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Master's thesis

Crossing-in-Air: A New Crossing-based Technique for Intangible User Interfaces

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Abstract

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The intangible user interface is a user interface in which a person interacts with digital information but not through any physical environment. Although the notion of intangible user interface has been around for decades, it didn ' t widespread because of the limited interaction paradigm and its ' awkward feeling of " touching " a mid-air display. In this work, we extend the design space of intangible interaction by proposing the concept of "Crossing-in-Air": after a standard direct touch input, since user's hand is potentially behind the virtual object, we take advantage of the fact that user's hand has to go back to propose an additional input. We designed the first experiment to validate the "Crossing-in-Air" interaction still follows Fitts' Law, and it can outperform the direct touch. We discuss and propose several design prototypes with "Crossing-in-Air" concept, and had a measurable experiment with the Crossing-keyboard, one of the prototypes. After two quantitative experiments and post-experiment subjective questionnaire, we can conclude that in one dimension situation, Crossing-in-Air interaction outperforms the normal direct-touch interaction, Crossing-keyboard is the second fastest text entry method among all the text entry methods so far, and participants also report a positive impression.

key words Virtual Reality, Mid-Air, Intangible Display, Text Entry

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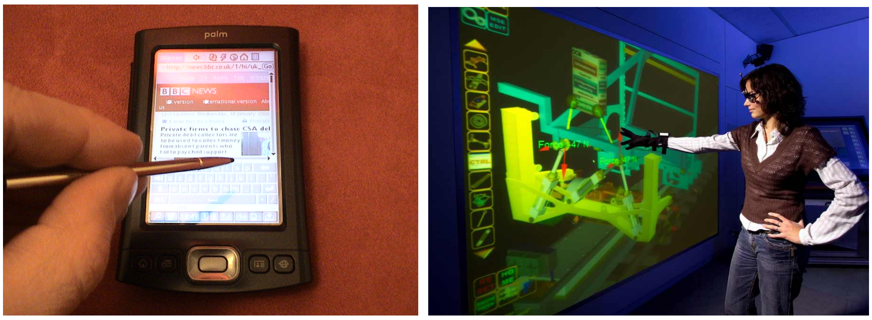
Chapter 1

Introduction

In the long computer era, we are used to working with the physical user interface: like a keyboard or stylus. But recent years intangible user interface become more known because of Virtual Reality (VR) and Augment Reality (AR)'s technology mature (Figure 1.1). The concept of intangible interaction has been around for decades, we witnessed most of it in science fiction movies like Star Trek and Iron Man. Intangible interaction offers users more convenience, for example, since intangible display doesn't have any hygiene issues, it's an ideal solution for kitchens and factories, where are easily become greasy and dirty. But still, intangible interaction didn ’ t widespread, mostly because of the limited interaction paradigm and its ’ awkward feeling of ”touching” a mid-air display. Finding an interaction paradigm that improves the performance or circumvents the drawbacks of pointing thus remains a worthy challenge. The ultimate goal of our research is to make intangible interaction more satisfying and more efficient.



(a) Traditional Physical Interface (b) Intangible Interface

Fig. 1.1 Evolution from traditional physical interface to intangible interface

The traditional physical user interface is common in our daily life. That makes modern human-computer interfaces are based almost exclusively on one type of motor actions - touching (pointing). Because of intangible's "untouchable" feature, designing interface for intangible display induces great possibilities and challenges in the field of human-computer interaction. In this thesis, we are taking advantage of this feature, came up with "Crossing-in-Air" concept, looked into how crossing interaction can be performed in intangible user interfaces, and explore the possibility of using crossing into real applications.

1.1 Motivation

Interaction technique is the fundamental factor for usage, and design for the intangible interaction creates a great opportunity and challenges for researcher of human-computer interaction.

In addition, interaction technique are developed to support a wide range of tasks in intangible interfaces. Our work in the thesis is based on the interest of exploring the "interaction of future", which drives our momentum to investigate crossing technique in the intangible interface and provide users with the fluid user experience.

1.2 Dissertation Overview

The goal of this thesis is to explore the usage of crossing technique in intangible interface. In particular, we will compare crossing technique's performance with the direct-touch's in different scenarios. We begin by discussing other attempts at improving intangible user interaction of in a variety of ways (Chapter 2). This includes ways of trying to understand the difference between intangible and tangible interaction, as well as crossing technique working in some scenarios. We then describe our crossing interaction technique in intangible interfaces, and in order to know about the effectiveness of crossing technique, we performed Fitts' Law experiment (Chapter 3). We applied our concept into a virtual keyboard and performed a three sessions' experiment (Chapter 4). We had a general discussion in Chapter 5. The contributions of this work and future research directions are discussed in Chapter 6.

1.3 Contributions

This dissertation contributes to the field of human-computer interaction in several ways. To the best of our knowledge, we proposed the concept of "Crossing-in-Air" for intangible user interfaces. We explore the crossing technique and its application in the intangible user interface.

This work also increases our understanding of interaction using direct-touch and the problems in crossing with regard to intangible user interfaces. We compare the performance between direct-touch technique and crossing technique under different angles and different working scenario. Empirical data gathered during the experiment demonstrates that crossing technique offers a more effective and fluid interaction experience and also significantly outperforms direct-touch technique in one dimension environment under all angles. For the study of crossing technique on the virtual keyboard, the experimental results suggest an alternative option for text entry. We also shared our design ideas to other intangible user interfaces.

Chapter 2

Literature Review

There are several areas of research which are highly related to our work. We will review these areas each in turn.

2.1 Intangible User Interaction

The notion of the intangible user interface has been around for decades, take the instantiations of such interface we have witnessed on Star Trek or other Sci-fi movies. The elderly could effortlessly manipulate the interfaces without using physical input devices. Moreover, the intangible interface does not suffer from the hygiene issues of their tangible counterparts. For example, shared touch-displays, such as kiosks and ATM machines, increase the likelihood of the communication of infectious disease due to direct-contact cross-contamination. Intangible interaction is also an ideal solution in environments such as kitchens and factories, where it is easy for tangible devices to become greasy and dirty.

But intangible interface has its own drawbacks. Unlike tangible physical interface, intangible user interface suffer from a lack of tactile feedback. With the absence of tactile feedback, direct-touch interaction has been shown to perform poorly even for simple target acquisition tasks in some scenarios.

In Chan et al. 's work "Touching the void"[1], they described three states of the direct-touch interaction in intangible interfaces: first, user's hand above the surface, and

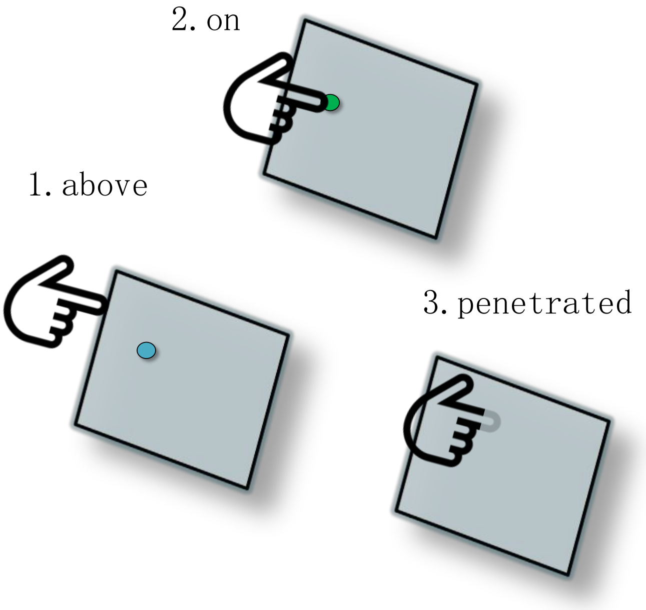


Fig. 2.1 Three states of a direct-touch interaction in intangible user interfaces: (1) above the surfaces, (2) on the surface, (2) penetrating the surface. The penetrable property is the main distinctive feature of the intangible display with respect to the tangible display.

about to touch the interface. Secondly, user's hand touching the interface. And user's hand will penetrate the interface. After their observation and interview, they point out potential issues in intangible display interaction: Directly touching an intangible interface not only cause awkward feeling but also user's hand penetrates the display surface. (Figure. 2.1)

2.2 Three Dimensional Interaction

A large part of studies on human-computer interaction mainly focus on two-dimensional space. Since the advent of 3D displays makes it possible to present a three-dimensional world with real depth, interaction with objects in 3D display became a new research direction.

Virtual-hand techniques allow users to acquire targets directly with a rare hand or

Fig. 2.2 Virtual-hand Techniques

controller (Figure 2.2), leading to a closely coupled visual and motor spaces.[2, 3, 4]

Ray-based techniques cast a virtual ray from a tracked hand, a hand-held controller or even an eye and the object intersecting the ray is selected when a trigger event is issued (e.g. [5]). Many studies have validated the effectiveness of ray-based selection. For example, Bowman et al. [6] showed ray-casting outperformed the Go-Go technique[2] which is a virtual-hand technique. Grossman and Balakrishnan[5] confirmed that ray-casting was faster than virtual hand for volumetric displays. Some studies also improved ray-based selection to address the difficulty of acquiring small objects by increasing the size of the ray cursor (e.g.[8, 9, 17]).

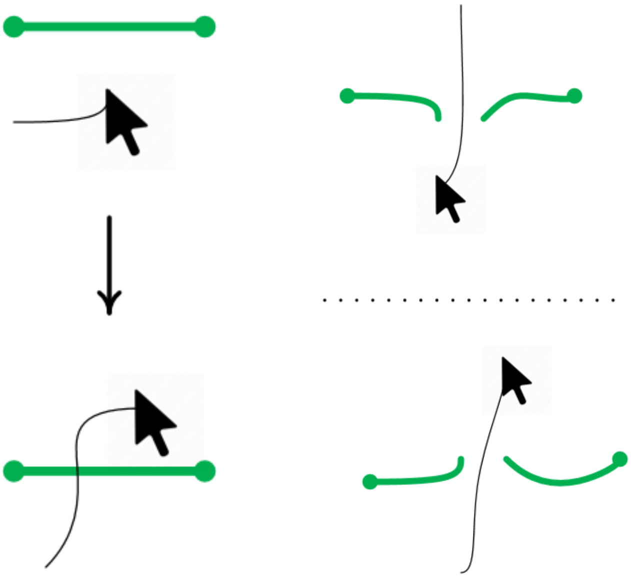
Compared to virtual hand techniques, ray-based pointing techniques allow for longer-distance object selection while requiring relatively less physical hand movements, thus have become a major selection method in current commercial VR devices (e.g. Oculus Rift and HTC Vive) and have been widely studied in intangible user interface design.

In this thesis, "Crossing in Air" mainly based on virtual hand technique.

2.3 Crossing-based Interaction

An early introduction of the crossing technique dates back to Accot and Zhai ' s study of steering tasks[11], in which the goal-crossing experiment formed a stepping stone towards devising the steering law.

In their follow-up crossing study[12], they first came up with "Crossing–a continuous action occurring more often in the natural world than discrete pointing and clicking" (Figure 2.3), and they systematically investigated four types of crossing tasks in comparison to two pointing tasks with indirect stylus input, they also did a qualitative evaluation with a graphics tablet. Generally, crossing task time was faster or equivalent to pointing. This work lay the foundation for designing crossing-based user interfaces.



(a) To trigger an action, instead of click, we cross the goal

(b) Unlike a traditional check box, a goal can "store" two visual states depending on the crossing direction

Fig. 2.3 Using Crossing in Graphical Widgets

A follow-up study by Dixon et al.[16] further examined crossing target density and orientation for parameter selection dialog boxes. It was found that crossing-based dialog boxes with direct pen input can be faster than their point-and-click counterpart while having spatially efficient.

Since Accot and Zhai ' s crossing study, researchers have applied the crossing paradigm to user interface design with stylus input, direct finger touch, as well as mouse and trackball input.

Apitz and Guimbretiere[15] designed a simple drawing application CrossY, which use crossing as the basis for the graphical user interface. In this application. They demonstrate that crossing encourages the fluid composition of commands which supports the development of more fluid interfaces. But, as a drawing application, it limited this technique only in two dimensions.

In three dimension related research, multiple targets can be crossed in a cascaded fashion, this idea mainly used in the digital table. In Subramanian's work [14],

Direct finger touch input has also been used to execute crossing tasks, although it suffers from finger-occlusion problem and relatively high contact friction on the display in comparison to pen input. Luo and Vogel[13] conducted a fundamental experiment to evaluate crossing-based selection tasks with direct touch input based on a close adaptation of indirect stylus crossing experiment design by Accot and Zhai[12]. Their study revealed similar trends for direct touch input and some differences (e.g. not all crossing tasks with finger input can be modeled accurately with standard Fitts ' law[18]).

There are many crossing-based applications and interaction techniques proposed for touch input. For example, Attribute Gates was designed to set a sequence of scale orientation and access multi attributes by crossing them on horizontal interactive surface[20], which is quite similar to [30]. HandyWidgets invoked widgets by crossing implicit goals defined by hand position on a multi-touch tabletop[21]. Pin-and-Cross was a one-handed command input technique which combines one or more static touches (“ pins ”) with another touch to cross a radial target[22].

Takashi et al.[19] devised an interaction technique called ”Double-Crossing”, which is extends crossing for interacting with large displays using hand gestures. In order to solve the stability problem of hand during interaction in mid-air, they propose to use a double-crossing action which is a crossing bar motion that occurs twice during a short time interval. This method, however, only abstract the user interface to a line, which misses a huge amount of applications.

Some studies are also focused on crossing with the mouse. Wobbrock and Gajos[23] compared pointing and crossing with mouse and trackball input for able-bodied and motor-impaired participants respectively. Data from able-bodied participants indicate that crossing was suboptimal for having lower Fitts ’ throughput[24] than pointing. Some techniques combined crossing with point and drag operations. For example, Dragicevic[25] proposed fold-and-drop, a method for seamlessly dragging and dropping objects between overlapping windows based on crossing techniques and paper-metaphor windows.

”Crossing in Air” extends the crossing idea with a bi-directional operation in intangible three dimension interaction.

2.4 Models for Pointing and Crossing Tasks

Direct-touch (pointing) and crossing in the intangible display are two task types examined in our study. Fitts ’ law is one of the most successful quantitative models in HCI[18]. It states that the amount of time required to move a pointer (e.g. mouse cursor) to a target area is a function of the distance to the target divided by the size of the target. Although multiple variants of Fitts ’ law formulas exist, a common form of the law for movement time (MT) predictions is:

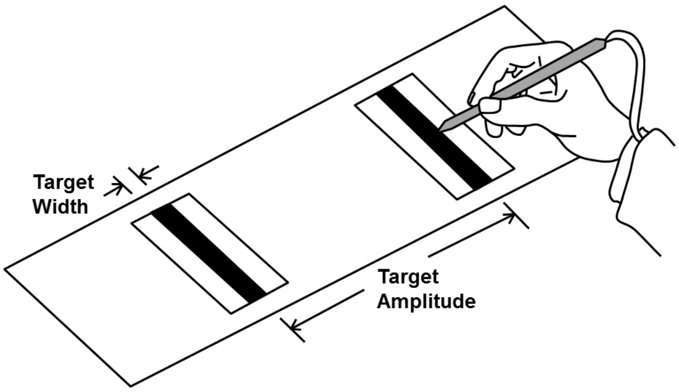


Fig. 2.4 Fitts' reciprocal tapping paradigm

$$MT = a + b\log_2(A/W + 1) \tag{2.1}$$

where A means the distance between the centers of the start target and the end target, W represents the width of the end target in the direction of travel, and a and b are constants reflecting the efficiency of the pointing system. The logarithmic term $\log_2(A/W + 1)$ denotes a pointing task's "index of difficulty" (ID), measured in bits. Initially, Fitts' law was applied to one-dimensional target acquisition tasks[18] (Figure 2.4). However, pointing tasks in most standard interfaces are typically two-dimensional (e.g. [26]) or three-dimensional (e.g. [27]) with the constraints of both target dimensions and movement (approach) angles. Many extensions of one-dimensional Fitts' law formulas thus have been proposed to account for effects caused by these constraints. It is beyond the scope of our study to review all Fitts' law studies and we refer the reader to [24] for a detailed review.

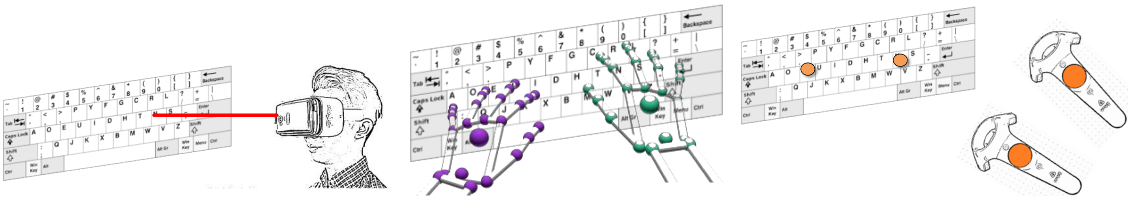
Accot and Zhai[11, 12] showed that Fitts' law holds for multiple types of indirect stylus crossing, that is, the time required to cross a goal depends on the distance to it yet correlates inversely to its width. The relationship among movement time, movement distance and the constraint of the goal width has the same form as in Fitts' law (Formula 1, where W represents goal width). Follow-up studies confirmed that Fitts' law can be applied to crossing tasks using direct stylus input with visual and tactile feedback[28], mouse and trackball input[23]. For direct touch crossing, most but not all tasks can be modeled accurately with standard Fitts ’ law[13]. Instead, “ FFitts ” law[29] shows better fits for discrete touch crossing with a directionally constrained target.

In our study, we will explore if crossing technique in the intangible interface can be modeled with Fitts ’ Law.

2.5 Text Entry in Intangible Interfaces

Text entry is an essential part of human-computer interaction. Text entry is also important when it comes to intangible systems (e.g. diaries, shops or social networks). So far, VR as the most widespread intangible device, most of the related research also performed with VR equipment.

In Speicher's recent work [32], they evaluate several popular VR's text entry methods' performance including the direct-touch. Following we introduce three of the methods in order to compare our method with these methods in chapter 4.



(a) Head Pointing (b) Freehand (c) Cursor Control

Fig. 2.5 Other Text Entry Methods in Previous Work

Head Pointing: The basic idea is to use a ray casting from the point of view (or object of interest) on the virtual keyboard (Figure 2.5a).

Freehand: Track the user's finger directly, to type on a virtual keyboard (Figure 2.5b). This technique does not require any tracked hand-held controllers, but rather the need to track the fingers (e.g. using gloves or Leap Motion)

Cursor Control: Discrete cursor control text input is performed by controlling a discrete cursor on a virtual QWERTY keyboard for character selection, and confirming the input by triggering the button. In continuous cursor control, pressing the touchpad on the controller triggers the text input (Figure 2.6c).

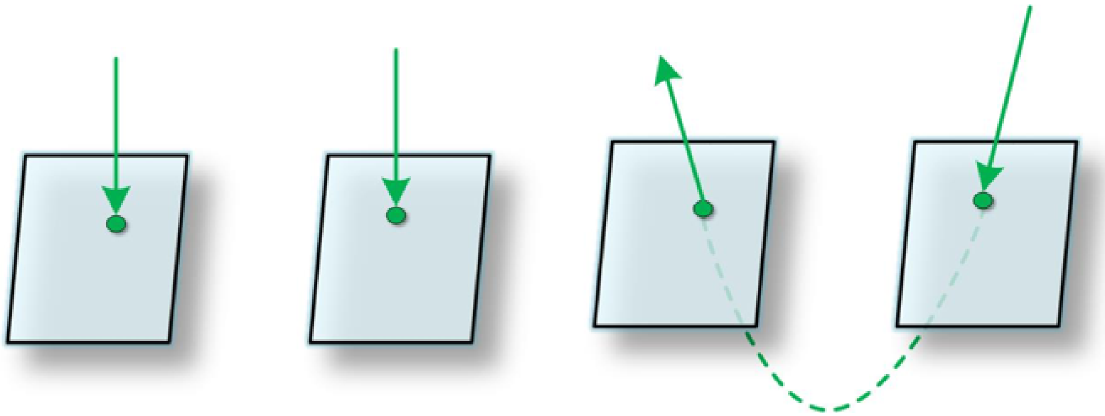
In this study, we will compare our text entry method (crossing keyboard) with the above previous text entry's performance.

Chapter 3

Crossing in Air: Concept and Performance

3.1 Technique Concept and Research Questions

Intangible devices (like VR and AR) today's input primarily through controller and gloves. Under such background, direct-touch interaction is still as a common interaction technique. Despite advantages from easy-understanding and accuracy, there are still flaws an intangible user interfaces technique: user's hand or controller can easily cross through the object they are interacting with and introduces a round-trip movement cost during the interaction.



(a) Direct-touch

(b) Crossing

Fig. 3.1 Two Different Techniques

Direct-touch: The direct-touch technique (as shown in Figure. 3.1a) is implemented within the pen and tablet metaphor and provides an isomorphic, direct and realistic interaction. Text entry using a digital pen is less common but advancing fast with the rise of the Apple Pencil and several other tablets which can be operated quickly and accurately with a stylus. In our approach, the HTC Vive controllers are used for tapping the virtual keys by holding them like digital pens. In contrast to pointing, this method requires physical manipulation, i.e. the virtual keys need to be pushed physically with the tracked hand-held controllers.

Crossing: The crossing technique (as shown in Figure. 3.2b) apply to two dimension target can be and can only be done in three dimension's intangible user interface. Due to the intangibility of the interface, the virtual panel can provide twice trigger in one single movement: after a standard direct touch input, since user's hand is potentially behind the virtual object, users can take advantage of the fact that their hand has to go back to propose an additional input.

In this experiment we aim to answer the following research questions:

- Can crossing technique be modeled by Fitts' Law?
- What is crossing technique's performance in one or two dimensions?
- How would different angle effects crossing technique's performance?

3.2 Experiment Design

3.2.1 Tasks

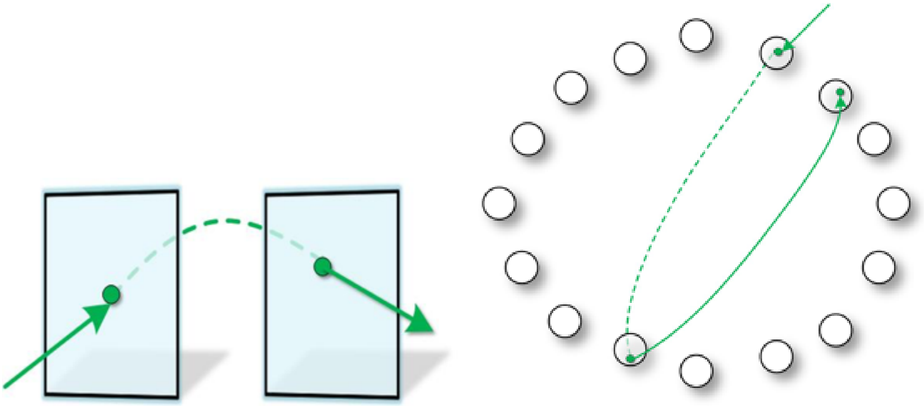
We used standard Fitts' law experiment in one and two dimensions under three angles (Figure 3.2). The experiment task was target tapping in one dimension and two dimensions with direct-touch and crossing technique.

In the one dimension experiment (see Figure 3.3a), the participants were instructed to tap ten times reciprocally to a pair of vertical strips on each session (angle) with a

(a) 90 (b) 45 (c) 0

Fig. 3.2 Three Angles

fixed distance and HTC Vive's controller. After each session, the program will change the angle automatically. In the two dimension experiment (see Figure 3.3b), participants need to tap within a circle of targets.



(a) One dimension (b) Two dimension

Fig. 3.3 The Crossing Technique in One and Two Dimensions

3.2.2 Apparatus

In this experiment, we used a virtual reality device as our intangible display. We used an HTC Vive head-mounted display connected to the computer via HDMI. The HTC Vive featured a resolution of 1080 × 1200 per eye, a 90Hz refresh rate and a 110-degree field of view. The experiment program was developed in Unity 5.4 with external libraries for the HTC Vive hardware. The experimental software was conducted on a i7 CPU, 16GB RAM 3.2GHz PC with an Nvidia Quadro K620 graphics card and Microsoft Windows 10 operating system. One single HTC Vive controller was used to perform the interaction technique.

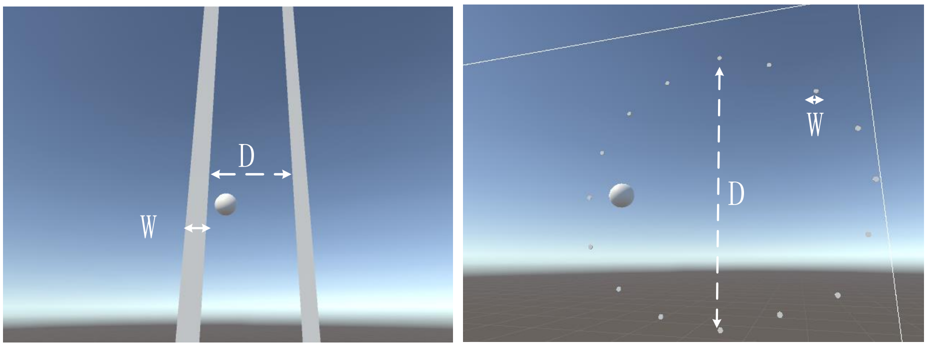
3.2.3 Participants

Fig. 3.4 Experiment One

Seven male and five female volunteers, 21-34 years old (average 25 years old), participated in the experiment (Figure 3.4). All were right-handed and naive with regard to the purpose of the experiment. All had normal vision. After signing a consent form and being briefed on the goals of the experiment, the experiment task was demonstrated to participants. Participants are standing in front of the tapping object and able to move freely during the experiment.

3.2.4 Procedure Design

The experiment design is within-subjects. The within-subject factors were the target distance, target width, target angle, and interaction technique. Prior to performing trials, participants were informed about the rough procedure of the experiment, then participants were given a short set of warm-up trials to familiarize themselves with two kinds of technique. Participants were instructed to perform the tasks as quickly and accurately as possible. The experiment lasted approximately 40 minutes for each participant. A green color change provided feedback when the participant successfully tapped the object.



(a) One dimension (b) Two dimension

Fig. 3.5 Screenshot of the experiment program

Target distance (D) was the length between two targets' centers (a target pair), and target width (W) was the width of square and the diameter of spheres (Figure 3.5). In order to make ID (Index of Difficulty) distribute evenly, we designed values of D and W as illustrated in Table 3.1.

	One D			Two D		
D(mm)	150	350	550	250	350	450
W(mm)	2.5	7.5	12.5	12.5	25	37.5

Table 3.1 Distance between Objects and Object's Width

Every participant need to perform 1 full practice block and 2 measurement blocks of trials, after every single block, participant need to rest about 5 mins. We intended the first block to function as a practice block since it is a full block, so we can use it for leaning effect.

Task order was counterbalanced using a Latin Square and the order for the set of D-W trial was randomized. 9 sets of D-W trials. Each set of trials covered.

The participants need to perform this experiment with two technique separately. Angle and technique's order have been counterbalanced with latin square.

In summary, the experiment consisted of:

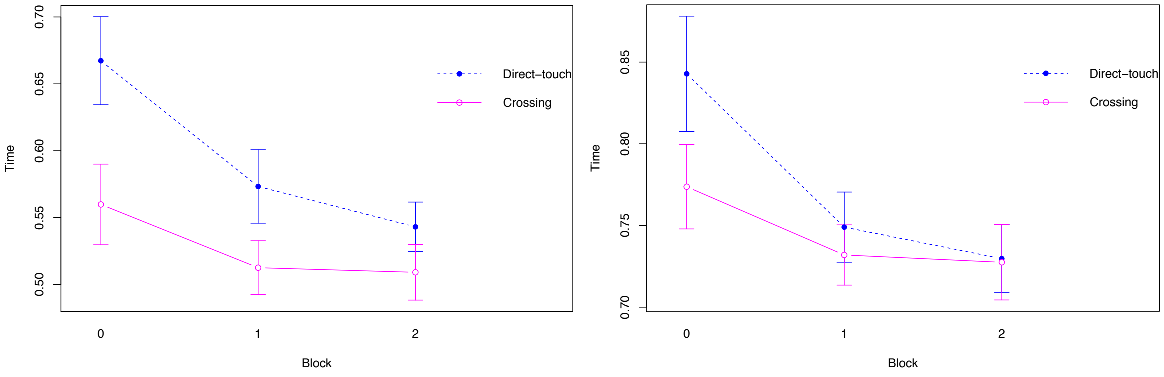
12 Participants*
2 Techniques*
2 Dimensions*
3 Blocks*
3 Angles*
3 Width*
3 Distance*(Each participants have 3 A-W combination)*
10 Repetitions (16 repetitions for 2D)
=16848 trials

3.3 Experiment Result

In this part, we discuss the above research questions according to data analysis results and conclude our study. The results of the experiment were analyzed by R using Friedman test.

3.3.1 Learning Effect

We first checked the learning effect on input time over the three blocks of trials (Figure 3.6). The y-axis is the average time (second) for one single input. In one and two dimension's experiment, there were both a significant main effect for block on selection time: one dimension $x^2 = 11.17$, $p = 0.00376$, and in two dimension



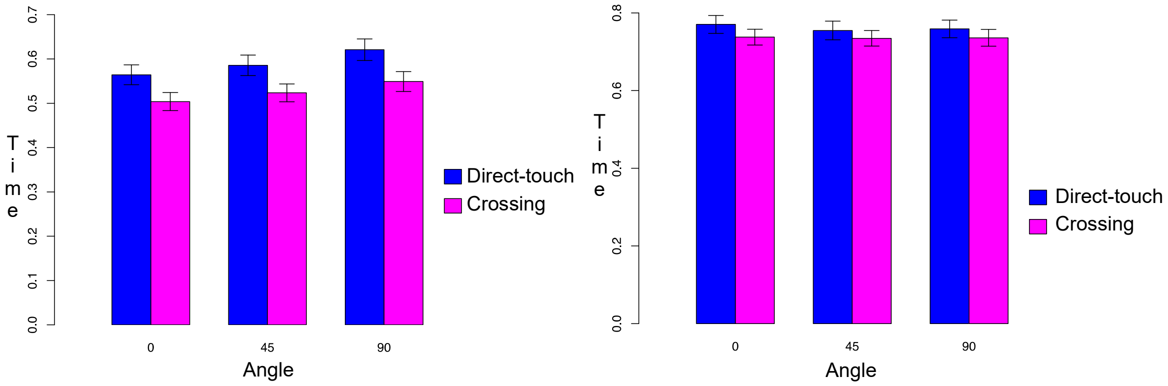
(a) One dimension (b) Two dimension

Fig. 3.6 Learning Curve

$x^2 = 6.5$, $p = 0.03877$. Which means learning is an important factor for both of these two techniques in one and two dimension.

3.3.2 Selection Time

Selection time is the mean duration of each measured selection.



(a) One dimension (b) Two dimension

Fig. 3.7 Selection Time with Two Techniques under Three Angles

Two interaction techniques selection time's comparison shows in Figure 3.7. From the statistical data, angle is a main effect in one dimension ($p = 0.04581$). But a later Wilcoxon signed rank test between each of two angles shows that the P-value between

0 and 45 is 0.7837, and the P-value between 45 and 90 just on the borderland ($p = 0.05019$). No significant interaction effect was found between angle and participant's performance in two dimensions ($p = 0.3679$). We can say that generally, the angle doesn ' t affect operation time much in one and two dimensions.

In one dimension's situation, crossing technique is faster than direct-touch no matter what angle significantly ($p = 0.02686$, effect size=0.45). But in two dimensions, task becomes more time consuming, even though in Figure crossing seems faster than the direct-touch, the crossing is not significantly faster than direct-touch ($p = 0.2334$), but still, is not slower than direct-touch.

3.3.3 Fitts' Law

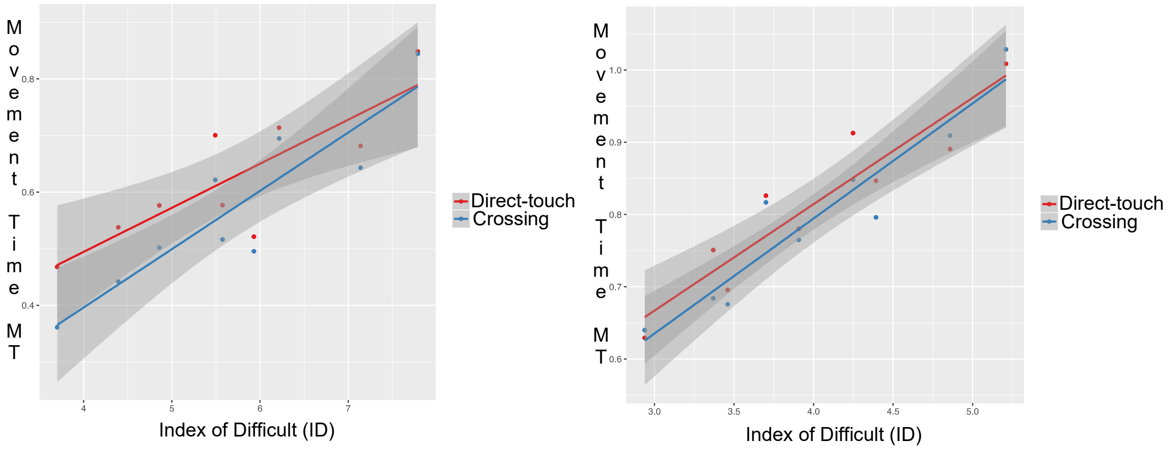
The relationship between movement time (MT) and the index of difficulty (ID) described in Eq.(3.1) is a model we used form to model Fitts' law.

$$MT = a + bID_e \tag{3.1}$$

$$ID = \log_2(A/W + 1) \tag{3.2}$$

We use experimental data did a linear regression with ID_e and MT, as illustrated in Figure 3.8.

Participants ' temporal performance in each of the interaction techniques was dependent on the index of difficulty formulated in the same way as in Fitts ' law (although the parameters differed by tasks) and data were modeled well with high fitness values (see below). From top to bottom: One dimension's direct-touch, one dimension's crossing, two dimension's direct-touch, two dimension's crossing. Note in one dimension's direct-touch experiment had a relatively lower R^2 than the other task in this experiment.



(a) One dimension

(b) Two dimension

Fig. 3.8 Linear Regression in One and Two Dimensions

$$MT = 0.0779 * ID + 0.1829,\ R^2 = 0.7002,\ p = 0.0049$$

$$MT = 0.1031 * ID - 0.0163,\ R^2 = 0.8176,\ p = 0.0008$$

$$MT = 0.1473 * ID + 0.2251,\ R^2 = 0.8701,\ p = 0.0002$$

$$MT = 0.1593 * ID + 0.1574,\ R^2 = 0.8971,\ p = 0.0001$$

According to the analysis of Fitts' Law Modeling, there was a lawful regularity between movement time and ID in each of dimensions. Crossing interaction follows a similar regression line to direct-touch interaction, suggesting a possibility of substituting the pointing task with the crossing task. And crossing interaction are faster than direct-touch for most IDs. The regression line of crossing intersects that of direct-touch at a high ID, indicating crossing can be an alternative to direct-touch for selecting big and near targets.

3.3.4 Post-experiment Questionnarie

A post-experiment questionnaire collected subjective participant opinion of crossing technique and direct-touch technique. Figure 3.9 shows the subjective feedback of participants.

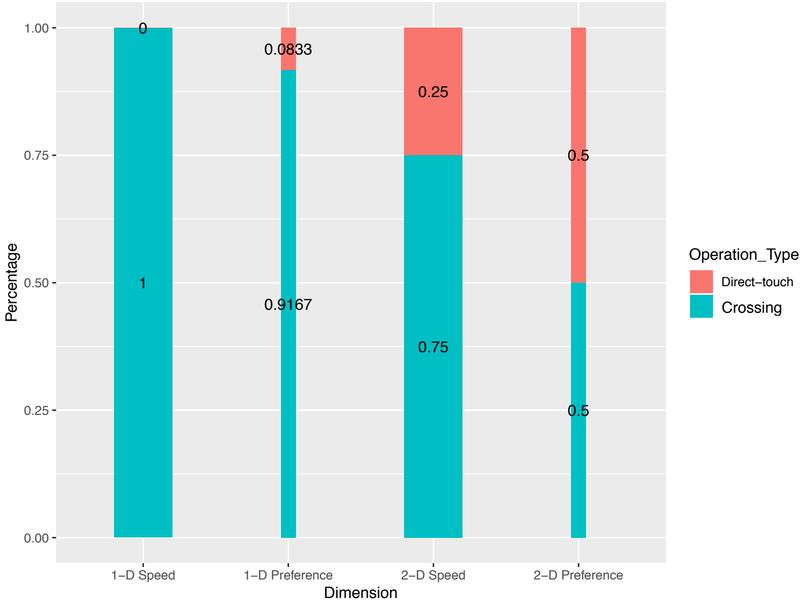


Fig. 3.9 Subjective Questionnarie Result

We observe a significant effect of technique on perceived Speed: all of the participants think crossing technique is faster than the direct-touch. 11 out of 12 participants said that they prefer crossing rather than the direct-touch in one dimension. In two dimension, even though 9 out of 12 participants think crossing is faster than the direct-touch, only 6 people prefer crossing rather than direct-touch. During interview, participants reports that even though crossing can be faster, but crossing technique is not easy to learn, and crossing technique is not as accurate as direct-touch technique in two dimension's environment.

3.3.5 Discussion

Results indicate that crossing technique significantly outperformed the direct-touch in one dimension's selection time. Especially, the advantages of crossing technique became more evident for tasks with low IDs. This confirms the better performance of crossing for big and near objects, proves that crossing technique can substitute direct-touch as a promising method for selection in intangible display.

Chapter 4

Crossing Keyboard: Concept and Performance

4.1 Technique Concept and Research Questions

VR (Virtual Reality) as a common intangible display system, the hardware (HMDs and controllers) are now widely available and affordable. Since the user cannot use physical keyboard with HMD (Head-Mounted Display), VR ' s text entry problem is still challenging. We believe there will be a need to support productivity applications such as email and messaging in intangible interfaces. These applications often require substantial text input.

We applied our concept to virtual keyboard (Figure 4.1). "Crossing-Keyboard" allows the user to do text input with both sides of the keyboard, and create a flow-like experience. Virtual keyboard's input task is similar to a two dimensions tapping task expect user need to think and find the character they need during the input. With the last experiment data, we assume that crossing keyboard also can be competitive.

We aim to answer the following research questions:

- How is the crossing keyboard's learnability?
- How is the crossing keyboard performance comparing with other text entry methods?
- How would people think about crossing keyboard?

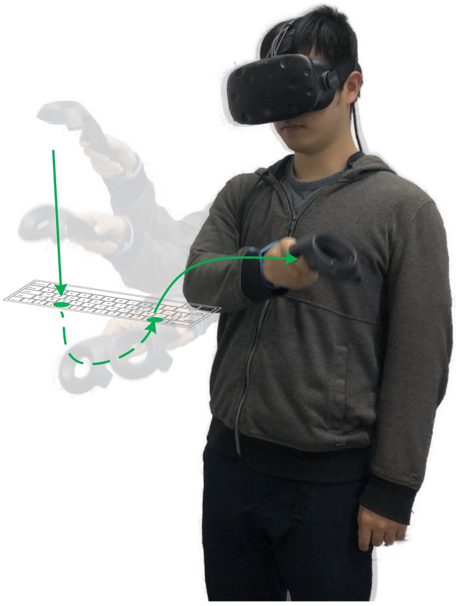


Fig. 4.1 Crossing Keyboard

In order to answer the above questions, we design and performed a three sessions' comparative experiment between our keyboard and VR's direct-touch keyboard.

4.2 Experiment Design

4.2.1 Tasks

The task was to transcribe ten phrases (trials) with direct-touching technique and crossing technique as fast and accurately as possible. Backspace is not allowed use for error correction. All phrases were randomly chosen from a set of 500 memorable phrases from the Mackenize phrase set [7], with 20-28 characters each.

4.2.2 Apparatus

The apparatus's software and hardware are same as the last experiment. The virtual environment consisted of a virtual representation of a standard QWERTY keyboard in the participants ' interaction zone at 1.3-1.7m in a comfortable distance for mid-air interaction and a text area for the output at eyesight. The position and orientation of the keyboard could be adjusted for each participant. For feedback, the participants got the controller's haptic feedback when selecting the virtual keys.

4.2.3 Participants

A total of 12 unpaid participants(6 males, 6 females) volunteered in this experiment, aged between 21 and 34 years(M=25, SD=3.789). All participants rated themselves as able to read and copy English sentences. All participants were right-handed. Three of them had visual impairment (glasses or contact lenses), but no participant was color blind. As the HTC Vive allows the user to wear glasses, no further adjustment was needed.

4.2.4 Procedure Design

The experiment was a within-subjects design, with one independent variable (Input Method). The input method conditions were counterbalanced using a Latin square.

In our experiment, participants used one single controller to perform the experiment. In the participant's perspective, participant manipulates a virtual ball to trigger keyboard's characters (Figure 4.2).

Hello, I'm VRKeys :)_

Fig. 4.2 Virtual Keyboard's Screenshot

In summary, the experiment consisted of:

12 Participants*

2 Input Techniques*

3 Blocks*

10 Phrases

=720 trials

The experiment took 40-60 minutes per participant. After the experiment, they were asked to provide subjective feedback. Using a 5-point scale, participants rated their level of preference and so on.

4.3 Experiment Result

In this part, we measured the text entry methods' performance in the form of objective data (input speed, accuracy), which indicate to what extent users are able to cope with the task and interaction method. We also collected data describing users ' preference for the techniques, including subjective feedback (user experience, workload, preference). The results of the experiment were analyzed by us using R.

4.3.1 Input Speed

WPM(Words Per Minute) is a calculation of how fast people type with no error penalties. The gross typing speed is calculated by taking all words typed and dividing by the time it took to type the words in minutes. The calculation formula is shown in Eq (4.1).

$$WPM = \frac{(All\,Typed\,Entries)/5)}{Time(Min)} \tag{4.1}$$

As shown in Figure 4.3, Even though both of two techniques getting better along

4.3 Experiment Result

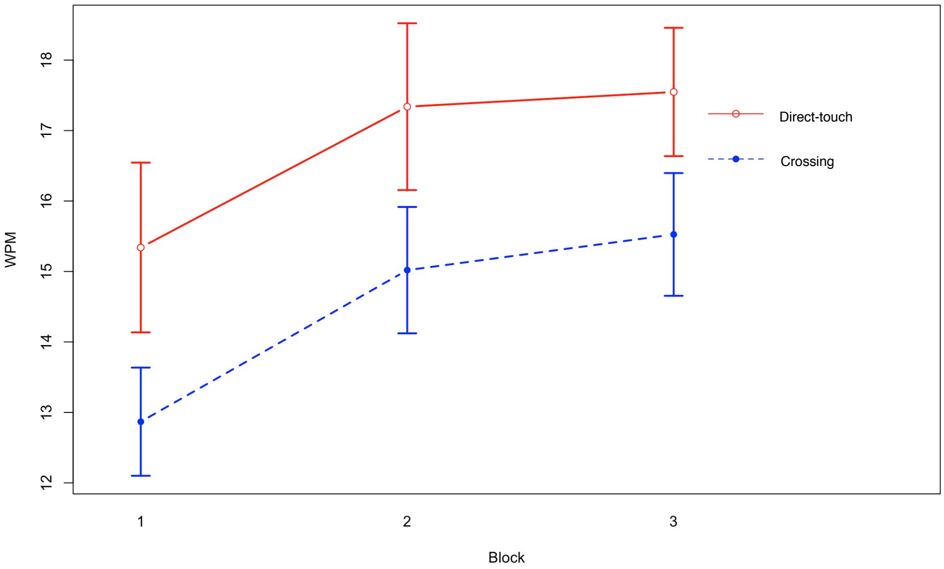


Fig. 4.3 WPM of Crossing and Direct-touch Technique

with the block, crossing technique's WPM is less than direct-touch ' s ($F = 7.615$, $p = 0.00738$). After the interview with experiment participants and analyze from the last experiment's result, we analyze this partly due to the small size of the virtual keyboard.

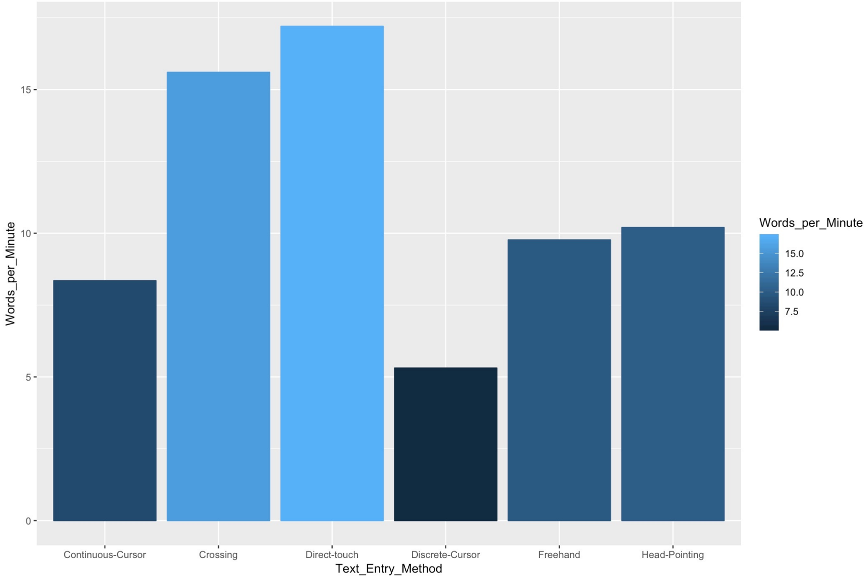


Fig. 4.4 WPM Comparison with Previous Work

We also compared our technique with other popular text entry methods in intangible user interfaces. This is possible because our experiment uses the same WPM formula and same experiment set. As illustrated in Figure 4.4, we can see that crossing keyboard is the second fast method among the different methods.

4.3.2 Error Rate

Error rate (%) is defined as the percentage of error entries out of the total entries typed. To calculate error rate mathematically, first need to calculate the minimum string distance (MSD) between the presented and transcribed text and dividing it by the larger number of characters, formally:

$$ErrorRate = \frac{100 * MSD(P, T)}{max(|P|, |T|)} \tag{4.2}$$

where P and T denote the presented and transcribed text. MSD is calculated using Levenshtein ’ s algorithm [31].

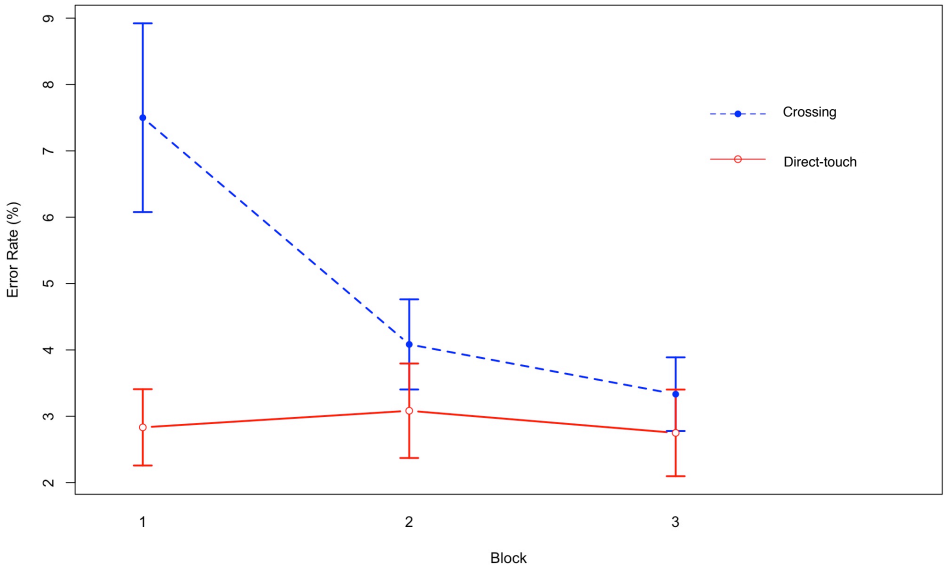


Fig. 4.5 Error Rate of Crossing and Direct-touch Technique

In Figure 4.5, crossing’s error rate is significantly high than direct-touch’s ($F = 8.3533$, $p = 0.005447$). Crossing interaction’s error rate is higher than direct-touch’s at the very beginning, but along with participants’ practice, crossing’s error rate drops quickly. And at the third block, crossing’s error rate is not more than direct-touch’s.

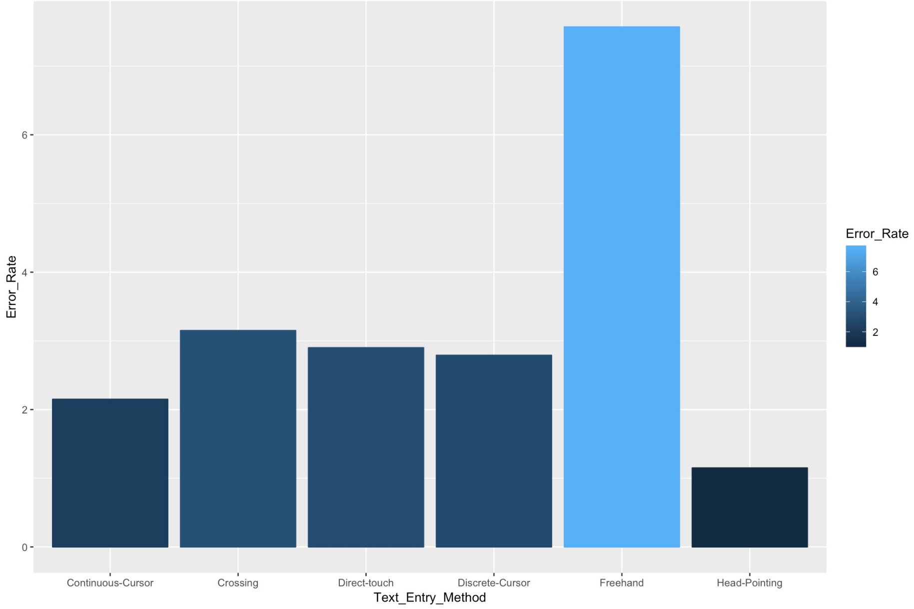


Fig. 4.6 Error Rate Comparison with Previous Work

We compared crossing technique with other popular text entry technique in intangible user interfaces. As illustrated in Figure 4.6, we can see that crossing keyboard’s error rate is very competitive compared with other methods.

4.3.3 Post-experiment Questionnarie

We collected a variety of subjective feedback to assess crossing keyboard’s user experience and workload.

As we can see from Figure 4.7, even though crossing gets more score on perceived speed, but crossing’s perceived speed is not significantly more than direct-touch ($F = 0.672$,$p = 0.422$). And from post-experiment’s interview, participants also report that crossing technique needs more practice in text entry, and keyboard characters are too

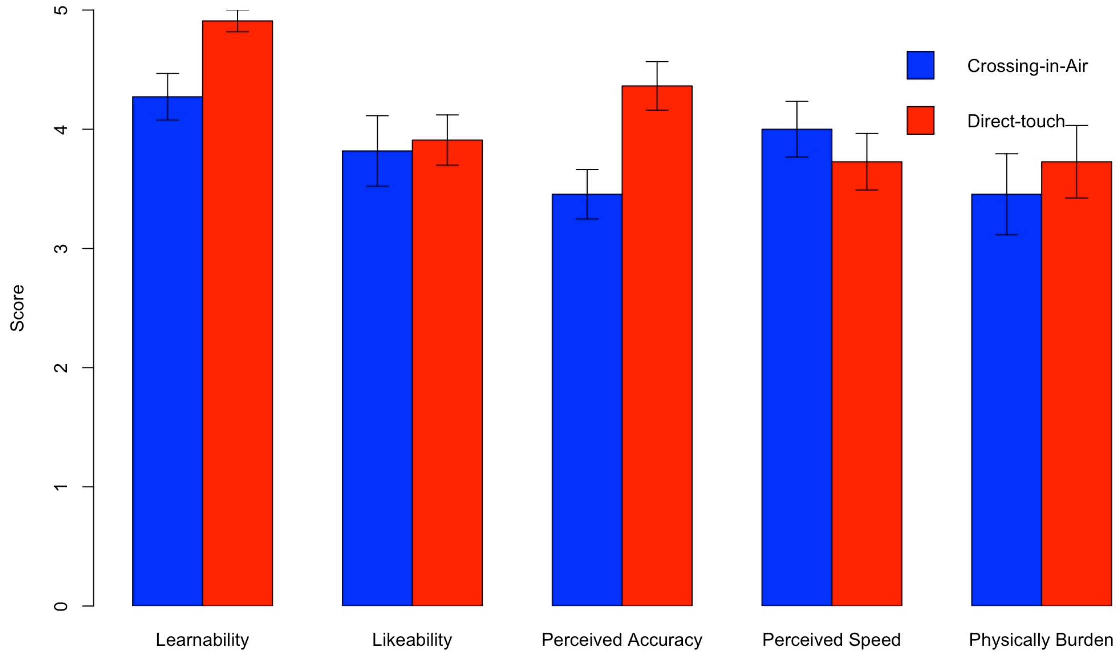


Fig. 4.7 The Subjective Evaluation of Crossing and Direct-touch Technique

small, and they made selection errors due to temporary loss of focus. Direct-touch's straight-forward method wins learnability without any doubt. But as a new text entry method, crossing get preference as much as direct-touch.

4.3.4 Discussion

In this chapter, we have studied crossing technique in intangible virtual keyboard, and also contrastive assessed direct-touch text entry method. Text entry is an essential part of human computer interaction and there is still much research needed. Instead of a full-factor text entry experiment, in our work, we mainly want to show crossing method's effectiveness, we leave out many variations. There are other detailed variations can effect participants' performance in text entry experiment: the distance between characters, the size of characters, even the transparency.

Considerable methods due to their good usability and performance ratings are direct-touch, crossing technique. Even though freehand technique performed better in

WPM than other studies found [33], which could be explained by its naturalism and realism. However, the cursor methods were rated worse, so we would only consider them if the other methods are not possible at all. So far, direct-touch technique is still rated best among all text entry methods in input speed, but crossing technique is the second best also offers an option comparing with other techniques.

In summary, we can claim that using tracked hand-held controllers result in better user performance, while pad-based cursor techniques (cursor) should be completely disregarded concerning user preference.

Chapter 5

Conclusions

5.1 Summary of Contributions

This dissertation has presented two types of contributions. First, we come up with ”Crossing-in-Air” technique, and we designed the experiment to validate the ”Crossing-in-Air” technique still follows Fitts’ Law. The experimental data showed that crossing technique provides excellent performance in one dimension’s task without regarding angle, and in two dimensions situation crossing also can be a good alternative solution for interaction. Fitts’ law model for crossing technique can be a theoretical tool for the quantitative evaluation of crossing technique in intangible user interface design. Second, we discuss and propose several design prototype applications with ”Crossing-in-Air” concept based on our concept, take crossing keyboard as an example, empirical data gathered during the keyboard experiment demonstrates that crossing keyboard outperforms all the text entry methods except direct-touch technique. And according to the post-experiment questionnaire, the crossing technique creates a fluid experience.

5.2 Possible Design for Other Applications

Game Design: One of the clear value of the crossing concept is that this concept is an exploration of new interactive technique and experience, and new interactive experience can always contribute to game design. In our case, we suggest "Crossing-in-Air" concept can be used in the game's bonus design. Crossing technique can also diversify the user interface and enjoyable to use. The game designer can add different ID ' s factors into the game, making the game with more features. Figure 5.1 depicts a game with a certain side for player to tap.

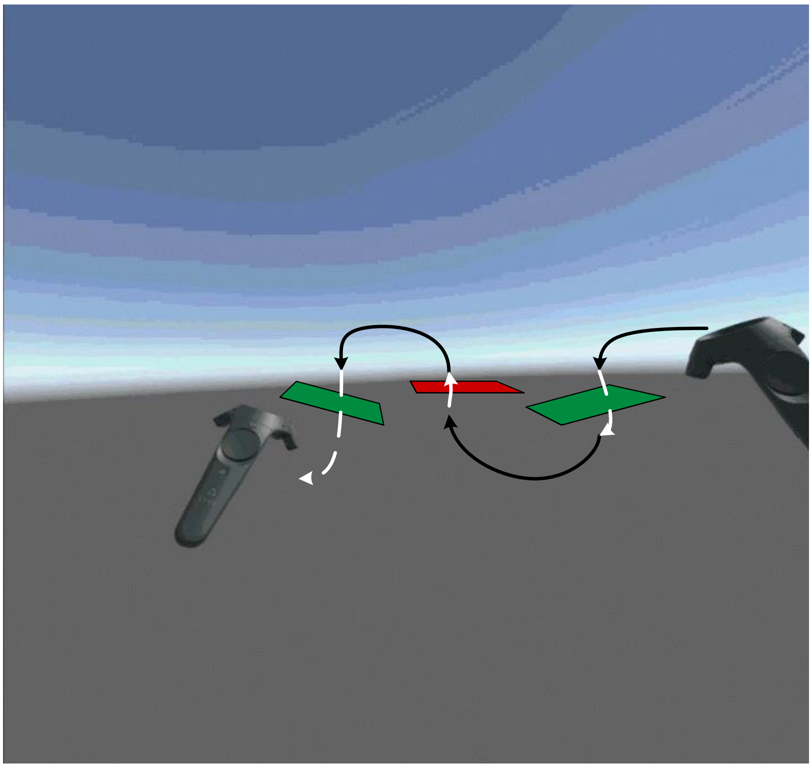


Fig. 5.1 Game Design Illustration

Interface Design: Crossing menu design enables the user with multiple functions: user can maintain multiple-layers of visual content and move between layers by moving their hand in the space between their body and the tabletop. This space is divided into multiple parallel planes with each plane corresponding to a layer. Multi-layer with crossing can be beneficial to many applications such as interactive map visualization and photo annotation. For example in the map visualization application, each layer can be used to represent bus-lines, nearby restaurants, attractions, live summer events, and traffic updates. By quickly moving the hand a user can easily explore different representations. From interaction's point of view, the user can easily cancel current interaction or perform a smooth, continuous selection. Figure 5.2 illustrates the multi-layer menu technique for a sketching application.

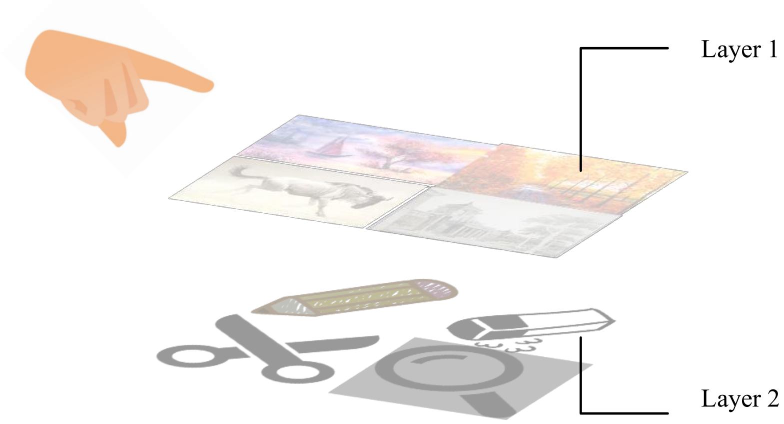


Fig. 5.2 Multi-layer Interface Design Illustration

5.3 Future Research Directions

Different performance from different crossing side: Crossing technique's two crossing sides also have a different performance like accuracy etc. This also needs to be explored.

Crossing with depth: All the work above was done just in front of participants, but three dimensions world contains depth. Since nowadays three dimensions interaction prefer to use ray casting technique, crossing can combine with ray casting technique, can create "ray crossing" technique. The depth (distance between target and user) can be an important factor in ray crossing technique ' performance.

Crossing with different directions: This thesis only studied two directions' crossing (up and down), there are more directions in three dimensions ' environment. Future research can continue exploring crossing technique ' s performance with different directions.

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Appendix A

First experiment's questionnaire

1. Which one do you prefer in one-dimension?

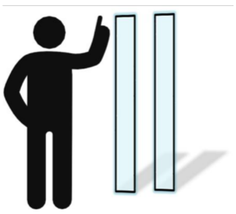
Crossing Direct-touch

2. Why do you prefer it?

3. Which one do you think is faster in one-dimension?

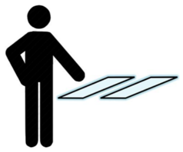
Crossing Direct-touch

4. Which angle do you think is the best for Crossing in one-dimension?



(a) 90

(b) 45



(c) 0

5. Which one do you prefer in two-dimension?

Crossing Direct-touch

6. Why do you prefer it?

7. Which one do you think is faster in two-dimension?

Crossing Direct-touch

8. Which angle do you think is the best for Crossing in two-dimension?

Appendix B

Keyboard experiment's questionnaire

1. What do you think Direct-touch's input speed?

Slow 1∼5 Fast

2. What do you think Crossing's input speed?

Slow 1∼5 Fast

3. What do you think about Direct-touch's accuracy?

Bad 1∼5 Good

4. What do you think about Crossing's accuracy?

Bad 1∼5 Good

5. What do you think about Direct-touch's physically burden?

Tired 1∼5 Easy

6. What do you think about Crossing's physically burden?

Tired 1∼5 Easy

7. Do you think Direct-touch is easy to learn?

Hard 1∼5 Easy

8. Do you think Crossing is easy to learn?

Hard 1∼5 Easy

9. Do you like Direct-touch in keyboard application?

Strongly No 1∼5 Strongly Yes

10. Do you like Crossing in keyboard application?

Strongly No 1∼5 Strongly Yes