mobile handheld device to browse or search the Web with <u>two hands</u>. (Please circle only ONE answer for each statement)

Browsing and searching for information on the Web using a handheld device with TWO hands is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly find information I want from Web sites using a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly click an item on a Web page using a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly zoom in/out content on a handheld device with TWO hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

5. How often do you use mobile handheld device with <u>one hand</u>?

□ Frequently □ Occasionally □ Rarely □ Never

6. Please describe your experience of using a mobile handheld device to browse or search the Web with <u>one hand</u>. (Please circle only ONE answer for each statement)

Browsing and searching for information on the Web using a handheld device with ONE hand is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly find information I want from Web sites using a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly click an item on a Web page using a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

I can quickly zoom in/out content on a handheld device with ONE hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

7. Comparing two-hand and one-hand interactions with mobile phones while browsing Web sites, which one do you prefer? Why?

8. What difficulties have you come across while interacting with mobile phones with one hand?

1). How often do you use Google maps on mobile phones?

□ Frequently □ Occasionally □ Rarely □ Never

2). How often do you use Google maps on mobile phones with one hand?

□ Frequently □ Occasionally □ Rarely □ Never

3). How often do you use Google maps on mobile phones with two hands?

□ Frequently □ Occasionally □ Rarely □ Never

Thumb Length:

Hand Length:

Hand Width:

Appendix 3: Prior-Study questionnaire of ThumbStroke Evaluation

1. Demographic information:

    - Age: □ below 20 (include) □ 21-25 □ 26-30 □ 31-35 □ 36-40 □ more than 40
    - Gender: □ male □ female
    - Education (status)

      □ Undergraduate student

      □ Master student

      □ Ph.D. student

      □ Other (Please specify)________________________

2. Familiarity with mobile handheld devices:

    - Do you currently own a handheld device (e.g., cell phone, Palm pilot, or Pocket PC)?

      □ Yes □ No

    - Have you ever used a handheld device to perform the following activities within the past 6 months?

a. Browsing Web pages □ Yes □ No

If the answer to the above question is yes, how often do you browse Web pages/sites on your handheld device?

□ Daily □ Weekly □ Monthly □ Rarely

b. Typing □ Yes □ No

If the answer to above question is yes, how often do you type on your handheld device?

□ Daily □ Weekly □ Monthly □ Rarely

3. How often do you type on mobile handheld device with <u>two hands</u>?

□ Frequently □ Occasionally □ Rarely □ Never

4. Please describe your experience of using a mobile handheld device with <u>two hands</u>. (Please circle only ONE answer for each statement)

- Typing using a handheld device with two hands is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly typing on a handheld device with two hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- Typing using a handheld device with two hands is comfortable.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly click on places I want to click on a handheld device with two hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly zoom in/out on a handheld device with two hands.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

5. How often do you type on mobile handheld device with one hand?

□ Frequently □ Occasionally □ Rarely □ Never

6. Please describe your experience of using a mobile handheld device with one hand.

(Please circle only ONE answer for each statement)

- Typing using a handheld device with one hand is easy.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly type on a handheld device with one hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- Typing using a handheld device with one hand is comfortable.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly click on places I want to click on a handheld device with one hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

- I can quickly zoom in/out on a handheld device with one hand.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

7. Comparing two-hand and one-hand typing with mobile phones, which one do you prefer? Why?

8. What difficulties have you come across while typing on mobile phones with one hand?

Thumb Length:

Hand Length:

Hand Width:

Appendix 4: User Experience Survey of ExtendedThumb and ContxtZoom Evaluation

1. Please read each of the following statements and indicate how strongly you agree or disagree with the statement by circling an appropriate number on the scale, with 1 indicating strongly agree and 7 indicating strongly disagree. Please write comments to elaborate on your answers.

Overall, I am satisfied with how easy it is to use this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

It was simple to use this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I could effectively complete the tasks using this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I was able to complete the tasks quickly using this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I was able to efficiently complete the tasks using this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I felt comfortable using this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

It was easy to learn to use this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I believe I could become productive quickly using this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

Overall, I am satisfied with this method.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

2. Have you come across any problems during the experiment? If so, what were they?

3. Can you identify the disadvantages of the proposed method?

4. Can you identify the advantages of the proposed method?

5. Do you have any suggestions on what other functions or tools that may help you improve single-handed interaction with Web browsing?

6. Is there anything else you would like to add or comment?

Appendix 5: User Experience Survey of ThumbStroke Evaluation

1. This survey is used to evaluate what you have experienced during the experiment.

Please read each of the following statements and indicate how strongly you agree or disagree with the statement by circling an appropriate number on the scale, with 1 indicating strongly disagree and 7 indicating strongly agree. Please write comments to elaborate on your answers.

(a picture of the keyboard will be presented)

Overall, I am satisfied with how easy it is to use this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

It was simple to use this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I could effectively complete the tasks using this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I was able to complete the tasks quickly using this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I was able to efficiently complete the tasks using this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I felt comfortable using this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

It was easy to learn to use this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

I believe I could become productive quickly using this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

Overall, I am satisfied with this keyboard.

STRONGLY DISAGREE 1 2 3 4 5 6 7 STRONGLY AGREE

COMMENTS:

1. How do you like the Qwerty keyboard?

Strongly Dislike	Dislike	Neutral	Like	Strongly Like
1	2	3	4	5

2. How do you like the Escape keyboard?

Strongly Dislike	Dislike	Neutral	Like	Strongly Like
1	2	3	4	5

3. How do you like the ThumbStroke keyboard?

Strongly Dislike	Dislike	Neutral	Like	Strongly Like
1	2	3	4	5

5. Please rank the four keyboards according to your preference:

a. Qwerty   b. Escape   c. ThumbStroke

Most Favorite:

Second Favorite:

Third Favorite:

6. Have you come across any problems during the experiment? If so, what were they?

7. Can you identify the disadvantages of the proposed ThumbStroke keyboard?

8. Can you identify the advantages of the proposed ThumbSroke keyboard?

9. Do you have any suggestions on what functions or tools that may help you improve single-handed interaction?

10. Is there anything else you would like to add or comment?

Appendix 6: Lewis' Keyboard Layout Rating Form (1995)

Please rate the method you just used. Circle the number that best represents your judgment.

Easy to Find Letters	1--------2--------3--------4--------5--------6--------7	Hard to Find Letters
Easy to Type Fast	1--------2--------3--------4--------5--------6--------7	Hard to Type Fast
Easy to Type Accurately	1--------2--------3--------4--------5--------6--------7	Hard to Type Accurately
Easy to Learn Letter Locations	1--------2--------3--------4--------5--------6--------7	Hard to Learn Letter Locations
Easy to Type	1--------2--------3--------4--------5--------6--------7	Hard to Type
Key Layout Acceptable	1--------2--------3--------4--------5--------6--------7	Key Layout Unacceptable

Appendix 7: Lewis' Keyboard Layout Attribute Importance Form (1995)

Please rate the importance of the following key layout usability features.

Circle the number that best represents your judgment.

1. Ease of finding letters

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

2. Ease of typing fast

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

3. Ease of typing accurately

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

4. Ease of learning letter locations

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

5. Ease of typing

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

6. Acceptability of key layout

Unimportant 1--------2--------3--------4--------5--------6--------7 Important

Appendix 8: Phrase set used in ThumbStroke Evaluation

my watch fell in the water

prevailing wind from the east

never too rich and never too thin

breathing is difficult

I can see the rings on Saturn

physics and chemistry are hard

my bank account is overdrawn

elections bring out the best

we are having spaghetti

time to go shopping

a problem with the engine

elephants are afraid of mice

my favorite place to visit

three two one zero blast off

my favorite subject is psychology

circumstances are unacceptable

watch out for low flying objects

if at first you do not succeed

please provide your date of birth

we run the risk of failure

prayer in schools offends some

he is just like everyone else

great disturbance in the force

love means many things

you must be getting old

the world is a stage

can I skate with sister today

neither a borrower nor a lender be

one heck of a question

question that must be answered

beware the ides of March

double double toil and trouble

the power of denial

I agree with you

do not say anything

play it again Sam

the force is with you

you are not a jedi yet

an offer you cannot refuse

are you talking to me

yes you are very smart

all work and no play

hair gel is very greasy

Valium in the economy size

the facts get in the way

the dreamers of dreams

did you have a good time

space is a high priority

you are a wonderful example

do not squander your time

do not drink too much

take a coffee break

popularity is desired by all

the music is better than it sounds

starlight and dewdrop

the living is easy

fish are jumping

the cotton is high

drove my chevy to the levee

but the levee was dry

I took the rover from the shop

movie about a nutty professor

come and see our new car

coming up with killer sound bites

I am going to a music lesson

the opposing team is over there

soon we will return from the city

I am wearing a tie and a jacket

the quick brown fox jumped

all together in one big pile

wear a crown with many jewels

there will be some fog tonight

I am allergic to bees and peanuts

he is still on our team

the dow jones index has risen

my preferred treat is chocolate

the king sends you to the tower

we are subjects and must obey

mom made her a turtleneck

goldilocks and the three bears

we went grocery shopping

the assignment is due today

what you see is what you get

for your information only

a quarter of a century

the store will close at ten

head shoulders knees and toes

vanilla flavored ice cream

frequently asked questions

round robin scheduling

information super highway

my favorite web browser

the laser printer is jammed

all good boys deserve fudge

the second largest country

call for more details

just in time for the party

have a good weekend

video camera with a zoom lens

what a monkey sees a monkey will do

that is very unfortunate

the back yard of our house

this is a very good idea

reading week is just about here

our fax number has changed

thank you for your help

no exchange without a bill

the early bird gets the worm

buckle up for safety

this is too much to handle

protect your environment

world population is growing

the library is closed today

Mary had a little lamb

teaching services will help

we accept personal checks

this is a non profit organization

user friendly interface

healthy food is good for you

hands on experience with a job

this watch is too expensive

the postal service is very slow

communicate through email

the capital of our nation

travel at the speed of light

I do not fully agree with you

gas bills are sent monthly

earth quakes are predictable

life is but a dream

take it to the recycling depot

sent this by registered mail

fall is my favorite season

a fox is a very smart animal

the kids are very excited

parking lot is full of trucks

my bike has a flat tire

do not walk too quickly

a duck quacks to ask for food

limited warranty of two years

the four seasons will come

the sun rises in the east

it is very windy today

do not worry about this

dashing through the snow

want to join us for lunch

stay away from strangers

accompanied by an adult

see you later alligator

make my day you sucker

I can play much better now

she wears too much makeup

my bare face in the wind

batman wears a cape

I hate baking pies

lydia wants to go home

win first prize in the contest

freud wrote of the ego

I do not care if you do that

always cover all the bases

nobody cares anymore

can we play cards tonight

get rid of that immediately

I watched blazing saddles

the sum of the parts

they love to yap about nothing

peek out the window

be home before midnight

he played a pimp in that movie

I skimmed through your proposal

he was wearing a sweatshirt

no more war no more bloodshed

toss the ball around

I will meet you at noon

I want to hold your hand

the children are playing

superman never wore a mask

I listen to the tape everyday

he is shouting loudly

correct your diction immediately

seasoned golfers love the game

he cooled off after she left

my dog sheds his hair

join us on the patio

these cookies are so amazing

I can still feel your presence

the dog will bite you

a most ridiculous thing

where did you get that tie

what a lovely red jacket

do you like to shop on Sunday

I spilled coffee on the carpet

the largest of the five oceans

shall we play a round of cards

olympic athletes use drugs

my mother makes good cookies

do a good deed to someone

quick there is someone knocking

flashing red light means stop

sprawling subdivisions are bad

where did I leave my glasses

on the way to the cottage

a lot of chlorine in the water

do not drink the water

my car always breaks in the winter

santa claus got stuck

public transit is much faster

zero in on the facts

make up a few more phrases

my fingers are very cold

rain rain go away

bad for the environment

universities are too expensive

the price of gas is high

the winner of the race

we drive on parkways

we park in driveways

go out for some pizza and beer

effort is what it will take

where can my little dog be

if you were not so stupid

not quite so smart as you think

do you like to go camping

this person is a disaster

the imagination of the nation

universally understood to be wrong

listen to five hours of opera

an occasional taste of chocolate

victims deserve more redress

the protesters blocked all traffic

the acceptance speech was boring

work hard to reach the summit

a little encouragement is needed

stiff penalty for staying out late

the pen is mightier than the sword

exceed the maximum speed limit

in sharp contrast to your words

this leather jacket is too warm

consequences of a wrong turn

this mission statement is baloney

you will loose your voice

every apple from every tree

are you sure you want this

the fourth edition was better

this system of taxation

beautiful paintings in the gallery

a yard is almost as a meter

we missed your birthday

coalition governments never work

destruction of the rain forest

I like to play tennis

acutely aware of her good looks

you want to eat your cake

machinery is too complicated

a glance in the right direction

I just cannot figure this out

please follow the guidelines

an airport is a very busy place

mystery of the lost lagoon

is there any indication of this

the chamber makes important decisions

this phenomenon will never occur

obligations must be met first

valid until the end of the year

file all complaints in writing

tickets are very expensive

a picture is worth many words

this camera takes nice photographs

it looks like a shack

the dog buried the bone

the daring young man

this equation is too complicated

express delivery is very fast

I will put on my glasses

a touchdown in the last minute

the treasury department is broke

a good response to the question

well connected with people

the bathroom is good for reading

the generation gap gets wider

chemical spill took forever

prepare for the exam in advance

interesting observation was made

bank transaction was not registered

your etiquette needs some work

we better investigate this

stability of the nation

house with new electrical panel

our silver anniversary is coming

the presidential suite is very busy

the punishment should fit the crime

sharp cheese keeps the mind sharp

the registration period is over

you have my sympathy

the objective of the exercise

historic meeting without a result

very reluctant to enter

good at addition and subtraction

six daughters and seven sons

a thoroughly disgusting thing to say

sign the withdrawal slip

relations are very strained

the minimum amount of time

a very traditional way to dress

the aspirations of a nation

medieval times were very hard

a security force of eight thousand

there are winners and losers

the voters turfed him out

pay off a mortgage for a house

the collapse of the Roman empire

did you see that spectacular explosion

keep receipts for all your expenses

the assault took six months

get your priorities in order

traveling requires a lot of fuel

longer than a football field

a good joke deserves a good laugh

the union will go on strike

never mix religion and politics

interactions between men and women

where did you get such a silly idea

it should be sunny tomorrow

a psychiatrist will help you

you should visit a doctor

you must make an appointment

the fax machine is broken

players must know all the rules

a dog is the best friend of a man

would you like to come to my house

February has an extra day

do not feel too bad about it

this library has many books

construction makes traveling difficult

he called seven times

that is a very odd question

a feeling of complete exasperation

we must redouble our efforts

no kissing in the library

that agreement is rife with problems

vote according to your conscience

my favourite sport is racketball

sad to hear that news

the gun discharged by accident

one of the poorest nations

the algorithm is too complicated

your presentation was inspiring

that land is owned by the government

burglars never leave their business card

the fire blazed all weekend

if diplomacy does not work

please keep this confidential

the rationale behind the decision

the cat has a pleasant temperament

our housekeeper does a thorough job

her majesty visited our country

handicapped persons need consideration

these barracks are big enough

sing the gospel and the blues

he underwent triple bypass surgery

the ropes of a new organization

peering through a small hole

rapidly running short on words

it is difficult to concentrate

give me one spoonful of coffee

two or three cups of coffee

just like it says on the can good

companies announce a merger

electric cars need big fuel cells

the plug does not fit the socket

drugs should be avoided

the most beautiful sunset

we dine out on the weekends

get aboard the ship is leaving

the water was monitored daily

he watched in astonishment

a big scratch on the tabletop

salesmen must make their monthly quota

saving that child was an heroic effort

granite is the hardest of all rocks

bring the offenders to justice

every Saturday he folds the laundry

careless driving results in a fine

microscopes make small things look big

a coupon for a free sample

fine but only in moderation

a subject one can really enjoy

important for political parties

that sticker needs to be validated

the fire raged for an entire month

one never takes too many precautions

we have enough witnesses

labour unions know how to organize

people blow their horn a lot

a correction had to be published

I like baroque and classical music

the proprietor was unavailable

be discreet about your meeting

meet tomorrow in the lavatory

suburbs are sprawling up everywhere

shivering is one way to keep warm

dolphins leap high out of the water

try to enjoy your maternity leave

the ventilation system is broken

dinosaurs have been extinct for ages

an inefficient way to heat a house

the bus was very crowded

an injustice is committed every day

the coronation was very exciting

look in the syllabus for the course

rectangular objects have four sides

prescription drugs require a note

the insulation is not working

nothing finer than discovering a treasure

our life expectancy has increased

the cream rises to the top

the high waves will swamp us

the treasurer must balance her books

completely sold out of that

the location of the crime

the chancellor was very boring

the accident scene is a shrine for fans

a tumor is OK provided it is benign

please take a bath this month

rent is paid at the beginning of the month

for murder you get a long prison sentence

a much higher risk of getting cancer

quit while you are ahead

knee bone is connected to the thigh bone

safe to walk the streets in the evening

luckily my wallet was found

one hour is allotted for questions

so you think you deserve a raise

they watched the entire movie

good jobs for those with education

jumping right out of the water

the trains are always late

sit at the front of the bus

do you prefer a window seat

the food at this restaurant

Canada has ten provinces

the elevator door appears to be stuck

raindrops keep falling on my head

spill coffee on the carpet

an excellent way to communicate

with each step forward

faster than a speeding bullet

wishful thinking is fine

nothing wrong with his style

arguing with the boss is futile

taking the train is usually faster

what goes up must come down

be persistent to win a strike

presidents drive expensive cars

the stock exchange dipped

why do you ask silly questions

that is a very nasty cut

what to do when the oil runs dry

learn to walk before you run

insurance is important for bad drivers

traveling to conferences is fun

do you get nervous when you speak

pumping helps if the roads are slippery

parking tickets can be challenged

apartments are too expensive

find a nearby parking spot

gun powder must be handled with care

just what the doctor ordered

a rattle snake is very poisonous

weeping willows are found near water

I cannot believe I ate the whole thing

the biggest hamburger I have ever seen

gamblers eventually loose their shirts

exercise is good for the mind

irregular verbs are the hardest to learn

they might find your comment offensive

tell a lie and your nose will grow

an enlarged nose suggests you are a liar

lie detector tests never work

do not lie in court or else

most judges are very honest

only an idiot would lie in court

important news always seems to be late

please try to be home before midnight

if you come home late the doors are locked

dormitory doors are locked at midnight

staying up all night is a bad idea

you are a capitalist pig

motivational seminars make me sick

questioning the wisdom of the courts

rejection letters are discouraging

the first time he tried to swim

that referendum asked a silly question

a steep learning curve in riding a unicycle

a good stimulus deserves a good response

everybody looses in custody battles

put garbage in an abandoned mine

employee recruitment takes a lot of effort

experience is hard to come by

everyone wants to win the lottery

the picket line gives me the chills

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